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São Gonçalo Channel as an Ecological Corridor for the Movement of Migratory Fishes: Environmental History and Perspectives for Fishery Management in the Mirim Lagoon, South Brazil

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Abstract

Ecological corridors are important for maintaining the flow of species between habitat patches. The analysis of historical records of the dam-sluice gate construction process and the ecology of known migratory fishes in the Patos-Mirim hydrographic system reveals large spatial scale environmental changes, such as the loss of potential estuarine area of 2,536 km² and the reduction of functional connectivity between the lagoons through the São Gonçalo channel corridor for five species: *Genidens barbus*, *Genidens planifrons*, *Genidens genidens* (sea catfishes), *Micropogonias furnieri* (whitemouth croaker) and *Mugil liza* (Lebranche mullet). Mitigation measures are indicated through the operation of the sluice gate system as well as the regulation of fishing along the São Gonçalo channel.

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Resumen

Los corredores ecológicos son importantes para mantener el flujo de especies entre hábitat. El análisis de los registros históricos del proceso de construcción de la compuerta de la esclusa y la ecología de los peces migratorios conocidos en el sistema hidrográfico Patos-Mirim muestra grandes cambios ambientales a escala espacial, como la pérdida de un área estuarina potencial de 2.536 km² y la reducción de la capacidad funcional. La conectividad entre las lagunas a través del corredor del canal São Gonçalo para cinco especies: *Genidens barbatus*, *Genidens planifrons*, *Genidens genidens*, *Micropogonias furnieri* y *Mugil liza*. Las medidas de mitigación están indicadas a través de la operación del sistema de compuertas y de la regulación de la pesca a lo largo del canal de São Gonçalo.

1. Introduction

The Patos-Mirim hydrographic system is the largest coastal lagoon in the world, covers a drainage basin of 201,626 km² (Kjerfve 1986) and has ecological and fishing relevance on a continental scale (Seeliger *et al.* 1998). In particular, the São Gonçalo channel watershed and Mirim lagoon are characterized by an ecologically important landscape, especially the wetland complexes, which host a large diversity of flora and fauna. Recognizing this value, both the Brazilian and the Uruguayan governments defined areas of ecological importance, such as the Taim Ecological Station located to the east of the Mirim lagoon, which is part of the Atlantic Forest Biosphere Reserve (UNESCO), and the Bañados del Este to the west, which is a Ramsar site and a wetland of international importance. Historically, increasing environmental pressure of anthropogenic origin in lagoon environments has been altering and degrading the services these ecosystems provide and raising global concern for ecosystem health, biodiversity risks, and human well-being (Tagliani *et al.*, 2003; Razinkovas *et al.*, 2008). The ecosystem services provided by such environments include the exploitation of biological resources, including marine, estuarine and freshwater fishes, which serve as a fishing resource (*i.e.*, source of income and food) and recreation and leisure activity (Reis & D’Incao, 2000; Welcome, 2001; Fontoura *et al.*, 2016). One of the anthropogenic impacts affecting the exploitation of these natural resources is the construction of dams and sluice gates,

which have effects on the structure of freshwater, estuarine and marine fish populations, such as a loss or reduction of connectivity of fish populations between aquatic ecosystems (Lucas & Baras, 2001; Carosfield *et al.*, 2004; Welcome *et al.*, 2005; Burns *et al.*, 2006b; Barletta *et al.*, 2010; Jutagate *et al.*, 2010). However, studies on the effects on fish populations in sea-connected lagoons and rivers are scarce in Central and South America considering the complex characteristics of the regional pool of species and the environmental filters established by natural and man-made barriers in each coastal aquatic system (Barthem *et al.*, 1991; Holmquist *et al.*, 1998; Lucas & Baras, 2001; Mouillot, 2007; Albuquerque *et al.*, 2010; Burns & Vieira, 2012; Mouchet *et al.*, 2013; Avigliano *et al.*, 2017).

The fish fauna of the Patos-Mirim lagoon system consists of more than 300 marine, estuarine and freshwater species (Chao *et al.*, 1985; Bertaco *et al.*, 2016) that present different types of marine, estuarine and freshwater habitat use (Chao *et al.*, 1985; Castelo, 1985; Pereira, 1994; Araújo, 1988; Lemos *et al.* 2014; Fontoura *et al.*, 2016; Avigliano *et al.*, 2017). The spatial arrangement of the Patos-Mirim lagoon system includes the “Barra” piers and the São Gonçalo channel, which are typified as corridors due to their rectilinear physiography that structurally interconnect marine, estuarine and freshwater habitat patches (*e.g.*, Seeliger *et al.*, 1998). In the 1970s, Brazil and Uruguay in partnership with the Food and Agriculture Organization

of the United Nations (FAO) developed a master plan for the Mirim lagoon to promote agricultural development around the Mirim lagoon and the São Gonçalo channel. One of the subprograms of that master plan was the construction of a sluice dam in the São Gonçalo channel. The objective of this system was to prevent the entry of salt water into part of the São Gonçalo channel and the Mirim lagoon during the dry season as well as to ensure the binational supply of freshwater (MI 1970). The effect of this environmental change re-

quires a reassessment of the ecological impact on the estuarine environment and long-distance migratory fish populations that use the São Gonçalo channel (Burns and Vieira 2012; Mouchet *et al.* 2013; Burns and Cheffe 2018). In this context, this study aims to describe the main environmental problems posed by sluice and related to the ecological corridor of the São Gonçalo channel and its implications for the migratory fish populations and fishery management in the Mirim lagoon.

