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Aquaculture: an Alternative Option for the Rehabilitation of Old Mine Pits in the Pampasian Region, Southeast of Buenos Aires, Argentina

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Abstract The Paso de Piedra mine pit lake (Batán, Buenos Aires, Argentina) was used to assess the potential conversion of a relict site into a productive aquaculture experience. The water quality and the productivity of its waters were determined in a baseline study of physicochemical and biological characteristics, including phytoplankton and zooplankton assemblages. This baseline study concluded that physicochemical values and nutrient concentrations were within the range for pejerrey (*Odontesthes bonariensis*) optimum development; and consequently, this pond was appropriate for seeding and growth of juvenile fish. After 2 years, fish specimens with an average total length of 38.15 ± 0.22 cm, a standard length of 35.10 ± 0.15 cm, and a mean weight of 520.50 ± 0.88 g were captured using *trasmallo* (gill-nets). Mature breeding stage males and females were detected. Thus, it appears possible to cultivate pejerrey at this site, and that this approach could be used in the Pampasian region to transform similar mine pits from environmental liabilities into attractive, productive sites.

Keywords Aquaculture · Argentina · Environmental liabilities · Mine pit rehabilitation · Mine pit restoration · *Odontesthes bonariensis*

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Introduction

The quarrying of rock material (i.e. quartzites) for road construction has been going in the Partido de General Pueyrredon, Buenos Aires province, Argentina, for several decades, mainly in the Chapadmalal Station and Batán areas. The old mine pits were mostly abandoned without concern for safety, erosion, and appearance (del Río et al. 2008; De Marco et al. 2005; Doupé and Lymbery 2005).

In Argentina, environmental protection for mining activities is now regulated by the National Mining Code, Law 24.585, Title XIII, Section II. The National Mining Code requires the presentation of an environmental impact report (EIR) before the start of each stage of mining, which has to be renovated and presented to the application authority every 2 years. The EIR describes the mining project, its environmental impact and the measures proposed for prevention, mitigation, rehabilitation, restoration, or reconstruction of the altered environment.

The mining industry usually works through a variety of strategies to reduce environmental and social damage caused by mining. Many of these strategies are focused around the concept of sustainability, including creating sustainable livelihoods (employment, community development and infrastructure), optimizing resource use, and final closure of mining operations (McCullough and Lund 2006).

Some of these pits are constructed either in part, or in whole, below the surrounding natural ground water levels. As a consequence, once dewatering operations stop and surface and ground waters equilibrate, these pits may fill with water and form pit lakes (McCullough and Lund 2006).

Although the target of a post-mining landscape is generally to restore the affected areas to the environment of the previous landscape, this is often impractical due to the high cost of earthworks, and the extended nonoperational times to relinquishment. However, achieving a planned landscape with equal or even greater social and environmental value is one way that the mining industry can contribute to a region′s long-term sustainability (McCullough et al. 2009). Doupé and Lymbery (2005) identified eight distinct end uses for mine lakes throughout the world: recreation and tourism, wildlife conservation, aquaculture, irrigation, livestock water, potable water, industrial water, and chemical extraction.

Aquaculture in pit lakes represents a potential means to rehabilitate these environments, improving their appearance and productivity (Axler et al. 1996; Doupé and Lymbery 2005; Mallo 2007; Miller 2008; Viadero and Tierney 2003). Mine water sources are often nearly ideal in temperature, alkalinity, and pH for raising fish such as trout, and have the additional value of being devoid of any serious fish pathogens. In West Virginia, a county park is now being used for educational and recreational purposes to the benefit of the whole community (Miller 2008).

Aquaculture can be intensive (i.e. fish farms) or extensive, in which the fish density seeding is low, and there is no external food supply or water exchange (Midlen and Redding 1998). Using mine water for aquaculture is a practical way to avoid pathogens and their hosts (snails, worms, birds, and other fish) that continually threaten fish farms (Miller 2008).

