LIFE HISTORY MOVEMENTS AND SPAWNING OF SÃO FRANCISCO RIVER FISHES, BRAZIL

A Dissertation Presented

by

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DEDICATION

To my beloved son Henrique and parents Hugo and Ica

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ABSTRACT

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The São Francisco River (SFR), a floodplain river southeast of the Amazon River, provides commercial and recreational fishing for thousands of people, but fisheries have collapsed in the last decade. During 32-months, I radio-tracked 37 curimbatás (*Prochilodus argenteus*, Characidae, 0.8–2.9 kg) and 24 surubims *(Pseudoplatystoma corruscans*, Pimelodidae, 9.5–29.0 kg), two important commercial and recreational fishes. I did the study to characterize their migratory style and to determine if the cool hypolimnetic discharge from an upstream dam (Três Marias Reservoir, TMR) would block their upriver migration. I also made a conceptual model of the biological, river, dam, reservoir, and economic factors for a supplemental water release (SWR) to enhance SFR fisheries using a release from TMR. Migratory style of both species was dualistic with resident and migratory individuals. Home range was 1–127 km for curimbatá and 1–210 km for surubim. The most important spawning area for curimbatás was the SFR mainstem at its juncture with the Abaeté River mouth, and for surubims, the most important spawning area was the mainstem at Pirapora Rapids. Pre-spawning adults of both species staged at or near the spawning grounds. Some curimbatás and surubims homed to pre-spawning staging areas and to spawning areas. Some curimbatás also homed to non-spawning areas. The movements and thermal fluctuations experienced by both fishes showed they are eurythermal with a broad short-term temperature variation tolerance. Also, water discharged from dams that is $< 5^{o}$C cooler than ambient river water will not disrupt their migrations. The best date for a SRW is when there is a natural flood, which triggers spawning. The SWR will intensify the natural flood, cover a greater floodplain area, and increase survival of early life stages of fish. The TMR frequently impounded enough water for SWR only in the second half of the fish spawning season (January–March). Lost revenue at TMR depended on release volume and ranged from US$ 0.493 million to US$ 3.452 million for the actual power rate. However, SWR could increase commercial fisheries income an estimated US$ 4.468 million. Planned construction of 16 dams in the mainstem and tributaries downstream from TMD will greatly affect curimbatá and surubim migrations and spawning habitat, extirpate populations, and eventually reduce their abundance.

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CHAPTER 1

INTRODUCTION

1.1. Brazilian Fish Diversity and its Social Importance

Freshwater fishes are one of the marvels of Brazil's natural resources. With 3,000+ known species, Brazil has the richest freshwater fish diversity on Earth (McAllister 1977). The numerous wonderful ornamental fishes like the popular neon-tetra, the huge aggressive recreational 'dourado' (*Salminus* spp.), the giant 'pirarucu' (*Araipama gigas*), the electric eel (*Electrophorus electricus*), the legendary 'piranha' (*Pygocentrus* spp.), the highly prized foodfish 'surubim' (*Pseudoplatystoma*), the 'candiru' (*Vandellia cirrhosa*), which is notorious for swimming into human urethra, make this a unique fish fauna.

Besides their diversity, Brazilian freshwater fishes provide food and jobs for millions of people all over the country. From 1984 to 1998, freshwater fisheries landings ranged from 152 to 183 thousand tons per year, numbers that do not actually represent the real magnitude of the fisheries due to the scattered nature of landings (Fischer *et al.* 2000).

The São Francisco River (SFR) is a medium sized watershed located near the east coast of South America, southeast of the Amazon River (Figure 1.1). It was once one of the fisheries hot spots in Brazil. Moojen (1940) wrote that its fisheries were a miracle and Menezes (1956) compiled several amazing reports of abundant fisheries during the first half of the last century. Several fishers' villages flourished along the riverbanks and fisheries were the main livelihood of thousands of commercial fishers.

Nowadays, hundreds of thousands of people still drive each year to the river for recreational fisheries. Numerous establishments like hotels, motels, restaurants, sport fishing clubs, and stores depend on the recreational fishery as the primary or secondary sources of income.

Despite the lack of systematic records of the São Francisco's fisheries, there is clear evidence that the fisheries have collapsed during recent years. Catch reduction has been frequently reported in the media, and anglers and commercial fishers complain often about it. Commercial fishers groups have requested changes in fisheries regulations that allow catching smaller fish. One of the strongest pieces of evidence of a collapse is the reduction in capture per unit of effort per commercial fishing boat at Pirapora, an important fishing area in the middle course of the river at river km (rkm) 1,978. The catch has declined from 11.7 $kg.fisher^{-1}.day^{-1}$ in 1987 to 3.1 $kg.fisher^{-1}.day^{-1}$ in 1999 (Godinho *et al.* 1997, Godinho pers. obs.). Surubim, which accounted for 86% of the biomass caught in 1987, represented only 27% in the 1997 catch.

1.2. Life History Movement, Dams, and Fish Passage

As in the rest of the world, where many commercially important freshwater fishes are migratory (Wootton 1990), the most important commercial and game fish species of the SFR are migratory. Despite their importance, their migratory behavior is almost entirely unknown. Two attempts to study adult migrations using mark and recapture methods provided only superficial insights (Paiva and Bastos 1982, Sato and Godinho 2003). Therefore, migratory routes, time of migration, and location of spawning and feeding grounds have not been described.

The SFR Basin hydropower potential is 26.3 GW, with 10.5 GW already developed (ANEEL 2002). All major developments are in the mainstem and most are in the lower section of the river. Only one major dam, Três Marias Dam (TMD), was built in the upper section of the mainstem (Figure 1.1). Within 506 km downstream of TMD, four dams are planned that will convert that entire reach of the mainstem into a series of large reservoirs (Figure 1.1). In the free-flowing Abaeté River, there are nine potential sites for dams and in the Velhas River, the second biggest tributary, three dam sites. There is no fish passage in any SFR dam.

The efficiency of a fish passage depends on free access of the migrants to the downstream passage entrance, which is always in the tailrace below the dam. However, the tailrace water at some dams may be cool enough to act as a movement barrier. For example, at TMD, located in the SFR at rkm 2,109 (Figure 1.1), the water intake is located at the hypolimnetic layer of the reservoir where the water is 5–7 ^{o}C cooler than the surface water during the rainy season (Esteves *et al.* 1985). Consequently, the tailrace water is also cool. Eventually, downstream of the dam the water temperature increases after receiving warmer water from tributaries (Sampaio and López 2003). Thus, if the Três Marias' tailrace discharge really acts as a physical barrier for migrants, this could preclude any attempt to provide an upstream passage for fishes at TMD or similar dams.

1.3. Fish Spawning and Supplemental Water Release

Many studies emphasize the importance of floodplain lakes to the rearing success and recruitment of many species of migratory fishes, including the fishes in the

SFR (Bonetto *et al.* 1969, Godoy 1975, Sato *et al.* 1987, Carolsfeld *et al.* 2003, Pompeu and Godinho 2003). The SFR has abundant floodplain lakes, but the largest of these is the 16 km wide floodplain at the city of Januária (rkm 1,700). It reaches a width of tens of km close to the city of Xique-Xique (rkm 1,062; Sato and Godinho 2003).

The migratory fishes in the SFR are broadcast spawners that spawn non-adhesive, semi-buoyant eggs that hatch in less than one day during the rainy season (October–March; Sato *et al.* 2003a, b). Spawning timing, characteristics of the eggs, and characteristics of the early life stages are adaptations that increase the probability that early life stages will reach floodplains lakes. Consequently, spawning timing of is a critical moment for recruitment.

The lack of big floods during the last decade may be the major cause of the fishery collapse of the SFR (Godinho and Godinho 2003). The last major flood occurred in 1992 when the water level reached 11.8 m at the city of São Romão (rkm 1,837). Since then, the floods have been lower, ranging from 5.9 to 8.7 m. The lack of major floods could reduce fisheries yield by preventing eggs and larvae from reaching floodplain lakes or by preventing young fish in the floodplain lakes from returning to the river, thereby increasing mortality due to predation and desiccation. Moreover, lack of floods reduces the flood pulse effect, which is the principal driving force responsible for the existence, productivity, and interactions of the major biota in floodplain river systems (Junk *et al.* 1989). The collapse of the fishery for *Prochilodus lineatus* in the Pilcomayo River in Bolivia during the 1990s was attributed to decreased river discharge due to the *El Niño* phenomenon (Smolder 2000).

Control of river water discharge by TMD was also suggested as a possible cause for the collapse of the São Francisco fisheries (Godinho and Godinho 1994). River discharge is controlled to avoid flooding as well as to improve commercial navigation and tourism. Spawning success and recruitment of migratory fishes, however, most probably depends on floods that no longer occur with the same frequency or intensity. Flow regulation is perhaps the most pervasive change by humans on rivers worldwide (Stanford *et al.* 1996).

Supplemental water release (SWR) has been used for fisheries restoration (Petts 1989, Welcomme 1989, Orth and White 1993, Godinho 1993, Swales 1994). Welcomme (1989) suggested that water discharge from dams could be released to provide a flood to stimulate fish spawning. He mentioned three cases in Africa where discharge was manipulated to enhance fisheries. Riverine fishes successfully spawned after flood augmentation in the Pongolo River, South Africa. Juveniles of several species appeared in the floodplains of the Zambezi River, Zambia/Zimbabwe, after artificial floods, and Welcomme (1989) concluded that artificial releases of water from dams could stimulate spawning of riverine fishes.

1.4. Objectives

The present multi-year research study is on basic and applied issues of migratory fishes in the SFR. It addresses topics related to the life history migrations of curimbatá, *Prochilodus argenteus* (= *Prochilodus marggravii*) Spix and Agassiz 1829 (Characiformes, Prochilodontidae) and surubim, *Pseudoplatystoma corruscans* (Spix and Agassiz 1829) (Siluriformes, Pimelodidae), two of the most important commercial and recreational SFR fish species. It also addresses SWR from TMD to restore fisheries.

For curimbatá, I used radio-telemetry to identify migrations, determine home ranges, identify spawning and non-spawning grounds, determine if fish homed, and determine the timing of spawning relative to river conditions. I also developed a conceptual model of migration that would contribute to understanding the species' life history (Chapter 2).

For surubim, I used radio-telemetry to identify river reaches used for spawning, pre-spawning staging and non-spawning activities and to determine home range, identify migration timing, determine detailed use of spawning area, determine if fish homed, and measured migratory ground speed. I used these data to develop a conceptual model of migration and spawning for the species (Chapter 3).

For both species, I radio-tracked fish movements at the junction of the cooler mainstem water with the warmer water of the Abaeté River to test the hypothesis that the cooler TMD discharge blocked upstream fish migration (Chapter 4).

I gathered biological data on spawning timing and river condition and information on TMD releases and storage, value of water for generation, and historical flooding patterns to make a conceptual model of the biological, river, dam and reservoir, and economic factors for a SWR in the SFR (Chapter 5).

1.5. Study Area

The SFR is located in the east coast of South America southeast of the Amazon River between the coordinates 13^{o} and 21^{o} L and 36^{o} and 48^{o} W (Figure 1.1). It is a medium sized basin of 631,000 km^2. It drains 7.4% of the Brazilian territory and flows 2,680 km generally northward (Paiva 1982). The climate is hot and humid (type Aw, Köppen system) with a dry winter in the upper portions of the basin upstream of rkm 1,250 (Bernardes 1951). High water discharge occurs during summer whereas low water occurs in winter. Mean river discharge is 3.150 $m^3.s^{-1}$, seven times larger than the discharge of the Connecticut River, USA (Boyd 1976). Between the cities of Três Marias and Pirapora, river water temperatures range from 18–29 ^oC, conductivity from 36–76 $\mu S\ cm^{-1}$, and pH from 6.3–8.2 (Sato and Godinho 2003). The river in that reach is characterized by high gradient, fast current, rocky bottom, and frequent short rapids. The Pirapora Rapids is 1,000 m long and 8 meters high. Downstream of Pirapora, the river gradient is low, current is slow, bottom is mostly sand, floodplain is wider, and rapids are absent.

There are 10 major hydroelectric developments in the basin, six of these are in the mainstem. Três Marias (rkm 2,109) and Sobradinho (rkm 750) dams are the biggest. The TMD has a flooded area of 1,042 km^2 and was filled in the early 1960s. Sobradinho Dam was built in the 1970s and has a flooded area of 5,805 km^2. These manmade reservoirs are respectively, 13 and 72 times bigger than the area of Quabbin Reservoir (80.3 km^2) in Massachusetts, USA.

The study area is the section of the SFR Basin between TMD and Sobradinho Reservoir. The core area is restricted to the 276 km directly downstream of TMD. The 1,090 km long section between TMD and Sobradinho Reservoir is the longest free flowing section in the basin. None of these tributaries in this part of the basin contain flood control facilities. Most of the biggest tributaries and floodplain lakes occur there.

The biggest tributaries are Velhas (rkm 1,952), Paracatu (rkm 1,866), Urucuia (rkm 1,719), Carinhanha (rkm 1,543), Corrente (rkm 1,395), and Grande (rkm 1,134). The floodplain is relative narrow in the first 247 km downstream from TMD. It increases in width after the mouth of the Paracatu River (rkm 1,866), and at the city of Januária (rkm 1,700), it is 16 km wide and reaches tens of km at the city of Xique-Xique (Sato and Godinho 2003). There is no information on how many floodplain lakes exist in the Três Marias-Sobradinho reach, but it may be thousands.

1.6. Study Fishes

Curimbatá (Figure 1.2) is a member of the family Prochilodontidae endemic to the SFR (Sato *et al.* 1996). Members of this family can be readily distinguished by their fleshy lips with two series of numerous, relatively small, falciform or spatulate teeth, movably attached to the lips (Castro and Vari 2003). Prochilodontids have bean-shaped body, a protractile mouth forming a sucking disc, and a pre-dorsal spine (Gery 1975). *Prochilodus argenteus* is an iliophagus fish that reaches 15 kg and is the largest species of its family (Sato *et al.* 1996). Adult curimbatás have a dorsal fin plain, 41–45 lateral line scales and body depth 2.5–2.7 times in the standard length (Gery 1975). It is one of the most common big fish in the SFR and a second/third grade fish for commercial fisheries. It was only a non-game fish, but new angling techniques have changed that. Curimatá is a long distance migratory fish (Sato and Godinho 2003), total spawner (Bazzoli 2003) that broadcasts many non-adhesive eggs (252 eggs per g of body weight; Sato *et al.* 2003a) from November to February (Bazzoli 2003). Females have a high gonadosomatic index (mean of 24%), non-hydrated egg have diameter of 1.6 mm, egg-hatching occurs around 19 hours after fertilization at 24 ^{o}C, and larval length at hatching is 4.2 mm (Sato *et al.* 2003a, b). The larval stage lasts for four days (Godinho *et al.* 2003).

Surubim (Figure 1.3) is a catfish in the family Pimelodidae. Pimelodids do not have any unique externally visible characteristics, but can be distinguished from other South American siluriforms by a combination of features (Lundberg and Littmann 2003). *Pseudoplatystoma* has a long depressed snout with four moderately long maxillary barbels. The width of the mouth is about equal to the maximum width of the head and less than the head length. The palatal teeth are arranged in two patches in the form of a curved and elongated comma (Burgess 1989). Surubim is blackish dorsally and white ventrally with dark spots all over the body, except ventrally and on most of the head. Surubim occurs in the São Francisco and Paraná-Paraguay-Uruguay basins. This piscivorous fish is one of the largest neotropical fishes growing to 3.3 meters in length (Ihering 1934); such a fish would weigh 435 kg according to the species' weight–length equation (Godinho *et al.* 1997). However, a fish that weight has never been documented. Sato *et al.* (2003a) mentione that the maximum weight of the species in the SFR Basin is 120 kg. Like curimbatá, surubim is a long distance migratory fish (Sato and Godinho 2003), total spawner (Bazzoli 2003) that broadcasts many non-adhesive eggs (126 eggs per g of body weight; Sato *et al.* 2003a) from November to January (Godinho *et al.* 1997, Brito and Bazzoli 2003). It reaches sexual maturity at a body length of 55 cm (Lamas 1993). Gonadosomatic index of females is low (3%; Lamas 1993), diameter of non-hydrated egg is 1.0 mm (Sato *et al.* 2003b), and eggs hatch in 20 hours at 24.4 ^{o}C. The larval stage lasts for four days (Godinho *et al.* 2003).

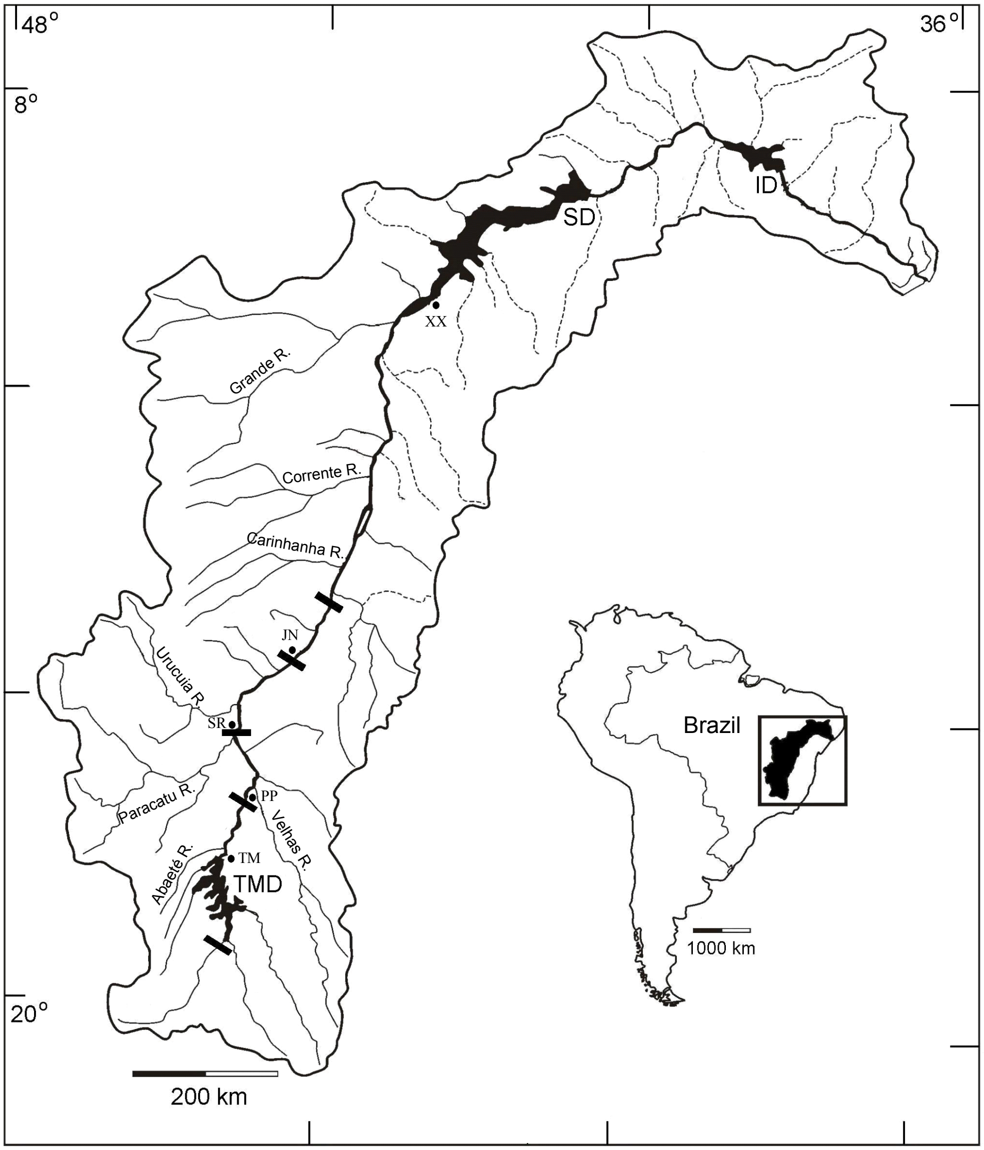


Figure 1.1. Map of the São Francisco River Basin showing the three major reservoirs (TMD = Três Marias Dam, SD = Sobradinho Dam, ID = Itaparica Dam), future hydropower developments in the mainstem (▬) and some of the major riverine cities (TM = Três Marias, PP = Pirapora, SR = São Romão, JN = Januária, and XX = Xique-Xique).

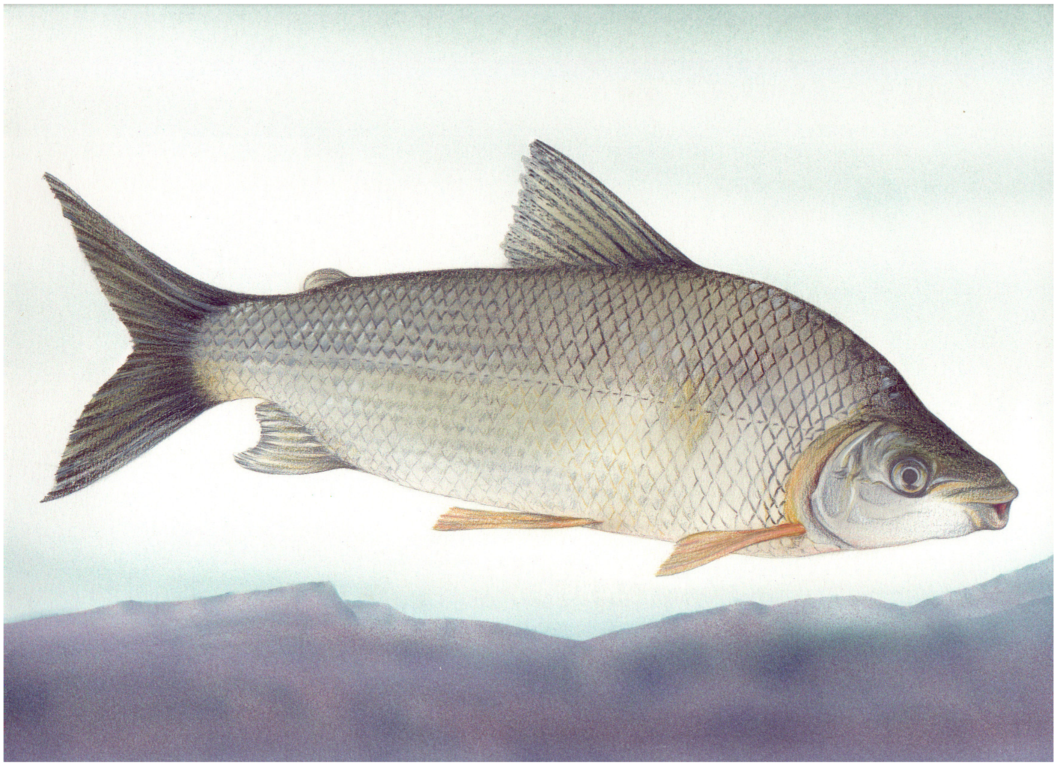


Figure 1.2. Curimbatá (*Prochilodus argenteus*).

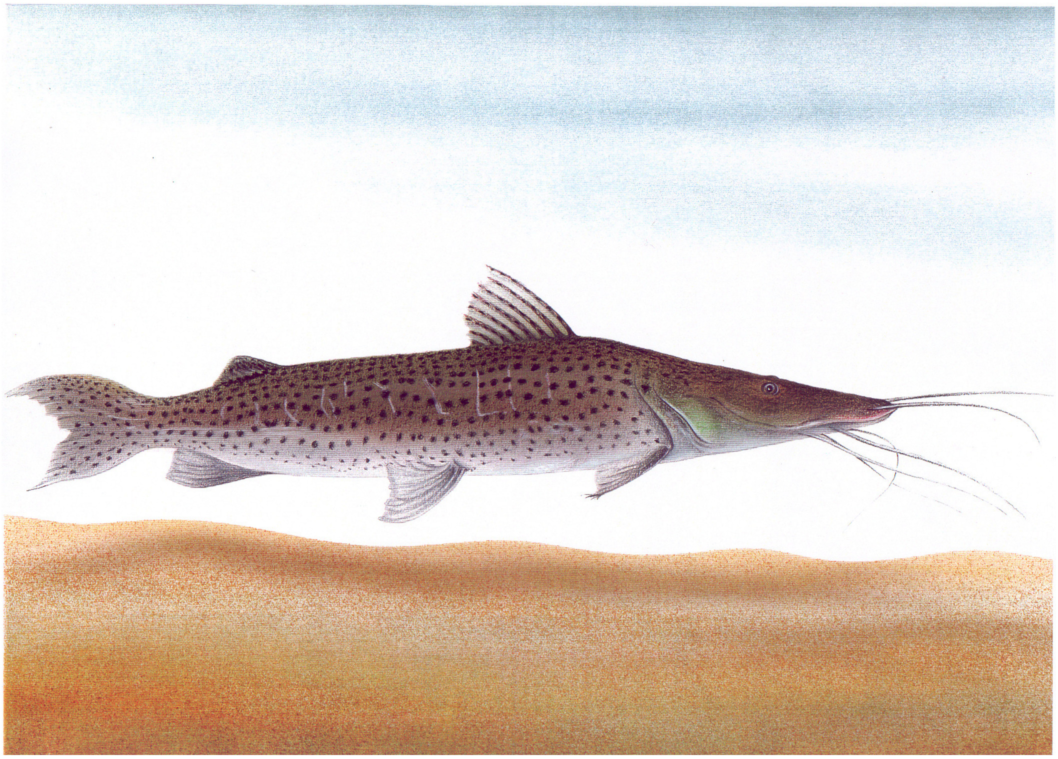


Figure 1.3. Surubim (*Pseudoplatystoma corruscans*).

CHAPTER 2

MIGRATION AND SPAWNING OF CURIMBATÁ (*Prochilodus argenteus*, PROCHILODONTIDAE) IN THE SÃO FRANCISCO RIVER, BRAZIL

2.1. Introduction

Fishes of the genus *Prochilodus* forage on detritus and periphyton and inhabit many South American rivers where they are an important fisheries resource (Castro and Vari 2003). *Prochilodus argenteus* (common name, curimbatá) is endemic to the São Francisco River, a large basin southeast of the Amazon River. Curimbatás grow to a maximum body weight of 15 kg (Sato *et al.* 1996) and are sexually mature at 3 years (Santos and Barbieri 1991). They are one of the most important recreational and commercial fish in the basin (Franco de Camargo and Petrere 2001, Godinho *et al.* 2003a). Despite the importance of curimbatás to the São Francisco River fisheries, most aspects of their life history (especially migrations, home range, and spawning locations) are not understood. This information is critically needed to evaluate the environmental impacts of the many dams and large reservoirs that are planned for the mainstem and tributaries.

Some information on spawning and early-life history of curimbatá is available. During spawning, a female broadcasts hundreds of thousands of small, non-adhesive eggs in a single batch in the rainy season between November and February (Bazzoli 2003, Sato *et al.* 2003b). Eggs are semi-buoyant, drift downstream with river flow (Chapter 5), and hatch in 19 h at 24 ^{o}C (Sato *et al.* 2003b). Drifting eggs and larvae are in the water column and density is highest during floods when spawning occurs (Chapter 5). During flooding, larvae drift into floodplain lakes, which are important nursery grounds for early juveniles (Sato *et al.* 1987, Pompeu and Godinho 2003). Some larvae may also rear in the river, but data are lacking. Preliminary observations suggest that at some point in development, juveniles migrate upriver in the dry season to join adults (Godinho pers. obs.).

The present conceptual model of adult *Prochilodus* spp. migration and home range is from mark-recapture studies on *P. lineatus* (= *P. scrofa* and *P. platensis*) in the Paraná–Paraguay River basin of Brazil and Argentina during the 1950s–1960s (Godoy 1959, Godoy 1962, Bonetto 1963, Bonetto and Pignalberi 1964, Bonetto *et al.* 1971, Godoy 1975). *Prochilodus lineatus* in the upper Paraná River basin, a neighbor basin of the São Francisco River, migrates a maximum round trip distance of 1,300 km between feeding grounds in the mainstem and spawning grounds in a tributary (Godoy 1975, Toledo *et al.* 1986). Upriver pre-spawning migration occurs during September–December and spawning occurs during November–February, mostly in a 4 km reach downstream of a waterfall (Godoy 1954). During spawning, thousands of noisy (males have a mating call), schooling adults swim at the water's surface, a phenomenon locally called ‘rodada’ (Schubart 1943). Thirty-one of 43 ‘rodadas’ studied by Schubart (1954) occurred when the river was flooding.

In the São Francisco River, two mark-recapture studies on curimbatás provide some information on home range of adults. Fish (presumably adults) from different reaches were quite different for home range, i.e., 1,100 km maximum for fish tagged in the lower region by Jucá (Sato and Godinho 2003) and 250 km for fish tagged in the upper region (Paiva and Bastos 1982). The few recaptures in these studies did not provide insight on size of spawning vs. non-spawning home range, adult migrations, and did not identify location of any spawning grounds.

Migrations of several South American fishes have been studied mostly using mark-recapture (Petrere 1985, Carolsfeld *et al.* 2003). Telemetry rarely has been used in South America to study migratory fish (Mochek *et al.* 1991). I radio-tracked curimbatás from three reaches in the São Francisco River for 2.5 years and I was even able to follow some individuals for two spawning seasons. At the time of tagging, I identified the sex and reproductive stage to link movements and behavior to reproductive stage. My objectives were to identify migrations, determine home ranges, identify spawning and non-spawning river reaches, determine timing of spawning relative to river conditions, and develop a conceptual model of migration that would contribute to understanding the species' life history.

2.2. Study Area

The São Francisco River is a large river on the east coast of South America that flows mostly northward 3,160 km and drains a basin of 645,067 km^2 (Kohler 2003). The reach where I tagged all fish and tracked fish most intensively extended 129 km downstream from Três Marias Dam (TMD) to Pirapora Rapids (PR; Figure 2.1). This reach of river has a high gradient with fast current, rapids, and runs. The bottom is mostly rocky. There are only a few narrow floodplains that seldom flood because of regulated flow at TMD. Within 506 km downstream of TMD, four dams are planned that will convert that segment of the mainstem into a series of big reservoirs. Abaeté River is the largest of the three major tributaries in the TMD-Pirapora reach. It drains an area 2.6 times larger than the combined areas of the other two tributaries which are the Janeiro and Formoso rivers. In the free-flowing Abaeté River, there are nine potential sites for dams. At PR, the river level declines 8 m over a distance of 1 km at a steep rapids. Downstream of PR, river gradient is low, current is slow, bottom is generally sand, and the channel meanders. Many wide floodplains are present, mostly below the Paracatu River mouth at river km (rkm) 1,866.