2. Methodology

Study area

The Mirim lagoon watershed occupies an area of approximately 62,250 km², of which 29,250 km² (47%) is located in Brazilian territory and 33,000 km² (53%) is located in Uruguayan territory; forming a transboundary watershed (Figure 1A). The main tributaries located in the west portion are the rivers Cebollati, Jaguarão and Piratini. The lagoon body has an approximate area of 3,749 km² and is mostly located in the Brazilian territory, and it is connected to the Patos lagoon through the São Gonçalo natural channel with an extension of 76 km. (Figure 1A and 1B). This channel has a sinuous course with a width ranging between 200 and 300 m and depth of up to 10 m. The sluice dam cuts the São Gonçalo channel at a distance of 15 km from the Patos lagoon and 61 km from the Mirim lagoon. The natural flow regime of the São Gonçalo channel is complex and periodically reverses the direction of its flow, which is why it is classified as a channel. The mean hydrological discharge is 700 m³/s, with a flow rate of approximately 0,6 m/s (MI 1970). The maximum freshwater discharge values of approximately 3,000 m³/s are reached during flood season, while the discharge is zero during prolonged droughts, when the direction of the current is usually inverted towards the Mirim lagoon (MI, 1970).

Structure and operation of the Sluice Dam

The dam has 18 sluice gates measuring 12 × 3 m (Figure 1C). On the left bank of the dam, where locking is performed, there is a 120 × 17 m chamber. This lock features two 17 m high and 8 m wide sluice gates with level equalization systems (chambers and By-Pass gates). The sluice gate system is operated based on the Mirim lagoon water level; when the mean water level of the Mirim lagoon is close to a meter below sea level, the control of the discharge of the São Gonçalo channel to the Patos lagoon is initiated. This period generally extends from December to April when the Mirim lagoon historically had a greater probability of salinization (MI, 1970; FAO, 1972). The control of the level of the Mirim lagoon in this period is accomplished through the partial or total closure of the sluice gates and the reduction of the lock operation hours. In the remaining period, the sluice gates remain partially open, and the lock is open four times a day at specific times for crossing of the vessels.

Literature review

To assess the environmental history of the sluice dam as well as the ecology of the long-distance migratory species, a literature review of technical documents provided by the Mirim Lagoon Agency, the managing

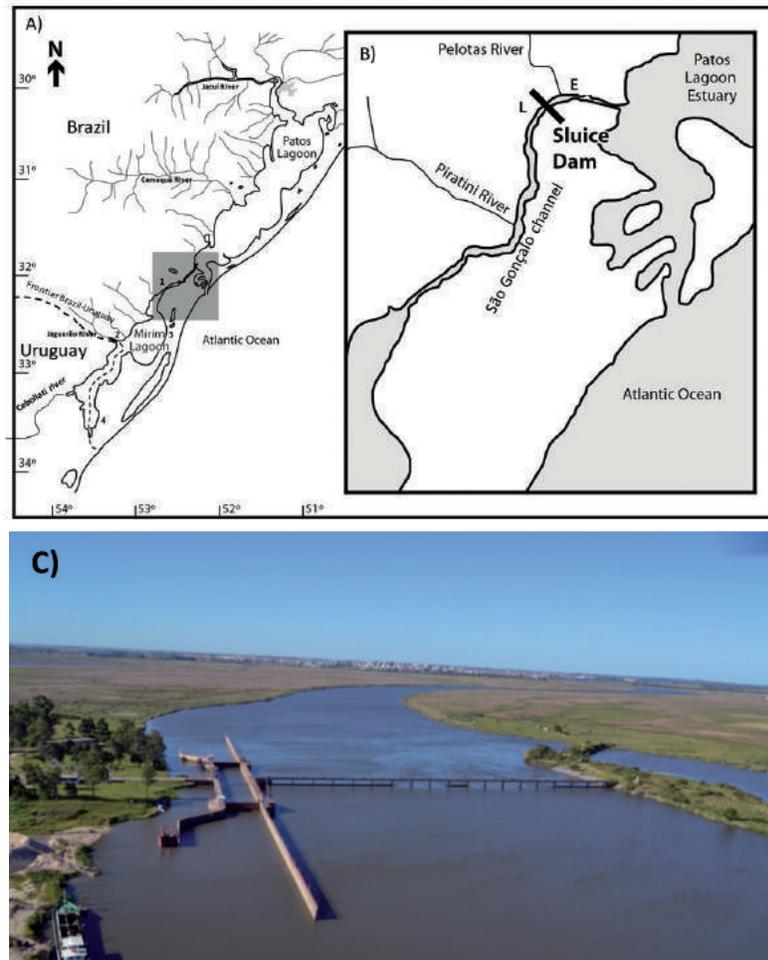


Figure 1. A) Geographic location of the São Gonçalo channel interconnecting the Patos and Mirim lagoons, in addition to the fishing communities in the Mirim lagoon (1-Santa Isabel; 2-Jaguarão; 3-Capilha e 4-Santa Vitória do Palmar); B) The São Gonçalo channel (gray box) cut by the sluice dam (black bar) forming the limnic (L) and estuarine (E) regions and C) Aerial view of the sluice dam; to the right are the sluice gates of the dam and to the left is the lock for boats.

body of the São Gonçalo channel and Mirim lagoon, was conducted, and secondary data (*i.e.* published data) on bioecology and fishing of long-distance migratory fish species in the Patos-Mirim watershed were also used. To calculate the availability of potential estuarine area in the Patos-Mirim lagoon system, the surface area (km²) of the Mirim lagoon, Patos lagoon and

São Gonçalo channel was considered before and after sluice dam construction only for the dry season (February-April) (MI, 1970; FAO 1972). In this period, the maximum salinity range recorded for each lagoon was considered (MI, 1970; Vassão, 1952; Cunha, 1953; Niencheski *et al.*, 1988).