Water used to develop aquaculture must have appropriate characteristics. Prior to the selection of the biological species to be cultured, a series of baseline studies must be done, mainly related to water quality and its availability, and sediment characteristics. Within these scenarios, autochthonous (e.g. pejerrey: *Odontesthes bonariensis,* catfish: *Rhamdia sapo*), as well as exotic (e.g. carpa: *Cyprinus carpio,* rainbow trout: *Onchorhynchus mykiis*) fish species may be cultured, considering that in these closed environments, there is no risk of introducing exotic species into natural water bodies.

In this paper, we present a study of the use of extensive aquaculture as an alternative option for the rehabilitation of old mine pits, with the goal of: (a) implementing fish culture as a low impact and productive alternative way to rehabilitate mine pit lakes, and (b) establishing a recreational alternative and sport fishing activity for these mine pits in the Argentina Pampas region, which at present are a potential liability.

Materials and Methods

Study Area

Previous to the aquaculture experiment, a baseline analysis of 14 mines pits lakes in the Partido de General Pueyrredon was conducted and hydrological parameters (dissolved oxygen, temperature, salinity conductivity, turbidity, and pH), nutrients, photosynthetic pigments, particulate organic material, and plankton assemblages were determined. The Paso de Piedra mine lake (see location in Fig. 1a, b) was selected, due to several logistical characteristics: its proximity to urban areas, the presence of control staff who could prevent unauthorized visits to the water body, and restoration practices that involve the recreational use of its adjacent land area. This mine pit has an approximate area of 2,924 m^2 and a maximum detected depth of 6 m (Fig. 2). The lake, like most pit lakes, has steep sides. The dominant aquatic vegetation consisted of: *Ricciocarpus* sp., *Typha latifolia* L., *Lemna* sp., *Juncus* sp. *Mentha pulegium* L., *Eleocharis* sp., and *Cyperus* spp.

Hydrological Parameters

In situ hydrological parameters (dissolved oxygen, temperature, salinity, conductivity, turbidity, and pH), were seasonally measured at the surface and different depth (1, 2, 4, and 6 m) in Paso de Piedra mine lake using a Horiba U-10 portable digital multiparameter device. The U-10 is flexible enough to use for checking the quality of a broad range of water samples, from factory effluent to urban drainage, river water, lake and marsh water, aquatic culture tanks, agricultural water supplies, and sea water. Salinity was calculated from the conductivity data, and U-10 provided automatic salinity correction for dissolved oxygen.

Nutrients, Photosynthetic Pigments and POM

Dissolved inorganic nitrogen (DIN: nitrates, nitrites, and ammonium) were measured using the methods of Treguer and Le Corre (1975); Grasshoff et al. (1983) and APHA-AWWA-WEF (1998), respectively. Dissolved inorganic phosphorous (DIP, phosphates) was determined by the method described by Eberlein and Kattner (1987). Chlorophyll *a* and phaeopigments concentrations were obtained according to Lorenzen (1967) and Jeffrey and Humphrey (1975). Particulate organic matter (POM) was determined according to Strickland and Parsons (1968), and silicates according to Corp (1973). Data were obtained at surface during summer and winter, since these are the most extreme seasons within temperate regions (Rosso 2006). The chemical analyses were conducted in the Laboratory of Marine Chemistry in the IADO-CONICET.

