

Transforming open mining pits into fish farms: Moving towards sustainability

Fred A. Otchere, Marcello M. Veiga, Jennifer J. Hinton, Renato A. Farias
and Robert Hamaguchi

Abstract

The legacy of mining activities has typically been land 'returned to wildlife', or, at some sites, degraded to such an extent that it is unsuitable for any alternate use. Progress towards sustainability is made when value is added in terms of the ecological, social and economic well-being of the community. In keeping with the principles of sustainable development, the innovative use of flooded open pits and tailings impoundments as commercial, recreational or ornamental fish farms should be considered in some locations, as it could make a significant contribution to the social equity, economic vitality and environmental integrity of mining communities. This article highlights the growing significance of aquaculture and explores the benefits and barriers to transforming flooded pits and impoundments into aquaculture operations. Among other benefits, aquaculture may provide a much-needed source of revenue, employment and, in some cases, food to communities impacted by mine closure. Further, aquaculture in a controlled closed environment may be more acceptable to critics of fish farming who are concerned about fish escapes and viral transmissions to wild populations. Despite the potential benefits, aquaculture in flooded pits and impoundments is not without its complications — it requires a site-specific design approach that must consider issues ranging from metals uptake by fish, to the long-term viability of the aquatic system as fish habitat, to the overall contribution of aquaculture to sustainability.

Keywords: Mining; Aquaculture; Sustainable development; Mining policy; Abandoned mines; Reclamation.

1. Introduction

Mine closure can have serious impacts on communities that rely on mining for their livelihoods. In many cases the mine has been a major economic player in the region, providing substantial fiscal revenue and many social services to the local community. Hence, mine closure raises concerns about the on-going environmental management of the mine, unemployment, and the continuation of social services, such as water, power, and health care. It is clear

that careful, advance planning for mine closure will not only mitigate negative economic impacts, but may also create opportunities to bring positive benefits to the local community. In order for mining to contribute to the sustainability of the affected communities, it is critical that planning for mine closure begin as early as possible — preferably before extractive work commences.

Although mines are often the key economic engines of the communities in which they operate, it has been suggested that, in many countries, the positive impact of foreign direct investment on local communities is often extremely limited, because of the lack of spillover effects (*Extractive Industries Review*, 2003). However, with appropriate local economic development (LED) instruments, mining projects could bring more than their own direct employment to a community. By voluntarily participating in or even driving a LED programme in a community, mining companies and other local stakeholders (local government, education institutions, other businesses) can work together to ensure that the local population, including the poorest segments, can benefit from the presence of new investments and share in the growth potential of the local

Fred A. Otchere, Researcher, Dept of Mining Engineering, University of British Columbia, Vancouver, BC, Canada.

Marcello M. Veiga, Associate Professor, Dept of Mining Engineering, University of British Columbia, Vancouver, BC, Canada and Consultant for the United Nations Industrial Development Organization (UNIDO), Vienna, Austria.

Jennifer J. Hinton, Research Assistant, Dept of Mining Engineering, University of British Columbia, Vancouver, BC, Canada.

Renato A. Farias, Post-graduate Researcher, São Paulo State University Aquaculture Center-CAUNESP, São Paulo, Brazil and CYTED-XIII, Brazil.

Robert Hamaguchi, Senior Environmental Engineer, Highland Valley Copper Mine, Logan Lake, BC, Canada.

economy. Importantly, LED programmes have increasingly been seen as entry points for national-level reform, especially in countries with weak governance and limited private sector development (for example in Latin America and Africa) (Balkau and Parsons, 1999).

The advancement of alternative sustainable livelihoods for local residents through the development of aquaculture in flooded pits and tailing ponds could contribute to sustainable development after the closure of mines, with a number of spin-off benefits to the local community, including economic diversification, increased food security and alternative land uses (e.g., tourism). This is progress towards sustainability. For example, when BHP's Island Copper Mine in Canada closed in 1995, the mine was instrumental in attracting and encouraging entrepreneurs who used buildings, dock facilities and water from the tailings ponds to establish wood processing and aquaculture operations, i.e., sustainable industries were made viable by the availability of the mine's infrastructure (Veiga *et al.*, 2001).