3. Results and discussion

Loss of potential estuarine area

Traditionally, the Patos lagoon estuary is characterized according to the salinity gradient towards the north (Niencheski *et al.* 1988; Bemvenuti and Antônio Neto 1998; Seeliger *et al.*, 1998; Möller *et al.*, 2001; Vieira *et al.*, 2010), with a maximum range of estuarine conditions reaching 2/3 of the total area of the lagoon. However, there is historical evidence that the estuarine region of this Patos-Mirim lagoon complex extends to the Mirim lagoon through the São Gonçalo channel. The first salinity data for the Mirim lagoon date is from the year 1850, when the whole lagoon became salty, and in the year 1856, when it reached the Jaguarão River at 190 km from the connection with the ocean (Ihering, 1885) (Figure 1A). Later, a feasibility study of the sluice dam construction started in the 1960s showed that the greatest probability of salinization of this area was during the dry season, which ranged from February to April and varied between 45% and 75% (MI 1970). Spatially, the salinization probability frequency was calculated (MI 1970; FAO 1972 *op. cit.*) for a historical period of 59 years, with the cutoff between saltwater and freshwater considered 500 ppm, which is the maximum salinity allowed for irrigation water. Thus, the probability of salinization varied from 85%

at the connection of the São Gonçalo channel with the Mirim lagoon, 25% near the Capilha beach located east of the Mirim lagoon in its central portion, and 5% in the port of the municipality of Santa Vitória do Palmar, which is the southern end of the Brazilian portion of the Mirim lagoon (Figure 1A). Historical records on the salinity range and concentration indicate salinity values of 5 - 35 (Vassão, 1952; Cunha, 1953; MI, 1970; Burns *et al.*, 2006b; Moura *et al.*, 2012). In addition to the climatic, meteorological and physiographic factors, which are admittedly important to the salinization process of the Patos lagoon (Möller *et al.*, 1996; Vaz *et al.*, 2006), the study also highlights the spatial orientation of the São Gonçalo channel in the NE direction, which coincides with the prevailing winds during the dry season and explains the high values of salinity frequently recorded in connection with the Mirim lagoon.

Considering 14,022 km² of available area in the Patos and Mirim lagoons the maximum range of the salinization process recorded in the pristine environment stretched for 9,363 km², which covered two thirds of both lagoons and the entire São Gonçalo channel (Table 1). After the sluice dam construction in 1977, the saltwater wedge was interrupted, resulting in the loss

Table 1. Comparison of the potential estuarine area available (km²; %) during the dry season in the Patos-Mirim lagoon system (data from: Vassão, 1952; Cunha, 1953; MI, 1970; FAO, 1972; Niencheski *et al.*, 1988).

Environment	Surface Area (km ²)	Area Available			
		Pristine Condition*		Current Conditions	
		Limnic	Estuarine	Limnic	Estuarine
Patos Lagoon	10,227	3,409 (33%)	6,818 (67%)	3,409 (33%)	6,818 (67%)
São Gonçalo channel	45	0	45 (100%)	36 (80%)	9 (20%)
Mirim Lagoon	3,750	1,250 (33%)	2,500 (67%)	3,750 (100%)	0
Total area	14,022	4,659	9,363	7,195	6,827

*The pristine condition is before construction sluice dam (1977).

of a potential estuarine area of 2,536 km², in the Mirim lagoon and the São Gonçalo channel. Currently, salinization occurs in only 20% of the area of the São Gonçalo channel that is connected to the Patos lagoon. In this area during the summer (January, February and March) and late spring (December), approximately 70 marine and estuarine species have been recorded, mainly juvenile and adult mullet, whitemouth croaker and sea catfishes, which are important for regional and local fisheries (Araújo, 1988; Burns *et al.*, 2006b; Burns & Vieira 2012; Moura *et al.*, 2012; Mouchet *et al.*, 2013). However, given the unique environmental typology of this lagoon environment and its ecological relevance to the subtropical marine environment (*e.g.*, Seeliger *et al.*, 1998), the negative impacts of this environmental change process that occurred with the sluice dam construction are difficult to measure. When we consider the spatial dynamics of the nekton in the southern portion of the Patos lagoon, such as the movement of fishes and crustaceans through the “Barra” piers, especially during dry periods, the likely changes in the ecological dynamics of the São Gonçalo channel and Mirim lagoon can be identified, particularly in the marine fauna that uses estuarine areas for breeding, growth and feeding (Castello, 1985; Pereira 1994; Seeliger *et al.*, 1998) as well as in the sustainability of fishing of species with high commercial value, such as the pink shrimp *Farfantepenaeus paulensis* (Perez-Farfante, 1967) (Reis & D’Incao, 2000).