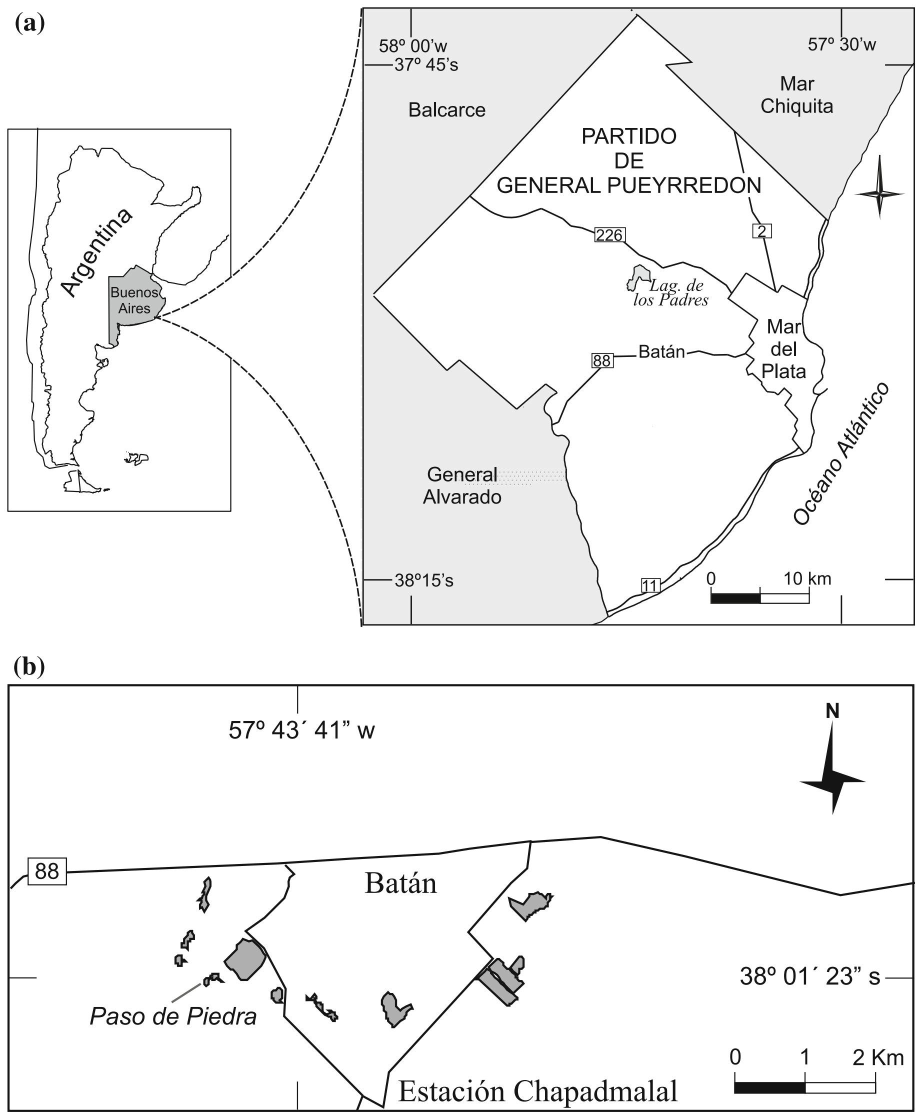

Fig. 1 **a** Small scale general-purpose map of location of the area of mine pits in the Partido de General Pueyrredon; **b** the location of the Paso de Piedra mine pit lake

Plankton

Samples of plankton assemblages (for qualitative and quantitative study) were obtained, only at surface, by filtration (50 L) through a *Hensen* net (mesh size 50 μm), with a reducing cone and detachable collector (Vernick 1995). Samples were preserved with formaldehyde solution (3%), and later analyzed using a Sedgwick-Rafter cell and a Leitz compound microscope with 10 × 10 magnifications (Lopretto and Tell 1995).

Species Selection, Type of Culture, Supply, Transport, Seeding, and Crop

Based on the results of the baseline study of the hydrology and water chemistry (discussed below), the species selected for this study was *O. bonariensis*, a common native species in freshwater pampasian environments. The common name for this species is pejerrey. It is one of many silversides (atheriniform) fishes distributed in marine, estuarine, and freshwater environments in tropical and temperate regions around the world. In South America, silversides occur mainly in coastal lagoons and marine waters of the southern region, and the genus *Odontesthes* comprises at least five freshwater and two marine species (Beheregaray and Levy 2000). Pejerrey is an inland water fish from the Pampas region within Argentina, Uruguay, and Southern Brazil. Pejerrey is a very popular fish in this region and has a long history of domestic and international introductions, which attests to the high quality and market value of its flesh, as well as its attractiveness as a game fish. The desirable characteristics of pejerrey also make it a good candidate for aquaculture, and the first trials on pejerrey cultivation (atheriniculture) were started more than a century ago in Argentina. Despite considerable interest in its development, little progress has been made, and

Fig. 2 Paso de Piedra mine pit lake

atheriniculture is still restricted to propagation and stocking for sport fishing purposes (Somoza et al. 2008).

