# Water withdrawal for brackish and inland aquaculture, and options to produce more fish in ponds with present water use

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#### Abstract

This paper reviews freshwater use in inland and coastal pond aquaculture, and focuses on options to increase productivity while reducing water use. Total freshwater use depends on system-associated and feed-associated water losses. System-associated water losses depend on total area, evaporation, infiltration and water replacement. About 8,750,000 ha freshwater and 2,333,000 ha brackish water ponds are in use today. Total water withdrawal in freshwater aquaculture is estimated at 16.9 m<sup>3</sup>/kg production, representing 429 km<sup>3</sup>/yr, which is 3.6% of flowing water globally. Infiltration and replacement water recharges aquifers; if these losses are clean, their re-use decreases aquaculture-related water withdrawal by nearly 60%. A further reduction in freshwater use in aquaculture can come from intensification and aquafeed development. The goal should be to feed the pond, not the fish. A tripling of average pond production should be possible, without increasing total freshwater use. Such improvements will also benefit brackish water aquaculture, which could in turn further reduce freshwater use by increasing the productivity of saline systems.

Keywords: Aquaculture; Aquifer; Brackish; Freshwater use; Inland

# 1. Introduction

This paper reviews freshwater use in inland and coastal aquaculture. Marine cultures, such as marine finfish cage culture (salmon, seabass, cobia, etc.), mollusc cultivation and seaweed production are excluded. Today, fishes and crustaceans are mainly raised in ponds; the 16 finfish species with the highest aquaculture production, for example, are mainly raised in ponds and represent 75% of the global finfish aquaculture production (Table 1; www.fao.org). Pond systems are even more important for crustacean culture, where almost the entire global production is raised in ponds. Therefore, this paper focuses on water use in pond aquaculture.

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Table 1. Ranking of most important finfish species, mainly produced in aquaculture ponds. (Source: www.fao.org, aquaculture production data, 2004 (Fishstat Plus)).

Finfish species	Production in 2004 (MT)
Silver carp	3,979,292
Grass carp ( $=$ White amur)	3,876,868
Common carp	3,387,918
Bighead carp	2,101,688
Crucian carp	1,949,758
Nile tilapia	1,495,744
Roho labeo	761,123
Catla	615,576
Milkfish	573,732
Mrigal carp	573,657
White amur bream	516,869
Channel catfish	351,357
Black carp	296,446
Amur catfish	246,857
Snakehead	239,056
Total	20,965,941
% global finfish production	74.4

MT: Metric Tonne.

Evaporation and infiltration water losses from ponds are on average  $35,000 \text{ m}^3/\text{ha/year}$  (Verdegem *et al.*, 2006). Various techniques help to reduce infiltration (Jayanthi *et al.*, 2004), and floating macrophytes (Sánchez-Carrillo *et al.*, 2004) or synthetic reflective covers (Cooley & Myers, 1973) can diminish evaporation. Unfortunately, such techniques are difficult or costly to apply; hence farmers seldom try to control infiltration or evaporation losses. The most practical option to reduce relative water use in ponds is by increasing the production per unit surface area (Verdegem *et al.*, 2006). With a production of 2,000 kg/ha/yr, evaporation and infiltration losses are on average  $17.5 \text{ m}^3$  per kg production. With production of 10,000 kg/ha/yr, this is reduced to  $3.5 \text{ m}^3$ , and with a production of 100,000 kg/ha/yr the evaporation and infiltration losses are reduced to  $0.35 \text{ m}^3$  water per kg production.

Pond production can be achieved by exploiting natural foods, supplying formulated feed or a combination of both. In organically fertilized ponds, production greater than 10,000 kg/ha/yr is commonly reported (Delincé, 1992), which compares well to productions achieved in feed driven ponds with no or minimal water exchange (Hargreaves & Tucker, 2003). Whereas there is no water consumption associated with the use of organic wastes as pond fertilizers (excluding collection and transport), the grains used in formulated feeds constitute a considerable additional water demand. It takes 450 to 4,000 l of water to produce one kg of grain, depending on grain type, production system and location (Chapagain & Hoekstra, 2004). Assuming 60% of the ingredients in an aquaculture feed are grains and that on average 2,000 l of water are consumed producing one kg of grain, then 2.4 m<sup>3</sup> of feed-associated water will be needed when the feed conversion ratio is 2.0. Consequently, the water use in feed-driven ponds is higher than in fertilizer-driven ponds.

The goals of this paper are: (1) to review the major types of freshwater use in aquaculture; (2) to estimate the global freshwater use in aquaculture; (3) to point out some socio-economic aspects of water use in aquaculture; and (4) to explore options to reduce it.