As far as environmental planning is concerned, large-scale spatial changes have occurred since the formation of the freshwater reservoir of the São Gonçalo channel and the Mirim lagoon, thus determining a new state of resistance and resilience of this, now fresh water only, ecosystem (Folke *et al.*, 2000). This information should be considered by the environmental management bodies, in particular by the Mirim lagoon Management Committee in the Brazilian territory, and collaboration and integration with environmental agencies in the Uruguayan territory should be fos-

tered. Similarly, the emergence of conflicts over water use, the decline in fish production (Piedras, 1994), the invasion and establishment of freshwater fish and molluscan species from other continents and watersheds (Burns *et al.*, 2006a; Harayashiki *et al.*, 2012), and the greater risk of eutrophication of the reservoir (Oliveira *et al.*, 2015) indicate the need for decision-makers to take action on the region’s development process (see section Mitigating Measures).

Migration routes and loss of connectivity

In total, eight long-distance migratory species have been recorded for the São Gonçalo channel-Mirim lagoon hydrographic system (Table 2). Three species are known as potamodromous in the Patos-Mirim lagoon system (Alves & Fontoura, 2009): the dourado *Salminus brasiliensis*, the streaked prochilod *Prochilodus lineatus* and the ‘piava’ *Megaleporinus obtusidens*. The only species considered to be endangered at the regional level is the dourado *S. brasiliensis*. The potamodromous species have recently been recorded for the São Gonçalo channel-Mirim lagoon watershed and are probably not directly affected by the sluice dam since their main habitat is the rivers located on the Plateau of Rio Grande do Sul west of the lacustrine body (Figure 1A) (Burns & Cheffe, 2018).

Of the eight marine migratory species recorded, sea catfishes *Genidens barbatus* and *G. planifrons* are endangered at both regional and national levels and have not yet been assessed at the global level (Table 2). On the other hand, *G. genidens* is classified as least concern (LC) at both regional and global levels and has not yet been assessed on a national scale. The evaluation of *G. genidens* globally emphasizes the need for research and monitoring of the harvest levels, fishing efforts and population numbers to confirm whether any serious population declines are occurring; if this proves to be the case, then a reassessment will result in the species being moved into a higher threat category (Acero & Bentancur, 2010). Such concern should be followed

Table 2. List of long–distance migratory fish in the in the ecological corridor of the São Gonçalo channel.

Order/Family	Species	Popular name	Status of Conservation			Migratory Patterns
			Brazilian Red List		IUCN	
			Regional	National		
Characiformes						
Bryconidae	<i>Salminus brasiliensis</i> (Cuvier, 1816)	dourado/dorado	EN	NA	NA	Potamodromy
Prochilodontidae	<i>Prochilodus lineatus</i> (Valenciennes, 1837)	grumatã/streaked prochilod	LC	NA	NA	Potamodromy
Anostomidae	<i>Megaleporinus obtusidens</i> (Valenciennes, 1837)	Piava	LC	NA	LC	Potamodromy
Siluriformes						
Ariidae	<i>Genidens barbatus</i> (Lacépède, 1803)	bagre-branco/Sea Catfish	EN	EN	NA	Diadromy
	<i>Genidens planifrons</i> (Higuchi, Reis & Araújo, 1982)	bagre-boca-larga/ Sea Catfish	CR	CR	NA	Diadromy
	<i>Genidens genidens</i> (Cuvier, 1829)	bagre-guri/Sea Catfish	LC	NA	LC	Diadromy
Perciformes						
Sciaenidae	<i>Micropogonias furnieri</i> (Desmarest, 1823)	whitemouth croaker/White-mouth Croaker	NA	NA	LC	Diadromy
Mugiliformes						
Mugilidae	<i>Mugil liza</i> Valenciennes, 1836	tainha/Mullet	NA	NA	DD	Diadromy
Source of the Conservation Status: IUCN (2015); National (MMA Ordinances no. 444/2014 and 445/2014) and Regional (Ordinance No. 51.797, 2014): Acronyms: EN - endangered; CR - critically endangered; LC - least concern; DD - deficient data; and NA- not evaluated.						

up in the reassessment of the conservation status of this species in the Rio Grande do Sul State, primarily because its spatial distribution is restricted to the continental portion of the Patos and Mirim lagoons and presents low frequency in the ocean (Fischer *et al.*, 2011). Thus, given the historical exploitation of the fishing resources in the region together with other anthropogenic activities, the *G. genidens* population has been placed under great environmental pressure in

this lagoon region. The conservation status of the lebranche mullet *Mugil liza* and the whitemouth croaker *Micropogonias furnieri* is less of a concern, given that those species use the estuarine region of the Patos lagoon as a growth and feeding area, mainly for juveniles (Chao *et al.*, 1985; Vieira, 2006), and the adult individuals explore the limnic region of the Patos and Mirim lagoons (Machado, 1976; Piedras, 1994; Fontoura *et al.* 2016).

On a larger scale, the five marine species recorded for the area do not represent a major concern regarding the species conservation status, mainly because they have a continental-scale spatial distribution, as in the case of the sea catfishes *G. barbatus* and *G. planifrons*, the mullet *Mugil liza* and the whitemouth croaker *Micropogonias furnieri* (Marceniuk & Menezes, 2007; Ace-ro & Bentancur, 2010; Aguilera Socorro *et al.*, 2015; Castro *et al.*, 2015). However, the degree of segregation of fish stocks for these species is not known, both among Brazilian regions and in Latin America, and as such, the conservation status and the state of the stocks can change drastically according to the geographical region evaluated, such as in the case of the species that supported artisanal fishing in the Patos estuary. Prior to the 1980s, the resources exploited by artisanal fishing consisted of fish, such as mullet, whitemouth croaker, black drum and sea catfish, as well as pink shrimp *F. paulensis* (Reis & D’Incao, 2000; Vieira *et al.*, 2010). However, as a result of the drastic decline in subsequent decades, *i.e.*, 20 years, at the beginning of the 21st century, estuarine fishing no longer exists as an economic activity except for shrimp and mullet fishing. Thus, considering the impact of fisheries in the coastal region adjacent to the continental area of the Patos lagoon on the stocks of these species (Haimovici & Cardoso, 2016), the extinction of the fishing activity due to overexploitation and population collapse provides a more accurate assessment of the negative impact of human activities on the coastal environment.