Physical and chemical quality of the river mainstem in the study area reflects the hypolimnetic discharge of Três Marias Reservoir, winter overturn, and contribution of tributaries (Sampaio and López 2003). Temperature ranges from 22.6 to 28.5 ^{o}C and dissolved oxygen levels range from 1.9 to 7.8 mg L^{-1}. The lowest dissolved oxygen level occurs in the TMD tailrace (Sampaio and López 2003). Tributaries bring large amounts of silt and mud to the mainstem during floods.

2.3. Methods

2.3.1. Tagging and tracking

I captured and tagged fish at three mainstem locations: Três Marias - TM (5–9 km downstream from TMD), Pontal (1 km downstream and 7 km upstream from the Abaeté River mouth), and Cilga (5 km reach centered on Cilga Island; Figure 2.1). I tagged fish in January–February 2001 and January 2002, i.e., during the November–February spawning seasons of 2000–2001 and 2001–2002.

I captured fish with gill nets or cast nets and held them in a nearby floating net pen for as long as 2 h prior to tagging. I held fish for tagging in a small portable tank filled with 30 L of river water and immobilized them using electronarcosis with non-pulsed 30 V DC current (Kynard and Lonsdale 1975, Ross and Ross 1999). Prior to tagging, I determined fish weight (W) and standard length (SL). Tags were inserted into the body cavity through a 5-cm long incision. I made the incision on the left lateral body wall about 4 cm behind the ventral fin base and 4 cm above the ventral line. The 27-cm long antenna extended posterior through the body wall and exited along the body mid-line. Tags were Lotek© coded radio tags (model MCFT-3FM, diameter = 11 cm, length = 59 cm) with a transmission life of 25 months at a 10 s burst rate. Tag weight in air (10 g) as a percent of fish weight was $\leq$ 1.3%. During the last 30 min of surgery, I added Stress Coat® or LabProtect® to the tank's water to aid recovery of fish. I completed surgery in 30–40 min and held fish in the net pen for 1–3 h to ensure recovery prior to release. I released fish within 1–3 km of the capture site, except for three fish released 5–7 km from their capture sites.

I determined sex and reproductive stage of fish during surgery using unaided visual observations of gonads through the incision for some fish, or for fish with very small gonads, using a fiber optic bioscope inserted through the incision (Kynard and Kieffer 2002). I classified reproductive stage of females using a scheme developed by Kynard and Kieffer (2002) as early-stage (ES, gonads not containing visible mature eggs) or late-stage (LS, ripe gonads). I classified reproductive stage of males as ES, if the gonad was so small that it could not be seen with the bioscope, and as LS, if the gonad could be identified with the bioscope or if the male was running sperm. The ES female category included adults that might have spawned and juveniles that would not spawn during the spawning period they were tagged. I tracked some ES fish during a second spawning season and characterized these fish as likely LS fish.

I manually tracked fish from January 2001 to July 2003 including, therefore, three spawning seasons: 2000–2001, 2001–2002, and 2002–2003. I located fish almost every month during each spawning season (November–February) and at least every other month during non-spawning seasons. Most mobile tracking used a boat, but I tracked by helicopter in July 2002 and July 2003 to survey all remote areas for tagged fish. I did most mobile tracking in the mainstem within 219 km downstream of TMD. Major tributary rivers (Abaeté, Espírito Santo, Janeiro, Jequitaí, Pandeiros, Paracatu, Paraúnas, Preto, Sono, Urucuia, and Velhas) and the mainstem to the city of Xique-Xique (rkm 1,062) were tracked at least once. A total of approximately 7,500 km of river was searched to locate tagged fish.

I also located fish using Lotek® fixed-location, data-logging receivers at TMD, Pontal, and PR from January 2001 to July 2003 (Figure 2.1). The TMD receiver had one antenna that surveyed the lower part of the dam's tailrace to determine if fish moved upstream to the dam. The Pontal receiver had two antennas oriented toward the mainstem (one surveying 0.5 km upstream and one surveying 1 km downstream) to determine movement direction of fish and a third antenna that monitored the lower 0.5 km of the Abaeté River to determine when fish entered or departed the tributary. The PR receiver had two antennas to determine movement direction of fish in the mainstem as they moved up- or downstream through the rapids.

I recorded temperature at the Abaeté River mouth each 3 h with an Onset© temperature logger. Daily river discharge of the Abaeté River was provided by CEMIG (Minas Gerais Power Company).

2.3.2. Data analysis

Receivers recorded tag code and number of tag detections (hits) for each 10-min interval. They also logged hits of tag codes not used in the study (absent codes). I called these false-positive records. False-positive records of tag codes that I actually used (present codes) were also recorded. I used two procedures to eliminate false-positive records of present codes. The first procedure was based on P_k, the probability of a record with k hits being a false positive. I calculated P_k using the formula:

$$P_k = 100F_k / \sum_{k=1}^{n} F_k ,$$

where F_k = percent of records of absent codes with k hits. I considered a record of present code as false-positive if $P_k > 1.0\%$ for the Pontal receiver and if $\sum_{k=1}^{n} P_k > 1.0\%$ for TMD and PR receivers. I set a higher threshold for TMD and PR because of the higher level of background noise in those areas. Because the maximum number of possible signal detections for a 10 s burst rate tag in 10 min is 60, I excluded from analysis all records with more than 60 hits.

The second procedure was to check data-log records for consistency. When a receiver recorded a tag signal, the tag code and time of first and last signal hits were recorded for each 10-min interval. I considered false-positive records within 30 min of a positive record as a positive record; I excluded other false-positive records.

The Pontal receiver detected short-term movements (visits) of LS and likely LS fish to Pontal during the spawning season. I determined frequency and duration of visits using arrival and departure day and time. I also determined the arrival and departure direction. I analyzed the frequency of visits for relationship with Abaeté River discharge and temperature. Using variability in these two physical variables, which ranged from peak to valley, I classified each visit as peak (during peak day or 1 d post-peak), decreasing (decreasing from peak), valley (during valley or 1 d post-valley), increasing (increasing from valley), or stable (variable unchanged for > 2 d). If a visit lasted longer than 1 d, I characterized the visit day as the day with the greatest number of signal hits. I tested data for differences in visit frequency and duration among classes of discharge and temperature.

I calculated total home range (the distance between the most up- and downstream locations, Young 1998) of all fish tracked during spawning and non-spawning seasons. I used only LS and likely LS in the calculation of total home range. For these fish, I calculated Fulton condition factor ($K = W\ SL^{-3}$).

I calculated the non-spawning home range (distance between the most up- and downstream locations) using fish located at least two times during the non-spawning season. I excluded the locations of fish during pre-spawning or post-spawning migration periods. If a fish used different river reaches in different non-spawning seasons, I estimated the non-spawning home range of the fish for each season.

I used the statistical software SAS for data analysis (SAS Institute 1999). I tested continuous data sets for normality (Shapiro-Wilk test, SAS' Univariate procedure). In case of non-normality, I transformed the data following transformations of Sokal and Rohlf (1995), and then tested again for normality. If normality was achieved after transformation, then I used Student's *t*-test (SAS' T-test procedure) according to the homogeneity of variances for comparisons of data between two groups, ANOVA (SAS' GLM procedure) for comparisons among three or more classes, and

Pearson correlation (SAS' Corr procedure) to test relationship between continuous variables. Tukey's studentized range test was applied if I rejected the null hypothesis using ANOVA. If I did not reject the null hypothesis, I determined the power of the test (Borenstein and Cohen 1988, Cohen 1988). In case of non-normality, I used Wilcoxon two-sample test with normal approximation and continuity correction of 0.5 (SAS' Npar1way procedure) to compare data between two groups. I used chi-square to test frequency data between groups. I set $\alpha = 0.05$ and power = 0.80.

2.4. Results

I tagged 37 fish in two spawning seasons: 20 were tagged in January–February 2001 and 17 were tagged in January 2002 (Table 2.1). Twenty-two fish were females (SL range = 36.0–50.5 cm) and 15 fish were males (SL range = 32.0–49.0 cm). Fourteen fish were ES (12 females and 2 males) and 23 fish were LS (10 females and 13 males). There was no significant difference between standard lengths of ES and LS fish (*t*-test: $t = 0.74$, df = 35, $P = 0.46$, power = 0.63). Thirty-two fish (20 females and 12 males) provided tracking data. I tracked these fish for 19–554 d (mean = 201). The number of locations per fish was 3–329 (mean = 21).

2.4.1. Tagging mortality and tag failure

I found tagged fish immobile (tag still on the bottom of the river) from 6–256 d after tagging with 11 of 37 (30%) of the fish immobile sometime during the study (Table 2.1). These fish almost certainly died and did not reject the tag because tag placement was the I/E style (internal tag–external antenna). Mortality may be related to tagging in cases where tags became immobile soon after release (< 36 d, n = 6, 16% of total). Other fish were immobile at > 80 d (n = 5), so death was likely the result of an unknown cause, not the result of tagging.

Five of 20 tags used in 2001 stopped transmitting after 224–514 d instead of the specified 755 d. All five tags were either returned by fishers or were from dead fish and were immobile on the bottom of the river.

2.4.2. Disappearance of tagged fish

The signals of 19 fish could not be found after 19–554 d (Table 2.1). One fish was last detected by the PR receiver and it could have moved downstream into a tributary and gone undetected or it could have been harvested. One fish was last located after 200 d; then, after 313 d, it was harvested and the tag returned with a dead battery. The 17 remaining fish were likely harvested or the tag stopped transmitting because I last tracked them in the mainstem or in tributaries upstream of PR and the PR receiver did not detect them moving downstream out of the study area.

2.4.3. TM fish

In January–February 2001, I tagged seven fish at TM (Table 2.1). I tracked two fish (54 and 55) for ≤ 21 d. Thus, five 2001 fish provided tracking information: two ES female (52 and 154), two LS females (50 and 51), and one LS male (53). In January 2002, I tagged five fish (Table 2.1). Three fish were ES females (77, 79, and 80) and two ES males (76 and 78). I tracked the 2002 fish for > 100 d. In summary, five ES females, two LS females, two ES males, and one LS male provided tracking data.

The two LS females (50 and 51) stayed within 5–12 km of the release site during the spawning season they were tagged (Figure 2.2). One LS female (51) swam downstream past Pontal and Cilga after the spawning season was over. The other LS female (50) was harvested 139 d after tagging and within 5 km of the release site. The one LS male (53) tagged in 2001 was tracked for 39 d within 2 km of the release site before it disappeared (likely due to harvest or tag failure). Four ES females and two ES males remained at TM during the spawning season they were tagged. I tracked two likely LS females (79 and 154) and one likely LS male (78) to the next spawning season. One of these likely LS females (154) migrated to Pontal during the second spawning season. The two other likely LS fish stayed within 1 km of the release site during the second spawning season. Four fish (three ES females and one LS female) departed TM at the end of their first spawning season or during the non-spawning season moving 18–53 km downstream.

2.4.4. Pontal fish

In January 2001, I tagged four fish at Pontal (Table 2.1). Although the signal was lost from one fish (64) after 19 d, it did provide tracking data. Thus, all fish tagged in 2001, i.e., one LS female (65) and three LS males (63, 64, and 66), provided data on movement. In January 2002, I tagged 10 fish. Two fish (82 and 161) died after 6 and 28 d. Thus, tracking information was provided by six ES females and two LS males. In summary, I tracked six ES females, one LS female, and five LS males.

The LS female 65 stayed at Pontal for almost 11 months before I lost the tag signal (Figure 2.2). Two likely LS females (73 and 81) tagged in January 2002 returned to Pontal during the 2003 spawning season. Two ES females (83 and 84) stayed at Pontal until their tag signals were lost after 57–70 d. One LS male (72) and one ES female (85) moved upstream 1–3 km where they died after 103–256 d. One ES female (70) moved upstream 9 km where it was harvested. One LS male (71) moved into the Abaeté River at the end of the 2002 spawning season. Two LS males (63 and 66) moved downstream 84–97 km near PR at the end or just after the spawning season.

2.4.5. Cilga fish

In January 2001, I tagged nine fish at Cilga (Table 2.1). The tag of fish 56 was immobile at 20 d. Six LS females (57, 60, 62, 67, 68, and 69) and two LS male (59 and 61) provided tracking information. In January 2002, I tagged two LS males (74 and 75). Although one tag was immobile after 34 d, it provided tracking data. In summary, I tracked six LS females and four LS males.

Two LS females (57 and 69) and two LS males (74 and 75) swam to Pontal 5–18 d after tagging (Figure 2.2). They were likely intercepted by me on their way to Pontal, so I categorized them as Pontal fish because that is where they stopped migrating for the spawning season. Four LS females (60, 62, 67, and 68) and two LS male (59, and 61) stayed within 1–7 km of the release site at Cilga during the spawning season they were tagged. Fish 59 and 67 stayed in the same area at Cilga during the spawning and non-spawning seasons (Figure 2.2). One was tracked briefly after entering a small tributary, the Janeiro River. I lost the tag signal of five fish at the end of the spawning season or the beginning of the non-spawning season likely due to harvest or because tag stopped transmitting.

2.4.6. Migration to Pontal

During the two spawning seasons, the Pontal receiver detected a total of 18 tagged fish at Pontal during 1–86 d (median = 4 d). Only 12 fish were originally tagged there, so four fish tagged at Cilga (57 and 69 LS females and 74 and 75 LS males) and two fish tagged at TM (77 ES female and 154 likely LS female) migrated to Pontal. All six fish stayed at Pontal for two or more consecutive days at least one time. One LS Pontal male (71) spent the non-spawning season in the Abaeté River, migrating downstream to Pontal during the next spawning season (Figure 2.2). The greatest number of fish detected at Pontal was in January–February, but fish occurred at Pontal every month of the year (Figure 2.3). Some fish migrated to Pontal more than one time during the same spawning season.

2.4.7. Visits to Pontal from pre-spawning staging areas

After fish arrived at Pontal during the spawning season, they stayed for a short time, then usually moved to a nearby pre-spawning staging area, and later returned to visit Pontal. During both spawning seasons, the Pontal receiver detected a total of 27 visits by 10 fish, i.e, five females (two LS and three likely LS) and five LS males. One ES female (73) was at Pontal in the same spawning season I tagged it but it was not classified as a visit because I characterized a visit only if fish were LS or likely LS. Most visits (59%) occurred in January and February.

The number of visits to Pontal per fish ranged from one to nine. Three fish (all LS males) visited Pontal only one time, six fish (two LS females, three likely LS females, and one LS male) visited two to four times, and one fish (LS male) visited nine times. The five males visited Pontal a mean of 2.8 times (range = 1–9) and the five females visited a mean of 2.6 times (range = 2–4). Likely LS females visited Pontal a mean of 2.3 times (n = 4, range = 2–3) and LS fish visited a mean of 2.9 times (n = 6, range = 1–9). There was no difference in number of visits between males and females (Wilcoxon two-sample test: $W = 33.5$, df = 1, $P = 0.23$) or between likely LS and LS fish (Wilcoxon two-sample test: $W = 19.0$, df = 1, $P = 0.64$). Visit duration ranged from 1–13 d (2.2 ± 2.8 d, mean ± SD). Most visits lasted 1 (63%) or 2 d (19%). The duration of 1-day visits was 4 min to almost 14 h (mean = 4 h 42 min). There was no difference in visit duration (min), between likely LS and LS fish (*t*-test: $t = -1.53$, df = 24, P = 0.14, power = 0.26) or between males and females (*t*-test: $t = -1.47$, df = 24, P = 0.15, power = 0.29).

Arrival time at Pontal for 19 of 25 visits (76%) was during the day between 0632–1757 hours. For 13 of 19 visits (68%), fish arrived between 0632–1300 hours. Three visits occurred at night (2147–0325 hours), two visits occurred at dawn and one visit occurred at dusk.

2.4.8. Abaeté River conditions during visits

Using the frequency of visits during different discharge and temperature conditions of the Abaeté River shown in Figure 2.4, there was no significant association between frequency of visits to Pontal and water temperature (chi-square test: $\chi^2 = 4.6$, df = 4, $P = 0.32$) or discharge (chi-square test: $\chi^2 = 1.7$, df = 4, $P = 0.79$). However, 59% of the visits occurred when temperatures were decreasing or at valley values. After I grouped these two classes (decreasing from peak and valley), the relationship between frequency of visits and water temperature was highly significant (chi-square test: $\chi^2 = 17.0$, df = 3, $P < 0.0007$), with significantly more visits during decreasing–valley temperatures.

There was no difference in duration of visits (min) among the classes of water discharge (ANOVA: *F* = 1.10, df = 4, P = 0.38, power = 0.26). Duration of visits was significantly related to classes of water temperature (ANOVA: *F* = 2.86, df = 4, P = 0.049). However, this relationship was eliminated after one outlier was removed from the analysis (ANOVA: *F* = 2.14, df = 4, P = 0.11, power = 0.59).

2.4.9. Pre-spawning staging areas near Pontal

During the spawning season, fish were at nearby pre-spawning staging areas before and after visiting Pontal. I located 90% of the fish that visited Pontal, 20 times at pre-spawning staging areas. Eighteen pre-spawning staging sites were upstream of Pontal 0.3–12.3 km (5.5 ± 3.9, mean ± SD) and two locations were 0.7 km downstream. One fish staged one time in the Abaeté River.

2.4.10. Mainstem and tributaries use

Curimbatá used the mainstem and two tributaries during the non-spawning season. Twenty-six fish used 128 km of the mainstem from 2 km downstream of TMD to PR, but 91% of the fish remained within 50 km of TMD. Two fish used tributaries, i.e., LS Cilga male 59 entered the Janeiro River soon after tagging and was never tracked again in the mainstem, and LS Pontal male 71 remained in the Abaeté River the entire 2002 non-spawning season (Figure 2.2). I detected some fish in the mainstem during some surveys, but not by others, suggesting these fish moved back and forth between the mainstem and tributaries. This was likely the situation for four fish (Pontal male 75, Pontal females 84 and 85, and TM male 76).

2.4.11. Homing fidelity

Some curimbatá returned (homed) to the same pre-spawning staging site between years and within a year, but others did not. The LS Cilga female 69 visited Pontal four times and used the same pre-spawning staging site about 3 km upstream from Pontal during 2 years (Figure 2.5). Likely LS Pontal females 73 and 81 visited Pontal during the 2002–2003 spawning season, and then returned to the same pre-spawning staging site (300 m long) 6–9 km upstream from Pontal (Figure 2.6). However, not all fish used the same pre-spawning staging site each year. LS Pontal male 71 used a pre-spawning staging site 1 km upstream from Pontal one spawning season and a site 3 km upstream the next spawning season.

Some curimbatás returned to the same non-spawning and spawning locations during two seasons. During the non-spawning season, two TM fish moved downstream (ES female 52 moved 19 km, ES male 76 moved > 23 km) before both returned upstream to TM after 3–5 months. Pontal female 73 returned to the same non-spawning spot (170 m long) downstream of Pontal during 2002 and 2003 (Figure 2.6). During the 2001 spawning season, Cilga LS females 57 and 69 were at 2,039 and 2,077 rkm, respectively. They migrated downstream 20–48 km in the non-spawning season, then returned upstream to the same rkm just before or at the beginning of the 2002 spawning season (Figures 2.5 and 2.7). Pontal female 73 occupied a spot at rkm 2,087 at the end of the 2001–2002 spawning season, spent the non-spawning period downstream, then returned to the same spot (190 m long) at rkm 2,087 before the 2002–2003 spawning season (Figure 2.6). LS Pontal male 71 returned to the same rkm in the Abaeté River during the non-spawning seasons of 2002 and 2003 (Figure 2.2).

2.4.12. Home range

The frequency of occurrence of 19 fish tracked during spawning and non-spawning seasons in 10-km long segments of the mainstem and tributaries is shown in Figure 2.8. I located most fish in the first 60 km downstream from TMD during spawning and non-spawning seasons. In both seasons, greater numbers of fish were at the tagging sites. The first segment just upstream of Pontal was the location of six fish (one TM, three Pontal, and two Cilga fish; all LS or likely LS fish) during the spawning season. Tagged fish used the river near PR and the Abaeté River during the non-spawning season only.

For the 19 fish tracked during both spawning and non-spawning seasons, total home range was 1–127 km (33 ± 39 km, mean ± SD). Four fish had a total home range > 80 km (Figure 2.9). Most fish (14) had a total home range < 26 km; six fish had a total home range < 6 km. There was no significant relationship between total home range size and the number of days I tracked fish (Pearson correlation: $r = -0.07$, df = 17, $P = 0.79$, power = 0.05), SL (Pearson correlation: $r = 0.26$, df = 17, $P = 0.29$, power = 0.19), and K (Pearson correlation: $r = 0.02$, df = 17, $P = 0.93$, power = 0.03). Also, mean total home range size was not different between males and females (t-test: $t = 0.31$, df = 17, $P = 0.76$, power = 0.07) or among fish tagged at TM, Pontal, and Cilga (ANOVA: $F = 0.19$, df = 2, $P = 0.83$, power = 0.37).

Twenty-one fish provided data on size of non-spawning home range (Figure 2.10). The non-spawning home range was 0–48 km (11 ± 15 km, mean ± SD). All non-spawning home ranges except one were either < 5 km or > 20 km. There was no difference between males and females for size of non-spawning home range (t-test: $t =$

0.81, df = 19, *P* = 0.43, power = 0.12) or among fish tagged at TM, Pontal, and Cilga (ANOVA: *F* = 1.99, df = 2, *P* = 0.17, power = 0.37). Also, there was no relationship between non-spawning home range and SL (Pearson correlation: *r* = 0.26, df = 19, *P* = 0.26, power = 0.21) and K (Pearson correlation: *r* = 0.09, df = 18, *P* = 0.71, power = 0.06). One fish (TM female 154) used different sections of the river during two non-spawning seasons (Figure 2.6).

Sixteen fish provided data on both total home range and non-spawning home range. The non-spawning home range represented 2–100% (48 ± 41%, mean ± SD) of their total home range.

2.4.13. Spawning during successive years

` Spawning during successive years of both females and males was indicated by movements of LS fish that were at Pontal in both spawning seasons. For example, LS Cilga female 69 moved upstream to Pontal soon after tagging in January 2001 (Figure 2.5). After the spawning season, this female moved downstream past Cilga for the non-spawning season; then returned upstream to Pontal the next spawning season. LS Pontal male 71, which used the Abaeté River during the non-spawning season, was at Pontal during two consecutives spawning seasons (Figure 2.2).

2.5. Discussion

2.5.1. Spawning grounds

Movements of pre-spawning curimbatás tagged at Cilga, Pontal, and TM indicated that Pontal was the major spawning ground. Curimbatás migrated to Pontal during the pre-spawning and spawning seasons from mainstem non-spawning locations up- and downstream of Pontal and from tributaries, like the Abaeté River. While some fish used the Pontal area all year, many fish migrated to Pontal only during the spawning season. Curimbatá spawning at Pontal was supported by the presence of male spawning calls in the mainstem right at the mouth of the Abaeté River (Godinho and Kynard unpublished).

Curimbatá also likely spawned at Cilga, just downstream from Pontal, also triggered by Abaeté River floods, but detailed information is lacking. I did not have a receiver at Cilga, like at Pontal; thus, no detailed movements or use of pre-spawning staging areas were noted for fish at Cilga. Sato *et al.* (2003a) captured ripe running females and heard male mating calls in the Cilga area, but did not record the exact location of the calls. The present study and the study by Sato *et al.* (2003a) indicate spawning occurs at Cilga, but neither study precisely located the spawning grounds.

Only few curimbatás likely spawn between Pontal and TMD where no large tributaries bring flood waters into the mainstem and mainstem flow is mainly discharge from Três Marias Reservoir (Sato *et al.* 2003a, and present study). Sato *et al.* (2003a) found the frequency of LS and spent females during the spawning season was 18% upstream of Pontal and 97% downstream of Pontal. Also, the percentage of females with atresic vitellogenic eggs was 25% upstream of Pontal and 4% downstream of Pontal. The gonadosomatic index of mature females was also significantly smaller upstream of Pontal compared to females downstream of Pontal. Finally, a smaller percentage of ripe and spent LS males was found upstream of Pontal (69%) compared to downstream of Pontal (99%). Sato *et al.* (2003a) concluded that hypolimnetic water from Três Marias Reservoir creates unfavorable conditions for spawning upstream of Pontal, whereas spawning conditions are favorable at and downstream of Pontal due to the inflow from the Abaeté River. All tracked LS females and males and most likely LS tagged at TM stayed the entire spawning season at TM. A few adults may spawn at TM, but the data of Sato *et al.* (2003a) and the absence of spawning calls at TM (Godinho and Kynard pers. obs.) suggest spawning is rare.

2.5.2. Visits to Pontal

Curimbatá are believed to be total spawners that spawn all their eggs in one batch during the spawning period (Bazzoli 2003, Sato and Godinho 2003). However, the back and forth movement of females from pre-spawning staging areas to Pontal suggests they could be spawning multiple times. However, I think that another explanation is likely the case. Fish may return multiple times to Pontal because the proper riverine spawning cues are not present during each visit. Fish staging upstream from Pontal are in water from Três Marias Reservoir, which has very different physical and chemical characteristics than the historical mainstem water before 1963 (pre-TMD), and thus, the present water likely lacks spawning cues. This explanation is supported by the absence of a relationship between frequency of fish visits to Pontal and discharge of the Abaeté River. A significant relationship was expected because spawning, as indicated by the presence of male spawning calls, occurs mostly during the few days of an Abaeté River flood (Godinho and Kynard pers. obs.). Apparently, flooding Abaeté River water adds the correct spawning cue(s) to mainstem water. During the evolution of pre-spawning staging behavior, the water characteristics of the mainstem and Abaeté

River were more similar than they are now. Presently, there seems to be a mismatch, with fish preferring the mainstem pre-spawning staging area upstream of the Abaeté River inflow, but an absence of spawning cue(s) in the mainstem water at pre-spawning staging area.

For males, a second explanation is possible for multiple visits. Because spermiogenesis occurs even in ripe males (Sato *et al.* 2003a), males are ripe much of the spawning season. Consequently, males can mate many times in a spawning season and each time with different female(s). The multiple visits of males to Pontal suggest they spawn with multiple females and that the species has a polygynous mating system.

2.5.3. Pre-spawning staging area

The evolution of pre-spawning staging behavior in riverine fishes is usually related to conferring an energetic advantage, but for curimbatá, location of pre-spawning staging area may also confer increased survival from predators and better feeding habitat. In North America, pre-spawning staging areas are known for *Stizostedion canadense* in the Tennessee River (Pegg *et al.* 1997), white sturgeon *Acipenser transmontanus* in the Kootenai River, Idaho (Paragamian and Kruse 2001), and shortnose sturgeon *A. brevirostrum* in the Connecticut River (Kieffer and Kynard pers. obs.). In these cases, the staging area is near (within a few kilometers) the spawning area, thus providing quick, low-energy expenditure access to the spawning site. The most important pre-spawning staging area of curimbatás was in the mainstem 0.3–12.5 km upstream of Pontal. Staging close to the spawning ground allows pre-spawning curimbatá rapid access to the spawning ground with low energetic costs, similar to the North American species cited previously.

Curimbatá may have evolved the use of distant pre-spawning staging area to avoid large predators and reduce competition for food. Dourado *Salminus brasiliensis* is a large predator that is abundant at Pontal during the curimbatá spawning season (Godinho pers. obs.). Staging away from Pontal may greatly reduce the exposure of pre-spawning curimbatás to this predator. Also, curimbatás stage near Pontal for weeks or months during the spawning season when water temperatures are the highest of the year. Thus, pre-spawning curimbatás must forage to meet energetic demands of metabolism and spawning. Staging away from Pontal spawning area likely reduces intraspecific competition for food.

2.5.4. Spawning periodicity

The return of two LS males and one LS female to Pontal in two consecutive spawning seasons suggests some fish spawn again after 1 year. One LS female stayed 23 km downstream Cilga during the second spawning season it was tracked and did not return to Pontal, which indicates that either it was not able to spawn or it spawned elsewhere.

2.5.5. Non-spawning grounds

Lucas and Baras (2001) identified two types of non-spawning grounds for riverine fishes, i.e., feeding and refuge. In the present study, I termed the river reaches used by tagged curimbatá outside the spawning season as non-spawning grounds. I did not gather data to determine if fish were foraging but all non-spawning grounds of curimbatá in this study were likely feeding grounds, not refuge grounds. Refuges are places fish go to avoid unfavorable physical conditions like water temperature, flow, desiccation, and low dissolved oxygen, as well as avoid unfavorable biological factors, like predators (Lucas and Baras 2001). In the study reach, temperatures and flows vary little in the mainstem from season to season, and except at TM, the water has medium to high dissolved oxygen content because the river is oxygenated by the many riffles and runs. Moreover, TM curimbatás were found in water with dissolved oxygen levels as low as 2.2 mg L^{-1} (Godinho personal data). They are tolerant to hypoxia, similar to their sibling species *P. lineatus* (Fernandes *et al.* 1995). Also, fish movement to avoid desiccation is rare because floodplains are few and narrow and flooding is unusual due to flow regulation by TMD. None of my tagged fish used a floodplain.

2.5.6. Homing

Homing is defined as returning to a place formerly occupied instead of going to other equally probable places (Gerking 1959). For South American fishes, homing has only been found in *P. lineatus*, sibling species of curimbatá, for adults returning to a spawning area in the Mogi-Guaçu River, Brazil (Godoy 1959, 1975). During a multi-year mark-recapture study at a major spawning area, adults were marked and some recaptured at the tagging site after one or more years. This spawning-site homing is similar to the homing to Pontal of radio-tagged curimbatá and suggests spawning site homing is widespread within the genus *Prochilodus*.

