

CARRYING CAPACITY LIMITS OF NET CAGE AQUACULTURE IN BRAZILIAN RESERVOIRS

LIMITES DA CAPACIDADE DE SUPORTE DA AQUICULTURA
EM TANQUES-REDE EM RESERVATÓRIOS BRASILEIROS

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ABSTRACT

Finfish aquaculture in net cages is widely used in Brazilian reservoirs, mainly for tilapia production. There is a large and increasing potential for production in the São Francisco river basin, and particularly the Itaparica reservoir. Tilapia production amounts to 24,000 t y⁻¹, with a licensed amount of 43,267 t y⁻¹. This intensive fish production in net cages is responsible for a significant biological oxygen demand, and phosphorus and nitrogen load on the reservoir, which promotes eutrophication. Particulate organic matter released from the net cages accumulates beneath the net cages, and a minimum water depth beneath the net cages of 10 m is required to limit the sediment increase to a few millimetres per year. Modeling of Icó-Mandantes bay has identified a reduced water exchange within the bay. Modeling of the effect of net cage aquaculture within the Icó-Mandantes bay points out clearly the significant increase in dissolved phosphorus and the accumulation inside the bay area. The carrying capacity of the reservoir was determined using the P load model, with a critical P concentration based on the phosphorus use efficiency. The critical P concentration amounts 25 µg L⁻¹, and the critical P load of the reservoir amounts 2.84 g m⁻² y⁻¹; the actual load is already 3.30 g m⁻² y⁻¹, such the reservoir is already overcharged by nutrients. A sustainable “blue” aquaculture must be implemented based on use of advanced systems, species selection, fish feed, and linked production systems.

Keywords: net cageculture; green aquaculture; tilapia; *Oreochromis niloticus*; Itaparica; São Francisco.

RESUMO

A aquicultura de peixe em tanques-rede é amplamente utilizada em reservatórios brasileiros, principalmente para a produção de tilápia. Os reservatórios presentes na bacia do rio São Francisco são vistos como tendo um elevado e crescente potencial de produção, principalmente o reservatório Itaparica. A produção de tilápia ascende a 24.000 toneladas por ano, com um licenciamento de 43.267 toneladas por ano. Essa produção intensiva de pescado em tanques-rede é responsável por uma carga significativa de fósforo, nitrogênio e demanda biológica de oxigênio, promovendo o processo de eutrofização no reservatório de Itaparica. A matéria orgânica particulada lançada é acumulada sob os tanques-rede, e uma profundidade mínima de 10 m é requerida como limite de água abaixo dos tanques-rede, necessário para limitar o aumento de sedimentos em alguns milímetros por ano. A modelagem da baía Icó-Mandantes tem identificado uma troca reduzida de água no interior da baía. A modelagem também aponta claramente o efeito da aquicultura em tanques-rede através do incremento significativo de fósforo dissolvido e seu acúmulo no interior da área

da baía. A capacidade de carga do reservatório é calculada usando o modelo de carga de P e uma concentração crítica de P, baseado na eficiência do uso de fósforo. A concentração crítica total de P de $25 \mu\text{g L}^{-1}$, e a carga crítica de P do reservatório de $2,84 \text{ g m}^{-2} \text{ y}^{-1}$; a carga real é de $3,30 \text{ g m}^{-2} \text{ y}^{-1}$, estando o reservatório já sobrecarregado por nutrientes. A aquicultura sustentável “azul” deve ser implementada com base na utilização de sistemas avançados, seleção de espécies, sistemas de produção e alimentação de peixes interligados.

Palavras-chave: tanques-rede; aquicultura; tilápia; *Oreochromis niloticus*; Itaparica; São Francisco.

INTRODUCTION

Fisheries in lakes and reservoirs are of interest due to the success and increasing significance of finfish aquaculture, with the aquaculture yield exceeding that of artisanal fisheries in many countries. A small-scale artisanal fishery is seen as a necessary part of the maintenance of an aquatic ecosystem, because it reduces fish biomass to the optimum level and prevents the over-aging of the fish population. The optimum fish biomass is determined by a balanced predation effect in the trophic cascade, due to the predation-pray functional chain: high abundance of carnivore fish → low abundance of planktivorous fish → increased development of zooplankton → reduced algae biomass due to zooplankton predation, or vice versa (GUNKEL *et al.*, 2016).

Fish aquaculture as a means of food production faces many challenges, due to overfishing, contamination, and degradation of natural water bodies. Additionally, the demand for fish is increasing worldwide, and new high price markets guarantee the economic success of aquaculture technologies. Today, global freshwater aquaculture production is rising at a rate of 7.5% p.a., compared to a rise in the commercial fishery yield of only 1.4% p.a. (FAO, 2013).

The significance of fish aquaculture has been increasing in Brazil for several decades, especially freshwater fish, and artisanal fisheries have been restricted due to the limited capacity of the water bodies and seasonal effects of low water levels. Fish aquaculture technologies have been established for about five decades, but their implementation in South American countries has been delayed. However, growth rates have been increasing for about 20 years, mainly due to the use of net cages of about 10–300 m³.

The use of reservoirs for aquaculture is still a common practice in many countries, with restrictive regulations implemented to limit the environmental impact. In

many countries, net cage aquaculture is prohibited or restricted in lakes and reservoirs (e.g. Chile and Germany). In Brazil, aquaculture is permitted to occupy 1% of a lake's surface, but there are concerns about the sustainability of this regulation (GUNKEL *et al.*, 2013; SUHET & SCHOCKEN-ITURRINO, 2013; CANOCICO *et al.*, 2015).

More advanced fish aquaculture systems use ponds, tanks, and raceways on the border of a reservoir, with a flow through of pumped lake water. This technology permits the treatment of the pond/tank wastewater with sedimentation units or artificial wetlands, before it is released in the reservoir. Ponds are used mainly for fry and fingerling (i.e., small fishes) production, while the growth of fish to their final weight occurs in net cages.

Fish aquaculture systems in lakes and reservoirs have to be evaluated in terms of both their benefits, such as food production and economic development, and their impact on nature, mainly due to contamination of water bodies, leading to eutrophication, and sediment, leading to anoxic conditions. Non-native species are often used for aquaculture, and it is not possible to avoid the escape of some of the cultured fish. Non-native species can change the natural fish community and spread as invasive species.

Several fish species have been used in aquaculture systems, such as the common carp (*Cyprinus carpio*), the grass carp (*Ctenopharyngodon idella*), the bighead carp (*Aristichthys nobilis*), and the Nile tilapia (*Oreochromis niloticus*). In addition, some native species of the São Francisco river are also used in aquaculture, such as the pacu (*Piaractus mesopotamicus*), tambaqui (*Colossoma macropomum*), and curimatá (*Prochilodus spp.*) (CHESF, 2003; SCOTT, 2013). However, the significance of these native species is small, with tilapia accounting for about 40% of the fish production in Brazil.