Based on previous cultivation records for pejerrey (Berasain et al. 2002, 2004; Colautti and Remes Lenicov 2001; Colautti et al. 2004; Gómez 1998; Grosman 1995; López et al. 1994; Luchini et al. 1984; Miranda and Somoza 2002; Mallo et al. 2004; Reartes 1987, 1995; Somoza et al. 2008), it appeared that pejerrey, which is a commercial fish, would rapidly acclimate to the mine lake culture without water exchange or exogenous feeding, and that only a low seeding density was required. This pit lake lacked fish before seeding, which meant that future development of its population within this closed environment could be important to the Chascomús Hydrobiological Station (Provincial Direction of Fishing, Ministry of Agrarian Affairs, province of Buenos Aires, Argentina), since seeding records within pejerrey virgin environments are important for this agency (Remes Lenicov pers. comm.).

Five hundred juvenile specimens of *O. bonariensis* were provided by the Chascomús Hydrobiological Station of 11.47 ± 1.49 cm standard length (standard length refers to the length of a fish measured from the tip of the snout to the posterior end of the last vertebra); 12.89 ± 1.67 cm total length (total length refers to the length from the tip of the snout to the tip of the longer lobe of the caudal fin), and 20.96 ± 10.12 g weight (all parameters registered at $t = 0$, time before seeding) were seeded.

At 24 h, the fishes were checked for stress and mortality events. No mortality or erratic swimming (an indicator of stress) was detected. At 24 months, samples were taken in order to observe growth. *Trasmallo* nets (gill nets) (20 m long, with 3 mesh sizes) were placed at an underwater depth of 1 m for 3 h (from 11.00 a.m. to 02.00 p.m.), and 38 specimens were captured.

Results

Study of the Physico-Chemical Characteristics

Values of temperature (°C), dissolved oxygen (ppm or mg L^{-1}), conductivity (µS cm^{-1}), salinity (g L^{-1}), pH, and turbidity (NTU) were determined to be appropriate for the cultivation of the selected species (Table 1). Temperature ranged between 8.5 and 23.1°C at the surface, and between 7.0 and 19.9°C at a depth of 6 m (winter and summer, respectively). Dissolved oxygen measurements were always in the range of oxygenated waters (a minimum of 5.64 mg L^{-1} at a depth of 6 m during the winter, and a maximum of 13.3 mg L^{-1} at the surface during the spring). The pH values obtained (7–9.28) indicated that this mine pit′s waters were slightly alkaline. The salinity values were very low: 0.0 g L^{-1} at the surface and 0.1 g L^{-1} near the bottom (6 m), as was turbidity (14–43 NTU). Conductivity at surface ranged from 206 µS cm^{-1} to 265 µS cm^{-1}, while conductivity at 6 m depth fluctuated between 265 µS cm^{-1} and 289 µS cm^{-1}.

All nitrogen (N) and phosphorus (P) nutrients concentrations (nitrites: 0.007 mg L^{-1} in winter and 0.002 mg L^{-1} in summer; nitrates: 4.60 mg L^{-1} in winter and 0.138 mg L^{-1} in summer; ammonium: 0.217 mg L^{-1} in winter and 0.242 mg L^{-1} in summer; and phosphates: 0.02 mg L^{-1} in winter and 0.02 mg L^{-1} in summer), as well as silicates (12.87 mg L^{-1} in winter and 8.14 mg L^{-1} in summer)