Some curimbatá showed very precise homing by returning to the same spot at the pre-spawning staging area, spawning ground, and non-spawning ground. Not all fish homed to the same pre-spawning staging site, spawning or non-spawning grounds different years, i.e., one LS female was at Pontal one spawning season and 38 km downstream of Pontal the following spawning season. Adults, even in the same reproductive stage, showed a diversity of migration and homing styles that would take years of tracking the same fish to understand.

2.5.7. Home range

I used the most up- and downstream locations of tagged fish to indicate total home range similar to Muhlfeld and Bennett (2001), and Pearson and Healey (2003). Tagged curimbatás had two total home range sizes: small and large. Most (68%) had a small total home range (< 26 km) and the remainder (22%) had a large total home range (53–127 km). The reason(s) for this dualistic pattern of total home range is not known. I found no pattern of total home range between males vs. females or among tagging sites, or correlation to fish SL or K. It would take a long-term tracking and feeding study of many fish in different reproductive stages to determine the significance of this pattern to life history. The small and large total home range pattern was also reflected in the dualistic migration pattern of fish: migratory and non-migratory. Some non-migratory fish (21%) had a total home range ≤ 1 km, and thus, virtually used the same grounds for spawning and non-spawning. Most fish were migratory with a total home range of 4–127 km.

Animal populations with migratory and resident individuals are termed partial migratory (Jonsson and Jonsson 1993). Partial migratory populations of fishes often show polymorphism with dwarf resident, mostly males, and large migrants, mostly females (Jonsson and Jonsson 1993, Klemetsen *et al.* 2003). The decision to migrate or not seems to be influenced by genetic and environmental factors (Jonsson and Jonsson 1993, Olsson and Greenberg 2004). The ultimate explanation for this polymorphism is that the fitness of the large morphs more than the dwarf ones depends on growth rate and size of the fish (Klemetsen *et al.* 2003). Migratory and resident curimbatás were similar-sized fish, not dwarfs; thus, the curimbatá dual migration style does not fit into the partial migration concept. Therefore, the term dualistic migration was used instead. A dualistic migration style has also been found between similar-size shortnose sturgeon yearlings (Kynard *et al.* pers. obs.) and surubim *Pseudoplatystoma corruscans* (Chapter 3).

Non-spawning grounds of curimbatá in the mainstem were located at Pontal and up- and downstream of Pontal, including Cilga. Fish seeking to move downstream to non-spawning grounds from Cilga, Pontal, or TM had free movement, but fish seeking to move far upstream would be artificially limited by TMD. However, no tagged LS Pontal or Cilga fish moved upstream to TM, so this did not affect the total home range estimate of these fish. The distance between spawning and non-spawning grounds of my tagged fish was a maximum of 98 km, but for most curimbatá (72%) it was ≤ 22 km. This is the smallest home range found for any South American migratory fish (Petrere 1985, Lucas and Baras 2001, Carolsfeld *et al.* 2003) and suggests that foraging habitat for adults is abundant near the spawning ground.

I tested total home range and non-spawning home range for differences between the sexes and among tagging sites, but found no difference between or among groups in all tests. I also tested the two home ranges for correlation with fish SL and K and again found no relationship in both tests. These results should be used with caution because all tests had low power. Due to the small sample size and large sampling variability, there is a high probability of making a type II error, i.e., not rejecting the null hypothesis when it should have been (Peterman 1990).

2.5.8. Juvenile migration

An early life history where eggs and larvae drift far downstream to rear also must include, at a later stage of ontogenetic development, the return upstream of juveniles to rejoin adults (Baras and Lucas 2001). In the beginning of the 2002 dry season (non-spawning season), a school of about 1,000 young curimbatá about 20 cm SL arrived at the TMD tailrace (Godinho pers. obs.). They remained for several days swimming at the water's surface seemingly searching for upstream passage. Anecdotal evidence from fishers indicates this migration happens every year. A similar upstream migration of young *P. lineatus* occurs in the Mogi Guaçu (Godoy 1954). This is likely the migration that brings the young life stage back to the reach inhabited by adults. This aspect of curimbatá life history has not been studied well in any river.

2.5.9. Metapopulation

Migration of curimbatás inhabiting the area downstream of PR appears similar to curimbatás in the present study. In a mark-recapture study of curimbatá tagged at PR – Velhas River mouth reach, Paiva and Bastos (1982) tagged 1,594 fish (presumably adults) and recaptured 18. Most recaptured fish (n = 14) were caught < 25 km from their original tagging site, including six fish marked one season and recaptured another season. Some fish marked during the pre-spawning, spawning, or non-spawning seasons moved upstream and some moved downstream. Only three fish migrated a long distance (90–250 km). Finally, some fish used tributaries and some used the mainstem. All these migration characteristics are similar to my tagged fish. The group of curimbatás studied by Paiva and Bastos (1982) and the Pontal group I studied do not overlap for their spawning grounds and only overlap for a small distance at PR.

Hatanaka and Galetti (2003) compared genetic similarity between curimbatás at TM and at Pontal (including Cilga) and found TM fish had a significant higher genetic similarity coefficient than Pontal fish. They suggested three hypotheses to explain the genetic difference between the two groups. Two hypotheses indicate that the two groups comprise different populations with separate spawning grounds. The third hypothesis suggests a panmictic population. My finding showed that TM fish do not seem to be part of the Pontal group although a rare TM fish spawned at Pontal (one likely LS female in the present study) and all other likely LS TM and all LS TM fish stayed at TM during the spawning season. Therefore, TM and Pontal fish have separate spawning grounds which supports Hatanaka and Galetti's hypotheses that these two groups comprise different populations.

Mutually exclusive movement patterns and spatially distinct spawning grounds of the TM, Pontal and PR groups of curimbatás indicate they are three populations of a larger curimbatá metapopulation. The TM population presents the smallest range that overlaps with the upper portion of the Pontal population. The PR population has the largest range with some overlap with Pontal population at PR.

The TM population may be part of another population with connections to curimbatá upstream of TMD. The young curimbatás that search for an upstream passage at the TMD tailrace are movements expected if they were returning recruits of upstream TMD curimbatá population(s). These recruits cannot pass upstream of TMD and must stay downstream where they eventually become adults. Tagged TM adults remained near the dam during the spawning season even though conditions to spawn are not favorable. Although adult curimbatá can tolerate poor dissolved oxygen conditions (Godinho pers. obs.), they may avoid entering the extremely low dissolved oxygen (1.9 mg L^{-1}, Sampaio and López 2003) present in the upper tailrace, and thus, appear not to be attempting to move upstream of the dam (zero tracks of fish by my data-logging receiver in the tailrace). All these evidences suggest that TM fish might be part of a larger upstream population that was segmented by the dam. Genetic analysis comparing curimbatá upstream of the dam and at TM could easily test this idea.

2.5.10. Population structure

Curimbatás in the three populations proposed differ in size at maturity. The TM curimbatás are largest at maturity (32.0 cm SL for males and 33.0 cm SL for females, Santos and Barbieri 1991). At PR, size of maturity is 22.4 cm SL for males and 22.8 cm SL for females (Bazzoli 2003). Bazzoli (2003) provided curimbatá size of maturity in total length. I converted that size to standard length using the equation SL = 0.8 + 0.8 total length ($r^2 = 0.99$, n = 657) determined with the same dataset used by Bazzoli (2003). The PR fish experience slightly warmer temperature than TM fish (Chapter 4) and, thus, reach sexual maturity at a smaller size. Due to an intermediate temperature at Pontal, I predict that Pontal curimbatá mature at an intermediate size between fish at PR and TM.

The TM population has a greater percentage of juvenile fish than Pontal. Sato *et al.* (2003a) found more ES curimbatá and smaller mean size of fish at TM than at Pontal (including Cilga). The mean size of the TM fish was smaller than the size at maturity which indicates a large proportion of juvenile fish at TM. The mean size of Pontal fish was bigger than the size at maturity suggesting a lower percentage of juvenile fish.

The smaller mean size of fish at TM was likely due to greater harvest at TM. The 2,700 Três Marias commercial fishers (Franco de Camargo and Petrere 2001) are just few km away from the TM population and much farther from the Pontal population. Anglers flock to the São Francisco River to fish for curimbatás at TM in greater numbers than at any other area (Godinho pers. obs.).

2.5.11. Conceptual model

I propose the following metapopulation structure and conceptual model for life history movement of curimbatás inhabiting the São Francisco River within 409 km downstream of TMD (Figure 2.11). Knowing the reproductive stage of my tagged fish was the key to placing movements of fish into a conceptual model of life history. All data indicate that three populations of curimbatá (TM, Pontal, and PR) live in this reach with some overlap of non-spawning ranges between the populations.

Eggs and larvae produced by each population disperse downstream during the spawning season (rainy season) to nursery grounds in floodplain lakes (Figure 2.11). The TM population has limited spawning and likely produces few eggs. Nursery habitat is abundant downstream of the Paracatu River mouth located 243 km downstream from

TMD. At about 20 cm SL, juveniles migrate upstream in schools from the nursery grounds to river reaches inhabited by adults (Figure 2.11).

Migration of adult curimbatás to Pontal are best documented (Figure 2.11), but similar movements are likely in other populations. Adults from up- and downstream of the spawning area and from tributaries, like the Abaeté River, initiate a pre-spawning migration months, weeks or days before or during the spawning season (November–February). Pre-spawning adults move to a spawning area, like Pontal at a tributary mouth, or to a nearby pre-spawning staging area. Pre-spawning females and males move back and forth between pre-spawning staging areas and the spawning ground, usually visiting the spawning site several times (spawning site homing). Sometimes, they return to the same pre-spawning staging spot (pre-spawning staging site homing). Part of the adults visits the same spawning site for more than one spawning season (spawning site homing). A small fraction of the post-spawning adults remains at the spawning site during the non-spawning season while the others migrate to non-spawning areas downstream in the mainstem or into tributaries. Post-spawned Pontal adults move mostly downstream as far as PR. Post-spawned adults leave the spawning site anytime during the spawning season or months after spawning ceases. Part of the post-spawning fish returns to the same non-spawning ground (non-spawning site homing) and the rest moves to other areas. During the non-spawning season, curimbatás are sedentary using only $\leq$ 4 km of river or occupy two or more different areas that are tens of kilometers apart.

The situation for TM fish is a special case because they live in a highly modified reach of river. During the spawning season, pre-spawning TM fish stay close to TDM where the water likely precludes spawning and lacks spawning cues, so many fish reabsorb gametes. Spawning is likely only by few fish that can spawn in the cold water lacking spawning cues provided by flood. After the spawning season, adults stay or migrate downstream (Figure 2.11). During the non-spawning season, ES TM fish stay at or near TM or migrate downstream and may return within few months. When ES TM fish develop into LS adults, most stay at TM during the spawning season, but few adults go downstream and spawn at Pontal. If so, they migrated downstream after spawning.

The Pontal population likely includes Cilga fish and a few other fish that spawn near Pontal. While I only documented spawning by Cilga fish at Pontal, a larger sample over more years would likely document spawning by the same fish during different years at Pontal, Cilga, and a few other sites near Pontal. After spawning, the Cilga fish moved up- and downstream no farther than 11 km. Their non-spawning range was included within the non-spawning range of Pontal fish.

Only total home range and migratory movements of the PR fish are known. Most fish have a small total home range, < 25 km. PR fish use tributaries (Velhas River and likely others) and the mainstem. Pre- and post-spawning migrations is up- or downstream, but location of spawning grounds and the details on non-spawning grounds are unknown (Figure 2.11).

2.6. Conservation and Management

The São Francisco River Basin hydropower potential is 26.3 GW, with 10.5 GW already developed (ANEEL 2002). In the free-flowing Abaeté River, there are nine potential sites for dams. New dams will block upstream migration to non-spawning grounds and reservoirs will stop floods that trigger spawning at Pontal and at other downstream locations. This will eliminate spawning by curimbatá and other migratory fishes at Pontal. To maintain populations of curimbatá and an entire suite of migratory fish species that use the Pontal spawning area (Godinho and Kynard pers. obs.), some tributaries like the Abaeté River must remain without dams. If key tributaries that serve as flood water to mainstem spawning areas are dammed, mainstem spawning grounds will be lost.

Among the four dams planned for the mainstem downstream of TMD, Formoso Dam is the most upstream one. It is proposed to be built 10 km upstream from PR. It will impede free movement of some curimbatá that spend the non-spawning season near or just downstream of PR, will flood mainstem non-spawning grounds of the Pontal population, will likely flood the Cilga and Pontal spawning grounds, and would certainly create a reservoir that traps and kills downstream dispersing eggs and larvae from any upstream spawning of curimbatá. Thus, it is hard to envision a scenario in which Formoso Dam is constructed and the Pontal population survives.

Curimbatás in the upper São Francisco River have evolved discrete populations that use discrete reaches of the river with some overlap in use by adults. Using only the adult home ranges, it seems possible that a mainstem dam could be built that would only affect one or two populations. However, this is misleading because the conceptual model suggests that more river is needed downstream for dispersal and rearing of early life stages to be successful. If all proposed dams are built on tributaries and the mainstem, it seems clear that curimbatá populations in the Pontal and PR reaches will be drastically reduced or even extirpated.

The TMD does not have an upstream fish passage for any species or life stage of fish. The conceptual model indicates that the TM population may be a fraction of an upstream population that is segmented by the dam, but there are many unanswered questions. Little is known about curimbatás that occur upstream of TMD other than they do occur; so the connection of TM adults to an upstream population segment needs to be verified and understood in terms of life history movements. This includes documenting downstream movement of any life stage at TMD and upstream migration of juveniles and adults to TM, and also, similar migrations of early life stages in other populations (Pontal and PR) to construct a conceptual model of up- and downstream movements. This conceptual model will provide agencies with the details of movement by life stages to design appropriate fish passage facilities, if needed.

Adult curimbatás in my study moved up- and downstream during two peak periods (pre-spawning and post-spawning). Migrations were complex with some fish migrating up- or downstream during most months. Thus, if up- and downstream fishways are needed, they will need to be operational for the entire year to accommodate curimbatás. Until the connection between TM curimbatás and curimbatás upstream of the dam is better understood, agencies will not have the information to make decisions regarding fish passage at TMD.

Table 2.1. Fish characteristics and tracking summary of radio-tagged curimbatá in the São Francisco River, 2001–2003. Fish were captured and tagged at three locations: Três Marias, Pontal, and Cilga. Sex and gonadal stages of fish were: F = female, M = male, ES = early-stage, LS = late-stage (ripe). Number of days tracked is the number of days between day of tagging and last day I located the fish. Number of locations is the number of mobile and data-logging tracks for each fish. Fate of fish was: L = lost (tag signal lost during the study while fish was still alive), D = died, H = harvested, A = alive.

Fish	Standard length (cm)	Sex and gonadal stage	Tagging date	Number of days tracked	Number of locations	Fate			
						L	D	H	A
			Três Marias (rkm 2,100–2,105)						
50	41.7	F-LS	15 Jan 01	139	12			X	
51	50.5	F-LS	14 Jan 01	319	17	X			
52	38.0	F-ES	14 Jan 01	137	9	X			
53	40.3	M-LS	15 Jan 01	39	5	X			
54*	36.0	F-LS	15 Jan 01	7	3			X	
55*	32.0	M-LS	15 Jan 01	21	5	X			
154	40.8	F-ES	06 Feb 01	419	25			X	
76	40.0	M-ES	22 Jan 02	259	7	X			
77	39.0	F-ES	22 Jan 02	101	6		X		
78	42.0	M-ES	22 Jan 02	411	8	X			
79	36.0	F-ES	22 Jan 02	545	15				X
80	38.5	F-ES	23 Jan 02	182	5		X		
			Pontal (rkm 2,075–2,083)						
63	35.3	M-LS	17 Jan 01	40	3	X			
64	35.6	M-LS	17 Jan 01	19	15	X			
65	40.3	F-LS	17 Jan 01	332	329	X			
66	39.7	M-LS	17 Jan 01	80	7		X		
70	47.0	F-ES	19 Jan 02	101	18			X	

Continue next page.

Table 2.1. Continued.

Fish	Standard length (cm)	Sex and gonadal stage	Tagging date	Number of days tracked	Number of locations	Fate			
						L	D	H	A
71	40.0	M-LS	19 Jan 02	548	17				X
161*	40.0	M-LS	19 Jan 02	6	2		X		
72	41.0	M-LS	20 Jan 02	103	5		X		
73	47.0	F-ES	20 Jan 02	413	26	X			
81	43.0	F-ES	25 Jan 02	344	12	X			
82*	47.0	F-ES	25 Jan 02	28	2		X		
83	49.0	F-ES	25 Jan 02	57	21	X			
84	39.0	F-ES	25 Jan 02	70	6	X			
85	42.0	F-ES	26 Jan 02	256	6		X		
			Cilga (rkm 2,061–2,066)						
56*	36.0	M-LS	16 Jan 01	20	5		X		
57	48.0	F-LS	16 Jan 01	473	16	X			
59	32.0	M-LS	16 Jan 01	554	5	X			
60	41.9	F-LS	17 Jan 01	67	8	X			
61	40.2	M-LS	17 Jan 01	36	6		X		
62	40.7	F-LS	17 Jan 01	60	7	X			
67	47.2	F-LS	18 Jan 01	200	7	X			
68	44.5	F-LS	18 Jan 01	35	4		X		
69	42.5	F-LS	18 Jan 01	357	23			X	
74	49.0	M-LS	21 Jan 02	34	11		X		
75	45.0	M-LS	21 Jan 02	344	8	X			

*Fish did not provide tracking data.

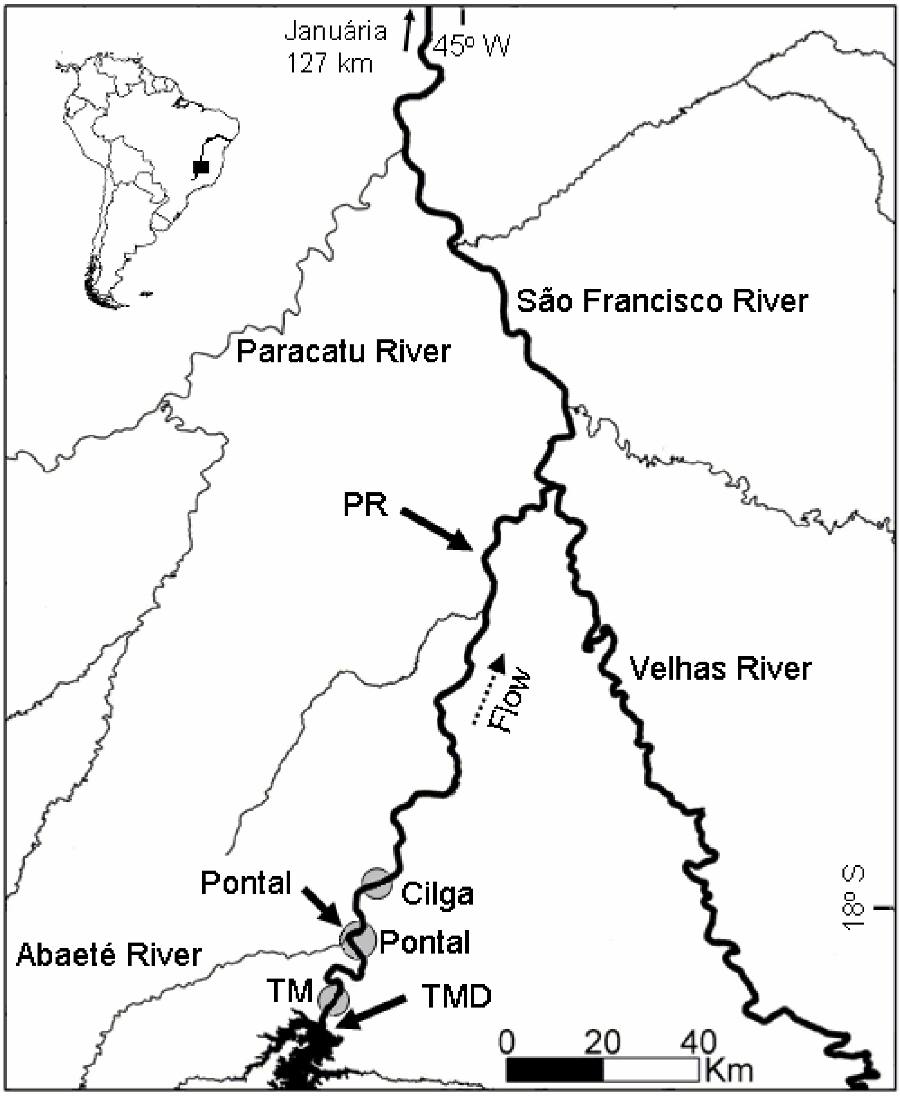


Figure 2.1. The study area for curimbatá in the São Francisco River Basin. Bold arrows show three sites with data-logging receivers: Três Marias Dam (rkm 2,109), Pontal (rkm 2,077), and Pirapora Rapids (rkm 1,980). Shaded circles show fish-tagging sites: Três Marias = TM (5 km reach), Pontal (8 km reach with Abaeté River mouth), and Cilga (5 km reach).

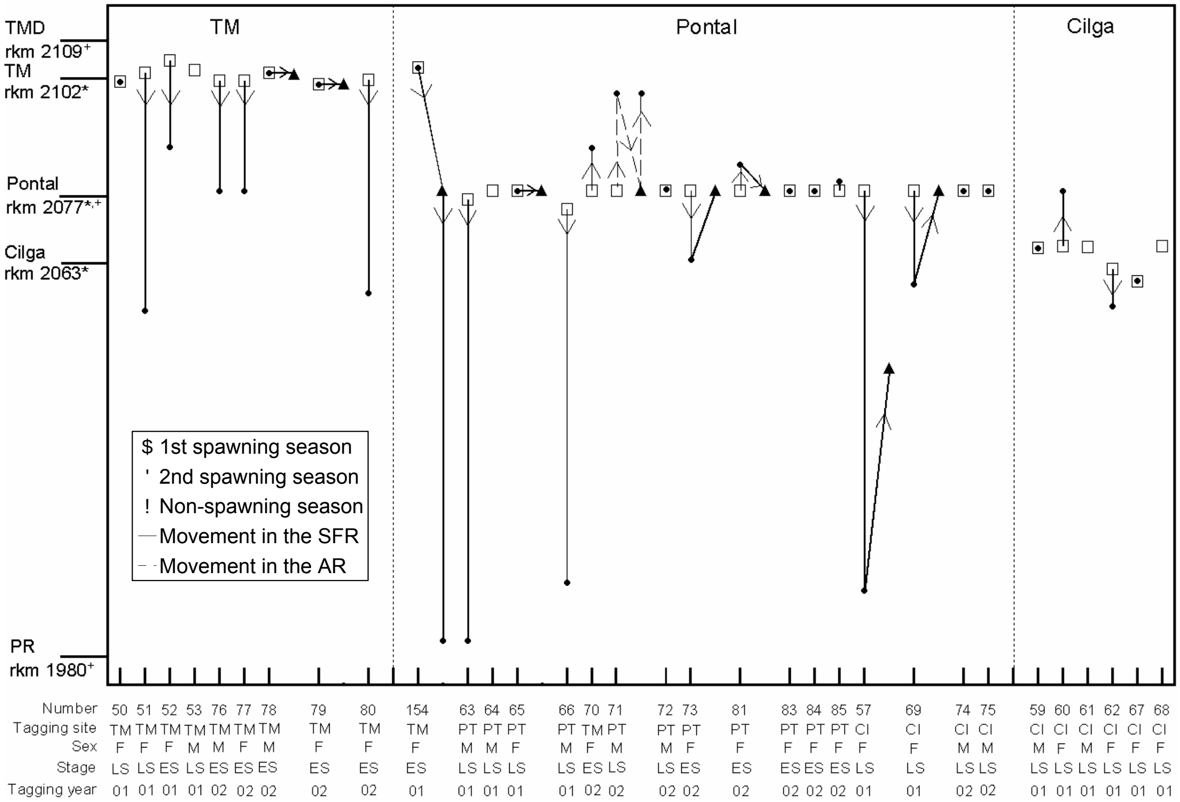


Figure 2.2. Curimbatá movements in the São Francisco River Basin. Fish were grouped in three clusters (TM = Três Marias, Pontal, and Cilga) accord to the river reach in which they were located more frequently during the spawning season. The y-axis shows tagging (*) and data-logging receivers (+) sites (TMD = Três Marias Dam, PR = Pirapora Rapids). The x-axis shows fish identification number, tagging site (TM = Três Marias, PT = Pontal, CI = Cilga), sex (F = female, M = male), reproductive stage (LS = late-stage, ES = early-stage), and tagging year. Squares indicate location during the first spawning season and triangles show location during the second spawning season. Dots mark the farthest fish location during the non-spawning season. Solid lines show movements in the São Francisco River (SFR) and dashed lines show movements in the Abaeté River (AR). Arrows indicate the direction of fish movement.

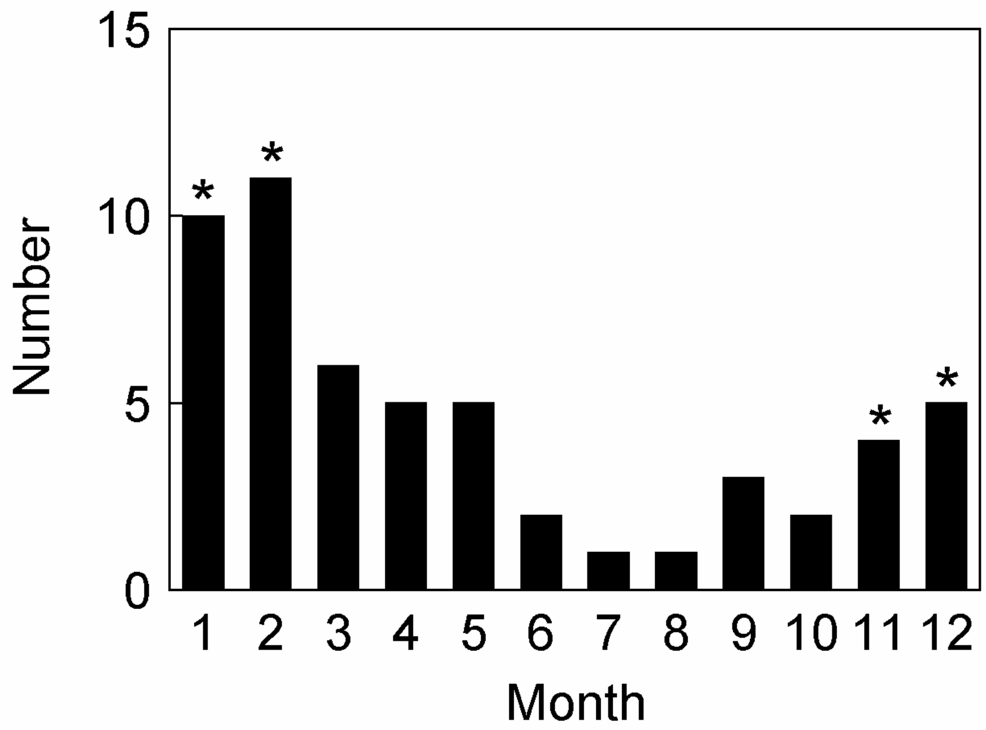


Figure 2.3. Monthly frequency of detection of tagged curimbatá by the Pontal receiver. A fish was not included in the calculation of the monthly frequency if it was only detected at Pontal during the tagging date. Asterisks indicate months of spawning for curimbatá (Bazzoli 2003).

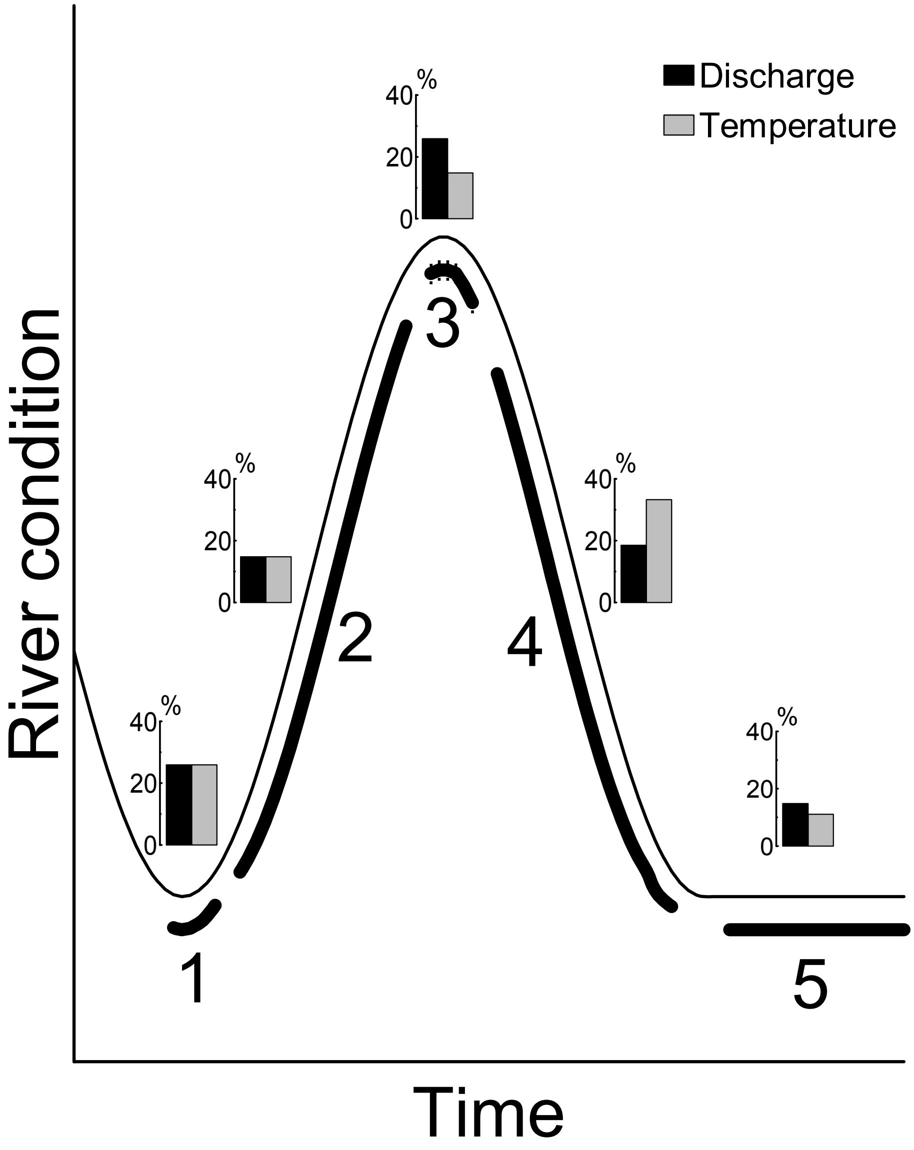


Figure 2.4. Frequency of visits by curimbatás to Pontal in the São Francisco mainstem during varying discharge and temperature conditions in the Abaeté River mouth where it joins the São Francisco River. The thin line represents hypothetical variation in river conditions (discharge and temperature) through time. The thick lines define timing of the following classes of river condition valley (1), increasing (2), peak (3), decreasing (4), and stable (5). Each histogram shows the frequency of fish visits during a class of river condition.