The main objective of this article is to demonstrate that the transformation of deactivated open pits and tailing ponds from metal and industrial mineral mines to commercial, recreational or ornamental fish farms may be a viable alternative end-use for land in some locations. First, this article reviews the main environmental issues and economic significance of aquaculture and highlights trends in productivity in this sector. Second, it explores the application of aquaculture in post-mining scenarios, describing the barriers which must be overcome to ensure its successful implementation. Two case studies are used as illustrations: a large-scale mine site in Canada and an artisanal mining context in Brazil. The article concludes with a discussion of the barriers to and benefits of aquaculture in terms of the sustainability in communities impacted by mining.

2. Aquaculture: Global and local implications

2.1. Main environmental issues

Aquaculture is defined as the production of aquatic organisms by the deliberate and controlled manipulation of their rates of growth, mortality, and reproduction, with the ultimate objective of harvesting products of commercial value. Aquaculture in open systems, or cage culture, involves placing a mesh or wire cage in a flowing, open water system, such as a lake, stream, reservoir or ocean. The constant water flow through the system is critical as it renews the oxygen supply and removes waste products (which are associated with fouling of cages) with little effort by the aquaculturalist. The size of mesh used for the cage is an essential parameter, as it must prevent the entry of predators, while retaining the valuable fish stock. Cage culture is often advantageous because it can be practiced on a small scale in almost any body of water. In addition,

cage culture is relatively unobtrusive to the landscape and leaves an opportunity for the water to be used in other ways, such as recreational fishing. Disadvantages include the possibility of fish escaping into the environment and the costs incurred to feed the fish, as they have less access to natural food sources in the caged structure. Also, cages are vulnerable to damage by pollution, storms and vandalism. One of the most significant concerns with cage culture is the potential for diseases, viruses, bacteria and artificial additives (e.g., antibiotics, fertilizers) to be dispersed to the natural environment, where wild fish stocks can be impacted (Iwama, 1991).

Closed water aquaculture systems are more technologically advanced than open water ponds, cages or raceway structures. Closed systems are essentially huge aquaria in which the water is filtered and re-circulated. Although they are very successful in terms of fish production, these systems require pumps and accessories and are expensive to maintain. Closed systems are designed to produce a high quality, reliable, uniform and consistent product. Closed system aquaculture also makes it possible to farm alien species, such as in Malaysia and Thailand, where crab, shrimp and lobster are raised with uniform and consistent sizes at highly competitive prices (FAO, 2000). High quality and uniformity come with healthy fish and adequate size grading. Closed systems can deliver more fish because they are capable of sorting more fish with less time and labour. In fact, calm fish remaining in cages or tanks commonly feed on schedule, continue to grow, and are less likely to incur diseases induced by physical damage or stress. The closed, confined environment can, on the other hand, lead to the rapid spread of diseases in these fish populations.

Diseases are inevitable in most aquaculture operations. The use of antibacterial drugs to control disease is commonplace today in both open and closed systems. Antibiotics including aureomycin, furazolidone, nitrofurazone, penicillin, oxolinic acid, amoxicillin, sulphamerazine and terramycin (oxytetracycline) have been used occasionally in fish farms in Europe and North America (Alabaster, 1982; Solbe, 1982). There is also evidence to suggest that much of the antibiotic administered with the feed is not consumed, because of a probable decline in appetite of sick fish (Iwama, 1991). Repeated use of antibiotics has resulted in antibiotic-resistant bacteria being found in the sediments under fish farms (Bjorklund, *et al.*, 1990; Austin, 1985, Herwig *et al.*, 1997). Public concern over the use of such products in food fish and the development of vaccinations to fight diseases have contributed to the trend of declining use of antibiotics (Iwama, 1991).