Regarding the three species of sea catfishes, the negative impacts of the sluice dam are of greater magnitude when we consider aspects of the ecology such as migratory routes and the reproduction and feeding habitat conditions described for this lagoon system. Historical records of the use of the São Gonçalo channel were provided by Devincenzi (1933) and Vaz-Ferreira (1969), where residents reported that every year from December to January, large schools, which were absent for the rest of the year, crossed the São Gonçalo channel

originating from the Patos lagoon, passed through the Mirim lagoon, and went up the Cebollati river during the spawning season, with some individuals measuring as much as 1 meter in total length (Figure 2A). In this river, specimens of the sea catfishes *Trachysurus barbatus* and *G. barbatus* (at the time listed as *T. barbatus*, and later as *Netuma barba*) were collected with eggs and juveniles in the oropharyngeal cavity, confirming the use of the Mirim lagoon in the Uruguayan territory for breeding. The distance traveled during reproductive migration by *G. barbatus* reached approximately 290 km considering the distance from the mouth of the “Barra” piers (connection of the Patos lagoon with the ocean) to the Cebollati river. Although the migratory route was not mentioned in the technical report of the environmental impact of the sluice dam, the species *G. barbatus* (= *N. barba*) was used as a target species in the study of fish passage because it uses the Mirim lagoon as spawning habitat (MI, 1970).

Thus, during migration for spawning, which occurred during flood periods (ocean-Mirim lagoon direction), the sluice should be open. However, juveniles travel from the Mirim lagoon to the sea when the sluice is closed, and the fish would need to pass through the sluice. Considering that these fish would swim near the surface, one of the water inlets was risen to the level of the hydrographic zero. The gates inside the chambers should be left partially open to allow the passage of fish from the Mirim lagoon to the Patos lagoon and potentially to the ocean (MI, 1970). To avoid reducing the flow rate and silting near the dam structures, only one of the water inlets has been designed to fulfill this purpose. However, the degree of blockage that the sluice dam has exerted on the movement of the target species *G. barbatus* has not been monitored since its construction in 1977, and recent observations indicated that the designed passage system was not functional for the three species sea catfishes included *G. genidens* and *G. planifrons* and not considered on environmental study of sluice dam (FAO, 1972; Burns & Vieira

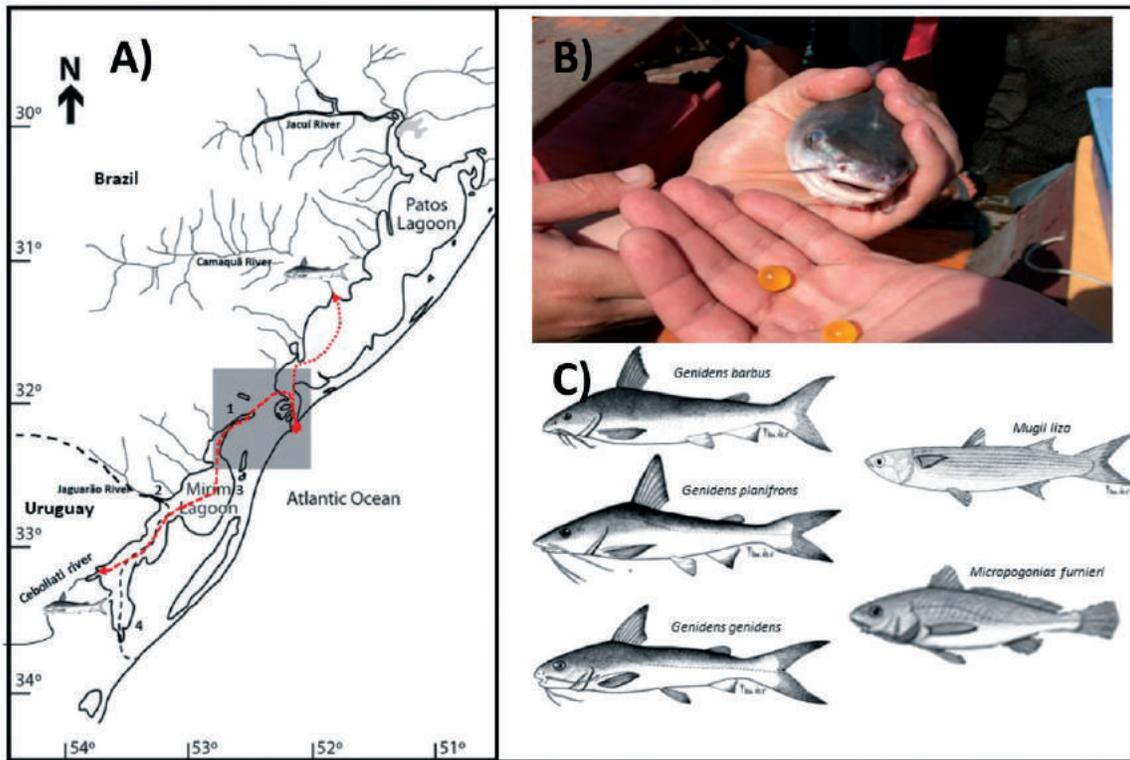


Figure 2. (A) Historical migratory routes described for *Genidens barbatus* in the Patos and Mirim lagoons (red line) in addition to the fishing communities in the Mirim lagoon (1 – Santa Isabel; 2 Jaguarão; 3 – Capilha e 4 – Santa Vitória do Palmar); (B) *Genidens genidens* male with eggs in the oral cavity collected from in the estuarine portion of the São Gonçalo channel (Source: Garcia *et al.* 2006); and (C) five diadromous species affected by the sluice dam construction.