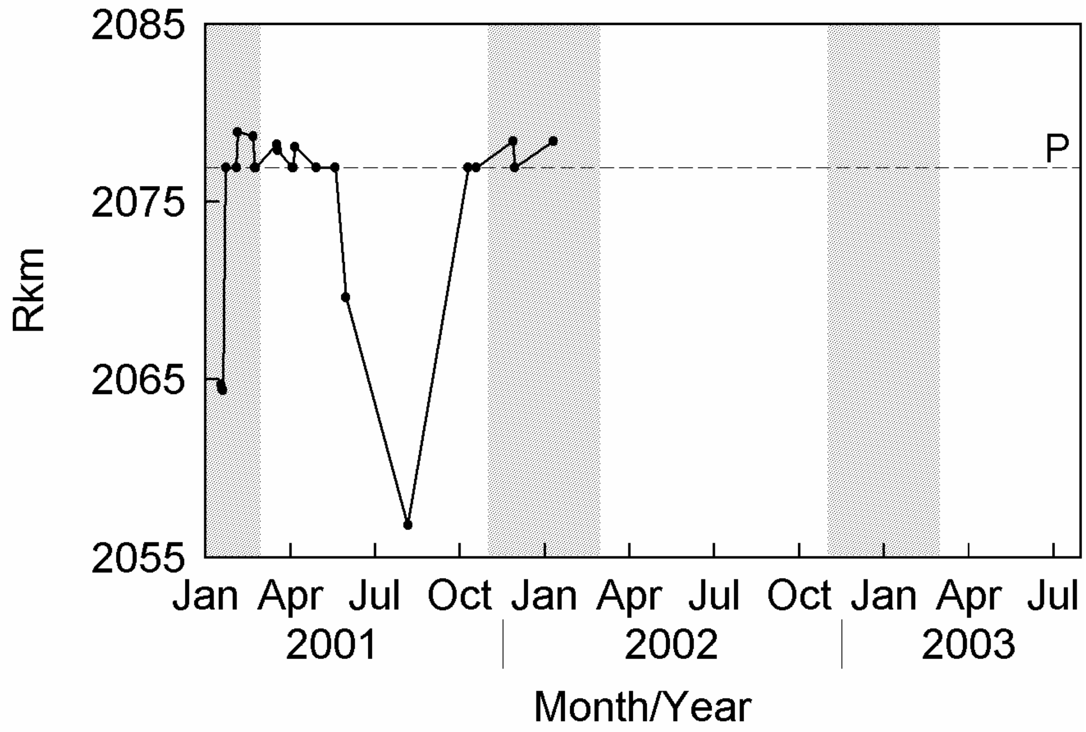


Figure 2.5. Migration of LS Cilga curimbatá female 69 in the São Francisco River. Gray vertical bars show spawning seasons and unshaded areas show non-spawning seasons. The P and the horizontal dashed line show the rkm location of Pontal receiver.

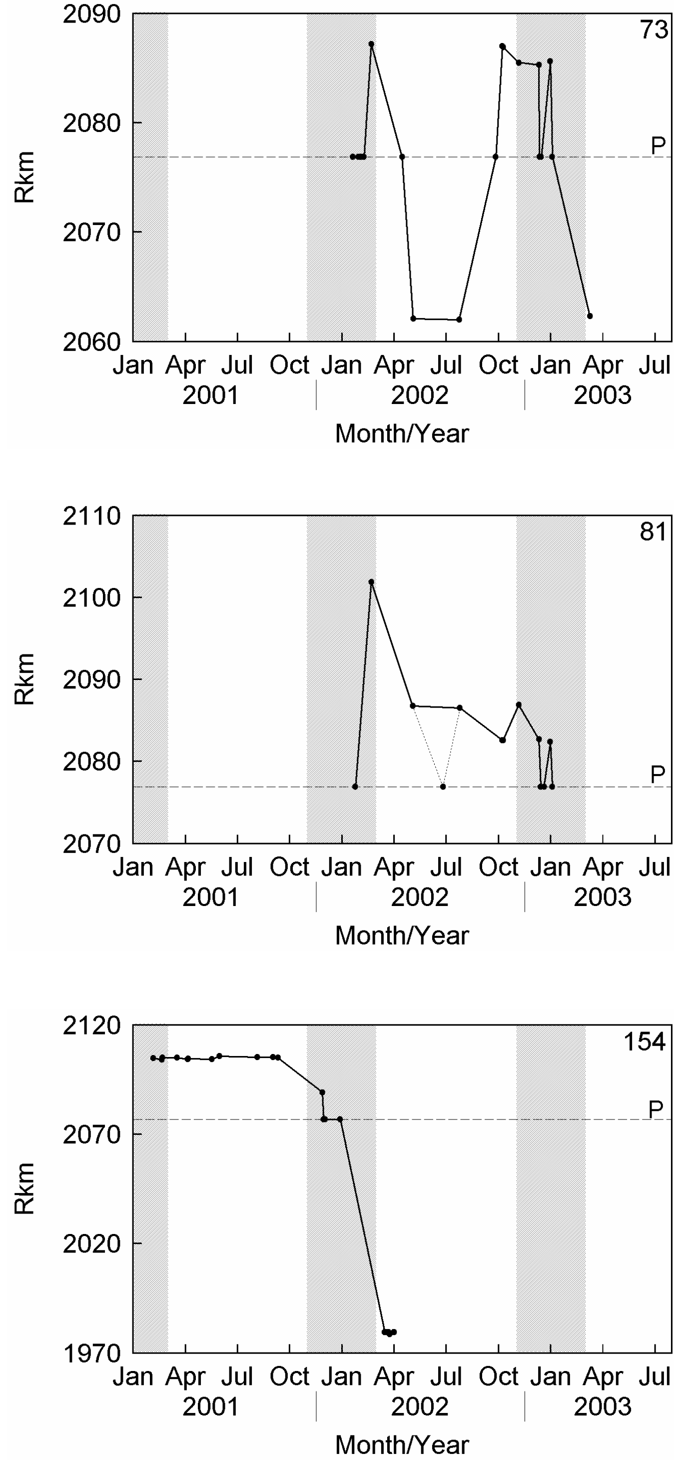


Figure 2.6. Migration of likely LS curimbatás (73, 81 and 154) in the São Francisco River. Dotted line indicates a possible alternative movement path of fish 81. Gray vertical bars show spawning seasons and unshaded areas show non-spawning seasons. The P and the horizontal dashed line show the rkm location of Pontal receiver.

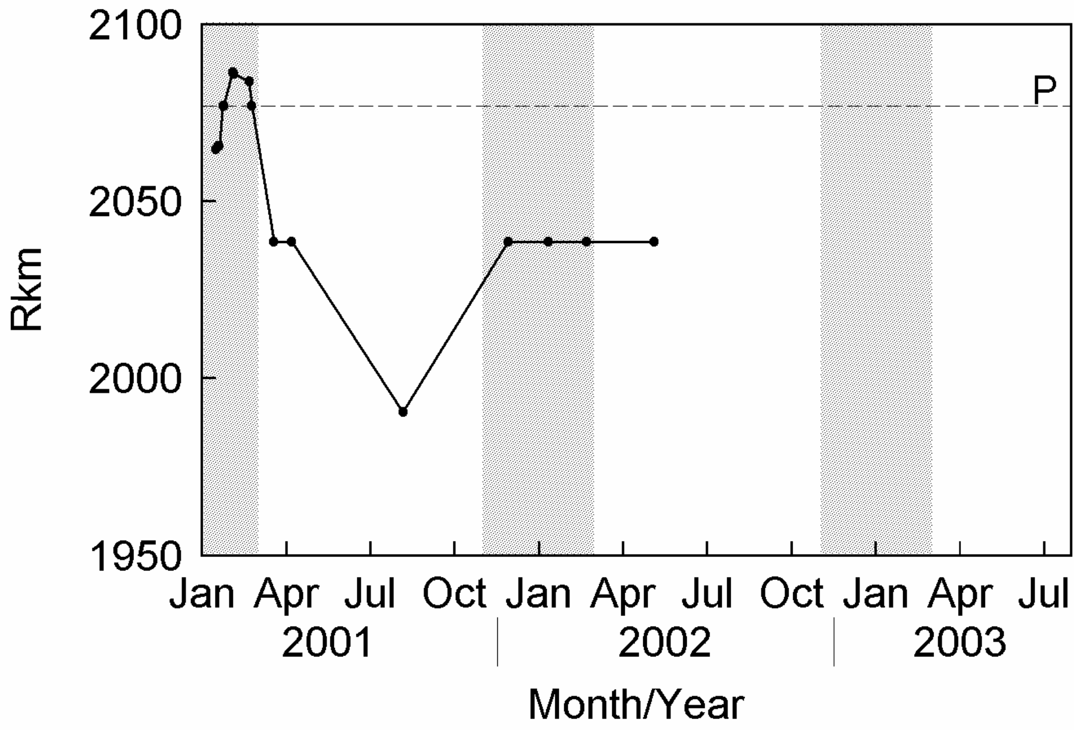


Figure 2.7. Migration of LS Cilga curimbatá female 57 in the São Francisco River. Gray vertical bars show spawning seasons and unshaded areas show non-spawning seasons. The P and the horizontal dashed line show the rkm location of Pontal receiver.

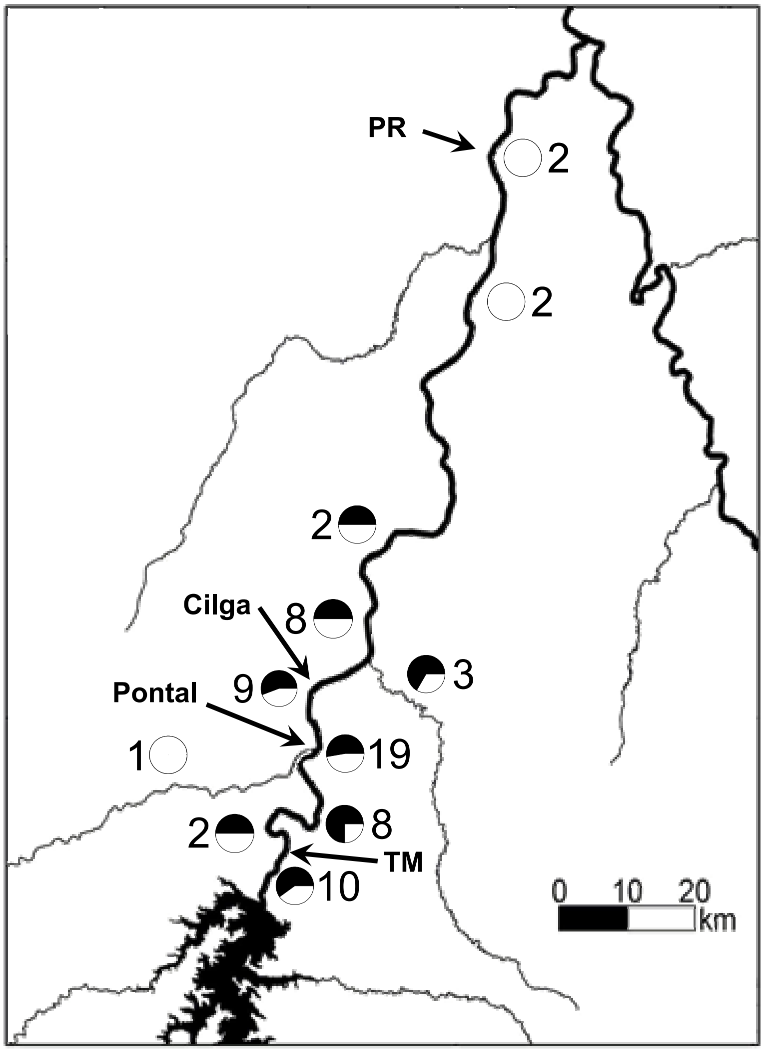


Figure 2.8. Frequency of occurrence of 19 curimbatás among 10-km long segments of the mainstem São Francisco River and two tributaries. Numbers represent the total number of fish located in each segment. Pie charts show percentage of fish located in each segment during spawning (black) and non-spawning (white) seasons. Map also shows the three fish-tagging sites (TM - Três Marias, Pontal, and Cilga), and PR (Pirapora Rapids, the most downstream location site for any fish).

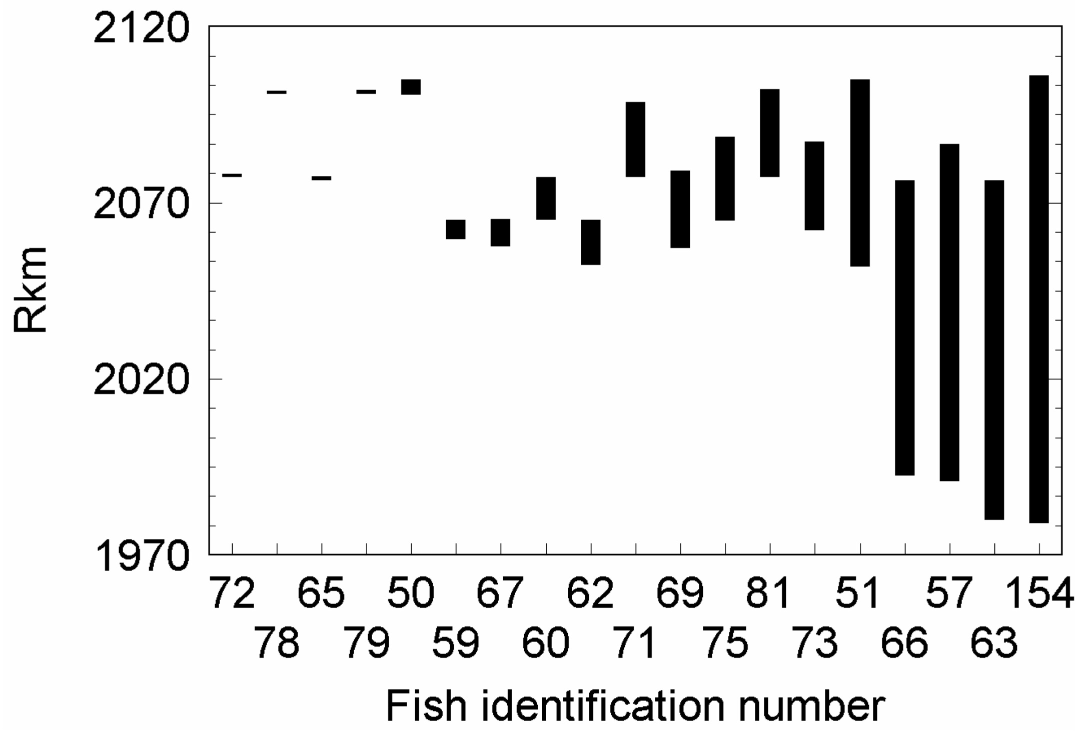


Figure 2.9. Total home range of 19 curimbatás (12 females and 7 males) tracked during the spawning and non-spawning seasons of 2001, 2001–2002, and 2002–2003. Total home range sizes are arranged from smallest to largest.

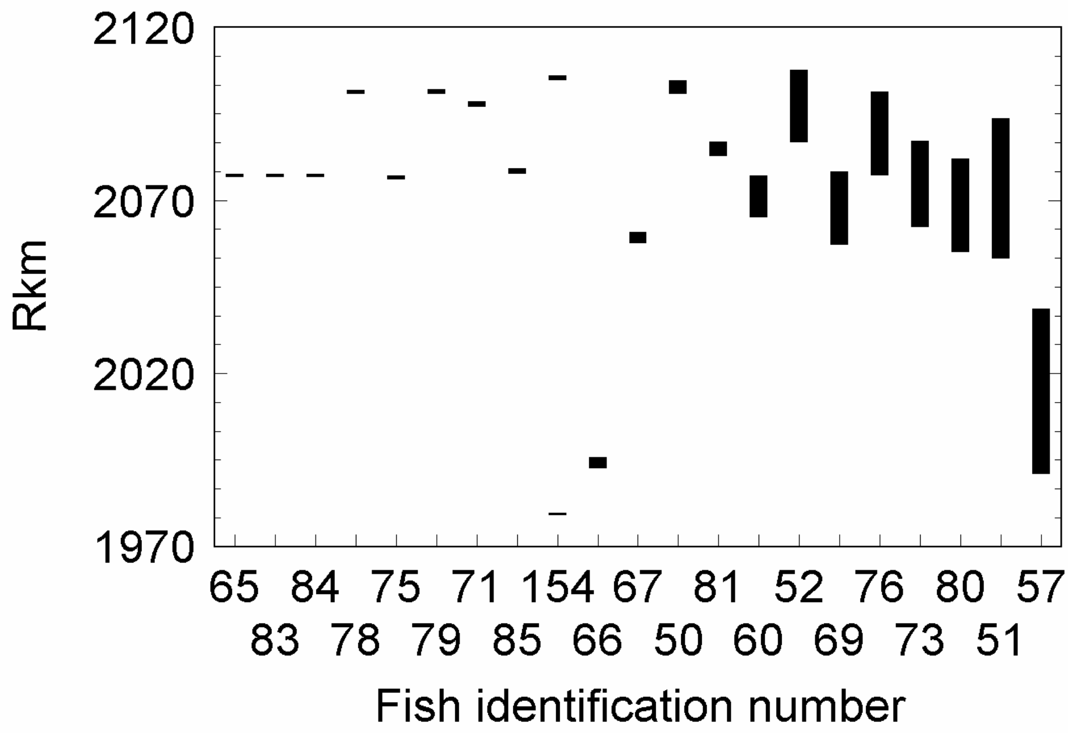


Figure 2.10. Non-spawning home range of 21 curimbatás (16 females and 5 males) during 2001, 2002 and 2003. Home range sizes are arranged from smallest to largest.

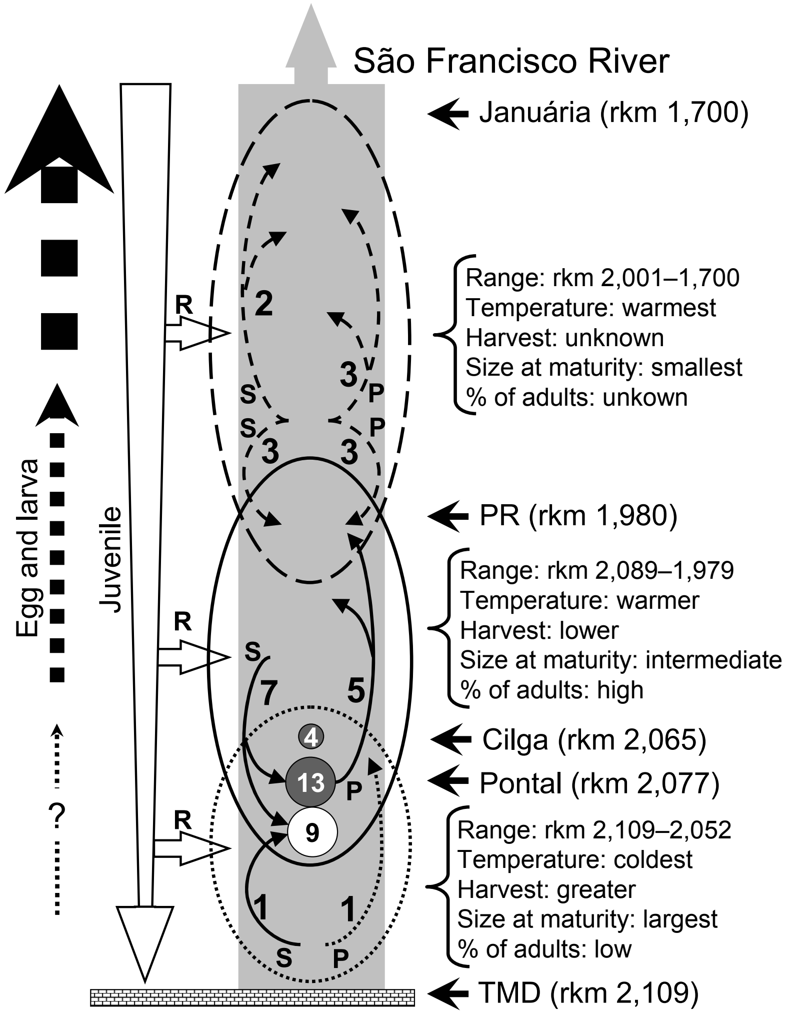


Figure 2.11. Metapopulation structure and conceptual model of life history movements of curimbatás in the São Francisco River between Três Marias Dam (TDM) and the city of Januária. Ellipses show the home range of adults in three populations: TM – Três Marias (······), Pontal (—), and PR – Pirapora Rapids (-----). Arrows within ellipses show mainstem pre-spawning (S) and post-spawning (P) migrations for the three populations: TM (······), Pontal (—), and PR (-----). Range of PR fish determined by Paiva and Bastos (1982), range of TM and Pontal populations determined by radio-tracking in present study. For each population, the range (km), water temperature, harvest intensity, and two aspects of population structure are shown. The two larger circles show the spawning ground (dark) and pre-spawning staging area (white) for the Pontal population. The smaller dark circle shows the Cilga spawning ground. Large arrows on the left show egg and larva downstream dispersal and a proposed upstream juvenile migration. Arrows connecting the juvenile upstream migration to the ellipses indicate recruitment (R). Numbers by spawning grounds and migration arrows indicate number of tracked fish that made the movement. Pre-spawning and post-spawning migrations of PR fish were based on data from Paiva and Bastos (1982).

CHAPTER 3

MIGRATION AND SPAWNING OF SURUBIM (*Pseudoplatystoma corruscans*, PIMELODIDAE), IN THE SÃO FRANCISCO RIVER, BRAZIL

3.1. Introduction

The piscivorous catfish surubim occurs in South America in the Paraná (Argentina, Brazil, Paraguay, and Uruguay) and São Francisco (Brazil) rivers (Lundberg and Littmann 2003). In the São Francisco River, it grows to 120 kg (Sato *et al.* 2003) and it is one of the most important fisheries resources (Menezes 1956, Godinho *et al.* 1997, Godinho and Godinho 2003). It is a major trophy for recreational anglers due to its large size and it is the most valuable fish species for commercial fisheries because of its outstanding taste.

Surubim is a migratory species (e.g., Agostinho *et al.* 2003, Diaz-Sarmiento and Alvarez-León 2003, Sato and Godinho 2003, Zaniboni Filho and Schulz 2003) but its life history movements are poorly known throughout its range (Carolsfeld *et al.* 2003). In the only previous study carried out in the São Francisco River, Paiva and Bastos (1982) tagged 284 surubims and recaptured only two fish. One was recaptured at the tagging site and the other was recaptured 50 km upstream. Surubim broadcasts about 1.5 million, 1-mm diameter, non-adhesive eggs (Sato *et al.* 2003) from November to January (Godinho *et al.* 1997, Brito and Bazzoli 2003). Spawning occurs in the river and the semi-buoyant eggs drift with the flow. Eggs hatch in 20 h at 24 ^{o}C (Sato *et al.* 2003).

In recent years, surubim harvest in the São Francisco River has shown evidence of collapsing (Godinho and Godinho 2003). Reports in the first half of the 20th century compiled by Menezes (1956) describe surubim fisheries that do not happen anymore. He, for instances, mentioned the capture of 6,000 surubims ranging from 5 to 50 kg in a floodplain lake in just one seine haul and other seine hauls capturing 12,000 surubims. Presently, in one of the most important fishing areas the fisheries catch has declined from 12 kg $fisher^{-1}$ day^{-1} in 1987 to 3 kg $fisher^{-1}$ day^{-1} in 1999 (Godinho *et al.* 1997, Godinho pers. obs.). Surubim comprised 86% of the total catch in 1987 and 26% in 1999. Construction of new dams in any of the 16 suitable sites in the mainstem and tributaries is a major concern to the surubim future in the São Francisco River.

In this study, adult surubims in the São Francisco River were radio tracked for 32 months (2000–2003) to identify river reaches used for spawning, pre-spawning staging and non-spawning activities and determine home range, identify migration timing, determine detailed use of spawning area, determine if fish homed, and measure migratory ground speed. This information was used to develop a conceptual model of migration and spawning for the species. The present study is one of the first to use biotelemetry to study migrations and spawning of a South American fish.

3.2. Study Site

The São Francisco River is a large river on the east coast of South America that flows mostly northward 3,160 km and drains a basin of 645,067 km2 (Kohler 2003). The reach where surubims were tagged and tracked most intensively was the first 219 km downstream of Três Marias Dam (TMD, rkm 2,109, Figure 3.1). From TMD to Pirapora Rapids (PR, rkm 1980), the river has a steep gradient with fast current, rapids, and runs. The bottom is mostly rocky. There are only a few narrow floodplains and these do not flood because of the regulated flow at TMD. At PR, the river level declines 8 m over a distance of 1 km at the rapids. Downstream of PR, the river gradient is low, the current is slow, the bottom is generally sand, and the channel meanders. Many wide floodplains are present, mostly after the Paracatu River mouth at river km (rkm) 1,866.

3.3. Methods

3.3.1. Tagging and tracking

Surubims were captured and tagged in the mainstem at Três Marias (TM, within 3–7 km from TMD) and within 1 km of PR. Fish were tagged in December 2000, December-January 2001, April 2001, and March 2002. Surubims were captured with ‘tarrafão’, a specialized bottom drift net (Sato and Godinho 2003), and drift nets. One fish was caught by harpoon. Fish were tagged immediately after capture but some surubims were tied, sometimes for several hours, to an anchored 5-m long rope before tagging. One surubim was kept overnight in a 300 L tank with water exchange prior to tagging.

Fish were held for tagging in a portable tank filled with 150 L of river water and immobilized using electronarcosis with non-pulsed 40–60 V DC current (Kynard and Lonsdale 1975, Ross and Ross 1999). Current was reduced to 25–40 V DC after immobilization for most fish. Tags were inserted into the body cavity through a 7–8 cm long incision made on the ventral middle line, ending just before the pelvic girdle. The 27-cm long antenna extended posterior through the lateral body wall and exited along the body mid-line. Tags were Lotek© coded radio tags (model MCFT-7SP, diameter = 32 cm, length = 140 cm) with a transmission life of 4 years at 5 s burst rate. Tag weight in air (170 g) as a percent of fish weight was $\leq$ 1.8%. During the last 30 min of surgery, Stress Coat® or LabProtect® were added to the tank's water to aid fish recovery. Surgery was completed in 40–60 min. Prior to releasing, fish were weighed and measured (total length). Surubims were released immediately after surgery within 1 km of the capture site.

Sex and reproductive stage of fish were determined during surgery using unaided visual observations of gonads through the incision. Reproductive stage of fish was classified similarly to Kynard and Kieffer (2002) as early-stage (ES, gonads not containing visible maturing or mature eggs) or late-stage (LS, ripe gonads).

Fish were manually tracked from December 2000 to July 2003 (three spawning seasons: 2000–2001, 2001–2002, and 2002–2003). I located fish almost every month during each spawning season (November–January) and at least every other month during non-spawning seasons. Most mobile tracking used a boat, but tracking by helicopter was done in July 2002 and July 2003 to survey remote areas for tagged fish. Most mobile tracking was in the mainstem within 219 km downstream of TMD. Major tributary rivers (Abaeté, Espírito Santo, Janeiro, Jequitaí, Pandeiros, Paracatu, Paraúnas, Preto, Sono, Urucuia, and Velhas) and the mainstem to the city of Xique-Xique (rkm 1,062) were tracked at least once. A total of approximately 7,500 km of river was searched to locate tagged fish.

Fish were also located using Lotek® fixed-location, data-logging receivers at TMD, Pontal, and PR (Figure 3.1). The TMD receiver had one antenna that surveyed the dam's stilling basin and the lower part of the tailrace to determine if fish moved upstream to the dam. The Pontal receiver had two antennas oriented toward the mainstem (one surveying 0.5 km upstream and one surveying 1 km downstream) to determine movement direction of fish and a third antenna that monitored the lower 0.5 km of the Abaeté River to determine when fish entered or departed the tributary. The PR receiver had two antennas to determine movement direction of fish in the mainstem as they moved up- or downstream through the rapids.

Water temperature, turbidity, and discharge of the São Francisco River at PR were measured to correlate with fish movements. Water temperature was recorded every 3 h with an Onset© temperature logger. Daily water turbidity was provided by SAAE (the Pirapora water supply company) and mean daily discharge was provided by CEMIG (the Minas Gerais state power company).

3.3.2. Data analysis

Receivers recorded tag code and number of tag detections (hits) for each 10-min interval. They also logged hits of tag codes not used in the study (absent codes) which were called false-positive records. False-positive records of tag codes that were actually used (present codes) were also recorded. Two procedures were used to eliminate false-positive records of present codes. The first procedure was based on P_k, the probability of a record with k hits being a false positive, which was calculated using the formula:

$$P_k = 100F_k / \sum_{k=1}^{n} F_k ,$$

where F_k = percent of records of absent codes with k hits. A record of present code was considered as false-positive if $P_k > 1.0\%$ for the Pontal receiver and if $\sum_{k=1}^{n} P_k > 1.0\%$ for TMD and PR receivers. A greater threshold was set for TMD and PR because of the greater level of background noise in those areas. Because the maximum number of possible signal detections for a 5 s burst rate tag in 10 min is 120, all records with more than 120 hits were excluded from analysis.