A number of other chemicals are also used in aquaculture to control other fish health issues and facility maintenance. Alabaster (1982) and Solbe (1982) documented the frequent use of malachite (CuCO₃) and formalin in European fish farms to control ectoparasites and fungus. Tributyltin (TBT), which had been extensively used as an antifouling agent (but is no longer used in Europe and North America),

Table 1. World fisheries production and utilization (million tonnes)

Production	1994	1995	1996	1997	1998	1999	2000	2001
INLAND								
Capture	6.7	7.2	7.4	7.5	8.0	8.2	8.8	8.7
Aquaculture	12.1	14.1	16.0	17.6	18.7	19.8	21.3	22.6
Total inland	18.8	21.4	23.4	25.1	26.7	28.0	30.1	31.3
MARINE								
Capture	84.7	84.3	86.0	86.1	78.3	84.1	86.7	83.7
Aquaculture	8.7	10.5	10.9	11.2	12.1	13.1	14.2	15.2
Total marine	93.4	94.8	96.9	97.3	90.4	97.2	100.9	98.9
Total capture	91.4	91.6	93.5	93.6	86.3	92.3	95.4	92.4
Total aquaculture	20.8	24.6	26.8	28.8	30.9	32.9	35.5	37.8
Total world fisheries	112.3	116.1	120.3	122.4	117.2	125.2	130.9	130.2

Source: Food and Agriculture Organization of the United Nations (FAO), 2000.

has received much attention as it has been shown to accumulate in the muscle of both finfish and molluscs (Davies *et al.*, 1986; Avarez and Ellis, 1990; Gabrielides *et al.*, 1990). Negative effects of TBT on the growth of shellfish (Paul and Davies, 1986; Davies *et al.*, 1987) and the inducement of imposex (i.e., wherein females develop part of the male reproductive system) in neogastropods have been demonstrated (Avarez and Ellis, 1990; Davies *et al.*, 1987). Fertilizers are another category of chemicals that are used to enhance natural productivity in farmed finfish and shellfish. While this is not as widespread an issue as antibiotics on a global scale, the possible toxic effect to the cultured species, which is of concern to the consumer, must be considered.

When aquaculture systems are isolated from open waters, these environmental impacts (diseases, chemicals, etc) are not transmitted to wild fish stocks. Aquaculture in mining pits introduces an interesting situation. As the pits are essentially isolated from open waters, more control can be exerted on water quality, food and system additives (e.g., prophylactics, fertilizers, etc), much like the scenario observed for closed systems. Due to the relatively large size of some mining pits (1–3 km²) and with the continued influx of rain and groundwater into the void, sufficient natural flushing and consequent dilution is anticipated in many locations. With the development of a unique ecosystem within the pits (i.e., through the growth of phytoplankton and zooplankton as well as organisms in other trophic levels), conditions may be created that prevent accumulation of waste (e.g., detritus) by breaking down this material. Changes within the aquatic ecosystem over time, such as the accumulation of waste, or the need to fertilize waters periodically, may hinder the sustainability of the venture or require the implementation of mitigative measures. For example, a fish waste recycling system, wherein material is collected and reconstituted into fish food is currently being developed by the Canada Department of Fisheries and Oceans (Gibson, 2003) and may be appropriate for these systems. Computer modeling of changing conditions

within these systems would be a useful tool for assessing the long-term viability of aquaculture and the efficacy of variations in design approaches.