Tilapia is widely used in aquaculture and its production has increased in Brazil, mainly in the south and north-east of the country. The fish are well suited to aquaculture because they are fast-growing and tolerant of a range of environmental conditions. These species adapt readily to changes in salinity levels and low oxygen availability, can feed at different trophic levels, and, under certain circumstances, can tolerate overcrowding (CANONICO *et al.*, 2005).

The main limiting factor for aquaculture systems in lakes and reservoirs is the eutrophication that occurs due to the input of feed rests and feces, as well as the excretion of ammonium by the fish. In a mass balance the input of nutrients (P, N, organic carbon compounds) exceeded their export by the fish yield by three and four times for phosphorous and nitrogen, respectively. Organic matter inputs lead to the consumption of oxygen by mineralization, as well as the contamination of sediment and the promotion of anoxic conditions.

MATERIALS AND METHODS

Study Area

The environmental impact of net cage fish culture in tropical reservoirs was studied in the Itaparica reservoir in São Francisco river, Northeast Brazil. The reservoir is located in the sub-middle course of the river. The São Francisco river is the 25th largest river in the world and flows from the rainy southwest to the semi-arid northeast of Brazil. Itaparica reservoir was built for hydroelectric power generation and has operated since 1988. It is located in a semi-arid area, with typical Caatinga fauna and flora. The reservoir has a regulated inflow of $2,060 \text{ m}^3 \text{ s}^{-1}$, a length of 149 km, a surface area of 828 km^2 and a subwater basin of $93,040 \text{ km}^2$. The maximum depth is 101 m (mean depth = 13 m). The reservoir's capacity is $10.7 \times 10^9 \text{ m}^3$.

For about 10 years, regular monitoring of the water quality has been undertaken by the Companhia Hidroelétrica do São Francisco (CHESF). Limnological and socio-economic studies have also been conducted (GUNKEL & SOBRAL, 2007; GUNKEL *et al.*, 2013). Since

2012, an interspecific binational research program, Interplay among multiple uses of water reservoirs via INNOVative coupling of substance cycles in Aquatic and Terrestrial Ecosystems (INNOVATE) has been ongoing in the area (INNOVATE, 2016). The reservoir is characterized by high flow through conditions, with a theoretical residence time of 2 months at high water level (304 m above sea level (a.s.l.)) and about 1 month at low water level (299 m a.s.l.). The water quality of the main stream is determined by low conductivity ($82.8 \pm 27.5 \mu\text{S cm}^{-1}$), and a midday water temperature of $27.5 \pm 1.9^\circ\text{C}$ with oxygen concentrations of $7.1 \pm 1.6 \text{ mg L}^{-1}$. Nutrient concentrations are small, with mean soluble reactive phosphorous = $6.9 \pm 11.5 \mu\text{g L}^{-1}$, total phosphorous (TP) = $16.9 \pm 10.2 \mu\text{g L}^{-1}$, and dissolved inorganic nitrogen = $90 \pm 136 \mu\text{g L}^{-1}$. Algae blooms have been observed, including cyanobacteria (*Cylindrospermopsis raciborskii*) blooms with a maximum Chl a concentration of $65 \mu\text{g L}^{-1}$ and the mass development of submerged macrophytes (*Egeria densa*).

The Aquaculture Systems

The environmental impact on the reservoir of two aquaculture net cage systems were investigated, Jovens Criadores de Peixes and Pé da Água, which both produce tilapia (*O. niloticus*). Jovens Criadores de Peixes consists of 65 net cages of 14 m^3 each. Up to 2,500 fish with a final body weight of 1 kg can be raised in each cage. The production cycle is 4–5 months. The total annual production amounts to 216 t tilapia. Pé da Água has 210 net cages of 6 m^3 each, with a yearly production of 300 t of tilapia (GUNKEL *et al.*, 2013).

Water quality parameters were analyzed using a multi parameter device (EXO water quality sonde, YSI, Yellow Springs, OH, USA) and chemical analyses were conducted according to US Standard Methods. Sediment samples were analyzed after a HNO_3/HCl digestion for P and N, respectively, by colorimetric method (FIASSTAR 5000, Gerber Instruments, Switzerland) using German standard methods (DEV, 2015).

Modeling Aquaculture Emissions In Icó-Mandantes Bay

The impact of dissolved ion emissions from aquaculture net cages was studied by modeling the accumulation, dilution, and spreading of N and P in the aquaculture wastewater plume. A small theoretical net cage culture system with a productivity of 130 t y^{-1} was assumed in the model. The ion emissions from an aquaculture system were simulated using TELEMAC-2D, which is a module of the TELEMAC-MASCARET system, a powerful integrated modeling tool for free-surface flows that solves the two-dimensional shallow water and transport equations (HERVOUET, 2007). A high-resolution unstructured mesh with triangu-

lar elements was established in a previous study (MATA *et al.*, 2014). The entire computational domain had an area of around 100 km^2 , covering Icó-Mandantes bay itself and containing part of the reservoirs mainstream, including the inflow and the outflow. The site selected to measure aquaculture emissions was around 100 m from the south-eastern shore of the bay, where the water depth was 5 m (Figure 1). A low water level of 300 m a.s.l. was used as the constant water elevation and a controlled discharge of $2,060 \text{ m}^3\text{s}^{-1}$ was set as the boundary condition at the inflow from Itaparica.

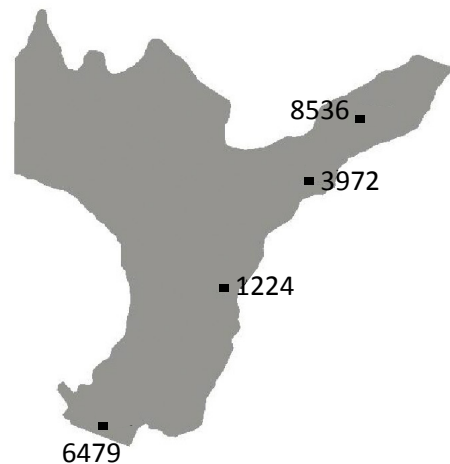
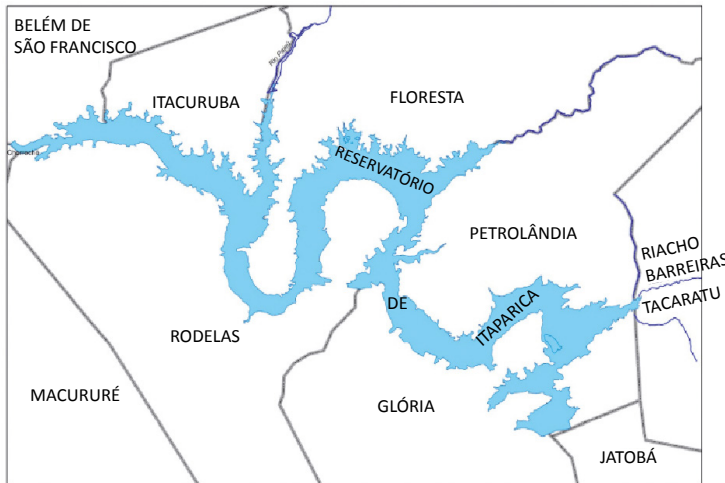


Figure 1 – Itaparica reservoir, São Francisco river, and observation points used for aquaculture emission modeling inside Icó-Mandantes bay.