The second procedure was to check data-log records for consistency. When a receiver recorded a tag signal, the tag code and time of first and last signal hits was recorded for each 10-min interval. False-positive records within 30 min of a positive record were considered as a positive record; other false-positive records were excluded.

The PR receiver detected short-term movements (visits) of surubim to PR during the spawning season. The frequency and duration of visits were determined using arrival and departure day and time. Arrival and departure direction were also determined. The frequency of visits was analyzed for relationship with São Francisco River temperature, turbidity, and discharge at PR. Using variability in these three physical variables, which ranged from peak to valley, each visit was classified as peak (during peak day or 1 day post-peak), decreasing (decreasing from peak), valley (during valley or 1 day post-valley), increasing (increasing from valley), or stable (variable unchanged for > 2 days). If a visit lasted longer than 1 day, the visit day was characterized as the day with the greatest number of signal hits. Data were tested using chi-square for difference in visit frequency among classes of temperature, turbidity, and discharge.

Migration was classified as pre-spawning staging if it occurred before the spawning season or, if it occurred during the spawning season, fish moved from non-spawning to pre-spawning staging grounds. Movement at the end or after the spawning season was classified as non-spawning migration.

Total home range, the distance between the most up- and downstream locations (Young 1998), was determined for all fish tracked during spawning and non-spawning seasons. The spawning season was considered from November to January (Godinho *et al.* 1997, Brito and Bazzoli 2003) and the rest of the year as non-spawning season. The non-spawning home range (distance between the most up- and downstream locations during the non-spawning season) was calculated using fish located at least two times during that season. The locations of fish during periods of pre-spawning staging or non-spawning migrations were excluded from the calculation of the non-spawning home range. If a fish used different river reaches in different non-spawning seasons, the non-spawning home range of the fish was estimated for each season. Total and non-spawning home ranges were tested for relationship with fish's body weight and Fulton condition factor. Mean body weight and Fulton condition factor were tested for difference between resident (total home range ≤ 2 km) and migratory fish.

Surubims migration over a long distance (> 32 km) in a short time (days) at ground speed ≥ 1.9 km day^{-1} was named sprint migration. Sprint migration from PR to TMD was analyzed for duration and ground speed. They were decomposed and analyzed for duration and ground speed to move from PR to Pontal and from Pontal to TMD.

The statistical software SAS was used for data analysis (SAS Institute 1999). Continuous variables were tested for normality (Shapiro-Wilk test, SAS' Univariate procedure). The non-normal variables were transformed (Sokal and Rohlf 1995) and tested again for normality. All non-normal variables achieved normality after transformations. Then, Student's *t*-test (SAS' Ttest procedure) according to the homogeneity of variances (Sokal and Rohlf 1995) was used for comparisons of data between two groups, and Pearson correlation (SAS' Corr procedure) to test relationship between continuous variables. If the null hypothesis was not rejected, the power of the test was determined (Borenstein and Cohen 1988, Cohen 1988). Chi-square was used to test frequency data between groups. Level of significance (α) was set = 0.05 and power = 0.80.

3.4. Results

3.4.1. Characteristics of tracked surubims

Twenty-four surubim females were tagged (Table 3.1). Two fish were tagged at TM during the non-spawning season and twenty-two fish were tagged at PR, 17 during the spawning season. Twenty were LS (ripe ovaries) and four were ES. Fish were tracked for 1–453 days (mean = 223 days) and the number of locations per fish ranged from 2–329 (mean = 61). Twenty-three fish provided tracking data. One tag became immobile just after the fish was released and that fish was excluded from the data. Six other tags were found immobile in the river because of tag rejection or death of fish after those fish had been tracked for 32–399 days. Thirteen fish were harvested. Fishers returned 12 tags and one was found at a house. Two alive fish disappeared from the study area before the end of the study and two fish were tracked during the entire study.

3.4.2. Locations during spawning and non-spawning seasons

During the spawning season, surubims were grouped in three areas, i.e., Pontal, PR and downstream of PR (Figure 3.2). Two fish were at Pontal, 11 fish were at PR, and seven fish were downstream of PR. Three fish were tracked during the non-spawning season only. Most fish (n = 12) used a different river reach during spawning and non-spawning seasons. Locations during the non-spawning season were up- or downstream from the fish location during the spawning season.

3.4.3. Tracks at PR reach

After release, 10 PR fish either stayed at the rapids or moved downstream, then returned after several days. Three fish were in the rapids almost every day during the spawning season. Two fish (37 and 124) returned to PR during the spawning season after remaining downstream for 6–8 months (Figure 3.2). Fish 124 was located at PR in November 2003 after the study period.

During the spawning season (November–January) and in February and March, eight surubims were detected 43 times by the PR receiver. Month and number of visits (in parenthesis) follow: November (0), December (8), January (15), February (8), and March (12). The number of visits per fish ranged from 2–10 (5.4 ± 2.6, mean $\pm$ S.D.). Duration of visits ranged from 1–6 days (1.8 ± 1.4 days, mean $\pm$ S.D.) and most visits (81%) lasted ≤ 2 days.

Arrival time was established for 34 visits. For 28 visits (82%), fish arrived during the day between 0638 hours and 1804 hours, with 15 arrival times in the morning and 13 in the afternoon. Five fish arrived at night between 2035 hours and 0136 hours on four visits.

There was a significative association between frequency of visits and river discharge (chi-square test, $\chi^2 = 28.5$, df = 4, $p < 0.0001$), water temperature (chi-square test, χ^2 = 11.8, df = 3, p = 0.008), and turbidity (chi-square test, χ^2 = 14.6, df = 4, p = 0.006). Most visits occurred during discharge peaks (49%), temperature valleys (47%), and turbidity peaks (42%; Figure 3.3). Simultaneously occurrence of peak of discharge, valley of temperature, or peak of turbidity was the prevailing condition during surubim visit. Thus, 35% of the visits occurred during peak of discharge and valley of temperature, 30% during peak of both discharge and turbidity, and 23% during peak of turbidity and valley of temperature.

3.4.4. Tracks of pre-spawning staging fish

During the period fish visited PR (November–March), six fish staged downstream of PR 21 times at distances of 0.4–10.6 km. For example, fish 24 was located four times 1.8–10.6 km downstream and fish 36 was located six times 1.2–2.0 km downstream (Figure 3.4). Most of the time (76%), the six fish were no farther than 2 km from PR. All locations of pre-spawning staging fish during manual tracking were downstream of PR, but the PR receiver detected pre-spawning staging fish approaching the rapids nine times from the upstream direction.

3.4.5. Tracks downstream from PR

Seven LS females tagged at PR moved downstream and did not return to the rapids during the spawning season. During 31–33 days after tagging, two tracking periods found six fish (25, 27, 31, 32, 34, and 35) in only three reaches (Figure 3.2). The reaches were 8–10, 25–27, and 39–43 km downstream of PR. Four fish were within < 2 km and one was within 8 km from one tracking period to the other. In the non-spawning season, most fish (4) were 20–202 km away from locations used during the spawning season.

3.4.6. Migration to Pontal

Surubims migrated upstream and downstream to Pontal just before or during the spawning season. For example, fish 225 migrated upstream past PR arriving at Pontal just before the spawning season and staying there the entire season (Figure 3.5). The ES female 40 moved from TMD downstream to Pontal in the spawning season when it likely had ripe gonads (Figure 3.5). While at Pontal, these fish stayed at the mainstem but each made several trips of short duration (usually < 2 days) into the Abaeté River.

3.4.7. Mainstem and tributary tracks

Surubim used a longer reach of the mainstem in the non-spawning season than in the spawning season (Figure 3.6). The greatest numbers of fish were at PR. Most fish used the mainstem and few used the Velhas River. Fish were only found in the Velhas River during the non-spawning season, but tracking in the mainstem indicated that one entered the Velhas River during the spawning season. Three fish migrated 12–47 km upstream in the Velhas River and one tag was found on land near the riverbank 183 km upstream of the Velhas River mouth.

3.4.8. Home range

Eighteen fish were tracked during spawning and non-spawning seasons. Ten of 18 likely spawned at PR or Pontal. Total home range of the 10 fish was 71 ± 72 km (mean ± S.D.). Total home range of the eight remaining fish was 107 ± 65 km. There was no significant difference between these two mean home ranges (*t* test, t = -1.09, df = 16, p = 0.29, power = 0.18). Thus, for the 18 fish, home range was 87 ± 70 km and ranged from 1–210 km. Four fish had home ranges ≤ 2 km, 11 had home ranges between 32–145 km, and three had home ranges > 191 km (Figure 3.7). Total home range did not have significantly Pearson coefficient of correlation with number of days that fish were tracked (r = -0.29, p = 0.27, power = 0.22), body weight (r = -0.16, p = 0.53, power = 0.09) and Fulton condition factor (r = 0.19, p = 0.45, power = 0.12). No difference in body weight (t-test, t = 0.22, df = 16, p = 0.83, power = 0.04) and Fulton condition factor (t-test, t = -1.34, df = 16, p = 0.20, power = 0.23) occurred between resident and migratory fish.

Non-spawning home range for 17 fish was 0–145 km and most (84%) were < 5 km or > 60 km (Figure 3.7). Two surubims were tracked for two non-spawning seasons: one used almost the same reach both years and the other used very different reaches each year (Figure 3.5). Non-spawning home range did not have significantly Pearson coefficient of correlation with body weight (r = -0.10, p = 0.69, power = 0.06) and Fulton condition factor (r = -0.23, p = 0.38, power = 0.15).

3.4.9. Homing

Four surubims returned to the same pre-spawning staging site or spawning ground they used previously. Fish 24 moved from a pre-spawning staging site at rkm 1,969 to PR and then returned to rkm 1,969. Fish 36 returned three times to a pre-spawning staging site at rkm 1,977–1,978 after visiting PR (Figure 3.4). Two fish (37 and 124) moved downstream after staying at PR during the spawning season and then returned to the PR the next spawning season (Figure 3.2).

3.4.10. Time of migration

Four surubims (22, 37, 40, and 225) provided data on pre-spawning staging migration and six (24, 26, 30, 35, 40, and 225) gave data on non-spawning migration. Pre-spawning staging migration occurred from early October to late December. Non-spawning migration happened from early January to early March.

3.4.11. Sprint migration

Five fish (22, 24, 26, 30, and 225) made a sprint migration that was detected by at least two tracking stations (Table 3.2). All fish except 22 made upstream sprint migration (Figures 3.5 and 3.8). Two fish made pre-spawning staging migrations and four fish made non-spawning migrations. Ground speed ranged from 1.9 to 31.2 km day^{-1}. For fish that migrated from PR to TMD (24 and 26), the first leg (PR to Pontal) was 1.7 to 2.9 times faster than the second leg (Pontal to TMD).

3.4.12. Use of TMD reach

Five surubims (22, 24, 26, 40, and 225) were at TMD for 8–211 days (Figures 3.5 and 3.8). All locations were in the dam's stilling basin or just downstream of the tailrace except for fish 26. This fish was located once in the tailrace and it was harvested there 5 days later. Most locations of fish at TMD were detected by the receiver, which tracked fish in the dam's stilling basin and the lower part of the tailrace.

Fish were not within the range of the TMD receiver all the time they were near TMD, so fish could have gone downstream or to the upper part of the tailrace.

3.5. Discussion

Adult surubims migrate among pre-spawning staging, spawning, and non-spawning grounds in the São Francisco River. The spawning grounds are discrete areas located in the mainstem and in the Abaeté River where these surubims visit multiple times during the spawning season from nearby pre-spawning staging areas. After spawning, most surubims migrate to the non-spawning ground, which occupies 274 km of the São Francisco River downstream of TMD and almost 200 km of the lower Velhas River.

3.5.1. PR spawning ground

The movements of pre-spawning surubims to PR suggest it is a spawning ground but the strongest evidence is from direct observations of spawning fish. During floods, surubims regularly moved from the pre-spawning staging area to visit PR for a short time and then returned to the pre-spawning staging area. Synchronization between the visits of surubims to PR and floods strongly suggest that the visits are related to spawning because floods trigger the spawning of the São Francisco River broadcaster spawners (Godinho *et al.* 2003b). However, the most important evidence is provided by observations of fishers who reported seeing the conspicuous spawning behavior of surubims at PR, i.e., females rolling upside down at the surface while releasing eggs fertilized by several males (Sato and Godinho 2003).

Tracking did not enable identification of the PR reach used for spawning, but evidences suggest it was likely small (several hundred meters) and was in the lower part of PR (transition zone between high-gradient reach and the downstream low-gradient run). It was in the transition zone that several fishers reported seeing spawning behavior of surubims. It was also there during floods that 88% of the surubims used in this study were captured. The transition zone was also the river reach where manual tracking located the highest number of surubims. Although these data suggest that the spawning ground is restricted to the transition zone of the rapids, further study is needed to verify these ideas.

3.5.2. Spawning downstream of PR

Spawning grounds of surubim also are likely present downstream of PR. In the spawning season, seven late-stage females tagged at PR went downstream, most (5) stayed within a small range, and did not return to PR. This behavior suggests that they could be staging close to or at other spawning grounds. At PR, surubims staged within 11 km from the spawning ground, and the three reaches used by six of seven surubims downstream were 2–4 km long and more than 12 km apart. It may be there are three more spawning grounds in the first 50 km downstream from PR.

3.5.3. Pontal spawning ground

Telemetry showed that the Abaeté River at Pontal is a potential spawning ground but its exact location was not determined. Two surubims migrated upstream or downstream to Pontal where they stayed for part or all of spawning season. The two surubims stayed most of the time in the mainstem while at Pontal. Both fish made several trips into the Abaeté River, which frequently lasted < 2 days. Short trips from the mainstem into the Abaeté River and return could correspond to the visits at PR from pre-spawning staging areas to spawn. Because most surubims staged less than 2 km away from the PR spawning ground, the spawning ground in the Abaeté River might not be far from the mainstem at Pontal. The sympatric migratory curimbatá, *Prochilodus argenteus* Agassiz, 1829, also spawns at Pontal, right at the mouth of Abaeté River (Chapter 2).

3.5.4. Multiple visits

What is the adaptive significance of multiple visits of females to the spawning ground? The answer depends on whether surubim is a single or a multiple spawner. Surubim is believed to be a single spawner (Bazzoli 2003, Sato and Godinho 2003). If correct, then a female surubim could visit a spawning ground multiple times waiting for the spawning conditions to be correct to trigger spawning. However, surubim seems to be a multiple spawner. Ovaries of post-spawning surubims had post-ovulatory follicles, oocytes with intact yolk globules, and oocytes with cortical vesicles (Godinho *et al.* 1997). The presence of these structures has been used to characterize multiple spawning of many fish species (e.g., Lamas and Godinho 1996, Rinchard and Kestemont 1996, Sylva and Breder 1997, Msiska and Costa-Pierce 1999, Sivakumaran *et al.* 2003). Thus, the multiple visits to a spawning area likely indicate that female surubim spawns multiple times.

3.5.5. Pre-spawning staging areas

Pre-spawning surubims migrated from early October to late December to pre-spawning staging areas at or near PR. Migration of pre-spawning fish to pre-spawning staging areas was also found in curimbatá (Chapter 2). From the pre-spawning staging area, surubim made a short distance movement to PR to spawn (spawning migration). After a visit, the fish moved back to the pre-spawning staging area, some to the same pre-spawning staging site (pre-spawning staging-site homing), or went to a non-spawning ground (non-spawning migration).

Staging at or close to the spawning ground reduces energy expenditure of multiple spawning fish that need to move back and forth from the pre-spawning staging ground to the spawning ground. Most surubims did not stage at PR because fisheries may have selected against staging there. Surubims have been fished at PR since the 16th century (Silva *et al.* 2000) and fishing at PR is intense (Godinho pers. obs.).

Pre-spawning staging area is also known for several riverine species (*Stizostedion canadense,* Pegg *et al. 19*97, *Acipenser transmontanus*, Paragamian and Kruse 2001, *Acipenser brevirostrum*, M. Kieffer and Kynard pers. obs, *Prochilodus argenteus,* pers. obs). Pre-spawning staging area for these fishes is near (within a few kilometers) of the spawning area, thus providing quick, low-energy expenditure access to the spawning site. In the case of *Prochilodus argenteus*, pre-spawning staging behavior may also reduce predation risk and intraspecific food competition (pers. obs).

Northcote (1978) proposed a general model of freshwater fish migration that has been recently republished with slight modifications by Lucas and Baras (2001). In both publications, migration is between three basic habitats: spawning, feeding, and refuge.

Migrations involving pre-spawning staging habitat has not been mentioned. Pre-spawning staging behavior, however, has been found in diverse fish species and it likely confers energetic and predation avoidance benefits to the individual. Pre-spawning staging behavior may be more widespread and important than it is presently believed. The Northcote model that includes pre-spawning staging habitat is presented in Figure 3.9.

3.5.6. Spawning season

Brito and Bazzoli (2003) suggested that surubim in the PR area spawn until January. My data suggest that the end of the spawning season may extend until March. First, the number of surubim that visited PR was the second highest in March. Also, five females (three with late-stage eggs) were tagged at PR at the end of March. The three females had developed ovaries with vitellogenic oocytes, which indicate spawning would occur soon.

3.5.7. Non-spawning grounds

There are two basic types of non-spawning grounds for riverine fishes, i.e., feeding and refuge (Lucas and Baras 2001). Refuges are places fish go to avoid unfavorable physical conditions like water temperature, flow, desiccation, and low dissolved oxygen, as well as avoid unfavorable biological factors (Lucas and Baras 2001). The river reaches used by tagged surubims outside the spawning season were termed non-spawning grounds. No data were gathered to determine if fish were foraging or escaping for unfavorable conditions, but all non-spawning grounds of surubims in this study were likely feeding grounds, not refuge grounds.

The surubim's non-spawning grounds are the first 274 km downstream of TMD and the lower Velhas River. Post-spawning surubims migrated up- and downstream in the mainstem and into the Velhas River to non-spawning grounds. Movements up- and downstream to non-spawning grounds were also detected in curimbatá (Chapter 2). Surubims were scattered along the mainstem with the greatest number of fish upstream of Pontal and at or close to PR.

3.5.8. TM reach

The TM is an important reach of the surubim's non-spawning habitat likely because of abundant prey biomass. Non-spawning upriver migration toward TMD was one of the most frequent surubim movements found. The importance of this movement was also provided by local fishery. When two tagged surubims migrated to the TM in February–March 2001, they likely did not arrive alone because surubim landings, which had been low during the preceding months, increased sharply after they arrived (Godinho pers. obs.). Surubim likely migrated to TM to feed. The TM was the area of the greatest landings of curimbatá in the entire non-spawning ground (Godinho pers. obs.) and curimbatá's sibling species is the main surubim prey in other Brazilian rivers (Marques 1993, Resende 2003).

3.5.9. Homing

Homing is the returning to a place formerly occupied instead of going to other equally probable places (Gerking 1959). For South American fishes, homing has only been found in *Prochilodus lineatus* adults returning to a spawning area in the Mogi-Guaçu River, Brazil (Godoy 1959, 1975). More recently, homing was discovered in curimbatá adults returning to pre-spawning staging, spawning, and non-spawning sites in the São Francisco River (pers. obs).

Surubim showed two types of homing: spawning-site and pre-spawning staging-site homing. Spawning-site homing was observed in two fish that returned to the PR spawning ground in the spawning season after being away for months. Surubim also homed to the spawning-site visiting the PR spawning ground multiple times coming from the pre-spawning staging area. The second type of homing (pre-spawning staging-site homing) was displayed by two surubims that returned to the same pre-spawning staging site after visiting the PR spawning ground. Homing to non-spawning grounds by post-spawning or non-spawning fish was not found for surubim as it was for curimbatá (Chapter 2).

3.5.10. Sprint migration

Surubim used sprint migration to move up- and downstream, before and after spawning. Post-spawning upstream sprint migration was mostly observed. No fish made a post-spawning downstream sprint migration. This was likely a technical bias because no data-logging receiver was set downstream of PR that could detect downstream sprint migration of fish that spawned at PR. Sprint migration ground speed was highly variable (1.9–31.2 km day^{-1}). This variation was at least partly due to the heterogeneous river geomorphology that fish traversed during migration. The mainstem between PR and Pontal has some slight rapids, but the river upstream of Pontal has more rapids and at least one, the ‘Cachoeira Grande’, might delay migration. The difference in ground speed between the two legs was likely due to that barrier. Fish drive also may account for part of the ground speed variability because some post-spawning fish moved the Pontal–TMD leg very slowly (1.9 km day^{-1}) and some swam much faster (10.2 km day^{-1}). The surubim's ground speed is among the highest upstream ground speed of any tropical seasonal fish listed by Lucas and Baras (2001).

3.5.11. Dualistic migration

Animal populations with migratory and resident individuals are termed partial migratory (Jonsson and Jonsson, 1993). Partial migratory populations of fishes often show polymorphism with dwarf resident, mostly males, and large migrants, mostly females (Jonsson and Jonsson, 1993, Klemetsen *et al.* 2003). The decision to migrate or not seems to be influenced by genetic and environmental factors (Jonsson and Jonsson 1993, Olsson and Greenberg 2004). The ultimate explanation for this polymorphism is that the fitness of the large morphs more than the dwarf ones depends on growth rate and size of the fish (Klemetsen *et al.* 2003). Migratory and resident surubims were similar-sized fish, not dwarfs; thus, the surubim dual migration style does not fit into the partial migration concept. Therefore, the term dualistic migration was used instead. A dualistic migration style has also been found between similar-size shortnose sturgeon yearlings (Kynard *et al.* pers. obs.) and curimbatá (Chapter 2).

Most surubims migrated, and therefore had a larger total home range (> 32 km) than residents (< 2 km). Such a small total home range for resident fish suggests that foraging for some adults is abundant near the spawning ground. This is similar to some Columbia River redband trout that did not migrate at the onset of winter because fall habitat provided adequate wintering habitat (Muhlfeld *et al.* 2001). One surubim was migratory one year and resident another year, which suggests that the dualistic migratory pattern in surubim might be individuals responding to environmental factors, like local food abundance, rather than an inherited trait, as in partial migratory fishes (Jonsson and Jonsson 1993). The surubim dualistic migration was also present during the non-spawning season, resulting in small and large home ranges during that season. Most non-spawning home ranges were smaller than several km so most surubim find enough food in a small area. The surubim total home range, together with the total home range for curimbatá in the São Francisco River (Chapter 2), are the smallest described so far for any South American migratory fish (Petrere 1985, Lucas and Baras 2001, Carolsfeld *et al.* 2003).

3.5.12. Conceptual model of migration

The present study suggests the following conceptual model for female surubim in the São Francisco River. Surubim is a dualistic migratory species with resident and migratory fish. Migration is the dominant behavior. Surubims range within 274 km downstream of TMD and likely up to 183 km in the Velhas River (Figure 3.9). Pre-spawning surubims migrate in early October to late December to pre-spawning staging area (pre-spawning staging migration) when they use sprint migration up to 31 km day–1. Surubim is a multiple spawner that spawns from November to March. Spawning grounds are located at several places in the mainstem. Migration of post-spawning fish to non-spawning grounds (non-spawning migration) occurs from early January to early March when surubims use sprint migration up to 29 km day–1. In the non-spawning season, surubim tend to stay in the same spot or use only a short river reach, although some show long distance displacements.

Surubim behavior at the PR spawning ground is best documented among other spawning grounds in the study area. The spawning ground is located at the downstream reach of the rapids and is likely short (several hundred meters long). During the spawning season, surubim make a short distance migration from the pre-spawning staging area to the spawning ground (spawning migration) multiple times (spawning-site homing) mostly during floods to spawn. They usually arrive during the day and stay for few days (visit). After a visit, surubim moves up- or downstream to a pre-spawning staging area located up to 11 km away, but most remain within 2 km. Some surubims return to the same pre-spawning staging site (pre-spawning staging-site homing). Most post-spawning surubims leave the spawning ground, but some stay until the next spawning season. Migration to non-spawning grounds is up- or downstream. Some surubims return the following spawning season to spawn at PR (spawning-site homing). Surubims also spawn in the Abaeté River at Pontal but the exact location is unknown. Pre-spawning staging area is in the mainstem at Pontal. There are likely few other spawning grounds within 50 km downstream PR but little is know about the use of these areas by surubim.

The conceptual model of migration of surubims shares several common features with the conceptual model of curimbatá migration (Chapter 2). This similarity suggests that the same selective forces in the São Francisco River have shaped the migration and spawning of these two species. The two species are similar in the selection of common spawning ground; visiting the spawning ground; pre-spawning staging near the spawning ground; homing to pre-spawning staging site and spawning sites; using reaches up- and downstream of the spawning ground during the non-spawning season; and a dualistic migratory pattern.

3.5. Conservation and Management

Construction of new planned dams in the São Francisco, Velhas, and Abaeté rivers will greatly affect surubim. Four sites in the mainstem, three in the Velhas River and nine in the Abaeté River are planned for dam development. One site in the mainstem, Formoso, is located about 10 km upstream of PR. The changes in water discharge, turbidity, and temperature that this dam will produce downriver will disrupt one of the most important surubim habitat in the entire São Francisco River, the PR spawning ground. This dam also will block the migratory route that connects that spawning ground to upstream non-spawning grounds. It will also change lotic non-spawning grounds into lentic habitat that might not be used anymore by surubim. The Pontal spawning ground might also be eliminated by Formoso Dam depending on the size of the reservoir. Reservoirs built in the mainstem will block the downstream migration of eggs and larvae to the nursery grounds. Some nursery grounds will be impounded. Dams built in the Velhas River will block surubim access to non-spawning grounds, reducing its range. Dams built in the Abaeté River will produce changes in water quality and quantity that will disrupt the Pontal spawning ground. These impacts will together produce a sharp decrease in the abundance of surubim and other fishes such as curimbatá (Chapter 2), and negatively affect the most valuable São Francisco River fisheries.

Surubim moved during the non-spawning season to the area just below TMD and at least one moved into the tailrace. Thus, a fraction of the surubim population that inhabitant downstream of TMD may want to pass around TMD during the non-spawning season. Providing them with a passage might allow them to do so. However, upstream passage technology is more suitable for surface-orientated fish because of the surface position of the entrance and, therefore, it is inefficient for passing bottom-orientated catfish (Oldani *et al.* 1998). Second, surubims would eventually try to return downstream if passed upstream because their spawning grounds are in the river below the dam. However, TMD does not presently have any downstream fish passage facilities so passed fish will never be able to spawn downstream again. These two points must be addressed before any attempt to pass surubim around TMD.

This study provides data that are helpful for solving a long-term conflict between law enforcement and illegal fisheries at PR. The PR has been a traditional fishing spot since the 16th century (Silva *et al.* 2000), but a Brazilian federal law forbade the fishery in 1967. This law did not eliminate fishing but, conversely, created a serious social conflict among local law enforcement and 50–100 fishers that still fish there. PR is famous for its fishing and there is no other spot on the entire river with as great an abundance of surubim. Surubim are present at PR all year, but the density increases (as indicated by landings) during floods because females concentrate there to spawn. This phenomenon is well-known among local fishers and this knowledge made possible the capture of the surubims used in this study. Prohibition of fishing at PR during floods could help reduce conflict between law enforcement and fishers, maximize the costs-benefits of law enforcement, and contribute to surubim conservation. A permanent surveillance, even when landings are low, seems to be a strategy that wastes resources. Concentrating surveillance during floods will focus the available resources at the time density of surubim is the greatest.

Table 3.1. Fish characteristics and tracking summary of 24 radio-tagged female surubims in the São Francisco River, 2000–2003. Fish were captured at two locations: TM (Três Marias) and PR (Pirapora Rapids). Gonadal stage of fish is: ES = early-stage, LS = late-stage (ripe). Number of days tracked is the number of days between day of tagging and last day I located the fish. Number of locations is the number of mobile and data-logging tracks for each fish. Fate of fish is: H = harvest, D = dead, L = lost (tag signal lost during the study while fish was still alive), A = alive.

Fish	Body weight (kg)	Gonadal stage	Tagging day	Number of days tracked	Number of locations	Fate			
						H	D	L	A
			TM (rkm 2,102-2,106)						
22	14.5	ES	06.04.01	269	199	X			
40	20.0	ES	02.06.01	494	25		X		
			PR (rkm 1,980)						
24	17.5	LS	20.12.00	152	28	X			
25	23.5	LS	20.12.00	245	9	X			
26	11.0	LS	20.12.00	93	17	X			
27	18.5	LS	20.12.00	284	7	X			
28	9.5	LS	21.12.00	230	5		X		
29	17.0	LS	21.12.00	159	38	X			
30	25.5	LS	21.12.00	434	16	X			
31	20.0	LS	21.12.00	32	3		X		
32	15.0	LS	21.12.00	61	8		X		
33	26.0	LS	22.12.00	173	96	X			
34	29.0	LS	22.12.00	60	5			X	
35	20.0	LS	22.12.00	6	4	X			
36	20.0	LS	22.12.00	257	23	X			
37	26.5	LS	22.12.00	357	154	X			
38	25.0	LS	22.12.00	228	196		X		

Continue next page.

Table 3.1. Continued.

Fish	Body weight (kg)	Gonadal stage	Tagging day	Number of days tracked	Number of locations	Fate			
						H	D	L	A
124	13.0	LS	18.12.01	447	161				X
125	12.0	LS	19.12.01	46	15	X			
20	23.0	LS	21.03.02	1	2		X		
126	23.0	ES	22.03.02	399	298		X		
225	17.0	LS	22.03.02	453	122				X
129	26.0	ES	24.03.02	263	5			X	
133	17.5	LS	24.03.02	202	29	X			

Table 3.2. Sprint migrations (pre-spawning staging and non-spawning) of five surubims in the São Francisco River. For the two fish (24 and 26) that went from PR (Pirapora Rapids) to TMD (Três Marias Dam), both PR–Pontal and Pontal–TMD legs were shown separately. Spring migration of all fish were upstream except for fish 22.