2.2. Potential for aquaculture development

Human population is ever increasing, but the total potential production of fish is limited, even considering the potential improvements of fish-harvesting methods in the future. Despite fluctuations in supply and demand, fisheries and aquaculture remain an important source of food, employment and revenue in many countries and communities. Reported global production of fisheries through capture and aquaculture in 2001 (Table 1) was about 130 million tonnes (FAO, 2004). The production increase of 20 million tonnes over the last decade was mainly due to aquaculture, as capture fisheries production remained relatively stable. For the two decades following 1950, world marine and inland capture fisheries production increased on average by as much as 6%/annum. During the 1970s and 1980s, the average rate of increase declined to 2%/annum, falling to almost zero in the 1990s. This leveling off of the total catch follows the general trend of most of the world's fishing areas, which have apparently reached their maximum potential for capture fisheries production (FAO, 2004). It is therefore very unlikely that substantial increases in total catch will be obtained. In contrast, growth in aquaculture production has shown the opposite tendency. Starting from an insignificant total production, inland and marine aquaculture production grew by about 5%/annum between 1950 and 1969 and by about 8%/annum during the 1970s and 1980s, and it has increased further to 10%/annum since 1990.

Worldwide employment in the primary capture fisheries and aquaculture production sectors in 1998 was estimated at approximately 36 million people, with about 15 million full-time, 13 million part-time and 8 million occasional workers. For the first time, there is an indication that growth in employment in the primary sectors of fisheries and aquaculture has increased (FAO, 2004). Production in

inland and marine aquaculture has been increasing, and is now estimated to account for about 25% of the world's total production. Marine capture fisheries account for about 60% and inland capture fisheries for the remaining 15%.

3. Post-mining aquaculture

Mining represents a temporal land use, disrupting relatively small areas of land for a specific (usually short) period of time. Once the ore deposit is depleted, the land is ideally reclaimed for other uses, including recreation. In Canada, only 26% (8,000 hectares) of the 30,000 hectares of land disturbed by mining (by the end of 1990) has been reclaimed (Errington, 1991). Over 50% of proposed reclaimed land use objectives are aimed at providing wildlife habitat, grazing and forestry opportunities. Aquaculture is one alternative for land reclamation and restoration after mining that could support diversification of the economy in certain towns. One example is found at a hematite iron ore mine found beneath Steep Rock Lake, near Atikokan, Ontario (Sowa, 2002). When the mine closed in 1980, the site was allowed to return to its natural state. Pumps were turned off and the pits began filling with water. Steep Rock Lake is now host to a commercial fish farm. Fast growing poplar trees and scrub provide wildlife habitat, while local residents enjoy hiking, biking, and rock-climbing (Sowa, 2002). At the Granny Smith Goldmine in Australia, an unusual aquaculture venture represents an attempt to put something back in a location where mining companies are often criticized for their culture of extraction. Some of the fish found there include trout, silver perch and goldfish — all against a massive background of ore crushers and pits (Hayhow and Lamont, 2001). The Cobble Hill limestone quarry pit (just north of Victoria, Canada) has also been used to raise trout, which are used to stock lakes on Vancouver Island.

Acid rock drainage (ARD) has been described as 'the largest environmental liability facing the mining industry' (Errington, 1991). It has been estimated that ARD costs between US\$ 2 to 35 billion in North America for remediation and control (Batterham, 1998). Flooding of pits after mining is often recommended to inhibit the generation of ARD. Island Copper Mine in British Columbia, a BHP Billiton mine that closed in 1995, was flooded with seawater in July 1996, creating a lake covering 530 acres (Welchman and Aspinall, 2000). In situations where flooding is recommended, either for ARD purposes or for safe closure of the site, alternative uses of these man-made lakes should be explored further. The Pit Lake at Island Copper is fertilized every 10 days throughout the year to promote continuous algae blooms that scavenge the water of dissolved zinc, copper and cadmium. In a six-month period, dissolved Zn decreased to a concentration of 2 ppb, with copper and cadmium levels of the same magnitude (Welchman and Aspinall, 2000). The high quality of the surface water attracted M & E Enterprises to farm sturgeon

in separate plastic tanks using water drawn from the pit (Poling, 2000).