# 2. Freshwater losses in pond aquaculture

#### 2.1. Water withdrawal vs water consumption

It is important to distinguish between water consumption and water withdrawal (Shiklomanov, 1998). Water withdrawal refers to water diverted from streams or rivers, or pumped from aquifers for human use. Part of the water is returned after withdrawal and can subsequently be reused or restored to the environment. The non-returned part represents consumed water, namely water that is evaporated or incorporated into products and organisms. Often, pollutants or pathogens need to be removed after water use to guarantee its safe (re)-use. In aquaculture, system-associated water withdrawal is used to compensate infiltration and evaporation losses and to regulate water exchange. Infiltration losses and exchange water from aquaculture partially contribute to return water flows. Decreasing groundwater levels and diminishing water volumes stored in aquifers are today a major concern. The recharge potential to groundwater and aquifers of large areas under rice cultivation recently received a lot of attention (Hamada & Komae, 1998; Liu *et al.*, 2005). Similar contributions can be expected from large pond areas, provided pollution is controlled.

## 2.2. Infiltration losses from ponds

Evaporation losses vary between 2.7 and 6.3 mm/day (Boyd & Gross, 2000; Verdegem *et al.*, 2006). In inland shrimp ponds in Thailand, water losses through evaporation and infiltration were 3.1 and 5.2 mm/day respectively, and the freshwater withdrawal in 14 inland shrimp ponds and reservoirs averaged  $8.3 \pm 1.4$  mm/day (Braaten & Flaherty, 2000). Braaten & Flaherty (2000) also found that the daily freshwater withdrawal in shrimp ponds and rice fields was not significantly different. Therefore, it is assumed that the same processes influence water use in ponds and rice fields. Infiltration losses consist of two components: vertical percolation and lateral seepage. Water from lateral seepage reaches aquifers through percolation (IRRI, 1965) which is influenced by factors like height of the water table, recharge coefficient, hydraulic conductivity and soil permeability (Collin & Melloul, 2001). Additional factors to consider for fish ponds include pond age and depth (Yoo & Boyd, 1994).

Water loss through the bunds (or dikes) of rice fields is three times higher than the volume percolating through the bottom (Chen *et al.*, 2002; Huang *et al.*, 2003). Bottom percolation losses from rice fields range between 0 to 10 mm/day (Bouman *et al.*, 1994; Huang *et al.*, 2003). Amongst a wide selection of locations in Thailand, percolation from rice fields varied on average from 0.5 to 3 mm/day (Tsubu *et al.*, 2005). Lateral seepage is in addition to soil and sediment properties influenced by the slope of the dike, water height above the dike's slope and, if present, the position and height of water in adjacent ponds, channels or rice fields. In a toposequence, low lying water bodies profit from seepage of higher positioned water bodies (Tsubu *et al.*, 2005). In ponds, the combined bottom percolation and lateral seepage (referred to as infiltration loss below) was estimated at 5 to 10 mm/day (Yoo & Boyd, 1994). However, in situations when the groundwater table is high, such as during the monsoon season in the Mekong delta, infiltration losses from fish ponds will be restricted to lateral seepage to surrounding fields and channels.

# 2.3. Water contamination through pond infiltration losses

The land management plans of several countries already consider the capacity of landscapes to recharge groundwater and aquifers with clean water (Collin & Melloul, 2001). Recharging from

fishponds can have negative impacts if the percolation water contains harmful substances. These substances can either be nutrients, metals, residues from pesticides and drugs, or disease agents. Agrochemical use in aquaculture is low compared to terrestrial crops because of their poisonous effects on culture organisms. Problems might come from the addition of feed or fertilizers in the form of crop residues, manure or human night soil, enriching and stimulating the food web in ponds. In consequence, pond water is rich in nutrients, including nitrogen (N) and phosphorus (P). Infiltration water from stagnant tilapia ponds in Egypt was enriched 6.5 times with N and 20.9 with P, compared to concentrations just above the pond bottom (Muendo *et al.*, 2005). Masuda & Boyd (1994) and Jiménez-Montealegre *et al.* (2002) also reported nutrient enrichment of percolation water from ponds. Through nutrient enrichment of infiltration water, considerable amounts of N and P can be lost; for example, assume the average concentration of dissolved N in the water column is 1 mg/l and 0.1 mg/l for available P. In ponds with an annual infiltration loss of 1,000 mm, and a dietary N and P input of 23 and 4.5 g/m<sup>2</sup>/yr, this would mean that 28% of the dietary N and 44% of P are lost through infiltration.

The above example shows that infiltration water from large pond systems might potentially cause N and P enrichment of ground water or aquifers. However, considering the limited number of studies available on percolation from ponds, until more research is done, care should be taken before jumping to conclusions. The transition of these nutrients to the aquifer depends on the activity in the soil below the pond and the flow of the groundwater. In general, mobility to the aquifer is low (Kunwar *et al.*, 2006). N and P can be demineralised and used by bacteria or vegetation before reaching the aquifer. Vegetation and especially trees can capture the main part of the percolating nutrients (Takatert *et al.*, 1999). In ponds surrounded by trees the contamination of the aquifer with N and P will be minimal.