Fish	Leg	Distance (km)	Time (hh:min)	Ground speed (km day^{-1})	Migration type
225	PR–near Pontal[1]	92.8	189:42	11.7	Pre-spawning staging
22	TMD–Pontal	32.2	24:45	31.2	Pre-spawning staging
24	PR–Pontal	97.3	162:42	14.4	Non-spawning
26	PR–Pontal	97.3	80:15	29.1	Non-spawning
30	PR–Pontal	97.3	153:03	15.3	Non-spawning
24	Pontal–TMD	32.2	92:24	8.4	Non-spawning
26	Pontal–TMD	32.2	75:48	10.2	Non-spawning
225	Pontal–TMD	32.2	411:42	1.9	Non-spawning
24	PR–TMD	129.5	255:06	12.2	Non-spawning
26	PR–TMD	129.5	156:03	19.9	Non-spawning

[1] Fish moved upstream to within 4.5 km of Pontal in 189 h. Then, it spent 104 h moving the 4.5 km to Pontal. This final movement was not included in calculation of ground speed.

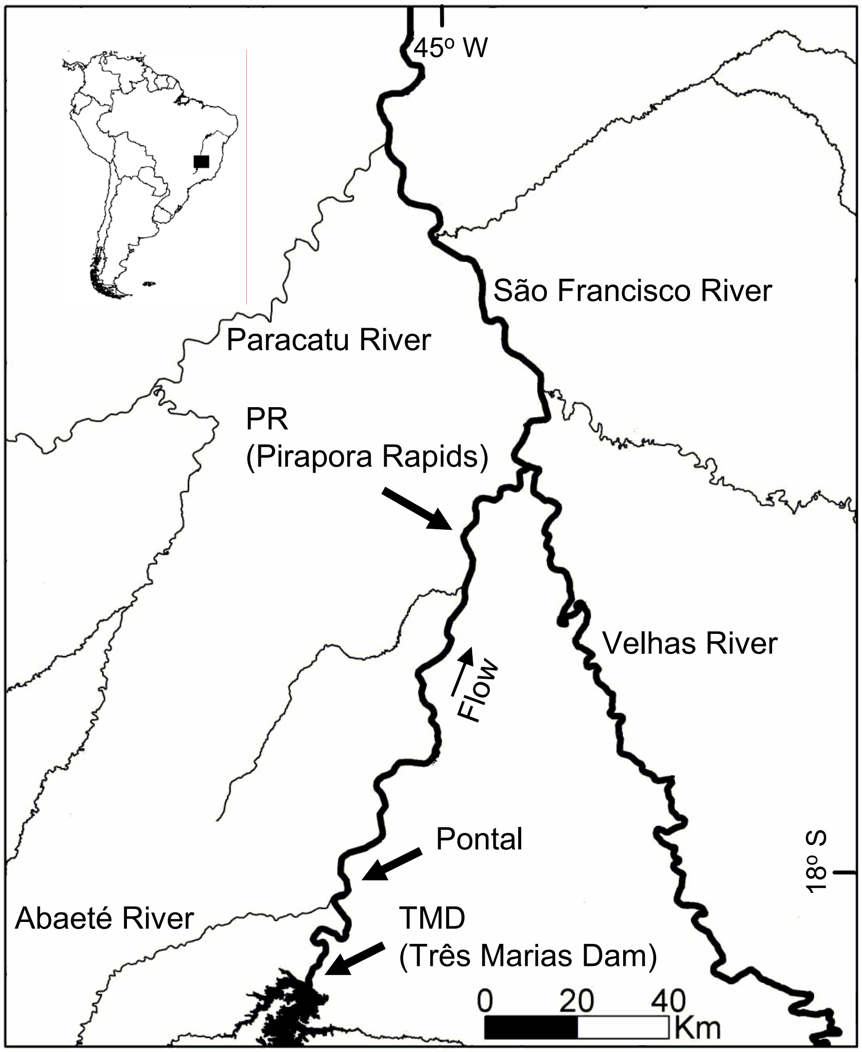


Figure 3.1. The study area for surubim in the São Francisco River Basin. Arrows show sites with data-logging receivers: TMD (rkm 2,109), Pontal (rkm 2,077), and PR (rkm 1,980). Only major tributaries are displayed.

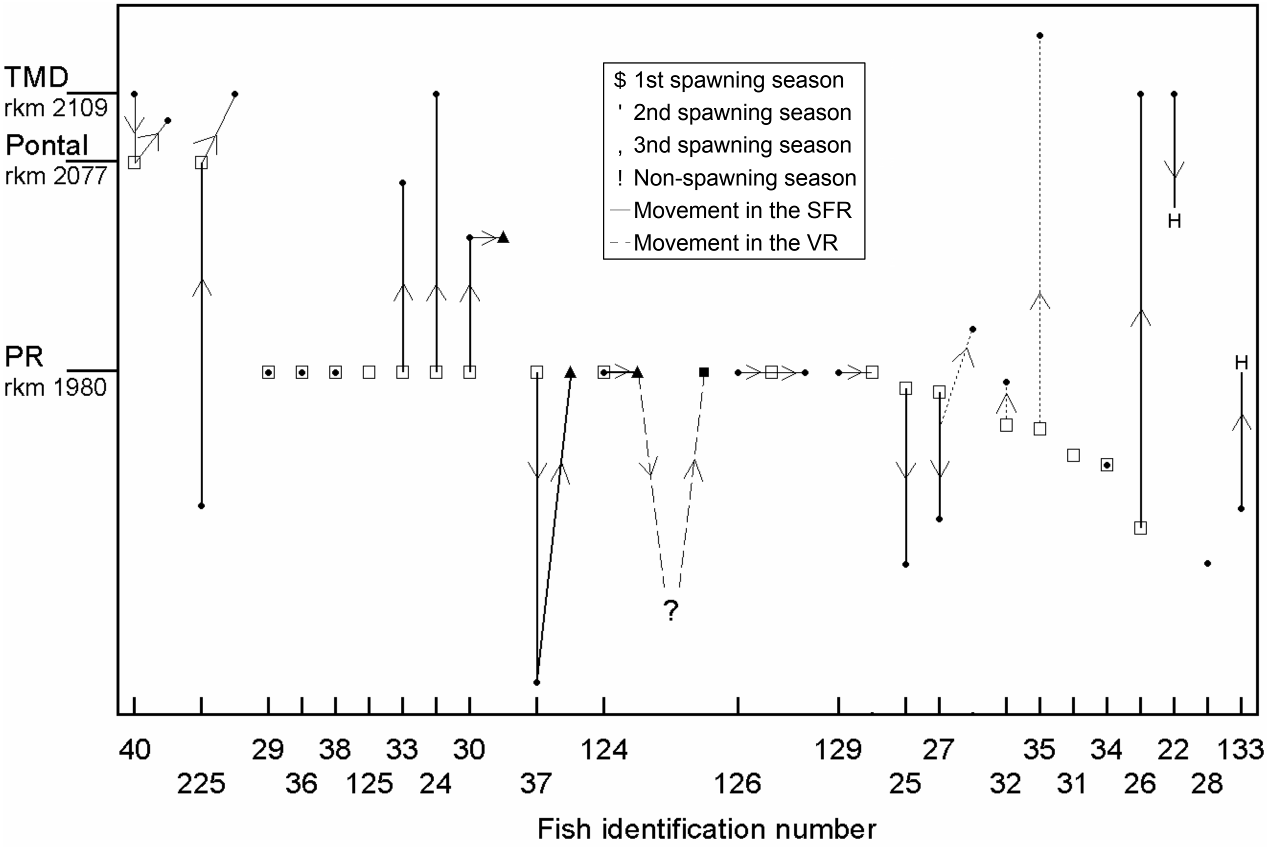


Figure 3.2. Surubim activity in the São Francisco River Basin. The y-axis shows data-logging receivers sites in the main stem (TMD = Três Marias Dam, PR = Pirapora Rapids). Squares and triangles indicate the most frequent location of fish during the spawning season. Squares specify location of fish during the first spawning season, triangles during the second spawning season, and fill square during the third spawning season. Dots mark the farthest fish location during the non-spawning season. Solid lines show movements in the São Francisco River (SFR) and dotted lines show movements in the Velhas River (VR). Arrows point the direction of fish movement. Symbols represent: H = harvest fish, ? = unknown destiny.

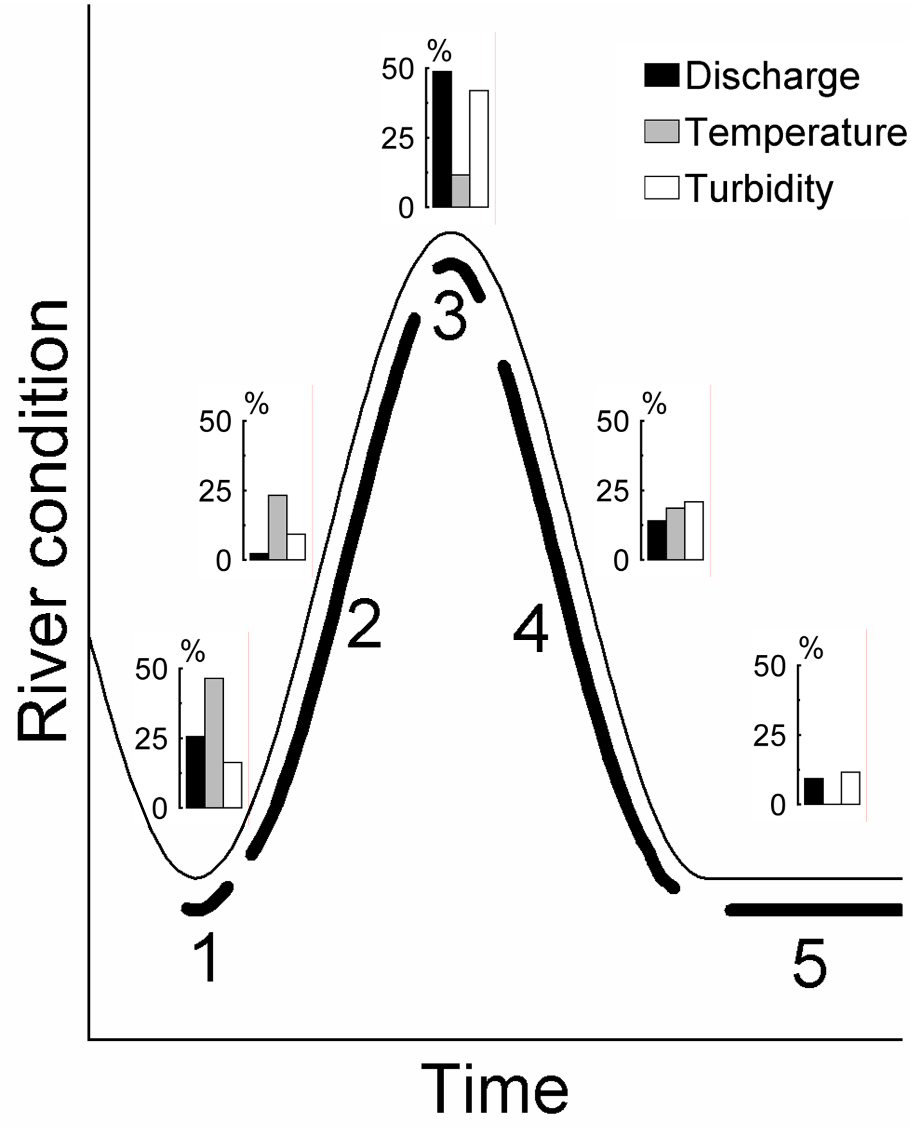


Figure 3.3. Frequency of visits of surubims to Pirapora Rapids during conditions of the São Francisco River. The thin line represents theoretical variation of the river condition (discharge, temperature, or turbidity) through time. The thick lines define timing of the following classes of river condition, valley (1), increasing (2), peak (3), decreasing (4), and stable (5). The frequency of visits of surubims for each class of river condition is shown in the histograms.

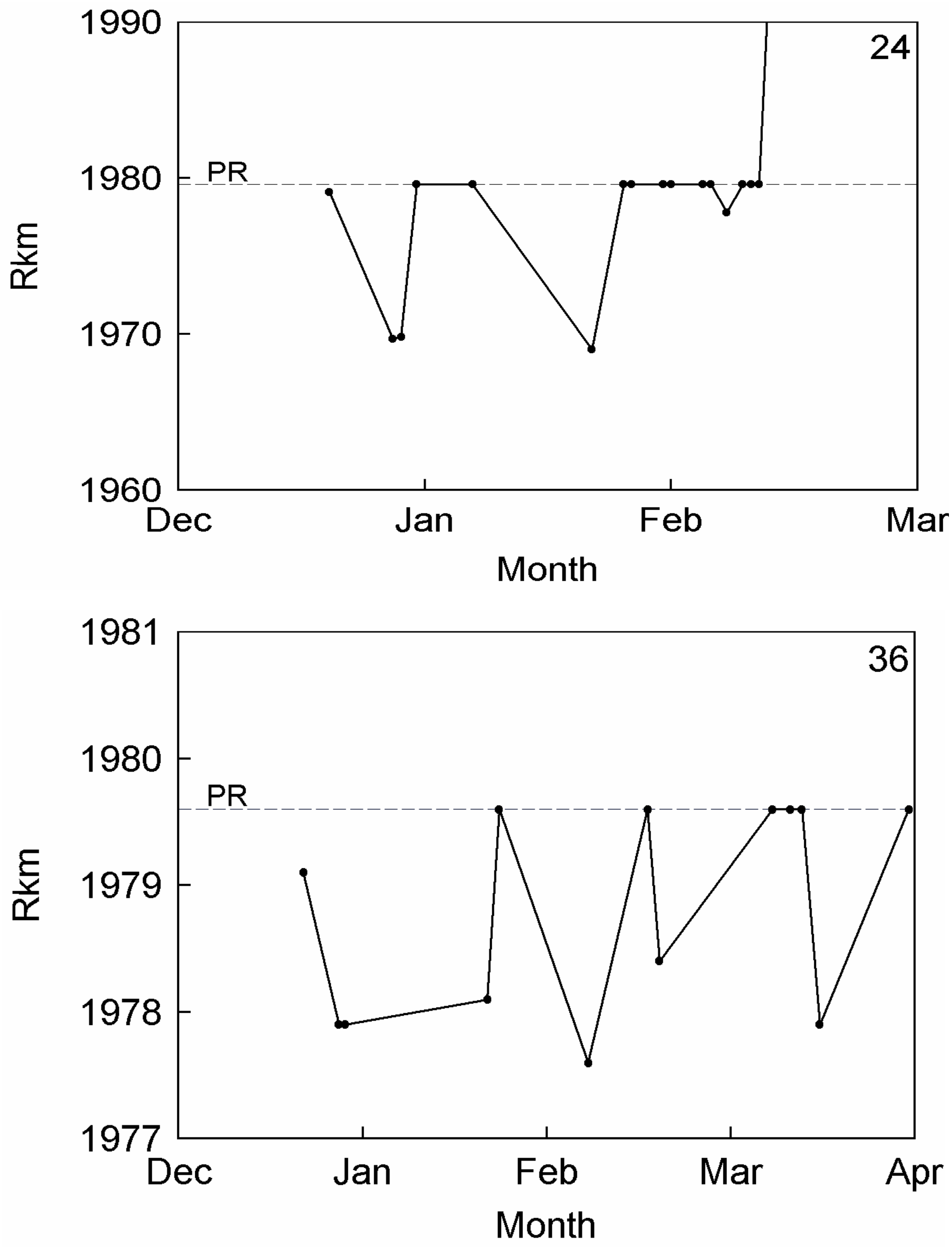


Figure 3.4. Movements of surubims 24 and 36 in the São Francisco River near PR (Pirapora Rapids, dashed line).

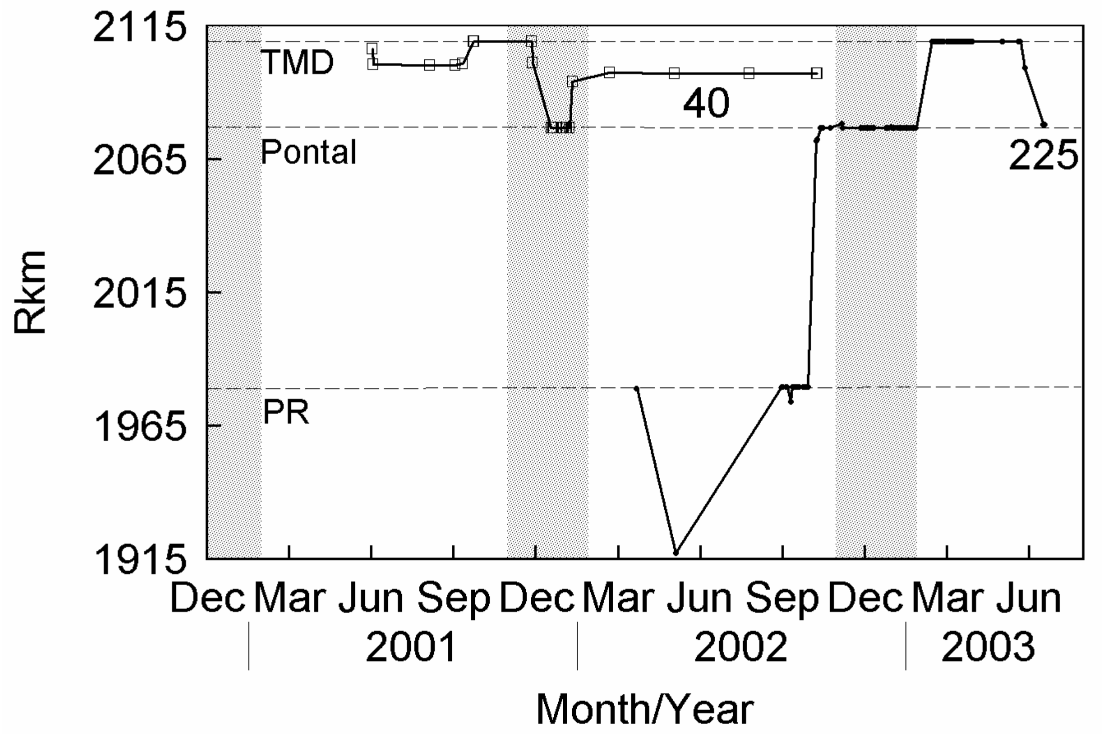


Figure 3.5. Migration of surubims 40 and 225 to spawning and non-spawning grounds in the São Francisco River. Gray vertical bars represent spawning season and unshaded areas show non-spawning seasons. Horizontal dashed lines mark location of TMD (Três Marias Dam), Pontal, and PR (Pirapora Rapids) receivers.

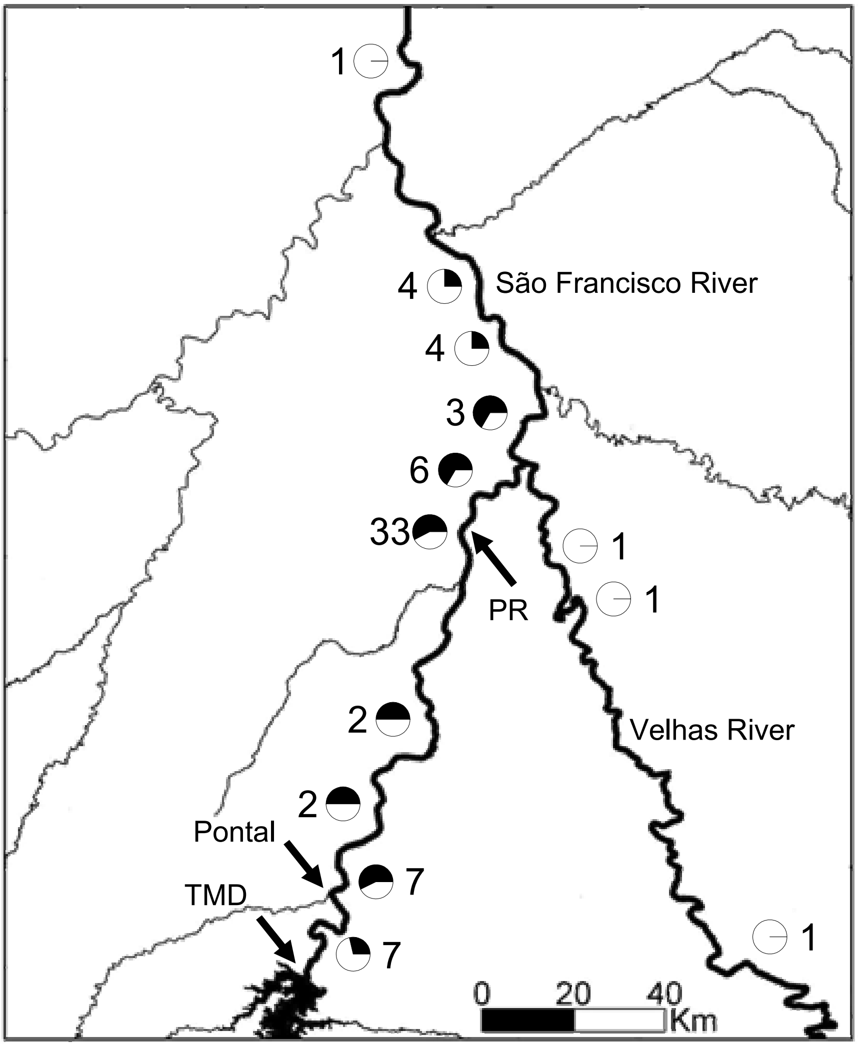


Figure 3.6. Frequency of occurrence of surubim in 20-km long segments of the São Francisco and Velhas River. Numbers represent the total number of fish located in each segment. Pie chart shows percentage of fish located during the spawning (black) and non-spawning (white) seasons. River locations of TMD (Três Marias Dam), Pontal, and PR (Pirapora Rapids) receivers are indicated. Only major tributaries are displayed.

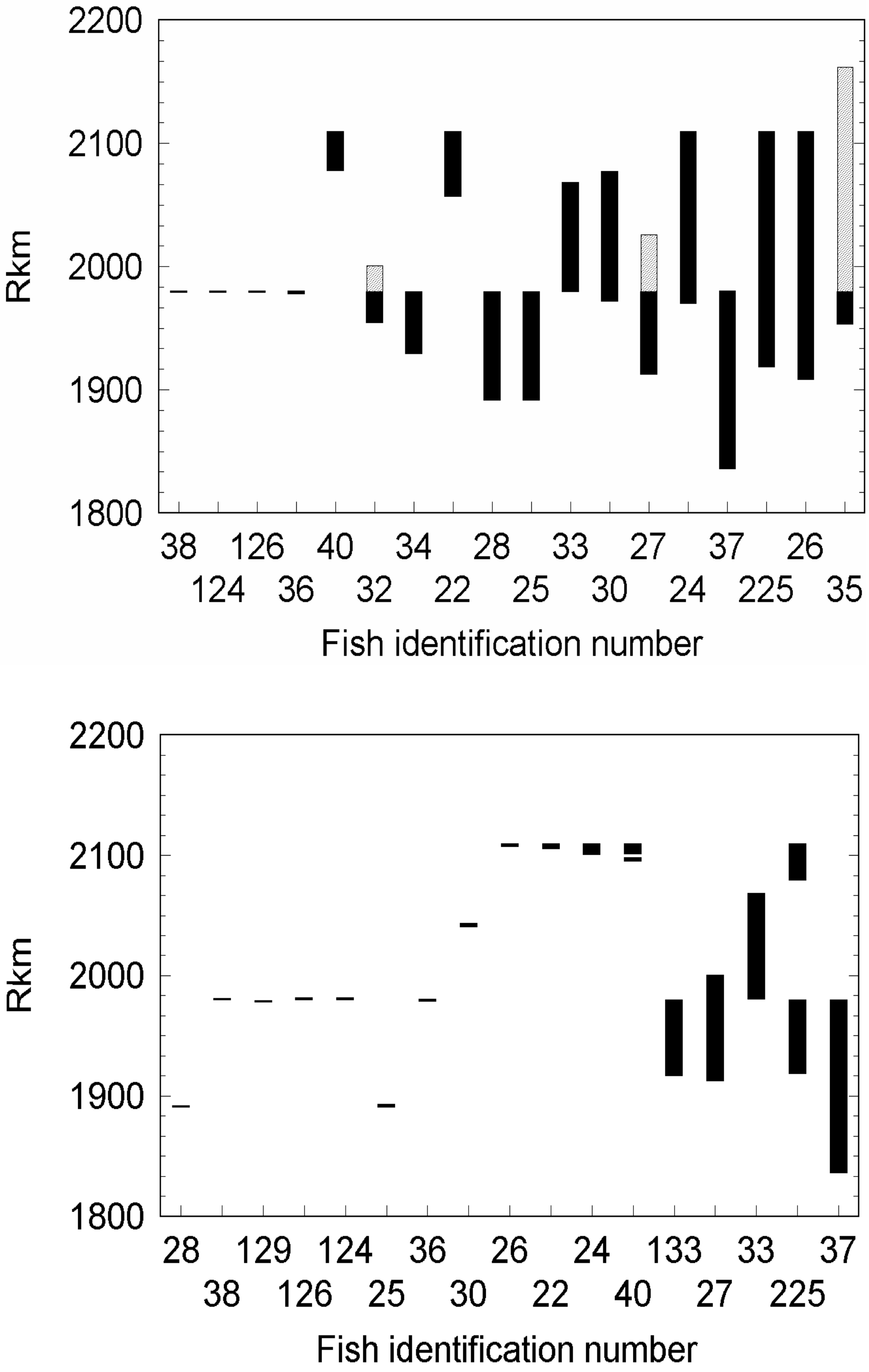
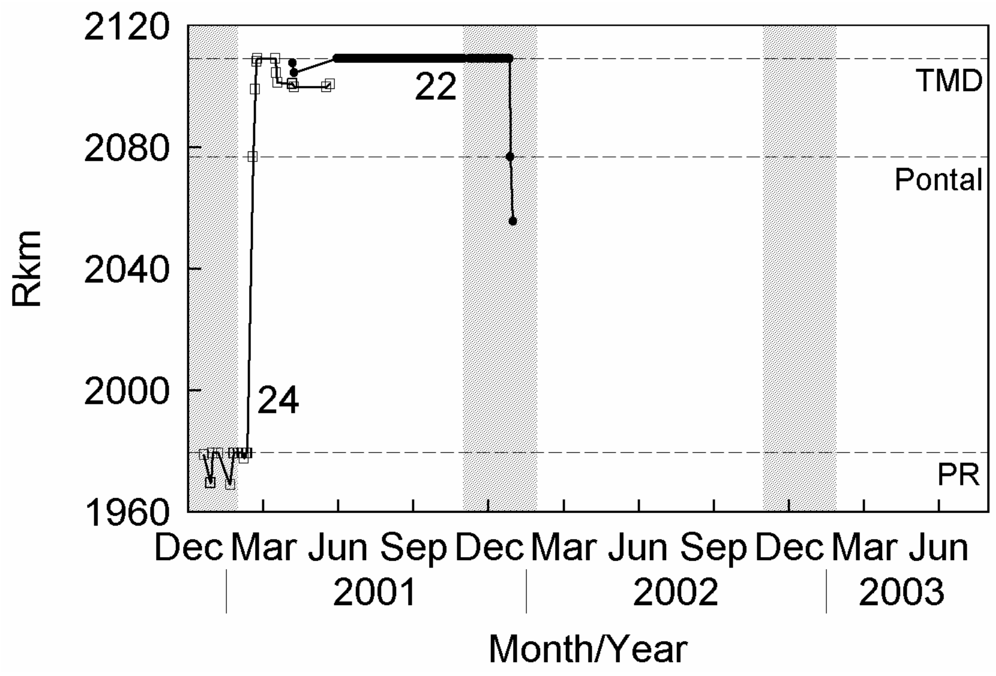


Figure 3.7. Total home range (top panel) and non-spawning home range (bottom panel) of surubims in the São Francisco (black bar) and Velhas (dotted bar) rivers. Fish were ordered according to the size of the home range.



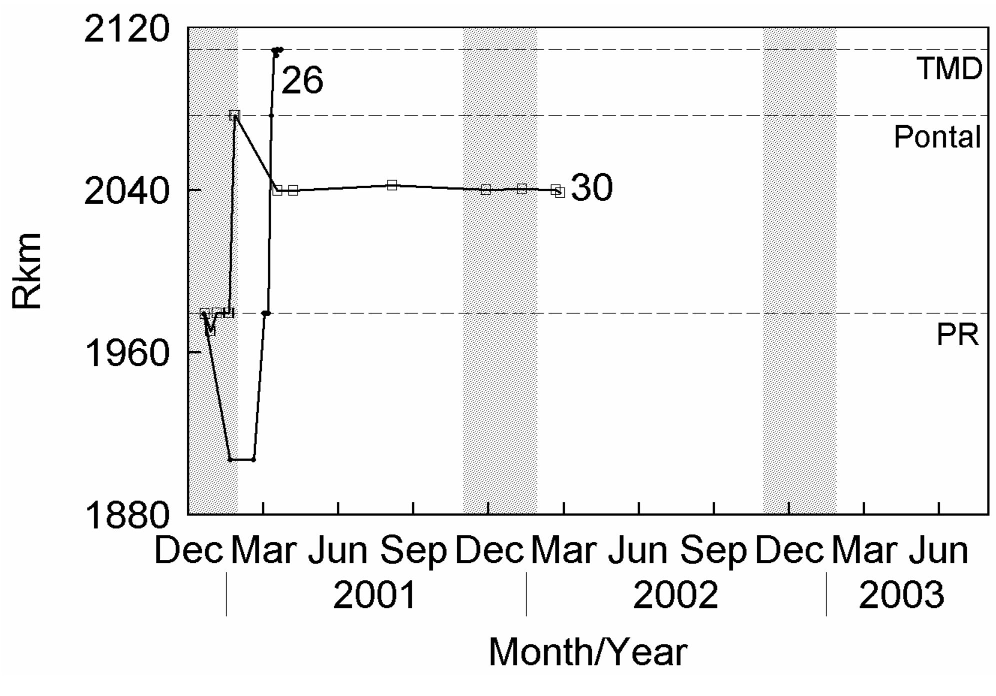


Figure 3.8. Migration of the surubims 22, 24, 26, and 30 in the São Francisco River. Gray vertical bars represent spawning season and unshaded areas show non-spawning seasons. Horizontal dashed lines mark location of TMD (Três Marias Dam), Pontal, and PR (Pirapora Rapids) receivers.