One of the most significant public concerns with aquaculture in mining pits relates to the uptake of metals by fish. Thus, it is of utmost importance to establish protocols to monitor metal concentrations in waters as well as biota. A number of parameters, including pH, Eh (redox potential) and DOC (dissolved organic carbon), have been shown to influence the speciation, and thus bioavailability of metals. For example, at low pH, copper — which can be highly toxic to most fish species and other aquatic organisms at relatively low concentrations — tends to be present as a free ion. In ionic form, Cu has been demonstrated to be more bioavailable than Cu complexed with natural organic acids. This is likely due to the competition for free Cu ions between dissolved organics and binding sites on fish gills or gut surfaces. Cu-organic complexes, despite their lower toxicity than free Cu, can be absorbed by plankton and bioaccumulated by fish.

Conversely, some metals have been shown to be more bioavailable as an organo-metal or metal organic complex (Parametrix, 1995). Mercury (Hg), for instance, is readily assimilated by organisms in the organo-metallic form, methylmercury. Mercury levels in fish from organic acid-rich (dark) waters are considerably higher than those from organic acid-poor waters. It has been suggested that the transformation of metallic mercury into its most toxic form, methylmercury, which is the Hg species found in most edible fish, seems to be mediated by the presence of humic substances in soils and aquatic environments (Meech *et al.*, 1998). Studies on the reaction of metallic mercury with organic acids have indicated that formation of soluble Hg-organic complexes is likely the main pathway for fish pollution (Veiga *et al.*, 1999). It is evident that the presence and abundance of organic matter plays a significant role in controlling metal mobility and bioavailability. Consequently, the mechanisms influencing organic matter complexation with essential and non-essential metals must be well understood to predict the impacts within a given system. The fraction of organic matter most relevant to metal behaviour in aquatic systems, humic substances, actually consists of a wide range of compounds with similar origins but variable properties.

Due to this heterogeneity, predicting the effects on metal complexation and bioavailability can be extremely difficult and will undoubtedly vary from site to site and may change over time with changing environmental conditions (Sparks, 1995). Laboratory studies, particularly bioassays, using different material from the pits and different water conditions can predict the effects of metal bioaccumulation, provide a means for monitoring the system, and may aid in the establishment of mitigation procedures. For instance, as fingerlings (post-larval stage or juvenile fish) are generally sensitive to some disruptions in water quality, they may be effective bioindicators; however, larger scale field tests must also be conducted to ascertain their efficacy in specific contexts. Metals cycling in the systems must also be assessed

prior to commencement of fish exposure. This involves sampling and analyses of metals and other physico-chemical parameters in various compartments (i.e., the water column), particulate matter and sediments. Hydrological parameters, such as rate of infiltration, flushing within the aquatic system, run-off water and groundwater conditions, must also be determined.

Other parameters, beyond water quality, also determine the suitability of open pits to aquaculture. Variables such as pit dimensions, physical stability of pit walls, ‘flood-ability’, proximity to natural water bodies, climate, accessibility, suitability for specific types of fish, presence of markets, land use, etc. must be considered. Significant re-contouring of pit walls, which may be costly or complicated, may be needed prior to flooding in order to ensure the pit is amenable to construction of aquaculture facilities.

Mining companies frequently are not interested in the aquaculture business and, when ARD is not an issue, other options for the pits are also considered. However, the public sometimes does not react favourably to the company reclamation/closure alternatives. For example, at Island Copper in Canada, the mining company proposed the transformation of the large pit into a garbage dump but the Port Hardy community reacted negatively to this idea (Nelson, 2000). Public involvement is fundamental to determine the best land use for reclaimed mine sites as well as the appropriateness of these artificial water bodies for commercial or recreational aquaculture (Roberts and Veiga, 2001).