Contamination of aquifers with heavy metals or pathogens constitutes another threat. If pig manure is added to the pond and the feed of these pigs contains copper (Cu), contamination of ground water and aquifer can be serious (Nicholson *et al.*, 2006). Added iron (Fe) gives fewer problems and may even increase the solubility of P (Takatert *et al.*, 1999). The contamination of groundwater with disease agents either from added manure or waste, or from culture organisms, may constitute a problem if the people depend on shallow wells for drinking water in the proximity of their ponds. The transport speed of microbiological contaminants is higher than chemical substances, but considerable attenuation of the bacteria and bacteriophages occurs (at least -100 fold, Sinton *et al.*, 1997). The attenuation of viruses was substantially lower than for bacteria, even though viruses move slower through groundwater (Gerba & Bitton, 1984 cited by Harvey *et al.*, 1989).

#### 3. Freshwater use in aquaculture

#### 3.1. Global freshwater withdrawal

About 70% of total global freshwater use goes to agriculture (Table 2). The water needed to produce food for the present world population is  $18,000 \text{ km}^3/\text{yr}$ . The prediction is that this will increase to  $27,000 \text{ km}^3/\text{yr}$  by 2050 (Anonymous, 2005). Total annual rainfall on land is estimated at  $110,000 \text{ km}^3$ , but economically accessible flowing or blue water amounts to  $12,000 \text{ km}^3$  (Shiklomanov, 1996 cited by Appelgren, 2004). Assuming that all food for the 3 billion extra people that need to be fed by 2050 will be produced in irrigated systems, an additional  $3,800 \text{ km}^3$  of water would be abstracted, on top of the  $3,600 \text{ km}^3$  supplied to irrigated agriculture today. This will bring the water extraction for irrigation to

Table 2	. Estimates of	relative total	water	withdrawal	and water	consumption	from	available	water	on the	continents,	by fo	our
main se	ectors in 1998	and 2000 (in	%).										

Sector	2000 (Anomynous, 2005) % water withdrawals	1998 (Shiklomanov, 1998) % water withdrawals	% water consumption
Agriculture	70	66	93
Industry	20	20	4
Domestic use	10	10	3
Evaporation from reservoirs	_	4	-

7,400 km<sup>3</sup>/yr, which is nearly 2/3 of the available blue water (Appelgren, 2004). Such a high level is considered unacceptable and most likely also unsustainable. In consequence, future growth of agriculture, including aquaculture, will be constrained by freshwater availability.

# 3.2. Global pond area

To estimate water withdrawal and consumption in aquaculture, the global pond area used by aquaculture should be known. A complete overview of the global aquaculture pond area is presently not available. There are, however, reports available for some countries on total aquaculture production in combination with average production levels per unit pond area (Table 3), making it possible to estimate the pond area dedicated to aquaculture. A summary of aquaculture production in freshwater and brackish water environments in a few selected countries is given in Table 3. Based on these country estimates and considering global aquaculture production, an extrapolation was made to the global pond area dedicated to aquaculture. Factors complicating such an extrapolation include:

- China produces 71% of the global production of finfish and 85% of crustaceans in freshwater, and 50% of finfish and 37% of crustaceans in brackish water environments. Hence, the global area dedicated to pond production is largely influenced by what happens in China.
- The productivity of ponds is highly variable between countries, and not all countries contribute equally to global production; e.g. systems in China are much more productive than in other parts of the world. Because an extrapolation is made to global production starting from a few countries, some bias in the final estimate cannot be avoided.
- Lakes and reservoirs that are managed for aquaculture production are also included in the estimate. Not all countries report the contribution from ponds, lakes and reservoirs in the same way.
- It is assumed that variation within country is accounted for in the national averages. This is not always easy, especially for the major aquaculture producing countries, and this too adds some bias to the estimate.
- Derelict pond areas are not included in the estimate, although some of these areas still consume water and are therefore accountable to aquaculture development.
- Different species of finfish and crustaceans can be produced in polyculture in the same pond but are reported separately in the database used (www.fao.org). Because the total pond area was calculated based on average total biomass production per unit pond area stated in country reports, correction of total pond area was not considered necessary.