2012) (Figure 2C). Araújo (1988) verified that these three species of sea catfishes move to the limnic region of this lagoon system, but did not consider the possible negative effects of the dam blocking the passage of the shoals, towards Mirim lagoon. Between 2005 and 2007, trawling was carried out daily and monthly and covering the two areas cut by the sluice dam on the São Gonçalo channel (Figure 3). Of the 3171 individuals captured, only 77 individuals were recorded in the limnic portion of the São Gonçalo channel; most individuals were identified as *G. genidens* (76 ind) and one as *G. barbatus* (Burns and Vieira 2012). The number of sea catfishes was highest during the summer and spring seasons in the estuarine area of the São Gonçalo chan-

nel, indicating that this areas was the breeding habitat of the *G. barbatus* and *G. genidens* species since most of the male individuals carried eggs and even juveniles with yolk sacs in the oropharyngeal cavity (Figure 2B) (Garcia *et al.* 2006), a typical reproductive behavior of these species (Yáñez-Arancibia & Lara-Domínguez 1988; Chao *et al.*, 1985; Reis, 1986; Velasco *et al.*, 2007; Dantas *et al.*, 2010; Mouchet *et al.*, 2013; Avigliano *et al.*, 2017) (Figure 2B). Although an extensive lagoon area located in the western portion of the Patos lagoon is drained by several rivers and sea catfish has potential usage as recorded for the mouth of the Camaquã River (Figure 2A) (Ihering, 1894, 1929), the blockage of the movement of sea catfish in the ocean

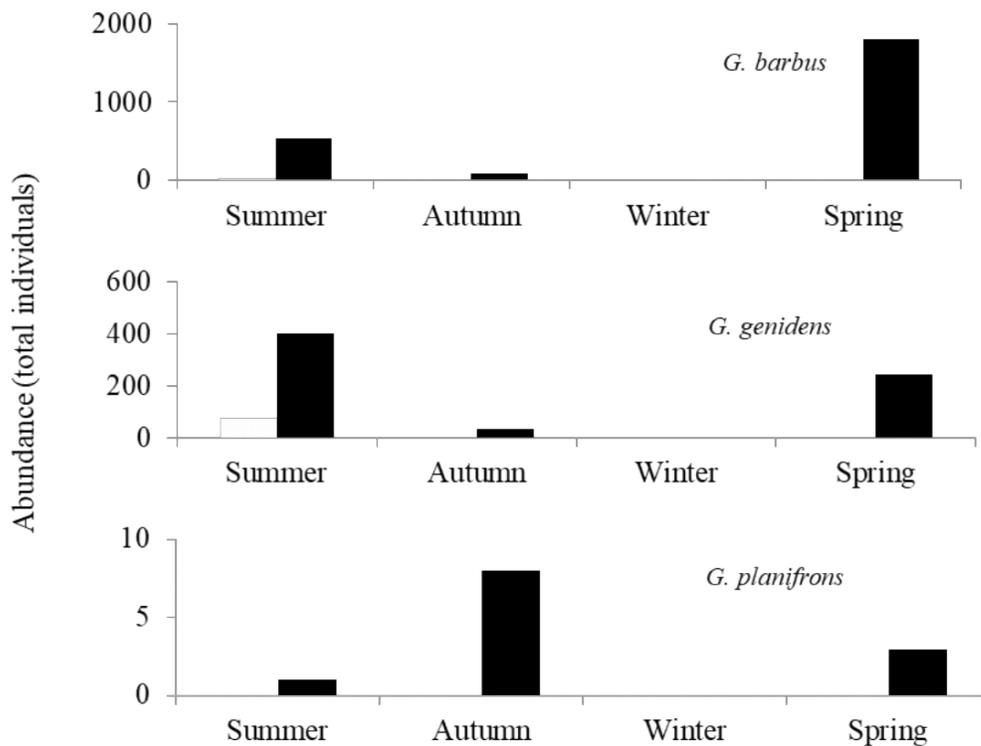


Figure 3. Total abundance and seasonal distribution of the three species of sea catfishes in the two areas of the São Gonçalo channel cut by the sluice dam: (gray bar) limnic area and (black bar) estuarine area (From: Burns & Vieira, 2012).

to the Mirim lagoon direction could be reduced with the development of a management plan (see Mitigating Measures).