In many locales, one of the main impediments to the implementation of innovative closure options, such as aquaculture in mine pits, relates to long-term liability. Despite the potential benefits to communities, the existence of mining policy that deters mining companies from implementing innovative, alternative end uses for land may preclude sustainable solutions for communities post-closure, particularly those reliant mainly on mining for their livelihoods. This is most unfortunate in situations where mining companies are concerned with environmental responsibilities during and after operations. Despite the liability hurdle, there are cases that demonstrate how challenges can be broached, if not overcome; two important examples in large scale and artisanal mining are presented below.

3.1. Case study: Aquaculture at a Canadian copper mine

Highland Valley Copper (HVC) has operated an open pit copper and molybdenum mine in the Highland Valley near Logan Lake since 1962. Stream run-off from the mine site is carefully monitored and controlled so that metal contamination of the surrounding region is prevented in accordance with environmental legislation and reclamation permits. Since the early 1970s, HVC has conducted annual environmental monitoring programmes in the vicinity of the mine to assess the effect of the mine on local water quality and fisheries resources. In the area surrounding HVC, rainbow trout (*Oncorhynchus mykiss*) occur naturally in



Figure 1. Trojan Tailing Pond at Highland Valley Copper Mine, B.C., Canada.

several creeks and rivers. From 1991 to 1994 some of the mining pits and tailing ponds were stocked with rainbow trout in order to ascertain their viability in these systems. Pits and ponds throughout the property were stocked with Kamloops rainbow trout obtained from a government operated hatchery at Loon Lake and at Abbotsford, British Columbia. Fish stocking has also been carried out on seepage collecting ponds from the Trojan tailings pond (Figure 1), which was shut down from active tailings disposal in 1987, and the Bethlehem main tailings impoundment. Fish have also been stocked in the Reclaimed Reservoir, where the effluent from the currently operating tailing impoundment is being pumped to feed back into the ore concentrator.

Highland Valley Copper has also been able to secure an aquaculture permit from the provincial government to raise salmon fries until smoltification (i.e., upon completion of the physical changes necessary for a young salmon to transition from a freshwater to saltwater environment). The smolts have been sold to fish farms on the Pacific coast. The pit lakes have been fertilized with about one tonne of phosphate per annum for the last 5 years. This has created algae blooms that adsorb metals in solution, carrying them down to the pit bottom. The food chain created as a result of fertilization has attracted insects to the pond surface, serving as a sustainable source of food for the trout. It is important to note that other fish species, such as Atlantic or Pacific salmon smolts, could not be raised economically on the natural food supply in a fertilized lake.

The success of the initiative in Trojan Pond is positively regarded by the general public. Every September for the last six years, a fundraising Fly Fishing Tournament and a public-pay fishing event have been held in Trojan Pond. With trout easily exceeding 5 pounds, fishing in the former

Table 2. Summary of average total metal concentrations (mg/kg wet weight) from rainbow trout *Oncorhynchus mykiss* liver collected at HVC from 1995 to 2001

Sample site	As	Cd	Hg	Cu	Zn	Mn	Fe	Mo
Highmont West Pit								
2001	0.11	0.07	0.054	126	31.1	1.36	322	1.31
2000	0.07	0.08	0.424	124	45.5	1.28	308	1.04
Highmont East Pit								
2000	0.14	0.12	0.044	374	30.1	1.36	486	1.71
1999	0.08	0.12	0.039	175	25.5	1.51	371	1.21
1997	0.17	NR	0.008	127	25.8	1.32	220	0.81
Reclaim Pond 4								
2001	0.03	0.01	0.011	28	24.1	2.54	204	1.31
1999	0.06	0.06	0.047	68	24.8	2.26	211	0.81
1997	0.03	NR	0.023	73	32.0	2.86	169	1.03
1995	0.06	NR	0.029	46	27.8	1.42	144	0.60
Trojan Tailing Pond								
2001	0.02	0.01	0.042	69	22.8	1.05	243	0.16
2000	0.04	0.03	0.070	77	26.8	1.62	189	0.17
1999	0.07	0.06	0.069	102	24.7	1.03	293	0.21
1998	0.03	NR	0.061	224	31.0	3.67	438	0.40
Billy Lake								
2001	0.02	<0.01	0.085	61	22.1	2.04	174	0.16
1999	0.07	0.06	0.177	38	24.6	1.70	111	0.18
1997	0.03	NR	0.664	64	23.7	1.15	136	0.18
1995	0.06	NR	0.499	74	23.0	1.46	102	<0.5
Mamit Lake								
2001	0.05	0.02	0.058	50	28.5	1.65	268	0.22
2000	0.03	0.03	0.088	49	27.8	1.95	271	0.25
1999	0.07	0.06	0.046	33	22.8	1.56	190	0.19
1998	0.02	NR	0.060	59	37.1	1.86	370	0.22
BC Lakes ^a (liver)	0.18	0.31	0.11	51.1	28.8	1.57	318	—