Country	Environment	Pond area (ha)	Production (MT/yr)	Mean production (kg/ha/yr)	Observations	Source
Bangladesh	Freshwater	151,000	358,115	2,609	Average production in about 1.3 million inland ponds is given. About 55% of total inland aquaculture production still comes from culture based fisheries and was not included in production estimate.	Gias (2006)
Bangladesh	Brackish	203,071	114,660	565	Average production estimated based on given area and total production.	Gias (2006)
China	Freshwater	5,583,276	17,782,734	3,185	74.5% of total inland production is realized in ponds with an average production of 5,217 kg/ha/yr, the rest in lakes or reservoirs with an average of 1,115 kg/ha/yr. Aquaculture production area was estimated.	Shuping (2006)
China	Brackish	676,184	5,091,330	7,530	Pond area and production refer to developments in coastal mud flats. The average production was estimated.	Shuping (2006)
Cuba	Freshwater	11,424	34,272	3,000	Pond area calculated on basis of total and average production.	Coto (2006)
Cuba	Brackish	1,383	830	600	Pond area calculated on basis of total and average production.	Coto (2006)
Chech Rep.	Freshwater	41,000	20,000	450	Production in ponds mainly based on natural productivity.	Adamek & Kouril (2006)
Egypt	Freshwater	64,100	240,000	3,744	Mostly large $2-8$ ha ponds are used.	Salem (2006)
Hungary	Freshwater	28,000	10,764	384	93% of production realized in ponds, 7% in geothermal systems. Average production for ponds is given.	Varadi (2006)
India	Freshwater	850,000	1,870,000	2,200	Figures for carp production.	Ayyappan (2006)
Indonesia	Freshwater	97,821	378,378	3,868	Assumption was made that 20% of the total inland aquaculture production comes from rice fields.	Sri Paryanti (2006)
	Brackish	480,762	501,977	1,044	40% of coastal aquaculture production is shrimp, 30% is milkfish.	Sri Paryanti (2006)
Nepal	Freshwater	6,000	18,060	3,000	The total pond area is estimated based on total and average production. Mainly carp species are cultured.	Pradhan (2006)
Total & mean	Freshwater	6,832,621	20,712,323	3,031		
incl. China	Brackish	1,361,400	5,708,797	4,193		
Total & mean	Freshwater	1,249,345	2,929,589	2,345		
excl. China	Brackish	685,216	617,467	901		

Table 3. Pond area, production and average pond production in freshwater and brackish water culture environments for a number of selected countries. (Source: FAO, 2005: www.fao.org from national aquaculture sector overviews).

The total area dedicated to freshwater and brackish water aquaculture extrapolated from individual country reports is given in Table 4. In total, around 8,750,000 ha are used for freshwater production and 2,333,000 ha for brackish water production.

#### 3.3. System-associated water use

On average, the evaporation loss from ponds is 1,500 mm/yr. The average infiltration loss amounts to 2,000 mm/yr (Verdegem *et al.*, 2006). Consequently, on a global level, 131 and 175 km<sup>3</sup>/yr of freshwater are withdrawn by inland ponds through evaporation and infiltration, respectively. This means 5.2 and  $6.9 \text{ m}^3$  water per kg fish from inland aquaculture for evaporation and infiltration, respectively. Assuming ponds are on average 1 m deep and that 90% are drained and recharged once every year, an additional 79 km<sup>3</sup> of freshwater is consumed, constituting 3.1 m<sup>3</sup>/kg aquatic product. This brings the total inland water use to  $15.2 \text{ m}^3$  per kg production. If the infiltration loss is considered to be green water, the total water consumption is 8.3 m<sup>3</sup> per kg. If in addition the draining and recharge water is also considered to be green water, inland aquaculture's freshwater consumption becomes  $5.2 \text{ m}^3$ /kg production. In summary, 385 km<sup>3</sup> freshwater/yr is withdrawn by inland aquaculture, of which 254 km<sup>3</sup> is potentially green water.

In low-lying coastal brackish water ponds, with daily tidal water exchange, freshwater use is negligible. However, many coastal ponds are constructed more inland on slightly higher grounds, where farmers have a better control of water exchange and salinity. When fresh water shrimp ponds were operated year round, the total water consumption was 30,300 m<sup>3</sup>/ha/yr (Braaten & Flaherty, 2000). No information was found on the global use of freshwater in coastal aquaculture. However, the amounts can be significant. Assuming that 20% of coastal ponds are operated as in Thailand, then 14 km<sup>3</sup> of freshwater will be consumed annually. If 50% of coastal ponds are operated in the same way, the water use will be 35 km<sup>3</sup> freshwater. Because this water is mixed with saline water, it cannot become green water. If 20% of farms are operated as in Thailand, 4.2 m<sup>3</sup> freshwater is consumed per kg produced.

#### 3.4. Feed-associated water use

Numerous feeding experiments have been carried out in ponds, providing data on feed formulations, use of local or internationally available ingredients and apparent feed conversion ratios. However, much less information is available on the contribution of aquafeeds to total pond production. New & Csavas (1995) summarized information on aquafeed production in 11 Asian countries. The results of this study for China, Indonesia, the Philippines and Thailand are summarized in Table 5. In 1992, aquafeeds were produced mainly for marine shrimp production, and to a much smaller extent for finfish production. Tacon (1998) estimated that, in 1992, 20% of common carp and tilapia production relied on commercial

Table 4. Estimate of total surface area for global inland aquaculture production. (Source: FAO, 2005: www.fao.org from aquaculture production data, 2004 (Fishstat Plus)).