DEVELOPMENT AND LICENSING OF FINFISH AQUACULTURE IN BRAZIL

There has been a rapid development of finfish aquaculture in Brazil and other countries in South America during the past 20 years. In Brazil, fish production increased from 45,000 t y^{-1} in 1995 to 209,400 t y^{-1} in 2001 and 415,700 t y^{-1} in 2009 (Figure 2). Tilapia accounts for about 40% of the fish production (133,000 t y^{-1} in 2009; KUBITZA, 2011). This is supported by low working costs and a strong local market mainly in South Brazil, but also by exports to North America.

The licensing of finfish aquaculture has been developed since 1997 by multi-decree/-resolution/-norm processes, based on three key values:

1. the use of a limit of 1% of the surface area of a reservoir for cage aquaculture (*Instrução Normativa Interministerial n. 7, 2005*);
2. a minimum water depth of $1.75 \times$ the underwater cage construction height, or at least 1.5 m; and
3. the CONAMA Resolution n. 357/2005, which establishes maximum limits for total P and Chl a of $30 \mu\text{g L}^{-1}$ (SCOTT, 2013).

In 2009, the National Environmental Council (CONAMA) established a clear processing of licensing (CONA-

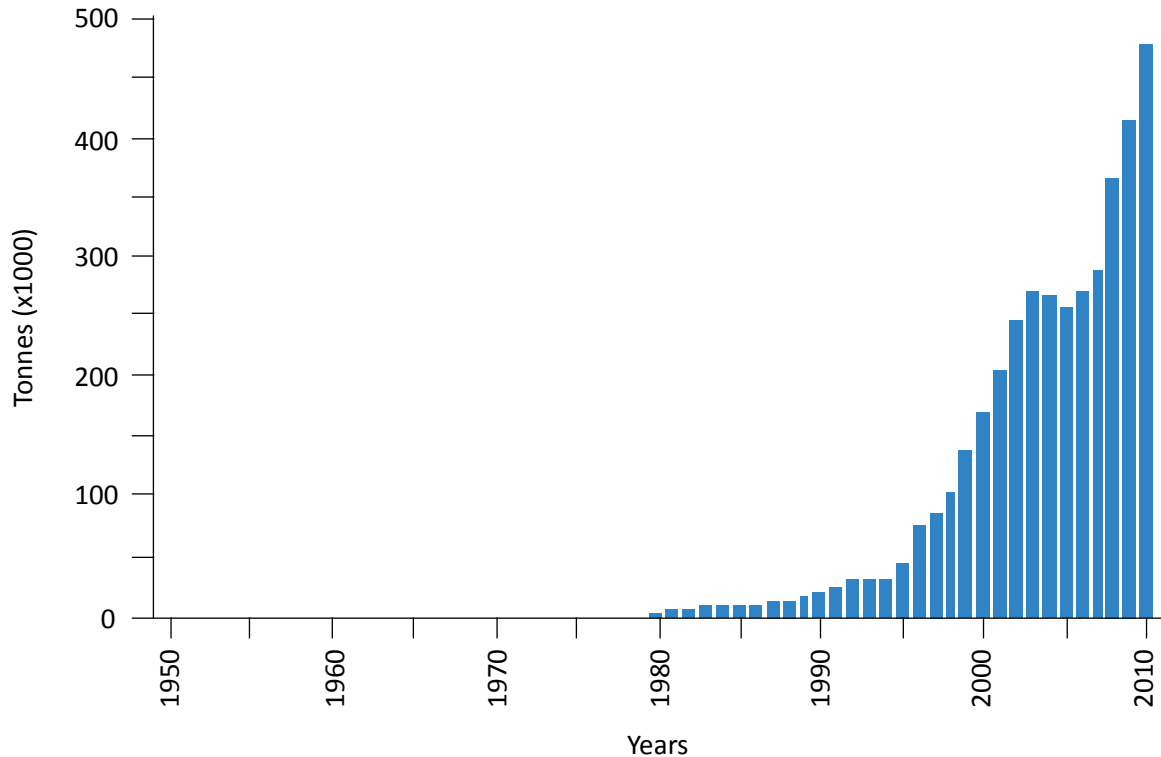


Figure 2 – Reported aquaculture production in Brazil (FAO, 2013).

MA resolution n. 413/2009). The licensing system classifies the potential impacts of a proposed aquaculture system, documents the environmental situation, sets minimum criteria for environmental reporting and ensures that a monitoring program will take place based on hydro-biological studies.

Nevertheless, a critical discussion is required regarding the periodic water level changes in reservoirs, which leads to a decrease in the lake area, e.g. about 26% in Itaparica. From an ecological perspective, net cages are not acceptable in areas with a water depth of <10 m beneath the cage, with a depth of about 4–6 m

required to guarantee the effective translocation and dilution of particulate organic material and avoid large increases in sediment beneath the cages (see below). The limits of the available lake area and minimum water depth are strongly influenced by the water level, and therefore licensing must take account of low water level conditions, otherwise a severe overcharge will occur during dry periods with low water levels. In Itaparica, the maximum water level is 304 m a.s.l., with a mean depth of 13 m, but throughout the year the low water level decreases down to 300–299 m, with a mean water depth of <8 m, and existing cage aquaculture systems must be translocated.

PRODUCTION OF TILAPIA IN NET CAGES

Tilapia culture technologies

Fish aquaculture is a two-stage process, the propagation and cultivation of the fry and fingerlings (young fish up to 12 cm) is followed by growth cultivation for commercial use. The cultivation of fry and fingerlings occurs in tanks or ponds, whereas the growth stage can proceed using low-cost technology, such as net cages of a few m³ or larger net

cages with a volume of >200 m³. Tilapia production has increased very rapidly due to the small volume/high density (SVHD) net cage technology used in reservoirs. These SVHD cages allow a fish yield of 80–250 kg m⁻³ crop⁻¹, with two crops per year (KUBITZA, 2011) or up to 330 kg m⁻³ crop⁻¹ with three crops per year (HALWART *et al.*, 2007).