Historical records of fish landings in the Mirim lagoon covering the period during and after the sluice dam construction (Machado, 1976; Piedras, 1994) show the predominance of freshwater species, such as the tigerfish *Hoplias aff. malabaricus* and silver catfish *Rhamdia quelen*, which combined represent approximately 81.30 and 83.22% of the total fish landed in the fishing sites of the Mirim Lagoon and São Gonçalo channel, respectively (Table 3). With regard to marine species, it is possible to identify the reduction and/or local extinction of the sea catfish share in addition to the reduction of the whitemouth croaker *M. furnieri* and the mullet *M. liza* shares between the evaluated

years (Machado, 1976; Piedras, 1994; Milani & Fontoura, 2007) (Table 3). Mullet had the largest reduction in annual production at 93,88%, followed by the whitemouth croaker at 92,03%. Currently qualitative data on fishing in the Mirim lagoon do not register the capture of marine species (Garcez & Saches-Botero, 2005).

The loss of functional connectivity of the São Gonçalo channel is more evident when we compare fish landing data of the marine species north of the Patos lagoon with the historical data from the Mirim lagoon (Table 3). To the north of the Patos lagoon, at a distance of more than 180 km from the “Barra” piers, the most predominant species in the fish landings were the mullet *M. liza* and the sea catfishes *G. barbus* and *G. genidens* (= *Genidens spp*) (Milani & Fontoura,

Table 3. Comparison of the relative importance (%) of the annual fish production in kilograms (kg) and tons (ton) of the target species in the Mirim lagoon and the Patos lagoon.

Target Species	Fish Production					
	Mirim lagoon				Patos lagoon	
	Machado (1976)		Piedras (1994)		Milani & Fontoura (2007)	
	kg	%	kg	%	ton	%
<i>Hoplias aff. malabaricus</i> (Bloch, 1794) Tigerfish	874,867	58.49	443,195	68.83	52.7	16.46
<i>Rhamdia quelen</i> (Quoy and Gaimard, 1824) Silver Catfish	341,278	22.81	96,066	14.91	15.4	4.81
<i>Micropogonias furnieri</i> (Desmarest, 1823) Whitemouth croaker	99,075	6.62	7,899	1.22	0.01	<0.01
<i>Pimelodus pintado</i> Azpelicueta, Lundberg and Loureiro, 2008 'Pintado'	73,869	4.93	9,580	1.48	2.0	0.62
<i>Odontesthes spp</i> Silversides	35,538	2.37	35,520	5.51	4.1	1.28
<i>Mugil liza Valenciennes</i> , 1836 Lebranche Mullet	34,901	2.33	2,136	0.33	41.7	13.03
<i>Cyphocharax voga</i> (Hensel, 1870) Characin	25,701	1.71			7.2	2.24
<i>Genidens spp.</i> Sea catfishes	5,077	0.33			23.4	7.31
<i>Catathyridium garmani</i> (Jordan, 1889) 'Linguado-zebra'					1.0	0.31
<i>Loricariichthys anus</i> (Valenciennes, 1835) 'Viola'					153.2	47.86
Other (freshwater species only)						6.057
Other (saltwater and freshwater species)*	5,421	0.36%				
Other (unidentified)			49,497	7.68		

**Australoheros acaroides*, *Geophagus brasiliensis*, *Rhinobatus sp.*, *Paralichthys sp.*, *Oligosarcus jenynsii*, *Oligosarcus robustus*, *Crenicichla punctata* and *Crenicichla lepidota*.

2007). In this study, the fishing activity was monitored for two consecutive years (2002-2004) and showed that the mullet *M. liza* and the catfishes *Genidens spp.* were fished throughout the observed period. The total catch of mullet ranged from 7.6 tons in the first year to 41.7 tons in the second year, with catch peaks during the months of November to February (Milani & Fontoura, 2007; Fontoura *et al.*, 2016). Sea catfishes, however, ranged from 4.5 tons in the first year to 23.4 tons in the second year, with catch peaks during the months of May to September. The variation in the catch of these species is attributed to hydrological and population cycles that are not yet understood and require continuous research programs and fishing data

collection since these species are under heavy fishing pressure in the northern region of the Patos lagoon (Ceni *et al.*, 2016; Fontoura *et al.*, 2016).

The current condition of the fishing activity in the hydrographic region of the São Gonçalo channel and the Mirim lagoon are not known by the relevant federal environmental agencies in Brazil. Historical fishing data in this region are available in two papers published in the last century and represent a monitoring time of 1 year (Machado, 1976; Piedras, 1994) (Table 4). The information available indicates that the number of boats operating in the two studied periods is similar and varies greatly between the summer and winter seasons (Table 5). Although the number of days

Table 4. Comparison of the fishing dynamics in the hydrographic region of the São Gonçalo channel and the Mirim lagoon during the years 1975-76 and 1993-94.

Characteristics	Machado (1976)	Piedras (1994)
Boats	Average length of 5 meters; all have engines, some of them run on diesel.	All powered by Diesel inboard engines.
Storage capacity	2 to 5 tons, with some up to 7 tons.	2 to 5 tons.
Number of boats	In the summer, it is approximately 80 and in the winter approximately 140 boats.	Ranged from 54 in the low season to 126 boats during the period of highest production (April and July). Number of boats per location: Jaguarão (31); Santa Isabel (27) and Santa Vitória (22).
Fishing Areas	Up to 3 meters deep.	Information not available.
Fishing trip duration	Between 1 to 5 days and the average time is between two and three days.	In summer the trip lasts up to two days and in winter it can reach 5 days.
Fishing gear	Nylon gillnets with mesh size between 45 - 50 mm knot-to-knot. Length of 30 to 50 m by 2.5 m of height. Each boat carries an average of 30 nets. Longlines with 80 to 400 hooks is also used by fishermen.	Each boat has between 30 and 100 gill nets, with mesh sizes between 35 and 70 mm knot-to-knot.