	Freshwater		Brackish water				
	Production (MT)	Yield (kg/ha)	Pond area (ha)	Production	Yield (kg/ha)	Pond area (ha)	
China	18,077,227	3,185	5,675,738	1,372,001	7,530	182,217	
World excl. China	7,210,029	2,345	3,074,771	1,937,892	901	2,150,520	
World (total)	25,287,256		8,750,509	3,309,893		2,332,737	

	Aquafeed (000'N	(Th	FAO production	(000'MT)	kg feed/kg production		
Country	Marine shrimp	Freshwater fish	Marine shrimp	Freshwater fish	Marine shrimp	Freshwater fish	
Thailand	336	46	185	131	1.82	0.35	
China	300	400	207	5,328	1.45	0.08	
Philippines*	46	12	81	116	0.57	0.10	
Indonesia*	20	35	144	213	0.14	0.16	

Table 5. Contribution of aquafeeds to shrimp and freshwater production in China, Thailand, The Philippines and Indonesia in 1992. (Sources: Aquafeed production: New & Csavas, 1995; Aquaculture production: www.fao.org).

\* In these countries, the production of fishes in brackish water environments was also high, and it is possible that the freshwater fish feeds were also applied to brackish water ponds.

MT: Metric Tonne.

aquafeeds, compared to 65% for marine shrimps. By 2000, this percentage increased to 25% for common carp and tilapia and to 80% for marine shrimps (Table 6). This trend continues; it is expected that by 2015 50% of common carp, 60% of tilapia and 90% of marine shrimp production will be based on commercial aquafeeds (Tacon, 1998).

The water use associated with the production of animal by-products like bone or blood meal can be considered minimal, as it is already accounted to human food production. The water use for the production of fish meal and fish oil can also be considered negligibly small, although it can be argued that capture fisheries claims the water body of its fishing ground (Folke *et al.*, 1998). Under these assumptions, feed-associated water use is mainly determined by the types and amounts of plant ingredients included in the feed. Depending on the crop, farming system and climate, 0.45 to  $3.6 \text{ m}^3$  of water are consumed to produce 1 kg of plant ingredient (Chapagain & Hoekstra, 2004). Chapagain & Hoekstra (2004) calculated the feed-associated water use per kg production assuming  $2.0 \text{ m}^3$  is consumed in the production of 1 kg of grain (Table 6).

Tacon (1998) gave estimates of the contribution of aquafeeds to total aquaculture production for selected species (Table 6). Considering fresh and brackish water aquaculture production of fishes and crustaceans in 2004, and assuming the levels for the contribution of commercial aquafeeds to aquaculture production for the major species groups in 2000, an estimation was made of total feed-associated water use (Tables 7 and 8). The total feed-associated freshwater use in aquaculture is

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Species	FCR	Plant ingredients in diet (%)	Water per kg production (Litres)	Production based on aquafeed (%)	Reference
Common carp	2.0	78	3,120	25	Tacon (1998) and Tacon (1990)
Tilapia sp	1.7	88	2,992	25	New & Csavas (1995) and Lovell (1989)
Catfishes	1.6	89	2,848	85	New & Csavas (1995) and Lovell (1989)
Milkfish	2.0	80	3,200	40	Tacon (1998) and Chamberlain (2000)
Shrimp	1.8	54	1,944	80	Pike (1997) and Lovell (1989)
Prawn	1.8	85	3,060	81	New & Csavas (1995)

FCR: Feed conversion ratio.

Environment	Examples of major species groups	2004 production (MT)	% Product, based on aquafeeds	Medium water use (l per kg)	Average FCR	Water use (km <sup>3</sup> )
Freshwater	Cypriniformes	18,215,331	25	3,120	2.0	28.42
	Percoidei (incl. tilapias)	1,930,570	25	2,992	1.7	2.45
	Siluriformes (catfishes)	984,634	85	2,848	1.6	3.81
	Aguilliformes (eels)	246,729	85	2,848	1.6	0.96
	Salmoniformes	396,115	85	2,848	1.6	1.53
	Brachyura (crabs)	421,982	50	3060	1.8	1.16
	Natantia (incl. Macrobrachium)	456,012	81	3060	1.8	2.03
	Gonorynchiformes (incl. milkfish)	475,455	40	3,200	2.0	1.22
Brackish water	Mugiliformes	146,291	25	3,120	2.0	0.23
	Percoidei (incl. tilapias)	282,803	25	2,992	1.7	0.36
	Natantia (incl. peneaid shrimps)	2,139,498	80	1,944	1.8	5.99

Table 7. Feed-associated water use in aquaculture for major species groups. Production data from www.fao.org. Medium water use based on information given in Table 6.

FCR: feed conversion ratio; MT: Metric Tonne.