Alternatively, growth can also occur in ponds, tanks, or raceways, albeit with higher capital costs (Figure 3). The fish yield in naturally managed ponds amounts to 8–10 t ha⁻¹, with a production cycle of one year, but with high flow-through rates and artificial aeration it can be increased to 60–80 t ha⁻¹ crop⁻¹ (KUBITZA, 2011).

The benefits of the net cage culture of finfish are:

- low-cost technology, no water pumping costs, the main costs are only the fish feed;
- high intensity of production;
- flow through of fresh water, constant (good) water quality;
- easy control of fish health and food intake;
- possibility to relocate the net cages during low water levels or when there are harmful plumes of toxicants or algae;
- many treatment options in cases of fish diseases (e.g. isolation of net cages, short-term

chemical treatment with quick dilution of the substances).

The risks of net cage culture are:

- eutrophication of the water body due to the use of isolated bays for aquaculture;
- contamination of sediments by particulate waste from fish culture;
- risk of decreased oxygen levels due to the natural day/night oscillation of oxygen concentrations in eutrophic water;
- risk of infection of cultured fish by wild fishes infected with disease;
- risk of infection of wild fishes by farmed fishes;
- reduced fish quality with increasing feeding rates due to the high fat content;
- escape of cultured fish and damage to the natural fish biocoenosis.



Figure 3 – Left: Net cage culture system in Itaparica, São Francisco; right: Raceway (AAT Company) at Paulo Afonso, São Francisco.

Feed Quality

Fish cultivation is based on artificial feeding in the form of pellets. The quality of the feed is determined by the content of fish proteins (fish meal), animal proteins (slaughtering, blood, plumes etc.), and supplementary plant

proteins (e.g. soy). Fish feed that contains a large amount of plant proteins can be used for the cultivation of omnivorous and herbivorous fish, whereas carnivorous and planktivorous species need a higher amount of animal

proteins. The quality of fish feed required also depends on the development stage (fry > fingerling > adults).

The availability of the fish proteins in the feed is the most limiting factor, and in many regions specific fisheries for fish meal production have been established, with no requirements to protect young fishes or endangered species. The fish feed used for tilapia production contains protein (>40%), mineral elements (<10%), water (>11%), fiber (>2.5%), and phosphorus (>1.3%). Kubitza (1999) reported a mean P range in feeds of 0.85–1.54%.

Tilapia Growth

The most important environmental factor for tilapia growth is the temperature. Tilapia grows at 15–32°C with an optimum of 25–26°C. Temperatures below the optimum lead to a reduced growth rate, with temperatures >26°C leading to a reduced food conversion rate (CODEVASF, 2010).

Tilapia is a fast-growing fish and reaches 600 g within 4 months. The mean production data are given in

Fish feed also has to be evaluated in terms of its potential for environmental contamination, as indicated by its P content and stability in water. The P content should not exceed 0.6%, with excess P leading to greater P excretion by the fish, without any growth increase. The stability of the pellets in water is an important factor in minimizing feed losses. The pellets should not start to disintegrate during the sedimentation process within the net cages, even though some have a height of >10 m.

Table 1. Two production cycles per year are common in warm water, in which the fish reach a final weight of up to 900 g (SAMPAIO & BRAGA, 2005).

The feeding rate for small fishes (75 g) is 5.0% d⁻¹ and for large fishes (350 g) is 2.0% d⁻¹ (CODEVASF, 2010). The amount of feed used for fish production is given by the food conversion ratio (used dry feed/total fresh body weight of fish) and amounts to 1.3–1.5.

Table 1 – Production studies with Red Tilapia in Ribeirão de Saloméa reservoir, Bahia at 27°C and with excess feeding (mod. after SAMPAIO & BRAGA, 2005).

Tilapia growth data	
Production period	130 d
Fish number per m ³	200
Initial fish weight	31 g
Final fish weight	658 g
Total fish yield	475 kg
Food conversion factor, feed with 32% crude protein	1.53
Total feed used (4 mm pellets >350 g, 6 mm pellets >350 g)	717 kg

ENVIRONMENTAL IMPACT OF TILAPIA NET CAGE CULTURE

Aquaculture is a controlled and intensive fish production technology, which supports limited artisanal fisheries, but with the increasing production level, the impact on aquatic ecosystems also increases. The use of net cages for aquaculture in lakes, reservoirs, and coastal areas is the simplest technology for fish production, and is also the most frequently used system in the São Francisco River reservoirs. However, the use of the simple net cages must be evaluated very critically, because the possibilities in wastewater

treatment are very restrictive (see bellow). Additionally, pond systems at the margins of lakes and reservoirs, as simple flow-through systems, are frequently used for stock fish production, here waste water treatment can be done without effort. Other more advanced technologies, which are mainly used in European and North American countries, are based on water recycling systems as integrated aquaculture-agriculture (IAA) technology, integrated multitrophic aquaculture, fish-plant linked systems (aquaponics),

and tank technologies with high flow through rates and aeration by oxygen gas.

The environmental impact of net cage culture can be grouped into three categories:

Water Quality Impact

The contaminants of aquaculture wastewater are:

1. solids, such as feces and feed rests;
2. dissolved compounds, mainly nutrients such as ammonia and phosphorus (excreted by fish) and with lower concentrations of feed additives, including metals (copper, zinc, manganese, and iron) as micro nutrition compounds;
3. a lack of oxygen, as well as an increased concentration of organic compounds, with the corresponding biological oxygen demand (BOD₅);
4. occurrence of harmful bacteria such as *Streptococcus*, which are emitted by infected fishes, but also grow in aquaculture waste water (SUHET & SCHOCKEN-ITURRINO, 2013); and
5. chemicals such as antibiotics, fungicides, and insecticides that are used to treat fish diseases.

The effects on water quality depend on water currents, fish biomass in the cages, and the feeding level,

Sediment Quality Impact

The intensive feeding of fish in net cages leads to feed losses, typically in the range of about 10%, and the emission of particulate organic matter in the form of feces (about 15–20% of the feed). There is an accumulation of organic materials beneath the fish cages. The sediment becomes enriched with organic materials and anoxic conditions can occur, which can damage the sediment fauna and flora. Under anoxic conditions, the mobilization of P from the sediment occurs through a redox process.