^a Relative levels in rainbow trout from uncontaminated British Columbia waters (Rieberger, 1992).

NR = not reported.

tailings pond is receiving widespread media coverage that attracts keen fly fishermen from all over the province and abroad. Proceeds from these events (totaling over \$50,000) have been donated to the Royal Inland Hospital Foundation to help purchase medical instruments. Trojan Pond has illustrated the Highland Valley Copper's slogan 'The Temporary Use of the Land for Mining.'

In monitoring surveys, metal levels in fish from HVC were compared to values in rainbow trout from 24 uncontaminated British Columbia lakes that were considered unaffected by human presence (Table 2) (Rieberger, 1992). Metals levels in fish liver from HVC fish were comparable to the BC lakes averages, with the exceptions of Cu and Zn, which often exceeded the average in the BC lakes. The level of arsenic was highest at Highmont pits and lowest at Billy Lake; in both situations they were below the BC lakes average concentrations. Manganese levels from Billy Lake, Mamit Lake and Reclaim Pond No. 4 exceeded the uncontaminated BC lakes average. Mercury concentrations on the other hand were relatively low at all locations.

Almost all the results were an order of magnitude lower than average BC lakes. Iron concentrations were also elevated above the BC lakes average in the Highmont pits, but, as Fe is an essential element, there is no health risk hazard associated with the levels observed.

These results suggest that metal uptake is not significant for most fish. As metals concentrations in muscles are not known, potential risks (if the fish were subject to human consumption), cannot be ascertained. However, as metals often bioconcentrate in the liver, low levels in that organ may be indicative of low muscle levels. The results at HVC are particularly interesting as fish food was derived from natural sources, i.e., although fertilizer was added to the systems, no food was given to the fish.

3.2. Case study: Aquaculture in Brazilian artisanal mining pits

The International Labour Organisation (ILO) estimates that the number of artisanal miners is currently around 13 million in 55 countries and rising, which suggests that 80 to 100 million people worldwide are directly and indirectly dependent on this activity for their livelihood (ILO, 1999). In the Brazilian Amazon alone, millions of artisanal gold miners have been using rudimentary techniques to extract more than 2,000 tonnes of gold since the beginning of the gold rush in the late 1970s.

Over the past two decades, more than 2,000 sites were mined and abandoned in the Amazon without any type of rehabilitation. Extensive use of mercury (as much as 4,000 tonnes) was employed and the pollutant released into the Amazon environment (Veiga *et al.*, 1999). The main problems related to artisanal mining are the environmental degradation and social destitution left when the easily extractable gold ore is depleted (Veiga and Hinton, 2002). As small-scale aquaculture can contribute to food security, increase the availability of a high protein food, and decrease economic risks through livelihood diversification (FAO, 2000), it could effectively contribute to well-being within an artisanal mining community context.