44.1 km<sup>3</sup> or 1.7 m<sup>3</sup>/kg produced; in brackish water systems, farming mainly shrimp, the food-associated water use is 9.7 km<sup>3</sup> or 2.9 m<sup>3</sup>/kg produced. Whereas in brackish water systems, system-associated water use is 45% higher than food-associated water, in freshwater systems system-associated water consumption is 200% higher than food-associated water use, assuming all infiltration loss and exchange water is green water. If the latter is accounted, the system-associated water use is >11 times higher than the feed-associated water use. It should be noted that the feed-associated water use is an average, including fed and non-fed ponds. In fed ponds, the feed-associated water use more than doubles.

#### 4. Socio-economic aspects of water use

Ponds fulfil multiple roles in integrated farming systems, including water storage, domestic water use (kitchen, bathing), watering crops and animals, storing of nutrients, disposal of excess nutrients, water purification/sanitation, trapping of wild fishes or aquaculture (Little *et al.*, 2007). In areas with regular flooding, ponds are commonly available as they are dug to raise the level of the land for creating a homestead (Bosma *et al.*, 2006). Traditionally, in areas were numerous water bodies are available, aquatic products contribute significantly to local diets, even in situations where little effort is put in managing these water bodies for fish production (Burlingame *et al.*, 2006). An important incentive for farmers to manage their water bodies for fish production is the option to generate cash income

Table 8. Estimation of total feed-associated water use in freshwater (inland) and brackish water aquaculture.

	Freshwater Km <sup>3</sup>	Brackish water Km <sup>3</sup>	Total Km <sup>3</sup>
Finfishes	41.8	2.3	44.1
Crustaceans	3.6	6.0	9.7
Total	45.5	8.3	53.8

(Nhan *et al.*, 2007b). Such a shift towards more controlled aquaculture practices to generate cash will mostly have a negligible impact on overall on-farm water use, or will in many cases stimulate farmers to better manage available water resources, considering the value of their aquatic crops. For instance, throughout Asia, the value of aquatic crops is much higher than the value of rice, which causes farmers to shift to aquaculture. In this case too, the overall on-farm water use will not increase as similar amounts of water are consumed in rice production and aquaculture (Braaten & Flaherty, 2000).

Although the potential benefits from aquaculture are higher than for other agricultural activities, the capital investments in aquaculture are also higher, raising the risks involved (Szuster *et al.*, 2003). Therefore, in a poor economy where capital is scarce, farmers will stick with extensive low-cost production methods, as minimizing risks and safeguarding food security are priorities for poor households. Only when the basic objective of risk control is satisfied farmers will be inclined to intensify. This applies to wealthy and better-off farmers with a secured access to markets and resources, not to poor farmers (Ruben, 2007). Therefore, the wealth status of farmers influences the level of intensification. Intensive production systems use less water than extensive systems per kg production (section 1), hence there is a need to develop affordable low-risk methods for intensification of pond aquaculture, when targeting poor farmers.

Development of aquaculture can reduce options to maintain a diversified agriculture. In Thailand, the national shrimp production expanded in the nineties by developing low salinity inland culture systems, while the production in coastal areas suffered severe disease problems. This caused changes in the salinity gradients in seasonally saline agricultural areas, reducing options to maintain agricultural crop diversity or reducing drinking water availability (Szuster, 2006). This strongly affects the livelihood of entire farming communities. At present, in an attempt to reduce conflicts related to salt intrusion, shrimp farming in Thailand is restricted to areas where saline sediments are relatively close to the surface, and shrimp farmers in low-surface-salinity areas are advised to switch to freshwater prawn culture (Szuster, 2006).

Economic benefits, in combination with past experiences, sometimes prevent farmers to switch to more water efficient production methods. In the Mekong delta in Vietnam, shrimp farmers can rely on natural recruitment through tidal water exchange or can stock hatchery reared Penaeus monodon postlarvae without tidal water exchange. Estuarine waters are highly turbid and with tidal water exchange enormous amounts of sediment are deposited in the ponds and need to be regularly removed. Due to prohibitive high costs for removing sediments, farmers dispose it on-farm by enlarging dikes, hence reducing the area available for pond production. Today, by relying only on hatchery reared postlarvae without water exchange, the potential annual income is 3% lower than for a system combining postlarvae stocking and natural recruitment. However, due to cumulative land losses, 50 years from now, the annual income from combining natural recruitment with postlarvae stocking will decline 37% while the annual income from a system relying solely on hatchery reared postlarvae with no water exchange will remain unchanged. Nevertheless, farmers perceive annual income from hatchery reared postlarvae to be much lower, because they often experienced severe losses due to poor postlarvae quality and/or viral disease. This makes it difficult to convince farmers to abandon relying on natural recruitment, even knowing this practice degrades the farming environment. Hence, until postlarvae quality becomes uniform and predictable and viral diseases are controlled, farmers will not consider switching to the more environmentally friendly and water conservative system (Brenan et al., 2006).