Natural Fish Population Impact

The growth in tilapia culture generally results in negative effects on the natural biocoenosis, due its predatory characteristics. Trophic interactions are important. The direct

- impact on water quality;
- impact on sediment quality; and
- impact on the natural fish population.

but significant changes in water quality have been reported when tilapia are raised in net cages. Oxygen depletion occurs with the concentration beneath the cages reaching 1.85 mg L⁻¹ (Jovens Criadores). The no effect level for tilapia is about 2.0 mg L⁻¹ (XU *et al.*, 2006). Total P in water increases at these oxygen levels, with a ΔP_{total} of 0.026 mg L⁻¹ and 0.064 mg L⁻¹, respectively, in the studied aquaculture systems. High concentrations of ammonium have also been reported at these oxygen levels, with a $\Delta \text{NH}_4^+\text{-N}$ of 0.030 and 0.052 mg L⁻¹, respectively (GUNKEL *et al.*, 2013; SUHET & SCHOCKEN-ITURRINO, 2013).

In Brazil, there are no studies available that have reported the environmental fate and distribution of antibiotics and other chemicals in rivers impacted by freshwater cage aquaculture. The water quality in aquaculture areas has deteriorated and the repeated use of antibiotics is expected to result in the development of antibiotic-resistant bacteria, making antibiotics actually ineffective against the target pathogens, with environmental health consequences for humans and the native biological community (RICO *et al.*, 2014).

The increase in sediment due to particulate organic matter released from the net cages depends on the water current and depth, with calculations indicating typical sediment increase rates of a few millimetres. For Jovens Criadores (Table 2) the increase amounted to 20 mm y⁻¹ for the 2,300 m² area covered by net cages. The normal undisturbed sediment accumulation in an oligo- to mesotrophic reservoir is in the range of 1–2 mm y⁻¹, and this must be used as the limit value (Figure 4).

impacts of tilapia culture include its influence on the interspecific competition between tilapia and the natural fishes. The sharing of food and habitats reduces the am-

Table 2 – Tilapia production, feed use and nutrient emissions rates at Jovens Criadores net cage aquaculture system.

Parameter	Calculation factor	Value
Fish production		130 t y ⁻¹
Feed used	Conversion factor 1.4	180 t y ⁻¹
P input	1.2% P in feed	2.16 t y ⁻¹
P export by fish yield	23% P assimilation	0.50 t y ⁻¹
Dissolved P emission	22% P dissolved excretion	0.48 t y ⁻¹
P accumulation in sediment	5% feed loss, 15% feces	1.19 t y ⁻¹
N input	40% protein content	11.52 t y ⁻¹
N export by fish yield	25% N assimilation	2.88 t y ⁻¹
Dissolved N emission	55% excretion (NH ₄ ⁺)	6.34 t y ⁻¹
N accumulation in sediment	5% feed loss, 15% feces	2.30 t y ⁻¹
Personal equivalents (P dissolved)		570
Personal equivalents (N inorganic)		2,300
Sediment increase		45 m ³

P: phosphorus ; N: nitrogen.

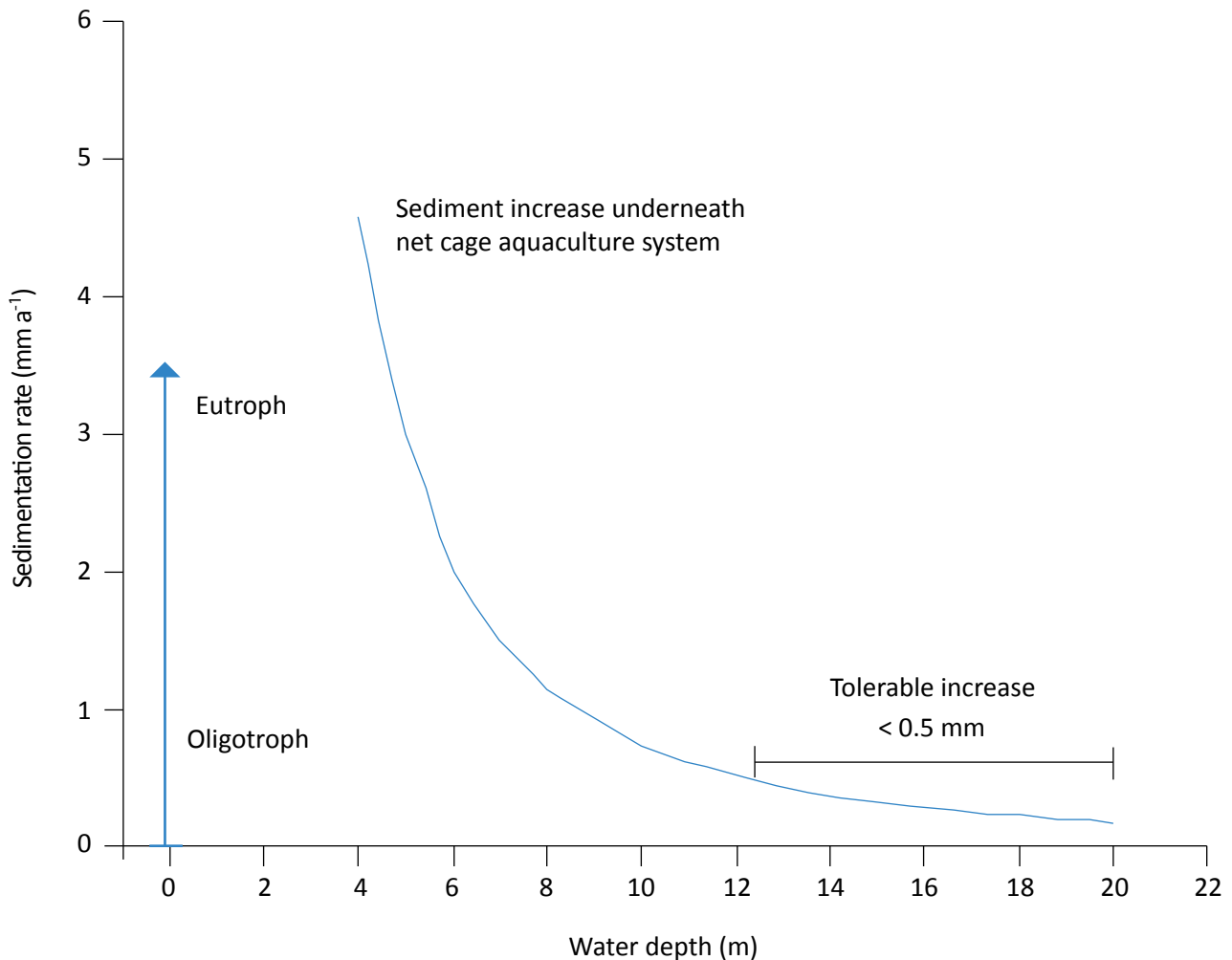


Figure 4 – The calculated sediment increase due to tilapia net cage aquaculture systems (Jovens Criadores de Peixes fish culture system, São Francisco, 65 cages, 200 t y⁻¹ fish production; data from Gunkel *et al.*, 2013).

plitude of the effective niche, and could lead to the extinction of natural species. Tilapia are generally considered to be herbivorous, detritivorous, or planktivorous, and have been documented to consume the eggs and larvae of other fish species, and even some small fish (CANONICO *et al.*, 2005). Additionally, there is a high risk of the introduction of parasites and diseases by virus, fungi, and bacteria following the import of fishes from other regions of the country or even other countries.