Table 5. Annual fish production in four locations in the São Gonçalo (SG) and Mirim (ML) watershed.

Fishing Locations	Annual Production (kg)	
	Machado (1976)	Piedras (1994)
Santa Isabel (SG)	437,664	250,312
Capilha (ML)	218,713	*
Jaguarão (ML)	553,020	246,385
Santa Vitória (ML)	286,330	143,079
Total Production	1495,727	639,776

of travel and storage capacity of the fish did not change between the monitored periods, the type of fishing gear, number of nets and mesh size showed changes, when we compare the annual fish production in this watershed between the four main fishing locations, it is possible to observe a decrease in the total annual production of all the locations of 42.77% (Table 5). Such evidence indicates that the region has been under large fishing pressure since the 1990s, and no information is currently available on the state of fisheries and exploited fish populations.

Mitigating measures

Measures to reestablish a greater degree of connectivity between the Patos and Mirim lagoons that aim to improve the flow of migratory species include recognition of the São Gonçalo channel as an ecological corridor. Such recognition may help in the determination and regulation of instruments for the protection and use of this environmental unit. Although the environmental studies carried out for the sluice dam have contemplated a series of social, economic and environmental variables, mainly regarding agricultural activity and water supply to promote the development of both the Brazilian and Uruguayan portions of the Mirim lagoon, the main management program to ensure reproductive migration of the target species *G. barbatus* was not properly implemented and monitored by the environmental agencies. Other species, such as the movement of adult mullet, whitemouth croaker as well as sea catfishes *G. planifrons* and *G. genidens*, should be included in a plan to reestablish the flow of species between the Patos and Mirim lagoons. To do so, the sluice dam operation system must be reviewed to evaluate the need

for a fishway system (FS). The development and design of FSS has been a challenge for engineers and ecologists in the area since the efficiency and selectivity of the current mechanisms in the Brazilian rivers raise a series of concerns as to its effectiveness in maintaining the functional connectivity of the populations (Lira *et al.*, 2017). In the case of marine species, an excellent example of a FS is discussed for the Santa Clara dam located on the Mucuri river at approximately 80 km from the connection with the Atlantic Ocean (Pompeu & Martinez, 2006, Pompeu & Martinez, 2007). In this dam, marine species are markedly diurnal and represent less than 1% of the total captured and consisted mainly of migratory fishes such as *Centropomus paralellus* Poey, 1860, *C. undecimalis* (Bloch, 1792) and *Mugil curema* Valenciennes, 1836. However, considering the difficulties in promoting downstream migration through the Santa Clara dam and the effect known as Ecological Traps (Pelicice & Agostinho, 2008), the passage of this group of species upstream was limited. Moreover, considering the lacustrine typology of the Patos-Mirim lagoon body, such as the hydrologic inversion of the current that characterizes the São Gonçalo channel, we recommend that a FS be developed or that the sluice gate operation system be changed to allow for the flow of diadromous species between the Patos and Mirim lagoons. In addition, the search for solutions for reestablishing the movement of these species between the Patos and Mirim lagoons can avoid fish stocking programs of both native and exotic fishes, which aggravate

the environmental impacts in the region.

Another important point to be considered by the measures to protect and maintain the ecological corridor status of the São Gonçalo channel is the regulation of the areas and periods for sand extraction and fishing, since both can significantly impact the movement of the fish (Lemos *et al.* 2014; Barletta *et al.* 2016; Ceni *et al.* 2016). In particular, in the case of fisheries, it is necessary to write up an ordinance on fishing activity in the area since it is still nonexistent (IN/MMA/SEAP 2004), thus making the fish shoals susceptible to capture when travelling between the Patos and Mirim lagoons. Similar to the channel created by the “Barra” piers, which serves as a corridor interconnecting the oceanic coastal region with the continental lagoon system, which has a no-fishing zone (MPA/MMA 2012) due to the movement of several fish species (Chao *et al.* 1985; Pereira 1994; Lemos *et al.* 2014), the São Gonçalo channel is the main corridor interconnecting the Patos and Mirim lagoons and should give similar protections. A review of the fishing regulations for the Mirim lagoon region is also recommended since measures for the control of fishing activity in the Patos lagoon have not been successful both in the estuarine and limnic regions, thus causing conflicts as to the seasonality of the fishing seasons and the movement of migratory species between the limnic and estuarine habitats (Reis and D’Incao 2000; Ceni *et al.* 2016; Fontoura *et al.* 2016).

4. Conclusions

The present work demonstrates historical evidence that the São Gonçalo channel is an important ecological corridor connecting the Patos and Mirim lagoons. Once assured that the Mirim lagoon remains the largest freshwater reservoir in South America, the reestablishment of functional connectivity for the long-distance

migratory species ensures the maintenance of the biodiversity and health of this lagoon system as well as an improvement of the integrated coastal management. Among the actors of this integrated management of natural resources are the Brazilian and Uruguayan environmental agencies. In this sense, measures related to

the sluice dam operation system must be adopted to maintain fishing activity in the Mirim lagoon and assist in the management of endangered species and/or overexploited stocks. Similarly, the development and regulation of fishing ordinances should be adopted as part of the protection of fish populations that use the

São Gonçalo channel during their movement. In addition, the recognition of the negative environmental impacts of sluice dam construction could help in the search for the reestablishment of better environmental conditions in this watershed.

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