Table 1 Seasonal physicochemical parameters in the Paso de Piedra mine lake

Depth (m)	Temp. (°C)	D.O.* (ppm)	Cond (µS cm^{-1})	pH	Salinity (gL^{-1})	Turbidity (NTU)**
Autumn						
Surface	15.6	9.62	257	8.90	0.00	25
1	14.8	9.38	260	8.99	0.00	25
2	10.7	9.40	255	8.98	0.00	26
4	10.0	8.01	257	8.90	0.00	32
6	9.0	6.64	265	8.71	0.10	37
Winter						
Surface	8.5	9.45	265	7.10	0.00	23
1	8.3	9.56	261	7.27	0.00	24
2	8.1	9.54	259	7.28	0.00	26
4	7.9	7.76	267	7.00	0.00	29
6	7.0	5.64	289	7.51	0.10	39
Spring						
Surface	18.6	13.3	206	8.20	0.00	43
1	14.8	11.8	210	8.78	0.00	42
2	12.3	9.63	235	8.21	0.00	28
4	11.0	9.26	268	8.20	0.10	14
6	10.1	6.94	286	8.10	0.10	27
Summer						
Surface	23.1	9.23	216	8.01	0.00	39
1	22.2	7.68	238	8.00	0.00	38
2	22.2	7.29	243	8.23	0.00	25
4	21.6	6.93	276	8.43	0.10	19
6	19.9	6.45	286	8.71	0.10	17

* *D.O.* dissolved oxygen, ** *NTU* nephelometric turbidity units

Table 2 Nutrients, chlorophyll *a*, phaeopigments, and particulate organic matter (POM) concentrations in Paso de Piedra mine lake during winter and summer

Parameters	Winter	Summer
Nitrites (mg L^{-1})	0.0073	0.0027
Nitrates (mg L^{-1})	4.6	0.138
Ammonium (mg L^{-1})	0.217	0.242
Phosphates (mg L^{-1})	0.02	0.023
Silicates (mg L^{-1})	12.87	8.14
Chlorophyll *a* (µg L^{-1})	28.37	10.74
Phaeopigments (µg L^{-1})	11.5	5.32
POM (mg C m^{-3})	1,771	2,843

(Table 2) were below the maximum suggested values for this species culture. Chlorophyll *a* and phaeopigments concentrations (10.74–28.37 µg L^{-1} and 5.32–11.5 µg L^{-1}) and POM (1,771–2,843 mg C m^{-3}) were within the range of natural pampasian clear water bodies.

Study of Plankton

A great abundance of phytoplankton species (Chlorophyceae, Cyanophyceae, Bacillariophyceae and Dinophyceae) was detected along the study period. *Ankistrodesmus* sp. (Chlorophyceae) and the dinoflagellate *Gymnodinium* sp. were abundant during the summer (24,232 ind L^{-1} and 16,286 ind L^{-1}, respectively). Blooms of *Anabaena* sp. (159,026.4 ind L^{-1}) and abundant *Ankistrodesmus* sp. (22,816.8 ind L^{-1}) were recorded in winter (Table 3a).

Regarding zooplankton, the rotifer *Keratella cochlearis* dominated during the winter (8,956.8 ind L^{-1}), together with nauplii (larvae) of Calanoidea copepods, Cladocera and Ostracoda were recorded. Total zooplankton concentrations were 9,201.6 ind L^{-1}. During summer, zooplankton reached 5,412.6 ind L^{-1}, with *Keratella cochlearis* still dominant, and *Brachionus caudatus*, *Brachionus havanaensis*, *Lecane lecane*, *Polyarthra* sp., and nauplii of Copepoda also present (Table 3b).

Seeding and Growth

At 24 months, 38 specimens were captured: mean total length (TL) was 38.15 ± 0.22 cm; mean standard length (SL) was 35.10 ± 0.15 cm. Mean weight of captured specimens was 520.50 ± 0.88 g. Percentage of growth was 196% of TL, 206% of SL, and 2,383% of weight. Sexually mature female as well as male specimens were captured, as indicated by the release of ovocites and sperm when pressing the abdomen.

Table 3 Phytoplankton (**a**) and zooplankton (**b**) abundance in Paso de Piedra mine lake