In the Alta Floresta region, north of the state of Mato Grosso, south of the Brazilian Amazon basin, the production of gold has resulted in almost 200 tonnes of mercury released over two decades (Hacon, 1996). As gold mining declined during the 1990s, populations drastically decreased from 120,000 to 38,000 and Alta Floresta was condemned to become a ghost town. After mining, the degraded land lost its value and was not amenable for agriculture. The local government, together with agriculture cooperatives, developed a strategy to return the region to its original use: agriculture. Among other ideas, the use of abandoned open pits for aquaculture was well received by the population (Figure 2). The newly established aquaculture association and the state government introduced financial incentives for locals and miners, who found new reasons to reside in the region. In conjunction with this initiative, the State



Figure 2. Typical abandoned flooded mining pit worked by artisanal gold miners in Alta Floresta, Brazil.

University of Mato Grosso and the Oswaldo Cruz Foundation from the Federal Ministry of Health have undertaken a meticulous monitoring programme to assess mercury in the area. They concluded that artificially-fed farmed fish had mercury levels compatible with the background levels found in wild fish (Farias *et al.*, 2001). The main species produced, ‘Tambaqui’ (*Colossoma macropomum*), has very low mercury levels, ranging from 0.04 ± 0.06 ppm, and the hybrid ‘Tambacu’ (*C. Macropomum* \times *Piaractus mesopotamicus*) has mercury levels of 0.05 ± 0.08 ppm, both of which are well below the World Health Organization and Brazilian guidelines of 0.5 ppm mercury. The support from the local university and the low cost of alevins (US\$ 10–12 per thousand) are encouraging local producers to invest in expanding their productions and to introduce other fish species. The main factors evaluated by the project researchers and producers are the adaptability of the species to conditions, factors contributing to increasing growth rates and feeding habits that allow use of inexpensive fish food, such as wastes from local agricultural activities.

In 2000, the fish production from abandoned open pits in the Alta Floresta region was 80 to 100 tonnes/year from 116 fish farms ranging in area from 1,000 to 10,000 m². About 900 people are directly involved in this activity. A small surplus of fish is sold in local markets, bringing the benefit of inexpensive fish to the surrounding community. Six farms have obtained capital to improve technologies, build local storage facilities and a fish processing plant, and increase their production in order to sell fish in the Mato Grosso capital, Cuiaba city.

4. Conclusion

If lands reclaimed from mining, or portions thereof, could be used for alternative revenue generating ventures — such as commercial fish farming and recreational (sport) fishing

— the well-being of communities which formerly relied on mining can be markedly improved. In addition to economic diversification and the value added to production in the area, one of the most significant benefits of establishing aquaculture is that it may strengthen the link between the community and the mine, thereby supporting the inclusion of the community in long-term monitoring programmes. Although it is clear that a number of innovative, alternative end uses for land should be explored by mining communities in conjunction with the surrounding communities, the implementation of aquaculture in mining scenarios has been the main focus throughout this review.

Aquaculture in mining pits is not a universal solution and must be analyzed on a case-by-case basis. Metals uptake by fish must be thoroughly assessed at any location considered, as well as the hydrology of the site (as it relates to flushing and chemical exchanges with natural systems) and other environmental issues (e.g., climate). Further, the costs of re-contouring mine pits may be prohibitively high in situations where it is required. In locations where the potential for metal uptake is high but fish health is maintained, sport fishing or ornamental fish farming can still be employed. Metals accumulation can also be reduced through shorter duration fish cultivation (i.e., using fast-growing fish species) and artificial feeding.

It is important to note that aquaculture must be evaluated on a site-specific basis. In the case of less developed regions, particularly in the often unregulated artisanal mining context, the capacity and resources to design aquaculture systems and monitor impacts (e.g., metals bioaccumulation) are severely lacking. Further, each context may have different objectives. For instance, a Canadian mine may seek to develop a recreational fishery in order to contribute to regional land use objectives (e.g., tourism), whereas in a developing country, aquaculture may provide an important source of food and employment. Aquaculture is just one option for alternative end uses for land at mine sites. It is an important example, nonetheless, of how progress towards sustainability can be achieved in communities where mining has taken place.

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