The ecological impacts of invasive species on inland water ecosystems vary significantly depending on the invading species, the extent of the invasion and the vulnerability of the ecosystem being invaded. Tilapia is considered to invasive species due to their high predation and successful breeding, which is enhanced due to egg and fry protection through mouth breeding.

While the use of aquaculture holds great promise for decreasing the fishing pressure on wild fish stocks, more studies of the natural fish biocoenosis are necessary to better understand the potential impacts of invasive tilapia on native fish (MARTIN *et al.*, 2010).

As a consequence of the environmental impacts of net cage aquaculture, the activity also has negative socioeconomic impacts on traditional fishing communities, because the environmental imbalance it produces contributes to the reduction of fish stocks. According to the FAO, it is estimated that more than 250 million people worldwide depend on artisanal fisheries, and in developing countries, such as Brazil, artisanal fishermen live near or below the subsistence level.

MODELING EMISSION PLUMES FROM NET CAGE CULTURE SYSTEMS IN ICÓ-MANDANTES BAY

The environmental impact of net cage culture systems within the reservoir is strongly regulated by their location and the water exchange processes, and the main stream, as the central part of the reservoir, and the main dendritic bays must be distinguished. This new approach for evaluating the reservoirs water quality and the risk of contamination has been proven by TELEMAC-2D modeling at Icó-Mandantes bay (Figure 5; MATTA *et al.*, 2014) and the eutrophication processes that have been observed (SELGE *et al.*, 2015).

The impacts of a net cage aquaculture system for tilapia were modeled using the emission data determined in this study, with a theoretical location of the cages at 100 m from the bank of the reservoirs and a water depth of 5 m, with low water level conditions (300 m above sea level) and a mean discharge of 2,060 m³ s⁻¹.

The results indicated that the exchange of water within Icó-Mandantes bay and the main stream of the reservoir were strictly reduced and the exchange processes inside the bay were very slow. After 1 month, the concentrations inside the bay (observation point in the middle of the bay) were only 0.2%, compared to the emission point (Figure 6). This led to the development of a plume of dissolved phosphorus (DP), which stretched, along the bank of the reservoir from the emission point to the south-west. The increase in DP in the water ranged from 4 to 8 µg L⁻¹ (Figure 6), while the mean DP concentration in the bay is already 18 µg L⁻¹ (sd = 13 µg L⁻¹) without aquaculture systems. This is a significant increase in the phosphorus concentration and lead to severe eutrophication, because the critical phosphorus concentration is only 25 g L⁻¹ (SELGE *et al.*, 2015).

CARRYING CAPACITY LIMIT OF THE ITAPARICA RESERVOIR

The determination of the carrying capacity is an approach that can be used to regulate the use of reservoirs and lakes for aquaculture systems. Limitations are given to avoid overcharging the water body, but a free capacity can be also established to enable aquaculture activities to increase.

In Brazil, the calculation of carrying capacity calculation was developed by Beveridge (1984) and is still

used to calculate the maximum fish production license. The sustainability of water quality and more ecosystem adapted methods should be applied to consider the sustainability of aquatic ecosystem services. An evaluation of water uses and the dynamics of water quality have to be considered along with natural effects, such as climate change. Thus, any use of reservoirs for aqua-

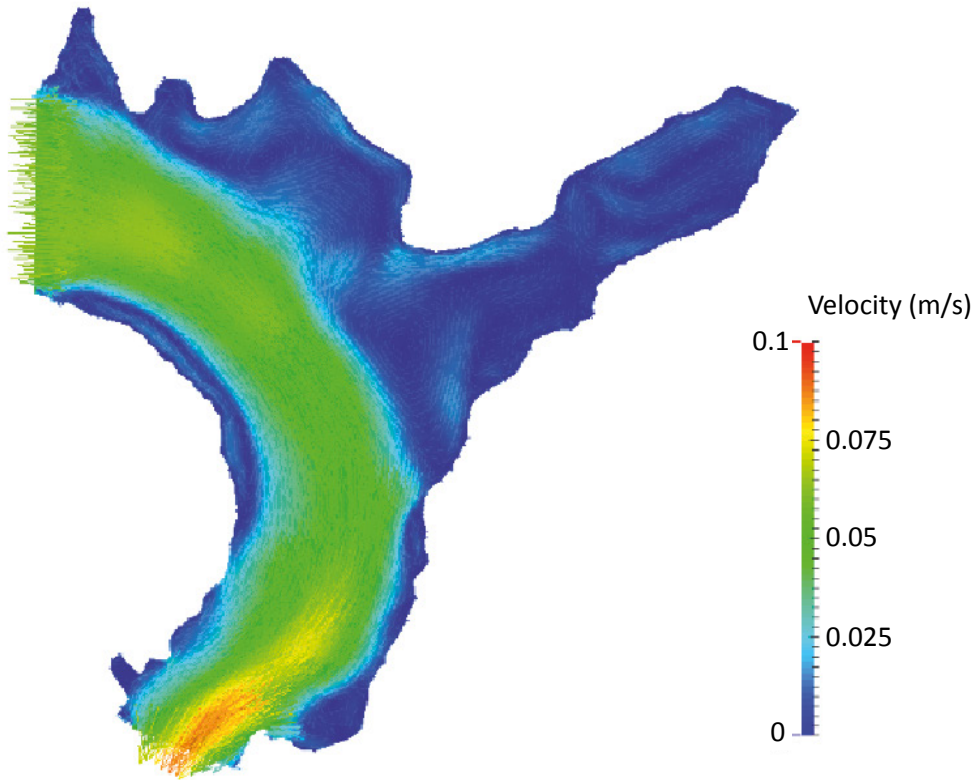


Figure 5 – Surface flow simulation results (mean discharge = 2,060 m³ s⁻¹, wind = 5.5 m s⁻¹).