Summer phytoplankton	(ind L^{-1})	Winter phytoplankton	(ind L^{-1})
(a)			
Class chlorophyceae		Class chlorophyceae	
Ankistrodesmus sp.	24,232	*Ankistrodesmus sp.*	22,816.8
Actynastrum sp.	31.2	*Actynastrum* sp.	7.2
Pediastrum boryanum	20.8	*Pediastrum boryanum*	7.2
Scenedesmus sp. 1	728	*Pediastrum simplex*	728
Scenedesmus sp. 2	457.6	*Scenedesmus* sp. 1	28.8
Scenedesmus sp. 3	1,716	*Scenedesmus* sp. 2	158.4
Scenedesmus sp. 4	312	*Scenedesmus* sp. 3	194.4
Scenedesmus sp. 5	114.4	*Scenedesmus* sp. 4	21.6
Sphaerocystis sp.	270.4	*Spirogyra* sp.	7.2
Staurastrum sp.	572	*Sphaerocystis* sp.	270.4
Tetraedron sp.	499.2	*Staurastrum* sp.	295.2
Zygnema sp.	20.8	*Tetraedron* sp.	7.2
Class bacillariophyceae		Class bacillariophyceae	
Amphora sp.	1,144	*Amphora* sp.	93.6
Cymbella sp. 1	187.2	*Cyclotella* sp.	187.2
Cymbella sp. 2	93.6	*Cymbella* sp. 1	223.2
Gomphonema sp.	156	*Cymbella* sp. 2	14.4
Navicula sp.	20.8	*Ephitemia* sp.	28.8
Nitszchia sp. 1	988	*Gomphonema* sp.	36
Nitszchia sp. 2	665.6	*Navicula* sp. 1	79.2
Schroederedia sp.	873.6	*Navicula* sp. 2	194.4
Synedra sp.	478.4	*Nitszchia* sp. 1	187.2
Class dinophyceae		*Nitszchia* sp. 2	14.4
Gymnodinium sp.	16,286.4	*Schroederedia* sp.	936
Class euglenophyceae		*Synedra* sp.	14.4
Phacus sp.	10.4	Class dinophyceae	
Class cyanophyceae		*Gymnodinium* sp.	43.2
Merismopedia sp.	4,524	Class cyanophyceae	
Oscillatoria sp.	83.2	*Anabaena* sp.	159,026.4
Spirulina sp.	145.6	*Aulacoseira* sp.	43.2
Total summer phytoplankton	54,631.2	Total winter phytoplankton	184,672.8
Summer zooplankton	(ind L^{-1})	Winter zooplankton	(ind L^{-1})
(b)			
Rotifera Monogononta		Rotifera Monogononta	
Brachionus caudatus	114.52	*Cephalodella* sp.	14.4
Brachionus havanaensis	323.66	*Keratella cochlearis*	8,956.8
Keratella cochlearis	4,451.6	*Polyarthra* sp.	108
Lecane lecane	229.05	*Cladocera*	100.8
Polyarthra sp.	199.17	*Ostracoda*	21.6
Copepoda nauplii	94.6		
Total summer zooplankton	5,412.6	Total winter zooplankton	9,201.6

Discussion and Conclusion

Pit lakes form when open-pit mining operations are discontinued or abandoned. These pits usually fill with water, most commonly by inflow of groundwater and by runoff from adjacent drainage basins (Castro and Moore 2000). The resulting water bodies are essentially artificial ponds. At the study site, the physicochemical conditions in the water and the biological assemblages indicated that aquaculture was feasible. Boyd (1990) reported water quality values in aquaculture reservoirs that were similar to those obtained in this research; which were within the range for pejerrey optimum development (Reartes 1995). Also, Bohn et al. (2004) indicated that nutrient concentrations were typical of shallow lakes in temperate areas, and Quirós et al. (2002) reported these values as characteristics of clear shallow lakes. The measured values indicated an oligotrophic state, and the N:P relation measured in winter indicated P-limitation. This P-limitation during winter may be related to a nutrient depletion as consequence of P consumption by *Anabaena* sp. bloom.

Although pejerrey is the most commonly stocked fish in Argentina, mainly in natural freshwater bodies in the Buenos Aires province (Grosman 1995), there are almost no published studies of culture or growth of *O. bonariensis* from juvenile to commercial size adults to compare our results with. Berasain et al. (2000) reported on intensive cultivation of larvae, juvenile, and reproductive stages of *O. bonariensis*. These cultures were developed in rectangular concrete tanks of 100 m^2 with artificial feeding and discontinuous circulation. After 18 months, a high survival rate (60.1%) was recorded, and individuals of 24.0 ± 0.43 cm SL and 168.2 ± 8.7 g were obtained. Berasain et al. (2002) developed pejerrey cultures with food supply in rectangular concrete tanks of 100 m^2. This resulted in specimens of 11.74 cm SL and 24.86 g, after 355 days of culture. These values are similar to those obtained by Luchini et al. (1984) in ponds of different sizes. These authors, although they recorded a low survival rate (7.4%), obtained specimens of 17.2 cm TL and 37 g weight after 434 days.