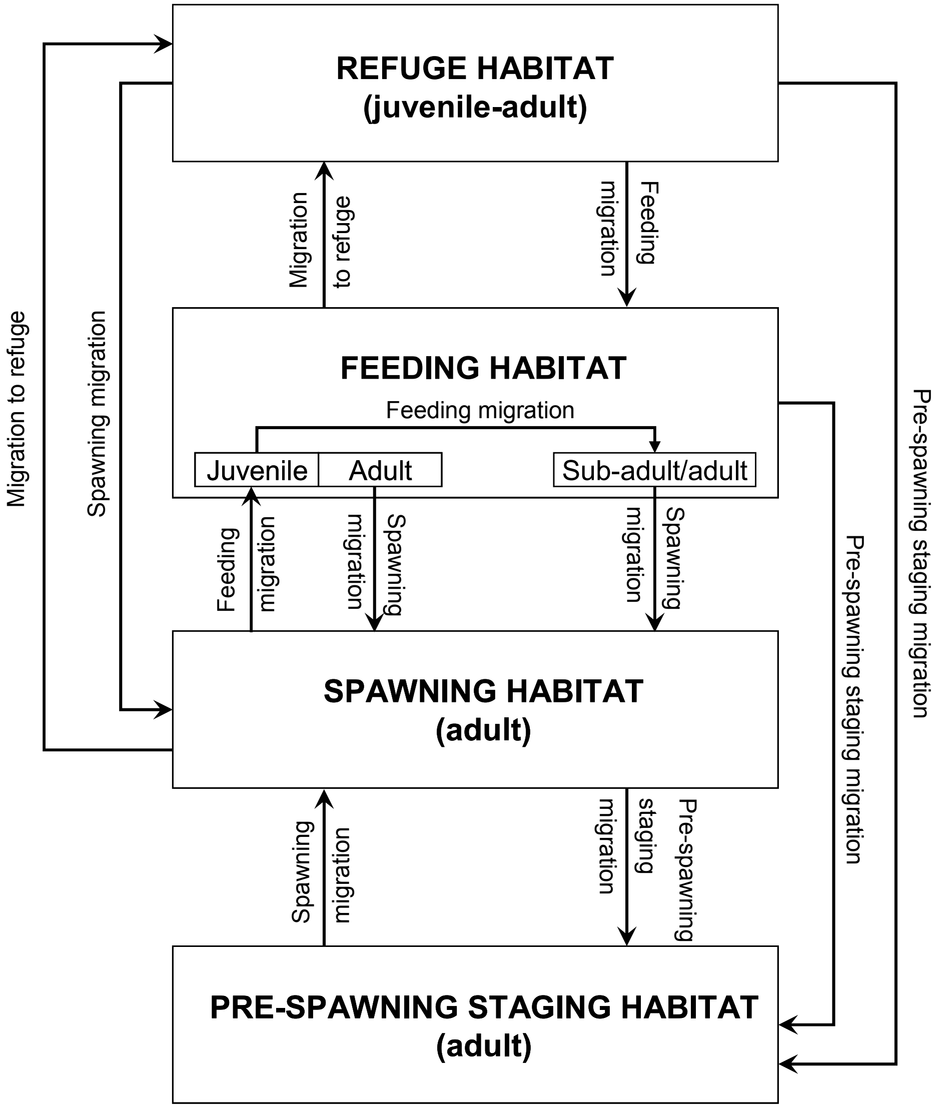


Figure 3.9. Model of generalized pattern of fish migration (Northcote 1978) which includes pre-spawning staging habitat. Modify from Lucas and Baras (2001).

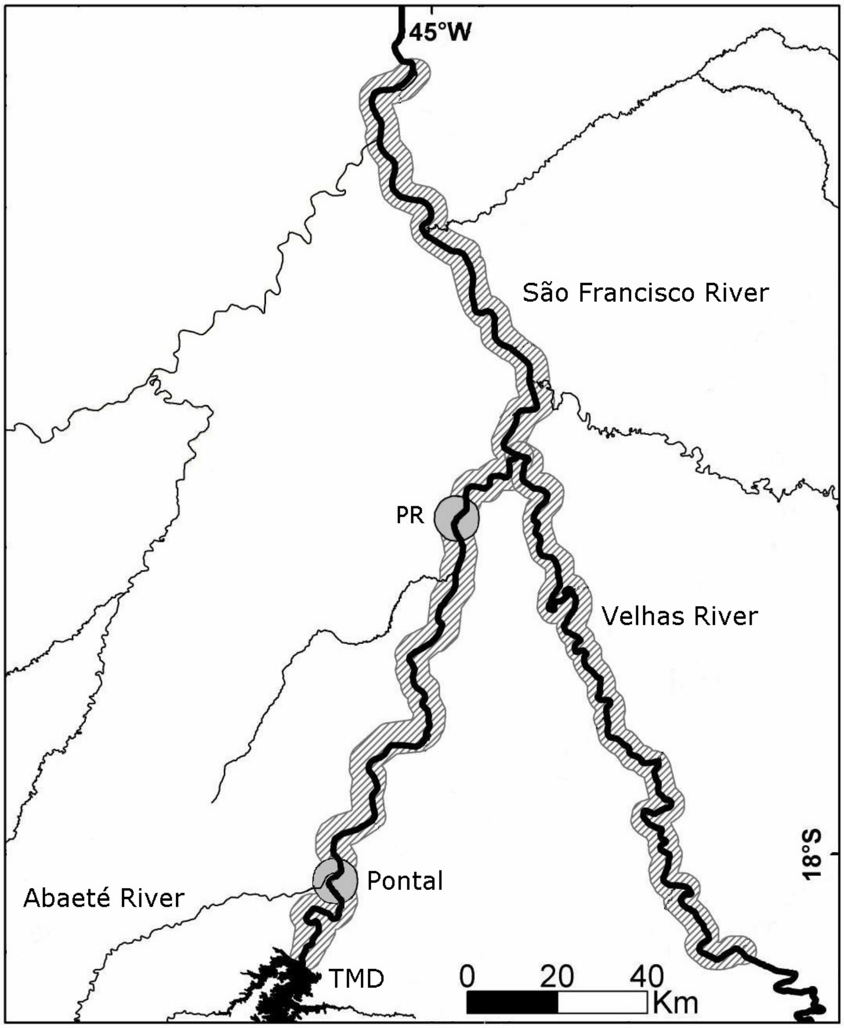


Figure 3.10. Spawning (dark circle; PR = Pirapora Rapids) and non-spawning (diagonal lines buffer) grounds of curimbatá in the São Francisco River Basin downstream TMD (Três Marias Dam). Spawning grounds are enlarged to facilitate visualization and include staging area.

CHAPTER 4

RESPONSE OF TWO BRAZILIAN FISHES TO ARTIFICIALLY COOL WATER DURING UPRIVER MIGRATION

4.1. Introduction

At hydroelectric reservoirs, withdrawal of hypolimnetic water for power generation results in the discharge of water that is cooler than ambient temperature downstream of the dam (Ward and Stanford 1979, Coutant 1987). This cooler water can produce major changes in fish populations. In Australia's Murray-Darling River, even a slightly cooler ($\leq 5^{o}$C) hypolimnetic discharge from Keepit Dam disrupted the thermal spawning cues for several native fish species (Preece and Jones 2002). Decline of native Colorado River fishes has been attributed to dams discharging water cooler than ambient temperature water (Clarkson and Childs 2000).

Upriver migration of fish can be blocked by water that is artificially warmer than ambient temperature (Hallock *et al.* 1970, Boubée *et al.* 1991, Lucas and Baras 2001). However, the effect of artificially cooler water on fish migration is poorly studied. In a rare example, warmer (19–21^{o}C) epilimnetic releases from Clanwilliam Dam, Olifants River, South Africa, were correlated with *Barbus capensis* moving onto spawning grounds, and cooler (16–18^{o}C) hypolimnetic water releases were associated with fish moving downstream away from spawning areas (King *et al.* 1998). I could find no other example of a study that examined the effect of cooler than ambient water on upstream migration of tropical or semi-tropical fishes.

The literature suggests that cooler discharge may disrupt upstream fish migrations. This might happen for three different reasons. First, a fish's temperature preference–avoidance response influences its movements (Giattina and Garton 1982). Second, the breadth of a fish's fundamental thermal niche might be only a few degrees centigrade (Magnuson *et al.* 1979). Third, fish acclimated to temperatures cooler than their final temperature preferendum will generally select higher temperatures when placed in a gradient (Giattina and Garton 1982). Also, fish that reach their fundamental thermal niche have greater selective fitness (Magnuson *et al.* 1979), so fish actively select temperatures that are optima (Giattina and Garton 1982, Kelsch 1996).

The water intake of Três Marias Dam (TMD), São Francisco River, Brazil, is located in the hypolimnion where water is 5–7^{o}C cooler than the epilimnion (Esteves *et al.* 1985, Sampaio and López 2003). The cooler discharge water gradually warms with increasing distance downstream from the dam and after receiving ambient temperature waters from tributaries (Sampaio and López 2003). The first large tributary downstream of TMD is the Abaeté River, located 33 km downstream (Figure 4.1).

In the mainstem São Francisco River, most upstream migrants are first exposed to the cooler TMD discharge when they swim upstream of Pontal past the mouth of the Abaeté River (Figure 4.1). To test the hypothesis that this cooler TMD discharge blocks fish migrating upstream of Pontal, I radio-tagged and tracked the movements of two fish species for 2.5 years as they swam upstream past Pontal. I tracked adult surubim, *Pseudoplatystoma corruscans* (Spix and Agassiz 1829) (Pimelodidae), a piscivorous catfish that grows to 120 kg (Sato *et al.* 2003) and large juvenile-adult curimbatá, *Prochilodus argenteus* Spix and Agassiz 1829 (Prochilodontidae), a large detritivore that grows to 15 kg (Sato *et al.* 1996). Both species are important fisheries resources in the São Francisco River (Franco de Camargo and Petrere 2001, Godinho *et al.* 2003a).

My objectives were (1) to describe the discharge and temperature regimes of the mainstem São Francisco River from TMD past Pontal and the Abaeté River, and (2) to track movements of upstream migrants and determine if they avoided entering the cooler water upstream of Pontal.

4.2. Methods

4.2.1. Thermal environment

I analyzed data on discharge and temperature of the São Francisco and Abaeté rivers for short-term (daily and seasonal) and long-term (annual) variations. Discharge of the São Francisco River was from gauging stations at Três Marias (TM) and Pirapora Rapids (PR); discharge of the Abaeté River was measured 32 km upstream from the mouth (Figure 4.1). I added the discharges of the Abaeté River and São Francisco River at TM to determine the discharge just downstream from Pontal. Discharge at the three gauging stations was measured once per day and provided by CEMIG (the Minas Gerais state power company). To measure temperature, I placed Onset© Optic StowAway Temp loggers at three sites in the São Francisco River mainstem, i.e., TM, Firmino (5 km upstream of Pontal), and at PR. Also, I placed a temperature logger 1 km upstream from the Abaeté River mouth. These loggers enabled me to determine the daily mean temperature of measurements taken every 3 hours. The temperature logger at Firmino provided data for only 219 days. Thus, I estimated the daily mean temperature at Firmino using a linear equation ($r^2 = 0.98$) of daily mean temperature at Firmino on daily mean temperature at TM.

I applied the first law of thermodynamics (Logan 1999) to estimate T_f, the temperature of the São Francisco River after the mixing of the Abaeté River. To estimate T_f, I used the equation:

$$T_f = ((T_a * Q_a) + (T_s * Q_s)) / (Q_a + Q_s),$$

where T_a = temperature of the Abaeté River, T_s = temperature of the São Francisco just upstream Pontal, Q_a = discharge of Abaeté River and Q_s = discharge of São Francisco River. The best estimator of T_s was the estimated temperature at Firmino; the best estimator of Q_s was the discharge at the TM gauging station; and the best estimator of Q_a was the discharge at the lowermost gauging station located 32 km upstream of the river mouth.

4.2.2. Radio-tracking

I captured and radio-tagged wild surubim and curimbatá from December 2000 to April 2001 and from December 2001 to March 2002. I captured fish at four mainstem locations: TM, Pontal, Cilga, and PR (Figure 4.1). I held fish for tagging in a portable tank filled with river water and immobilized them using electronarcosis with non-pulsed DC current (Kynard and Lonsdale 1975, Ross and Ross 1999). I inserted a tag into the body cavity leaving the antenna extended posterior through the body wall. I tagged 24 surubims (body weight = 9.5–29.0 kg) with Lotek© MCFT-7SP coded radio transmitters (diameter = 32 cm, length = 140 cm, weight = 170 g, and transmission life = 48 months). I also tagged 37 curimbatás (body weight = 0.8–2.9 kg) with Lotek© MCFT-3FM coded radio transmitters (diameter = 11 cm, length = 59 cm, weight = 10 g, and transmission life = 25 months). Tag weight in air as a percent of fish weight was $\leq$ 1.8%. I tracked fish from December 2000 to July 2003.

I monitored tagged fish moving upstream in the mainstem past the Abaeté River – São Francisco River junction into the cooler mainstem water upstream at Pontal using a Lotek© data-logging radio receiver. The receiver had three antennas: one to detect all the fish that approached Pontal, one to detect fish that successfully passed upstream of Pontal into the cooler water, and one to detect fish that left the mainstem and entered the Abaeté River. I eliminated false-positive records of tags using the same methodology described in the Chapters 2 and 3.

For each fish that passed upstream of Pontal into the cooler water, I determined the migration function (spawning, pre-spawning staging, or non-spawning) and origin–destination using the complete movement record of fish in Chapters 2 and 3. I also determined $\Delta T = T_a - T_s$ for the day each fish passed Pontal. I excluded all cases in which $T_a \leq T_s$. I tested ΔT data set of each species for normality (Shapiro-Wilk test, SAS' Univariate procedure, SAS Institute 1999), and then used a paired t-test (SAS' Ttest procedure, SAS Institute 1999) of mainstem and Abaeté temperatures to test the null hypothesis that $\Delta T = 0$ when fish passed Pontal. I set $\alpha = 0.05$.

4.3. Results

4.3.1. Thermal environment

The regulated hydrograph of the São Francisco River at TM showed small peaks on a non-regular basis and lower discharge during weekends and holidays (Figure 4.2). Major changes in discharge that lasted weeks to months were not linked to dry or wet seasons. Hydrographs of the Abaeté River and at PR showed long-term fluctuations associated with dry and wet seasons, and peaks related to floods. At PR, discharge variations were also due to TMD operation because most of the water that reached PR came from the reservoir, except during floods.

Thermal-amplitude of the daily mean temperatures was lower in the São Francisco River at Firmino (21.9–26.7^{o}C) than in the Abaeté River (18.3–31.9^{o}C) or in São Francisco River at PR (20.5–28.3^{o}C; Figure 4.3). Water temperatures at Firmino tended to be lower than the temperatures in the Abaeté River during August–April and higher during the rest of the year. The difference in water temperature between the Abaeté River and São Francisco River at Firmino ranged from -4.2 to 6.1^{o}C.

Short-term thermal fluctuations in the Abaeté River occurred frequently (Figure 4.3). These thermal changes were due to short-duration floods during the wet season (October–March) and to cold fronts during the dry season. In the mainstem São Francisco River, short-term thermal changes increased with distance downstream from TMD, i.e., intense short-term fluctuations occurred frequently at PR and short-term thermal fluctuations at Firmino were almost absent. In the Abaeté River, short-term thermal-amplitude was 8.5^{o}C and long-term thermal-amplitude was up to a maximum of 13.6^{o}C (Table 4.1). Thermal-amplitudes were a few degrees lower in the São Francisco River at PR.

After the mixing of the Abaeté River with the São Francisco River, discharge peaks appeared in the mainstem hydrograph (Figure 4.2) and temperature changed between -0.8 to 1.8^{o}C (Figure 4.3). The 99% quantile of thermal change was 0.9^{o}C. The greatest thermal changes occurred during floods when the Abaeté River discharge was 50–361% of the São Francisco River. When the Abaeté River discharge was < 17% of mainstem discharge, which occurred 95% of the time in the dry season and 50% of the time in the rainy season, the temperature of the mainstem after the inflow of the Abaeté River changed -0.5 to 0.3°C.

4.3.2. Fish movements

Radio-tagged surubim and curimbatá moved upstream through the mixing zone with Abaeté River with no avoidance of the cooler water at Pontal. Three surubims moved upstream of Pontal a total of 10 times (Table 4.2). Most passes were by only one fish that moved back and forth from a spawning ground in the Abaeté River to a staging area in the mainstem just upstream Pontal. The ΔT was 2.0 ± 1.6°C (mean ± SD, range = 0.1–4.9°C) when the surubims passed Pontal. Five curimbatás moved upstream of Pontal six times (Table 4.2). In most cases, they were moving to a pre-spawning staging area in the mainstem upstream of Pontal. The ΔT was 0.9 ± 0.6°C (mean ± SD, range = 0.1–1.8°C) when they passed. Paired t-test of mainstem and Abaeté temperatures showed that ΔT were significantly > 0 when surubim and curimbatá passed upstream of Pontal (surubim: $t = 3.90$, $df = 9$, $p = 0.004$; curimbatá: $t = 3.42$, $df = 6$, $p = 0.019$).

4.4. Discussion

4.4.1. Thermal environment

The temperature of the São Francisco River just downstream of TMD was determined by the temperature of hypolimnetic reservoir discharge. This reach had virtually no short-term thermal fluctuations and the long-term thermal amplitude was lower than in the free flowing, non-thermally polluted Abaeté River (6.3°C vs. 13.6°C). The TMD discharge water also caused the São Francisco River to have a smaller and delayed annual maximum temperature and a greater minimum temperature compared to the Abaeté River. Similar temperature differences between dam discharge and natural waters have been reported elsewhere (Petts 1986, Preece and Jones 2002).

As the São Francisco water flows downstream, temperature fluctuation gradually becomes similar to what may have been the natural thermal regime prior to the construction of TMD. At PR, 130 km downstream of TMD, short- and long-term thermal fluctuations were similar to those of the Abaeté River although amplitudes were a few degrees lower. A similar altered thermal regime existed downstream of the Keepit Dam, Murray-Darling River, Australia (Preece and Jones 2002). In that system, the natural thermal regime of the river was restored to the pre-dam condition 100 km downstream of the dam.

The return of the São Francisco River close to its original thermal state at PR was mostly due to heat exchange between the mainstem and the surrounding environment. Tributaries also contributed, but likely to a lesser extent. For example, for 99% of the study period, the Abaeté River produced thermal changes on the São Francisco River $< 1.0\ ^{o}C$. This was because its low discharge could not cause major changes in mainstem temperature. Also, when the Abaeté River discharge was high during floods, the rains had a cooling effect on its temperature, bringing it closer to (or sometimes even lower than) the mainstem temperature. I did not study the temperature of other tributaries, but because they are smaller than the Abaeté River, which drains an area 2.6 times larger than the combined areas of the other two biggest tributaries, they likely produce an even smaller change in mainstem temperature.

4.4.2. Thermoregulation of surubim and curimbatá

Surubim and curimbatá are likely eurythermal species that may not require time for acclimation. Johnson and Kelsch (1998) proposed and tested a model relating temperature-preference and the thermal fluctuations experienced by fishes. Eurythermal species experience the greatest long-term thermal extremes and live in water with an annual thermal amplitude > 5°C. Temperature-preference relationships have not been studied for surubim or curimbatá, but the model of Johnson and Kelsch (1998) predicts that both are eurytherms because their habitat has an annual thermal-amplitude > 5°C. Moreover, the short-term thermal-amplitude, which was 8.5°C in the Abaeté River and 7.1°C in the São Francisco River at PR, was only few degrees less than the long-term thermal amplitude. For species that experience short-term thermal fluctuations, evolution should favor individuals with broad temperature tolerances that do not require time for acclimation (Johnson and Kelsch 1998).

The theory of fish behavioral thermoregulation predicts that the preferred temperature for eurythermal fishes is primarily a function of recent thermal history of the individual (Kelsch and Neill 1990), and further, that fish acclimated to temperatures below their final preferendum will generally move to a higher temperature when placed in a thermal gradient (Giattina and Garton 1982). However, when surubim and curimbatá passed Pontal moving upstream they did not prefer the warmer water. All fish swimming upstream past Pontal when ΔT was positive chose the slightly cooler water in the mainstem, not the warmer water in the Abaeté River. Moreover, fish moving downstream in the warmer Abaeté River to the São Francisco River did not avoid moving into the cooler water.

Surubim and curimbatá did not behave as predicted by the theory of behavioral thermoregulation. This is likely because their thermal preference and avoidance are altered by biotic and abiotic factors (Giattina and Garton 1982). Surubim spawn in the Abaeté River near its mouth and stage in the São Francisco just upstream of Pontal (Chapter 3). Curimbatá spawn at the intersection of the Abaeté and São Francisco rivers and stage in the São Francisco River upstream of Pontal (Chapter 2). Most fish that passed upstream of Pontal were moving to a staging area coming from non-spawning grounds (curimbatá) or spawning grounds (surubim). Thus, the behavioral drive to move to a functional habitat was stronger than the preference for warmer temperature, a behavioral response that is frequently showed by eurythermal fish in laboratory tests (Johnson and Kelsch 1998).

The present study indicates that water discharged from dams on tropical or sub-tropical rivers that is < 5°C cooler than ambient will not disrupt migrations of eurythermal fish species such surubim and curimbatá. This information provides guidance on the level of acceptable thermal change for Brazilian fishes that live in rivers with similar short- and long-term thermal amplitudes.

Table 4.1. Short- and long-term (annual) thermal-amplitude of the Abaeté River and São Francisco River at Pirapora Rapids.

River	Short-term (^oC)	Long-term (^oC)	
		2001	2002
Abaeté	8.5	13.6	11.1
São Francisco	7.1	10.3	8.2

Table 4.2. Surubim and curimbatá tracked moving upstream past Pontal into cooler mainstem São Francisco River water. All fish tracked when the difference between the daily mean temperature of Abaeté and São Francisco rivers were positive. Life history function of the movement is from Chapters 2 and 3.

Fish number	Date	Functional habitat	
		Origin	Destination
		Surubim	
24	Feb 2001	Spawning*	Non-spawning
30	Jan 2001	Spawning*	Non-spawning
225	Oct 2002	Non-spawning*	Staging
225	Nov 2002	Spawning**	Staging
225	Dec 2002	Spawning**	Staging
225	Dec 2002	Spawning**	Staging
225	Dec 2002	Spawning**	Staging
225	Dec 2002	Spawning**	Staging
225	Jan 2003	Spawning**	Staging
225	Jan 2003	Spawning**	Staging
		Curimbatá	
57	Jan 2001	Non-spawning*	Staging
69	Jan 2001	Non-spawning*	Staging
69	Oct 2001	Non-spawning*	Staging
71	Nov 2002	Non-spawning**	Staging
73	Sept 2002	Non-spawning*	Non-spawning
84	Apr 2002	Non-spawning**	Non-spawning

Functional habitat in the São Francisco River (*) or in the Abaeté River (**).

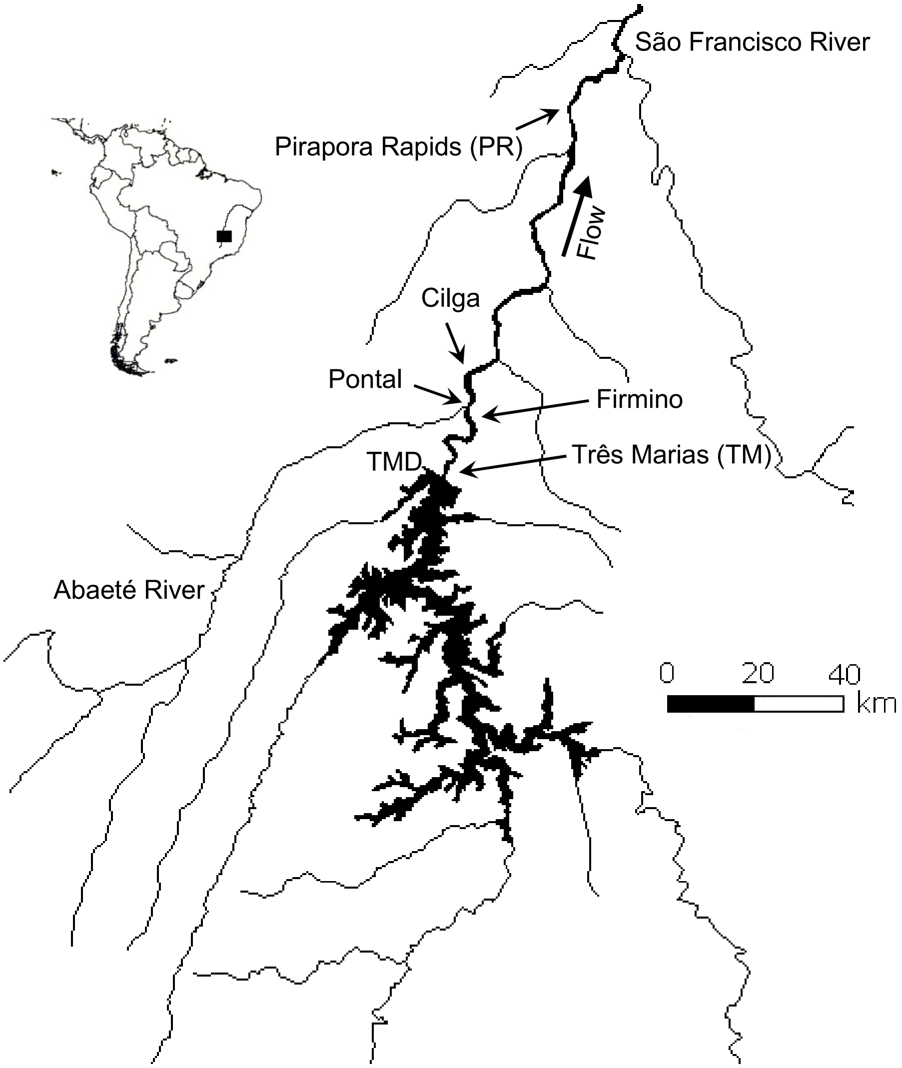


Figure 4.1. Map of the São Francisco River basin showing the study area downstream of Três Marias Dam (TMD) to Pirapora Rapids. Upstream movement of radio-tagged fish in the mainstem São Francisco River was monitored at Pontal, where migrants chose between Abaeté River water or mainstem water.

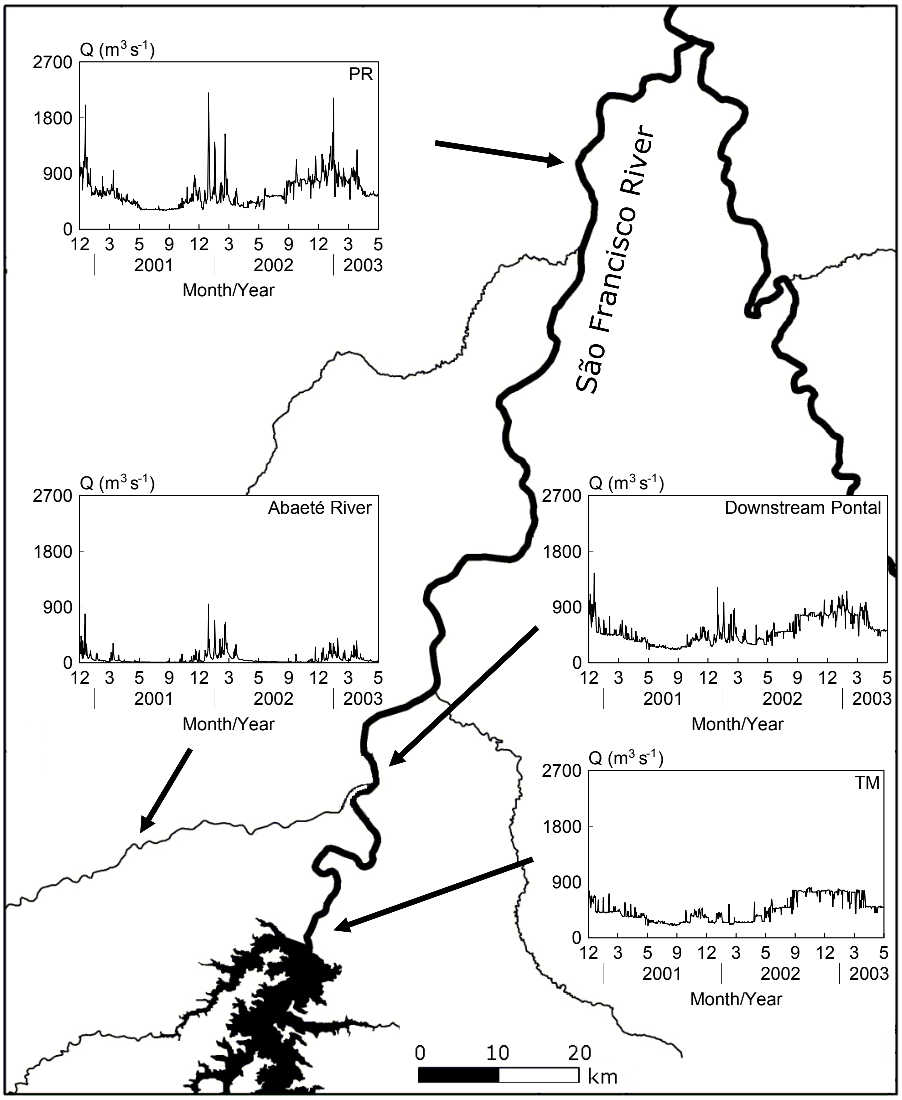


Figure 4.2. Hydrographs of the Abaeté River (32 km upstream from the mouth) and at three locations in the São Francisco River: TM = Três Marias, downstream of Pontal after the mixing of the Abaeté River, and PR = Pirapora Rapids.