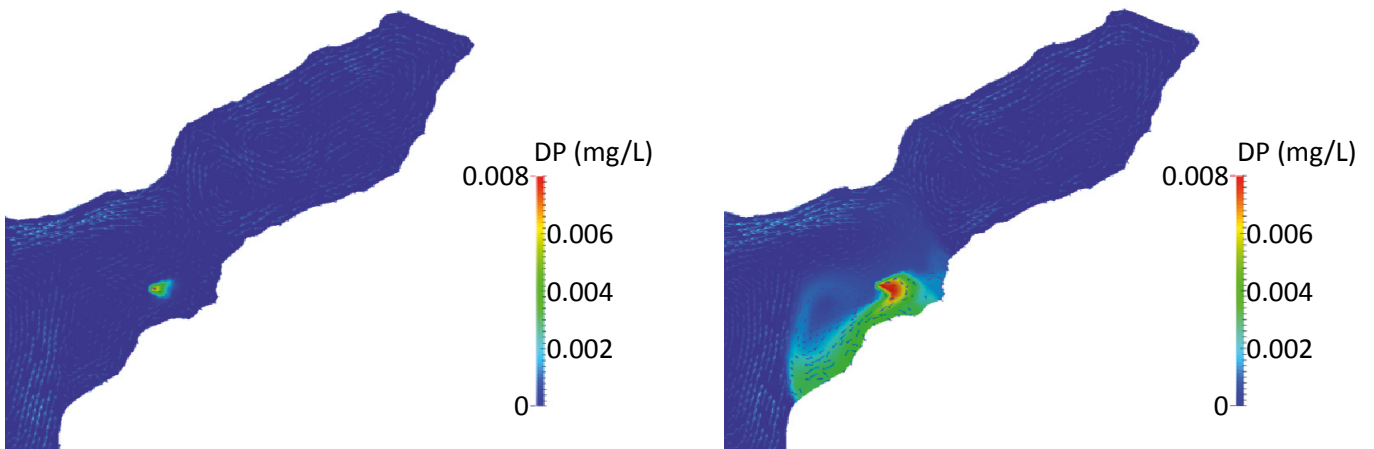


Figure 6 – Contamination plume from a hypothetical net cage aquaculture system in Icó-Mandantes bay due to tilapia production with a capacity of 65 cages (area 2,300 m²) and an annual production of 130 to fish. Left: simulation after 1 day, right: simulation after 1 month.

culture is limited by water quality and the morphometric conditions (depth, flow-through, mixing processes, critical phosphorus load, and also nutrient export from the watershed), and the carrying capacity has to be calculated individually for each water body.

The determination of the carrying capacity of a reservoir or distinct reservoir branches is an auspicious new approach in reservoir management, and is a key factor, which will allow the limited development of aquaculture.

Different parameters can be used to calculate carrying limits:

- Flushing rate is given as the theoretical water exchange time of the reservoir, and with an increasing flushing rate, the risk of eutrophication decreases. The flushing rate must be calculated under low discharge conditions to ensure a sufficient water exchange and net cage flow-through during dry periods to avoid fish kill.
- Initial water nutrient concentration must be considered. The P concentration should not increase to $>30 \mu\text{g L}^{-1}$ (the maximum limit of the CONAMA Resolution nº 357/2005) or $>25 \mu\text{g L}^{-1}$ (the critical P concentration; see below). The critical ammonium concentration is given by the toxic threshold of 0.78 mg L^{-1} (EU fish directive). Chlorophyll a should not exceed $30 \mu\text{g L}^{-1}$ (CONAMA Resolution).
- The water depth to cage height ratio should be 1:1.75 according to a CONAMA Resolution. A depth of about 10 m would produce a dilution of the particulate matter. The available reservoir area must be calculated at low water level, using a bathymetric model of high resolution.
- Sedimentation rate is given by the free water height beneath the cage system as well as the water current and the feed quality. The sediment increase should not exceed about 1 mm y^{-1} as a mean value for oligotrophic to mesotrophic water bodies.
- The oxygen concentration is very significant for fish health and should not decrease to below 2 mg L^{-1} for tilapia culture. Other species are more sensitive to a lack of oxygen. The minimum O_2 concentration occurred after midnight due to the respiration of fish, algae, macrophytes, and the biochemical use

of oxygen. In the daytime, the oxygen concentration is increased due to photosynthesis of the algae.

Water quality is a dynamic parameter with seasonal eutrophication periods and the mass development of algae in locally contaminated areas of the reservoir. Emergency plans in case of cyanobacteria blooms and a lack of oxygen (especially nocturnal oxygen deficits) are necessary.

The evaluation of the eutrophication risk has to be done using the P load concept of Vollenweider (OECD, 1982) and the determination of the critical P concentration is done using the phosphorus use efficiency relationship. This critical load concept must also be applied for aquaculture emissions (Selge *et al.*, 2015). This model is used worldwide and has been modified by Pan American Center for Sanitary Engineering and Environmental Sciences (CEPIS; SALAS & MARTINO, 1991). The differences in the critical P concentration as determined by different methods are very small. The application of the Vollenweider load concept for the Itaparica reservoir leads to a critical P concentration of $25 \mu\text{g L}^{-1}$, which corresponds to the CONAMA Resolution nº 357 (2005; SELGE *et al.*, 2015). The carrying capacity of Itaparica reservoir is given by CONAMA as $43,267 \text{ t y}^{-1}$ used as concept for further development (AURELIANO *et al.*, 2007). However, this leads to an overcharge of the reservoir if the P load concept is applied (Table 3).

The calculation of the P load of Itaparica reservoir gives a value of $3.32 \text{ g m}^{-2} \text{ y}^{-1}$ with a critical load of $2.84 \text{ g m}^{-2} \text{ y}^{-1}$, thus the Itaparica reservoir is already overcharged by nutrients, and eutrophication phenomenon, such as the mass development of algae and submerged macrophytes are observed. An increase in the extent of aquaculture production to the CONAMA license amount of $43,267 \text{ t y}^{-1}$ would increase the P load to $3.68 \text{ g m}^{-2} \text{ y}^{-1}$, which exceeds the critical value by 130%. However, the calculation of the P load and carrying capacity for the whole reservoir was not supported by the water exchange conditions, and the effect of it being an isolated bay must also be considered. For Icó-Mandantes bay, the actual P load is $1.54 \text{ g m}^{-2} \text{ y}^{-1}$, without any aquaculture system, which significantly exceeds the critical load by 324%. If 1% of the bay area is used for aquaculture, the load would increase to $2.22 \text{ g m}^{-2} \text{ y}^{-1}$, which corresponds to an overcharge of 467%.

SUSTAINABILITY OF AQUACULTURE IN RESERVOIRS

Aquaculture is an effective and nearly unlimited technology for fish production, but the environmental impact has to be reduced, in many locations intensive aquaculture has already led to an overcharge of aquatic ecosystems. Under Brazilian law (Lei Federal nº 9.433 from 08.01.1997), multiple water uses are established and aquatic ecosystem services must be protected. The sustainability of aquaculture is based on (1) the selected species, (2) cultivation systems, and (3) the feed type and origin.