# 5. Options to reduce freshwater use in pond aquaculture

#### 5.1. Better water management

In some regions large quantities of surface waters are available. For instance, in the Mekong delta, in intensive catfish ponds, the total water withdrawal was as high as  $848,000 \text{ m}^3/\text{ha/yr}$ , or  $171 \text{ m}^3/\text{kg}$  fish produced. In semi-intensive ponds the water withdrawal was  $165,000 \text{ m}^3/\text{ha/yr}$  but, because the production level was lower, the water use per kg fish produced even reached  $300 \text{ m}^3/\text{kg}$  (Nhan *et al.*, 2006). Depending on the type of farming system and the type of nutrient considered, freshwater aquaculture operations in the Mekong delta enrich or strip the surrounding surface waters from nutrients. In semi-intensive ponds, the N load of the flow-through water was reduced by 4.3%. In the intensive system, the N load was enriched by nearly 50%. For P, the load was enriched by 30 and 48% in the semi-intensive and intensive systems, respectively (Nhan *et al.*, 2007a). By reducing the water flow through these ponds, nutrient losses were reduced resulting, in most cases, in higher production (Table 9).

# 5.2. Selecting feed ingredients that need little water

There is a large variation in the water use between grain types and crop production systems (Chapagain & Hoekstra, 2004). In consequence, there is scope to minimize feed-associated water use. Feed companies select feed ingredients based on least-cost linear programming. The quality of the formulated diet is guaranteed by setting constraints, e.g. minimum protein content, essential amino acid content, range for fat content, avoidance of anti-nutritional factors, etc. If the water consumption necessary to produce one kg of each feed ingredient is known, diets can also be formulated for leastwater-use, while maintaining the constraints guaranteeing dietary quality. For a 32% protein pond diet used in Puerto Rico, the feed-associated water use of a least-cost diet was 6.2 m<sup>3</sup>/kg. In the least-wateruse diet, the feed-associated water use was 1.1 m<sup>3</sup>/kg. Unfortunately, the price of ingredients used in the least-water-use diet was twice as high as for the least-cost diet. In the Puerto Rican situation, there is a clear trade off between water use and price in animal feed ingredient selection (Verdegem et al., 2006). Assuming a food conversion ratio of 1.5, the food-associated water use with the least-cost diet is 9.3 m<sup>3</sup> per kg fish produced. With the least-water-use diet, the food-associated water use will be 1.65 m<sup>3</sup> per kg fish produced, or a reduction of  $7.65 \text{ m}^3$  per kg fish produced. Compared to an evaporation loss and infiltration loss of 5.2 and  $6.9 \text{ m}^3$  respectively, this constitutes a considerable reduction in water use. It should be noted that these calculations are situation specific and that care must be taken in generalizing. The food-associated water use in the Puerto Rican situation was high, and the least-wateruse diet too costly.

Table 9. Reduction of water exchange and effect on fish yield and nutrient content of outflow water during on-farm experiment in the Mekong Delta.

Type of system	Reduction of water exchange (volume% /day)	Effect on fish yield (ton/ha/year)	Nutrient load in outflow water
Fruit-dominated low feed input	7.9 to 2.6	0.5 to 1.2	Reduced
Rice-dominated home-made feed	1.5 to 0.6	6.2 to 5.1	Reduced
Rice-dominated waste fed	21.4 to 5.3	3.8 to 10.3	Reduced

On the basis of the above analysis, one could conclude that fertilizer-driven systems are a better deal for the farmer than feed-driven systems, as the cost of feeding is less. However, this contradicts the observation that farmers switch to pellets as soon as they can finance the feed. Pellets have the advantage that they are easy to transport, store and apply in contrast to organic fertilizers which are bulky, difficult to store and handle, and labour intensive to apply daily in the correct quantity to ponds. In consequence, to promote water efficient aquaculture systems, the challenge is to create fertilizer-driven systems that are as user-friendly as feed-driven systems.

## 5.3. Feed the pond, not the fish

In stagnant or recirculating aquaculture systems, the total water consumption per kg production is reduced through intensification. Concurrently with intensification, the share of food-associated consumption to total water consumption increases (Verdegem *et al.*, 2006). Formulated pond feeds were often developed in aquarium studies where the administrated pellets are the sole nutrient source. In consequence, pond diets typically contain a vitamin mix and trace minerals, essential fatty acids and a balanced amino acid composition, whereas these nutrients are at least partially present in algae (Brown *et al.*, 1997; Reitan *et al.*, 1997), bacterial flocs (Burford *et al.*, 2003) or zooplankton (Watanabe *et al.*, 1983) already present in ponds. Even in fed ponds, culture organisms obtain a considerable fraction of their nutritional requirements from the natural foods present. In fact, expensive formulated diets to a large degree function as a fertilizer stimulating the food web in the pond (Verdegem *et al.*, 1999).