Reartes (1987) developed pejerrey cultures in concrete pools with organic compost fertilization, and after approximately 4 months (141 and 130 days, respectively); specimens between 10.10–11.9 g were obtained. According to that author, 2 or 3 years are needed to reach commercial lengths and weights (27 cm and 300 g, respectively). Considering this is a low growth species, extensive restocking was recommended.

Colautti and Remes Lenicov (2001), worked with different sizes of floating net cages in Navarro lagoon (Buenos Aires, Argentina), in order to obtain juvenile specimens (6–10 cm SL) at low cost, and then to seed the individuals in natural water bodies to be fattened up to commercial length and weight values. These authors obtained individuals of mean SL of 9.78 ± 0.976 cm and mean weights of 9.62 g after 242 days.

Our study provides information on growth of this species (up to commercial sizes) in an artificial water body. Values obtained (in length and weight) were highly satisfactory, considering that after 24 months, specimens of 38 cm (mean length) and 520 g (average weight) were obtained. Consequently, it can be concluded that the pejerrey extensive culture in anthropogenic pampasian temperate water bodies is very feasible. Considering that these quartzite quarry pits are currently a liability, rehabilitation of these water bodies into fish ponds would be a very positive option, in alignment with the recommendations of Vila and Soto (1986), who suggested that this species might be raised in artificial ecosystems for future development of artisanal fisheries. Moreover, such ponds could also be an alternative recreational and sporting activity, since it could be offered in a "pay for fishing" modality.

The potential for pit lakes to provide a benefit to companies, communities, and the environment is frequently unrecognized and yet may be a vital contribution to the sustainability of the open-cut mining industry. Sustainable pit lake management aims to minimize short and long term pit lake liabilities and maximize short and long term pit lake opportunities. Improved remediation technologies are offering more avenues for pit lakes resource exploitation than ever before, at the same time mining companies, local communities, and regulatory authorities are becoming more aware of the benefit these resources can offer (McCullough and Lund 2006).

The final water quality of a mine lake can be difficult to predict, and depends on factors such as the initial groundwater quality, the geological composition of the void wall and surrounding landscape, and the dynamics of evaporation and precipitation. Two major water quality problems often associated with mine lakes are salinisation and acidification (Doupé and Lymbery 2005). Salinisation occurs when evapotranspiration exceed precipitation and acidification problems are associated with sulphide mineral oxidation. In this region, the quarrying of rock material is just an extractive activity without chemical agents, and salinisation and acidification are not a concern. Inflow of groundwater is a physical process and pits fill with this water. Consequently no contamination was detected in the analysis of the pit lake water, which proved ideal for aquaculture purposes.

Concerning aquaculture, the primary risks to the environment are water nutrient enrichment or threats to aquatic biodiversity, if exotic species escape into natural waterways (Axler et al. 1998; Doupé and Lymbery 2005; Yokom et al. 1997). Nutrient enrichment is a problem associated with intensive aquaculture, where external food is supplied. In this extensive aquaculture experiment, that was not a problem, and the selected O. bonariensis is an autochthonous fish.

The mining industry has benefited from this post-mining land use in a number of ways. By converting a mine site into a productive aquaculture facility, a positive image was built, since sensitive game fish are being commercially produced from mine facilities. Another advantage to using aquaculture as a post-mining land use is the potential savings in reclaiming the land (Miller 2008).

Regarding environmental quality, these flooded and potentially dangerous pits, which after exploitation can be considered environmental liabilities without a social use, can be transformed into rehabilitated areas that are environmentally balanced and economically productive. The authors conclude that this experience can be transferred to other mine pits in the Southeastern Pampas region.

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