The use of native or already introduced species is a fundamental requirement to protect the natural fish bio-

coenosis. When new species are used some will escape from aquaculture systems and can become predators of natural species, act as vectors of (new) fish diseases or replace native species by being more competitive in the local ecosystems.

The use of adapted culturing systems makes land-based systems, such as ponds or tanks with wastewater treatment facilities, a more appropriate alternative. The treatment of aquaculture ponds or tanks with flow-through systems is a necessary practice. Treatment technologies were reviewed by Snow *et al.* (2012). Net cages used in lakes and reservoirs are not

Table 3 – The phosphorus load calculation and critical load as a limit value for the eutrophication of Itaparica reservoir and Icó-Mandantes bay.

P sources (half-life in years of leaching)	g P m ⁻² year ⁻¹	
	Itaparica reservoir 2013	Icó-Mandantes bay 2013
Natural sources		
Inflow main stream in reservoir/in bay	1.561	0.274
Subwater basin (Caatinga)	1.279	0.397
P mobilisation from sediments (internal load)	0	0
Mineralisation of inundated soils (2 years)	<0.001	<0.001
Mineralisation of inundated trees	0.036	0.032
Atmospheric deposition by rain	0.054	0.054
Sub-Sum	2.927	0.758
Anthropogenic sources		
Water level changes and inflow in bay	0	0.048
P mobilisation from the desiccated littoral zone	0.013	0.014
P mobilisation from desiccated macrophytes	?	0.335
Actual aquaculture (24,000 t y ⁻¹)	0.312	0
Maximum aquaculture limit (43,267 t y ⁻¹)	*0.675	*0.675
Drainage water from agricultural areas	0.096	0.010
Wastewater inflow	0.026	0.100
Sub-Sum	0.369	0.459
Total load	3.318	1.217
Total load with maximum aquaculture	*3.681	*1.892
Critical load	2.838	0.475

*theoretical value at the maximum aquaculture capacity (feed with 1.2% P, conversion factor = 1.4); P mobilisation from desiccated macrophytes = 821 g m⁻² *Egeria densa* (dw), 0.2 % P, 65% covering of desiccated area.

a sustainable technology due to the contamination of the aquatic system. Additionally newly developed technologies, such as large planes beneath the net cages, with a water pumping system to collect organic matter (feed residue, feces) can reduce the environmental impact of aquatic systems, but this is cost intensive and does not have an effect on the excretion of dissolved nitrogen, phosphorous, and organic substances.

More advanced fish aquaculture systems use ponds and tanks on the border of reservoirs with a flow through by abstracting lake water. This technology permits the treatment of the wastewater in tanks, ponds, or in artificial wetlands, before it is released into the reservoir.

The feed used in aquaculture should be altered to minimize its environmental impact, e.g. no excess phosphorus and nitrogen, high digestibility, a high consistency in water, and a controlled feeding regime (TACON & FORSTER, 2003).

There is much interest in the more sustainable aquaculture – agriculture linked systems that use the aquaculture wastewater for the irrigation of farmland (IAA). The nutrients and organic matter support agricultural productivity and will meliorate the soils. During percolation through soils self-purification occurs, and the infiltration water released to the reservoir will be purified.

For natural lakes with limited water exchange and with an adopted fish biocoenosis, these effects generally prohibit net cage culture, but for reservoirs private property is often given, with a very high flow through and no natural fish biocoenosis exists, thus aquaculture is seen to offer opportunities for economic development.

Additionally, aquaculture within lakes or reservoirs should be prohibited, as it is already in many countries, e.g. Chile, or at least limited to the carrying capacity of the reservoir (GUNKEL *et al.*, 2013).

Aquaculture is practiced in many countries for export, and to develop good standards for fish production, international certification such as GLOBALGAP are of high significance, which is private business certification focusing mainly on food safety standards, but too, on animal welfare, environmental protection, and social risk assessment (BOSTOCK *et al.*, 2010).

The proposed rules for good sustainable aquaculture, often referred to as “blue” or blue aquaculture, are as follows:

- No routine use of antibiotics, with the only use for bacterial infections, and with a sufficient elimination period from the fishes before they are sold.
- Water used for aquaculture must be free of cyanobacteria to avoid the accumulation of cyanotoxine in fish.
- The fish should be free of contaminants (pesticides, xenobiotica, heavy metals), which means the quality control of inflow water, feed, and cage construction.
- Use of feed with a low P content, to reduce the risk of eutrophication in the lake.
- Cultivation of native species or already introduced neozoans, but no introduction of new species, because some will escape and establish a new population.
- Sufficient water depth to avoid the accumulation of organic matter beneath the cages, e.g. by feces and feed loss.
- No excess feeding to minimize the feed loss. Use of only feed with a sufficiently high persistence in water to minimize losses.

CONCLUSION

The use of net cage culture systems for tilapia aquaculture is an inappropriate low-cost technology, because the potential for net cage emission treatment (dissolved nutrients, feed residue, and feces) is very restricted; in pond systems and raceways, wastewater treatment can be done with a simple sedimentation tanks or with secondary treatment steps by

aeration and denitrification. More advanced systems use aquaculture–agriculture linkage with wastewater used for the irrigation of farmland (IAA). In case of net cages, large planes beneath the net cages with a water pumping system to collect organic matter (feed residue, feces) enable the re-use of the wastewater in agriculture.

In Itaparica reservoir, aquaculture systems are licensed for 43,267 t y⁻¹, the actual productions amounts about 24,000 t y⁻¹ and lead already to eutrophication processes in the reservoir, especially in the bays where a reduced water exchange occur.

The site of net cages must consider the flushing rate and the theoretical water exchange time, which is normally decreased in bays of the reservoir. Additionally, licensing must be calculated for periodically occurring low water level with reduced water depth and reservoir area, otherwise eutrophication processes are triggered by the low water periods.

From an ecological perspective, net cages are not acceptable in areas with a water depth of <10 m beneath the cage, to guarantee the effective translocation and

dilution of particulate organic materials and avoid large increases in sediment beneath the cages.

The reservoir carrying capacity for aquaculture can be calculate by the P load (as sum of natural and anthropogenic phosphorus input), compared to the critical P load (given by the relationship between phosphorus and algae development), the critical P concentration in water corresponds to mesotrophic conditions with <10 µg Chl a L⁻¹. The critical P load of the Itaparica reservoir is already overcharged, and any increase of aquaculture will increase the eutrophication effects.

Feed used in aquaculture should minimize phosphorus and nitrogen content, optimize digestibility, and stability in water; additional, fish protein in feed should not be of wild fish catches.

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