Giving more attention to the fertilizing effects of aquafeeds, and the exploitation of the associated natural foods produced, looks promising. Various technologies exist that enhance the production and exploitation of natural foods in ponds. A first technology is biofloc technology, originally developed in active suspension ponds, in which the metabolic wastes from feeding stimulate the development of microbial communities (Avnimelech, 2003). Metabolic wastes from fishes are relatively rich in nitrogen and poor in carbon. By adding carbonaceous substrates, microbial production is enhanced. The microbial communities also immobilize ammonia and nitrite, hence controlling potential toxicity. Dietary protein utilization in biofloc ponds is twice as high as in normal ponds, and the protein level in the diet can be reduced up to 40%, without noticing a decline in production. The systems can be operated without water exchange, realizing annual yields of  $20-40 \text{ kg per m}^2$  tank area. Recent studies by Hari *et al.* (2004, 2006) show biofloc technology can also be applied in extensive shrimp ponds, increasing yield by 50%, doubling protein utilization and increasing profits five times.

A second technology to consider is periphyton technology. Deploying submerged surfaces in ponds to stimulate the development of attached microbial communities increased pond yields by 50 to 180% (Azim *et al.*, 2005). The attached bacterial communities are maintained in the water column and hence develop under oxygen rich conditions, typically maintained in active suspension ponds. In fed ponds, protein utilization also doubles after the installation of substrates to stimulate periphyton development (Azim *et al.*, 2005). Finaly, biofloc technology and substrate addition can be combined in ponds as recent studies showed additive effects on production (Asaduzzaman *et al.*, 2008).

Exploiting synergism between species in polyculture is a third technology, already widely applied. Not all species combinations induce synergism, but gains can be considerable. Stocking low densities of common carp in rohu ponds increased rohu production by 40%, while nearly doubling total production, without increasing nutrient inputs to the ponds (Rahman *et al.*, 2006).

The challenge is to make these technologies part of the feeding strategy. Aquafeeds could be developed to be simultaneously a feed and a fertilizer, and pond design and operation should aim to stimulate natural productivity and mineralization processes. Ideally, feed composition, feeding strategy and pond design are linked. This might sound trivial, but considering the complexity of pond ecosystems, this is not a simple task. However, if successful, the net result can be a doubling or even tripling of the average production achieved in ponds. The latter should be our goal, as it would allow us to satisfy the growing demand for aquatic products without increasing the present area dedicated to aquaculture, without increasing aquaculture-related freshwater use, and without further increasing the environmental impact from aquaculture.

#### 6. Conclusions and implications

Freshwater use in inland aquaculture is high, withdrawing on average 16.9 m<sup>3</sup> per kg production. Infiltration losses account for 6.9 m<sup>3</sup> and water replacement for 3.1 m<sup>3</sup> per kg production. These can be considered as green water, provided pollution is controlled. Here lies a first research priority: to assure infiltration losses and replacement waters from aquaculture are green water. This means focusing on purification of effluents, re-use of nutrients, and control of percolation losses. When successful, nearly 60% of water withdrawn for inland aquaculture can be recuperated, and should no longer be considered as a loss.

On average,  $5.2 \text{ m}^3$  water per kg production is consumed through evaporation from ponds. Intensification of aquaculture can drastically reduce the evaporation loss per kg production. A tripling of present production levels will reduce evaporation loss to  $1.7 \text{ m}^3$  per kg production. A second priority for research is to increase pond productivity while reducing environmental impacts. This will only be possible if feeding strategies are geared towards managing the pond ecosystem, which is more than just the culture animals.

Aquafeeds also consume water. About  $1.7 \text{ m}^3$  water per kg production is indirectly consumed through evaporation during the production of grains incorporated in aquafeeds. In the future, grain associated water consumption will increase, as the contribution of aquafeeds to total inland aquaculture production increases (Tacon, 1998), but will level off at  $2.5-3.0 \text{ m}^3$  water per kg production with present technology (Table 6). However, if the fertilizer effect of aquafeeds is enhanced, less grains might be needed in aquafeeds. Here lies a third priority for research, to diminish our dependence on grains in aquafeeds. When focussing on feeding the pond ecosystem, the latter might be possible.

If 20% of global shrimp consumption would be produced in inland ponds, than  $4.2 \text{ m}^3$  water per kg production will be used. This water cannot be recuperated, due to salinization. A fourth research line should focus on improving productivity in brackish water ponds with high or fluctuating salinity level. In addition, the  $2.9 \text{ m}^3$  feed-associated water use per kg produced will also benefit from intensification (second research priority) and a reduction of our dependence on grains in aquafeeds (third research priority).

The research priorities given above focus on aquaculture related water use. Adoption or rejection of options to reduce water in aquaculture by farmers depends on the social, economic and environmental contexts in which they live and operate. For the research output to be applicable, practical and successful, the social, economic and environmental contexts should be incorporated right from the start, in cooperation with all stakeholders involved.

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