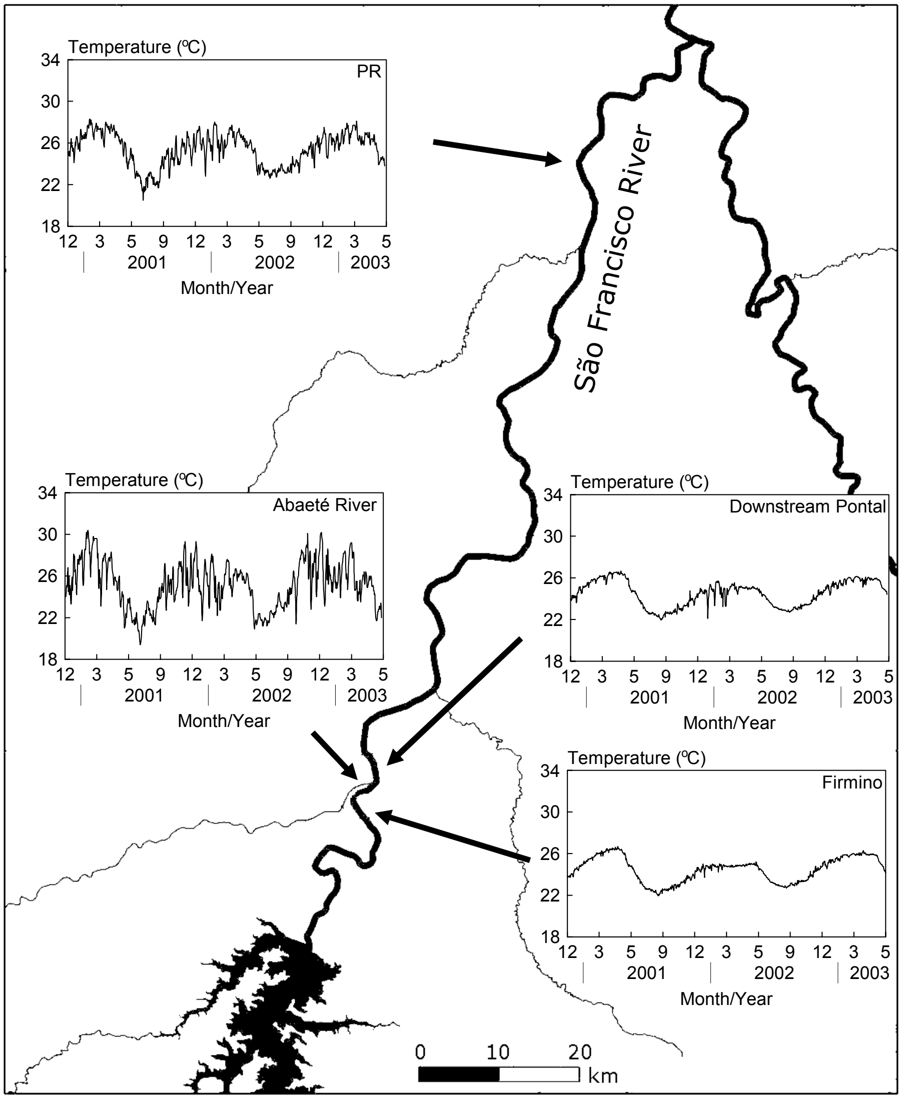


Figure 4.3. Daily mean temperature of the Abaeté River (at the mouth), and at three locations in the São Francisco River: Firmino (5 km upstream of Pontal), downstream of Pontal after the mixing of the Abaeté River, and PR = Pirapora Rapids.

CHAPTER 5

SUPPLEMENTAL WATER RELEASES FOR FISHERIES RESTORATION IN A BRAZILIAN FLOODPLAIN RIVER: A CONCEPTUAL MODEL

5.1. Introduction

Millions of people around the world count on highly productive floodplain rivers for commercial, subsistence, and recreational fisheries (Bayley 1981, Thuok 1998, Craig *et al.* 2004). These fisheries ultimately depend on floods because flooding is the principal factor responsible for productivity in floodplain rivers (Junk *et al.* 1989). Fisheries harvest is directly related to the frequency and intensity of natural floods (Welcomme and Hagborg 1977, Moses 1987, Smolders *et al.* 2000). However, fisheries in floodplain rivers are threatened by anthropogenic activities such river damming, which attenuates intensity of floods, and construction of dikes along river banks, which prevent flood waters reaching floodplain lakes.

Supplemental water releases (SWR) from dams can be used to create the high water conditions required to restore fisheries that have declined (Cowx 1994). A series of water releases in the Pongolo River, South Africa, induced fish to spawn and flooded the floodplain lakes fish use for rearing (Welcomme 1989). Also, SRW from Shire River Dam, Malawi, improved the fisheries catch, and controlled discharge from the Kariba Reservoir, Zambezi River, Zambia/Zimbabwe, resulted in the occurrence of juveniles of several species in floodplain lakes. An in-depth discussion of the importance of supplemental water releases for biota is found in Stanford *et al.* (1996), Galat *et al.* (1998), and Koel and Sparks (2002).

The São Francisco River (SFR; Figure 5.1), Brazil, located southeast of the Amazon River, was once a major inland fishing river. Menezes (1956) cited several impressive fisheries reports from the river during the first half of the last century. For instance, Carneiro (1921) reported that 6,000 surubims (*Pseudoplatystoma corruscans*) weighing 5–50 kg were harvested in one floodplain lake with just one seine haul. Seine hauls that captured 12,000 surubims and 3,000 fish of various species were reported and harvests of 4,000–5,000 fish were common (Magalhães 1942).

Contemporary fisheries landings in the SFR are much lower than the historical level and they continue to decline (Godinho and Godinho 2003). For instance, the yield of commercial fishers' at Pirapora, an important fishing area in the middle course of the SFR at river km (rkm) 1,978, decreased from 11.7 kg per fisher.day^{-1} in 1987 to 3.1 kg per.fisher day^{-1} in 1999 (Godinho *et al.* 1997, Godinho and Godinho 2003). Harvest was also reduced in quality. Surubim, the most valuable fish, was 86% of the yield in 1987, but only 27% in 1999 (Godinho *et al.* 1997, Godinho pers. obs.). This collapse of the fisheries threatens a traditional livelihood of thousands of families along the river (Valêncio *et al.* 2003).

The São Francisco River has experienced changes in flood intensity and frequency due to both natural and human changes. Lack of significant floods that occurred historically is likely one of the major factors responsible for the recent fishery collapse in the SFR. Flooding controls river productivity (Junk *et al.* 1989), affecting rearing success and recruitment of fisheries species that use floodplain lakes as their main nursery ground (Sato and Godinho 2003). Additionally, floods are needed for successful spawning (Godinho and Kynard pers. obs.). The last major flood was in 1992 when the river reached 11.8 m (a 20-year recurrence interval flood) in its middle course at river km 1,837. After 1992, all floods had recurrence interval of less than 3 years with maximum annual water levels ranging from 5.9 to 8.7 m. Collapse of the fishery for *Prochilodus lineatus* in the Pilcomayo River was attributed to the absence of floods due to El Niño (Smolders *et al.* 2000).

I proposed a conceptual model for SWR to address important information needs on biological, river, dam and reservoir, and economic factors. The questions I asked to generate data for the conceptual model were: (I) Biologically, what is the best release date? (II) How much water will be released? (III) What is the pattern of impoundment and how much impounded water will be released? (IV) What is the lost revenue to the power plant associated with SWR? (V) What is the relationship between river discharge and the area of floodplain that is flooded? (VI) What is the relationship between SWR and fisheries value?

I applied questions I to IV of the conceptual model to the situation in the SFR to plan for potential SWRs from Três Marias Reservoir (TMR, Figure 5.1). The goal of the SWRs is to increase fish recruitment and ultimately the fisheries by spilling water during the fish spawning season. This should enable early life stages to reach floodplain lakes where they rear, and enable them to return back to the river at a later time. I sampled ichthyoplankton to answer question I, and further, tested the hypothesis that flooding triggers fish spawning by comparing ichthyoplankton density in a regulated river (SFR) and a non-regulated river, the Velhas River (VR; Figure 5.1). I analyzed discharge data of the rivers and the impoundment at TMR to answer questions II and III. To address question IV, I estimated lost revenue for a range of SWR durations based on the TMR hydraulic head during each month of the spawning season and for a range of power rates. I alternatively estimated the annual drop in income using commercial fishery yield in the SFR before and after the fisheries collapse to estimate how much the fisheries income would increase due to SWR.

5.2. Fisheries and Study Site

5.2.1. Fisheries

The SFR basin is home to almost 160 species of freshwater fishes (Britski *et al.* 1988, Sato and Godinho 1999, Alves and Pompeu 2001). Seven most important commercial species are migratory fishes that broadcast their semi-buoyant eggs (Sato *et al.* 2003, Sato and Godinho 2003) during the rainy season (Bazzoli 2003). Hatching 16–22 h after fertilization is a common feature among these fishes (Sato *et al.* 2003), and the larval stage ends within 3–5 days for five of these important species (Godinho *et al.* 2003). Floodplain lakes are the major nursery grounds for early life stages and juveniles of important fisheries species (Sato *et al.* 1987, Pompeu and Godinho 2003).

5.2.2. Três Marias Dam and the river downstream

The TMR was built in the early 1960s at rkm 2,109 for flow regulation, flood control, irrigation, and power generation (Britski *et al.* 1988). It has never been used to produce a SRW to restore the fishery, but a 2002 state law requires dam owners to repair the damage if river flow regulation disrupts the nursery function of floodplain lakes. The TMR live storage is 15,278 km^3 and maximum hydraulic head is 57.5 m. The power plant installed capacity is 396 MW and maximum penstock discharge is 900 $m^3.s^{-1}$. To avoid flooding downstream, maximum allowed discharge is 3,500 $m^3.s^{-1}$.

Downstream of TMR, the river runs free for 1,090 km until Sobradinho Reservoir and flows through the states of Minas Gerais and Bahia (state border at rkm 1,543). The mouths of the two largest tributaries, VR and Paracatu River, are located 157 and 243 km downstream of TMR. Mainstem discharge just downstream of these two tributaries is 73% of the total river discharge that reaches the ocean. Floodplain lakes along the mainsteam are abundant mainly downstream of the Paracatu River. The floodplain area downstream of TMR is estimated at 2,000 km^2 (Welcomme 1990). The rainy season is from October to March when rains supply 91% of the annual 1.13 m rainfall. December and January are the two rainiest months.

5.3. Methods

5.3.1. What is the best release date?

I sampled for ichthyoplankton in the SFR and VR at sites located 3.5 km upstream from the junction of the two rivers (Figure 5.1). I sampled daily early in the morning and late in the afternoon from late November to early February during two consecutive spawning seasons (1998–1999 and 1999–2000). I used a conical net (32 cm mouth diameter, 140 cm long, and 0.35 mm mesh size) set in the river channel 50 cm below the surface during 10–15 min to sample the ichthyoplankton. The net's mouth had a mechanical flowmeter to measure the volume of filtered water. I preserved the samples in a buffered solution of 5% formalin. After I sampled for ichthyoplankton, I measured water temperature, conductivity, and turbidity with a Horiba U10 multi-parameter water quality meter.

I sorted each ichthyoplankton sample once and classified each individual in the following early life stages: egg, yolk-sac, preflexion, flexion, and postflexion (Kendall *et al.* 1984). The stages from yolk-sac to postflexion correspond to the larva stage (Kendall *et al.* 1984). I classified damaged individuals that could not be classified into a development stage as unknown. I divided the number of individuals by the volume of filtered water to calculate density per m^3. I calculated density per m^3 for each early life stage and for total ichthyoplankton, which included the unknown-stage individuals.

Water level at gauging stations was determined once each day. I used data from two gauging stations in the SFR and four stations in the VR (Figure 5.1). I also used data from one gauging station located in the largest tributary upstream of each ichthyoplankton sampling site. Data from all gauging stations were provided by third parties except data for the most downstream station in the VR.

I used SAS (SAS Institute 1999) for statistical analysis. I used chi-square to test for differences in frequency data between groups. For analysis of continuous variables, I used non-parametric statistics because most variables did not have a normal distribution. I used Wilcoxon two-sample test with normal approximation and continuity correction of 0.5 to compare data between two groups, Kruskal-Wallis test for comparisons when there were more than two groups, and Spearman correlation to test relationships between two continuous variables. For each early-stage except postflexion, I calculated the cross-correlation between daily fish density and water level with maximum delay time of 8 days, sufficient time for most migratory fishes to complete development of the larval stage (Godinho *et al.* 2003).

5.3.2. How much water will be released?

To calculate the SWR volume, I used an operating rule for a SWR with three discharge phases: increasing, stable, and decreasing. Duration of both increasing and decreasing discharge phases was 24 hours. During the increasing phase, discharge increased from 900 $m^3.s^{-1}$ (= maximum penstock discharge) to 3,500 $m^3.s^{-1}$ (= maximum allowed discharge) at the rate of 108.3 $m^3.s^{-1}$ per hour. I used the same rate during the decreasing phase to reduce discharge from 3,500 to 900 $m^3.s^{-1}$. For the stable phase, I set the discharge = maximum allowable discharge, and then I calculated the volume released during 1, 2, 3, 4, 5, and 6 days. I then calculated the SWR volume adding the volume of water used in each phase for SWR with total duration of 2 days (1 day increasing discharge and 1 day decreasing) to 8 days (1 day increasing discharge, 6 days stable, and 1 day decreasing).

5.3.3. What is the pattern of impoundment and how much impounded water will be released?

I used the TMR historical data to determine the volume of water impounded in TMR every month from 1976–2003. I also calculated the percentage of SWR volume in relation to daily live storage for every day from November to March (the fish spawning season) from 1976–2003.

5.3.4. What is the lost revenue to the power plant associated with SWR?

To determine Três Marias power plant lost revenue (R), I used the following equation:

$$R = \sum_{t=1}^{n} (Q_t.h.g.\varepsilon.\$).10^{-3}$$

where t is hours since the beginning of spill, Q_t is spill discharge (m^3.s^{-1}) at time t as determined by the SWR operating rule, h is hydraulic head, g is gravity acceleration (= 9.8 m.s^{-2}), ε is power unit efficiency (= 0.84), and *$* is power rate in US$/MWh. To convert currency, I used the exchange rate of US$ 1.00 = R$ 2.79 (R$ = Brazilian real) as of November 2004.

I calculated R using mean h for each month from November to March 1976–2003. In addition, I calculated R for three values of *$*, i.e., US$ 18.00, US$ 30.00, and US$ 42.00. The lowest value of *$* was slightly lower than the power purchase agreement (i.e., US$ 18.83) between producer and the distribution companies that negotiate power produced by Três Marias power plant (ANEEL 2004). The greatest value was 14.3% greater than the mean power purchase agreement in Brazil in 2000 (ELETROBRÁS 2001), so estimates of R already incorporate future adjustments in the power purchase agreement.

5.3.5. What is the relationship between SWR and fisheries value?

To forecast the income increase, I used the decrease in commercial fishery annual income that followed the fisheries collapse in the SFR. I determined the commercial fishery annual income (I) before and after the collapse using the following equation:

$$I = f.d.w.CPUE$$

where f is the number of commercial fishers, d is the number of working days, w is the commercial value of a kilo of fish, and *CPUE* is the capture per unit of effort in kg. fisher^{-1}.day^{-1}. I considered $f = 1{,}946$, which is the number of fishers downstream of TMR in Minas Gerais state (Miranda *et al.* 1988); $d = 188$, which is the number of days during the fishing season, excluded Saturdays, Sundays, and holidays; and w = US$ 1.42, which is the mean cost per kilogram of the three fish species that comprise most of the fisheries in 1997 (Franco de Camargo and Petrere 2001). I used the CPUE of the commercial fishers' of Pirapora in 1987 (= 11.7 kg.fisher^{-1}.day^{-1}) and 1997 (= 3.1 kg.fisher^{-1}.day^{-1}), i.e., before and after the SFR fisheries collapse, to calculate two values of I. Then, I used the difference between them to forecast the increase in I after a SRW.

5.5. Results

5.5.1. What is the best release date?

During the 2-year sampling period, water level varied only 0.81 m in the SFR, but varied 3.38 m in the VR (Figure 5.2). Several floods happened each sampling season and they were always more intense in the VR. In the SFR, water level at Pirapora was significantly correlated with three physical-chemical variables — conductivity, temperature, and turbidity (Spearman coefficient of correlation - r_s; Table 5.1). A similar relationship occurred between water level and physical-chemical variables at Guacuí in the VR (Table 5.2). In both rivers, conductivity and temperature were negatively related to increasing water level while turbidity had a positive r_s. Absolute values of r_s were greater in the VR than in the SFR.

I sorted 15,803 eggs and larvae in the SFR and 25,921 eggs and larvae in the VR. Total ichthyoplankton density ranged from 0 to 39.9 individuals per m^3 in the São Francisco (median = 0.9) and from 0 to 51.8 individuals per m^3 in the VR (median = 2.8). Total ichthyoplankton density was significantly smaller in the SFR (Wilcoxon two-sample test: $W = 63653$, df = 1, $P < 0.0001$). Egg density was greater in the morning than in the afternoon in the SFR (Wilcoxon two-sample test: $W = 17824$, df = 1, $P = 0.01$) and in the VR (Wilcoxon two-sample test: $W = 22899$, df = 1, $P = 0.004$).

Daily variation of egg and larva densities was similar in both rivers (Figure 5.3). Density peaks were more frequent and, most of the time, greater in the VR than in the SFR. Egg and yolk-sac stages were more abundant among SFR ichthyoplankton while preflexion and flexion were more abundant in the VR. I caught very few postflexion: 68 in the SFR and 113 in the VR.

Eggs and larvae occurred during the entire sampling period (Figure 5.4). However, the Kruskal-Wallis test showed that mean density was not constant during the spawning season in the SFR (spawning season of 1998–1999: $H = 57.2$, df = 7, $P < 0.0001$; spawning season of 1999–2000: $H = 31.7$, df = 7, $P < 0.0001$) and in the VR (spawning season of 1998–1999: $H = 40.9$, df = 7, $P < 0.0001$; spawning season of 1999-2000: $H = 36.0$, df = 7, $P < 0.0001$). Greater mean densities were more common until the first 10 days of January in both rivers and spawning seasons. Floods also occurred more frequently until January in the Abaeté River (chi-square test: $\chi^2 = 52.8$, df = 14, P <0.0001) and in the VR (chi-square test: χ^2 = 124.4, df = 14, P <0.0001; Figure 5.5).

Among all gauging stations, egg density in both rivers had greatest correlation with water level of the largest upstream tributary (Tables 1 and 2). Peaks of egg density in the SFR and VR were associated with floods in these tributaries (Figure 5.6). For instance, near the end of the 1998–1999 sampling season in the SFR, egg density peaked due to a 3-day, 22-cm flood in the Abaeté River after 20 days of very low density or no drifting eggs and constant water level in the mainstem SFR. Furthermore, the total change in water level from one day to the next of the largest upstream tributary was associated with change in the egg density in the SFR (Kruskal-Wallis test: H = 18.4, df = 8, P = 0.02) and in the VR (Kruskal-Wallis test: H = 26.8 df = 14 P = 0.02). In both rivers, I found the greatest egg densities when water level variation was positive (Figure 5.7). On the other hand, variations in discharge of TMR did not influence egg density in the SFR (Table 5.1) and several small floods in SFR caused by only discharge from TMR were not followed by an increase in egg density.

The egg and yolk-sac stages had the strongest cross-correlations with water level with a time lag of 0 or 1 day at all gauging stations (Table 5.3). In general, the closer to the gauging station, the greater the correlation for these life stages. Preflexion had the strongest cross-correlation with water level mostly with a time lag of 2 or 3 days. The flexion stage had the strongest cross-correlation with water level with a time lag of 3 days in the SFR and 4–7 days in the VR.

5.5.2. How much water will be released?

During the 24-hour increasing phase of the SWR, 0.190 km^3 of water was used to increase the discharge from 900 to 3,500 m^3.s^{-1} at the rate of 108.3 m^3.s^{-1} per hour. The same amount of water was used during the decreasing phase of the SWR. Therefore, SWR volume for a 2-day release (1 day increasing and 1 day decreasing) was 0.380 km^3 (Table 5.4). Water released during stable discharge was 0.302 km^3 per day. Thus, SWR volume was 2.192 km^3 for an 8-day release (1 day of increasing discharge, 6 days stable, and 1 day decreasing).

5.5.3. What is the pattern of impoundment and how much impounded water will be released?

From November to March 1976–2003, mean monthly water accumulation was 1.204 $\pm$ 1.173 km^3 (mean $\pm$ SD; range = -1.096 to 4.657 km^3). During the spawning season, negative accumulation occurred during all months, but November was the only month with negative mean (Figure 5.8).

From November to March 1976–2003, daily storage varied greatly (range, 1.322–15.162 km^3; mean and SD, 9.290 $\pm$ 3.552 km^3). Consequently, the percentage of SWR volume in live storage had a large range of variation (Figure 5.9). Mean percentages and ranges were greater in November and December and smaller in January to March. Mean percentage reached 13% in November and December for short-term SWR (up to 3 days) and 28–42% for long-term SWR (6–8 days). In the other months, mean percentage was < 21% for most SWR except for 7 and 8-day release in January and 8-day release in February.

5.5.4. What is the lost revenue to the power plant associated with SWR?

The mean hydraulic head (*h*) increased gradually from 48.7 m in November to 54.9 m in March during 1976–2003. Thus, lost revenue (*R*) was 13% greater for a SWR in March compared to a SWR in November. That difference did not depend on SWR duration or power rate ($).

For $h = 52.3$ m, which was the mean *h* for January to March 1976–2003, *R* for a 2-day SWR ranged from R$ 0.493 million ($ = US$ 18.00) to US$ 1.151 ($ = US$ 42.00; Figure 5.11). For every extra day, *R* increased in US$ 0.493 million ($ = US$ 18.00), US$ 0.822 million ($ = US$ 30.00) or US$ 1.151 million ($ = US$ 42.00). Thus, *R* for an 8-day SWR varied from US$ 3.452 ($ = US$ 18.00) to US$ 8.056 million ($ = US$ 42.00).

5.5.5. What is the relationship between SWR and fisheries value?

The commercial fishery annual income in the SFR downstream Três Marias Reservoir was estimated to be US$ 6.078 million in 1987 (prior to the fishery collapse) and US$ 1.610 million in 1997 (after the collapse). Thus, the annual income decrease following the fishery collapse was US$ 4.468 million.

5.6. Discussion

Supplemental water releases are of growing importance in many countries (Lubinski *et al.* 1991, Peterken and Hughes 1995, Waal *et al.* 1995, Acreman and Hollis 1996). Restoration of the river-floodplain connectivity to enhance fisheries is frequently one of the goals of SWR (Galat *et al.* 1998, Lusk *et al.* 2003). In Brazil, riverine fisheries are an important economic activity (Petrere 1989), but the fisheries are threatened in many rivers due to hydropower development. Hydropower generation accounts for 90% of all electric power produced in Brazil and many more dams will be built to support a steady growing demand for power, which was 5.2% per year during the 1980s and 1990s (ANEEL 2002). To mitigate the negative effects of hydropower development on Brazilian riverine fishes, restocking and, more recently, fish passage have been used to enhance fisheries. To date, these mitigation methods have produced few significant results to restore fisheries. Supplemental water releases have not been used for fisheries restoration in Brazil although many studies have shown this technique can restore floodplains in Africa, North American, and Europe (Acreman and Hollis 1996, Michener and Haeuber 1998, Buijse *et al.* 2002).

5.6.1. What is the best release date?

Water level and physical-chemical variables were significantly correlated in both rivers. The lower correlations in the SFR may have occurred because most of the water came from the TMR hypolimnion where water quality differed from the metalimnion and tributaries downstream (Esteves *et al.* 1985, Sampaio and López 2003). Conductivity and temperature decreased and turbidity increased as water level increased during rains. Because water level was responsible for the changes in the three other variables, the influence of abiotic variables on ichthyoplankton density could be limited to only water level.

Eggs drifting in the SFR and VR showed that spawning occurred near the sampling sites because hatching within 16–22 h is common among the fishes spawning in both rivers (Sato *et al.* 2003). In fact, spawning grounds of two important fisheries species have been located near upstream from the egg sampling site in the SFR, i.e., 1 km for *Prochilodus argenteus* and 23 km for *Pseudoplatystoma corruscans* (Godinho and Kynard pers. obs., Chapter 3). A greater density of eggs drifting in the morning indicated that spawning was most intense during the afternoon, night, and early morning.

Low density of preflexion and flexion stages in the SFR were due to a trapping effect of TMR, which stopped the downstream drift of the ichthyoplankton. Rivers upstream of TMR must carry eggs and larvae into the reservoir because the fish communities in those rivers are similar to the communities found downstream (Sato *et al* 1987, Alves and Vono 1998). However, the ichthyoplankton that drifts into TMR does not reach the SFR because ichthyoplankton density just downstream from TMR is virtually null (Godinho and Kynard pers. obs.). Consequently, most of the preflexion and flexion collected in the SFR come from the Abaeté River, the longest tributary upstream from the ichthyoplankton sampling station. The trapping effect of TMR may also be responsible for the smaller total ichthyoplankton density in the SFR compared to the VR. The greater density of preflexion and flexion in the VR indicated that distant spawning grounds produced more offspring than the spawning sites just upstream from the sample site. Possibly, spawning sites far upstream are more numerous or have a greater abundance of spawning adults. I captured very few postflexion larvae (0.4% in both rivers). This result may be due to fish developing into the postflexion stage only after they moved downstream past my sample sites or because postflexion larvae can avoid the net.

All data support the hypothesis that floods trigger spawning of SFR fishes. Thus, egg density had the highest correlation with water level, peaks of egg density were associated with peaks in water level, egg density increased after a positive water level change, and density of initial early life stages had the strongest cross-correlation with nearby gauging station levels while density of older life stages were most correlated with distant, upstream gauging stations. Spawning during floods is also supported by observations that *P. argenteus* produce mating calls during floods, and pre-spawning *P. corruscans* visit spawning grounds mostly during floods (Godinho and Kynard pers. obs., Chapter 3). Fish spawning during floods was also noticed in a watershed near SFR where most spawning occurred when water levels were increasing (Schubart 1949, 1954).

The positive correlation between increasing egg density and increasing water level also suggests a positive relationship between flood intensity and number of adults that spawn. In rivers where floodplain lakes are the most important nursery grounds for broadcast spawning fish, eggs and larvae have an increased probability of reaching the best nurseries if parents spawn during a major flood. Thus, fish that spawn only during large floods may have a selective advantage. However, a small fraction of the spawning adults spawned during small increases in water level (small floods), conditions where offspring clearly cannot reach floodplain lakes. Survival of offspring is also likely possible in the river, but survival is probably lower because ichthyoplankton density was lower during small floods. Finally, water level fluctuation explains only a fraction of the variation in egg density; therefore, other unknown factors likely influence the number of spawned eggs. There is a great need to examine the relationship between survival of young fish and rearing habitat (river vs. floodplain) in the SFR.

The biological data in the present study suggests the best time for a SWR is when a natural flood is occurring downstream of TMR. Spilling water simultaneously with a natural flood will increase the probability that the combined water level will be high enough to carry the ichthyoplankton produced during natural flood from the river into floodplain lakes. Supplemental water releases at TMR should only be done when a natural flood is happening downstream because normal water releases from TMR do not trigger spawning of SFR fishes.

Spawning by SFR and VR fishes produced a slightly increasing number of drifting eggs from November to early January. Interestingly, the historical frequency of natural flooding gradually increased until early January. Spawning at the beginning of the spawning season reduces the time fish spend waiting for a flood near the spawning ground so they can resume other activities (see Chapters 2 and 3 for details on pre-spawning movements of two SFR migratory fishes). Spawning early in the rainy season may also allow juveniles rearing in floodplain lakes to return to the river in the same rainy season they were born. Juveniles must leave many floodplain lakes to escape desiccation during the 6-month dry season.

My egg and larva data indicated that SWR might be done any time during late November to early February. Other data, however, show that a SWR might be done after early February and even in March. For instance, three important fisheries species spawn in February and one spawned in March (Bazzoli 2003). Also, pre-spawning *P.*

corruscans visited spawning grounds in March (Chapter 3). Natural floods also occur in February and March, although they are not as frequent as in December and January.

5.6.2. How much water will be released?

The SRW volume was mostly determined by maximum discharge and SRW duration. I set the maximum discharge equal to the maximum allowed discharge because TMR discharge plus discharge from tributaries cannot surpass 4,000 $m^3.s^{-1}$ at Pirapora (ONS 2002a) to avoid flooding two harbor patios (ONS 2002b). This means that a SWR with maximum allowed discharge might not be enough to reach the floodplain lakes. In this case, SWR must be used to intensify a natural flood that is occurring downstream of Pirapora, particularly those floods coming from the Paracatu and Velhas rivers, the two biggest tributaries located, respectively, 28 and 114 km from Pirapora.

The larger the SWR the greater should be the increase in fish productivity and harvest. Studies by Welcomme (1976), Welcomme and Hagborg (1977) and Petrere (1983) indicate that fisheries yield in floodplain rivers is directly related to the area of the floodplain. Thus, flooding a large floodplain area would result in greater recruitment than flooding a smaller floodplain area. This justifies the use of maximum allowed discharge (or even larger, if possible) during SWR, even if discharges of that intensity were historically rare events at Pirapora. The use of maximum allowed discharge, does not guarantee yield increase because there is no available data that would enable me to determine the relationship between discharge and area of the floodplain actually flooded. Therefore, determining this relationship is vital for planning and evaluating any SWR strategy.

The SWR should last enough time to increase fisheries yield. Short-term SWR will cause less lost revenue, but may also result in limited fisheries benefits because of flooding a small area. The two last large natural floods in the SFR, which happened in 1979 and 1992, were famous for significant increased catch afterwards and they each lasted a few weeks.

The best scenario is that a natural flood plus a SWR would reach the great floodplains of the SFR in Bahia located upstream of the Sobradinho Reservoir. These floodplains are up to tens of kilometers wide (Sato and Godinho 2003). The presence of young fish in floodplain lakes is known for several regions of the basin (e.g., Braga 1964, Sato *et al.* 1987, Pompeu and Godinho 2003), but the reports described in Menezes (1956) on fish abundance in the Bahia floodplains lakes are unique for the basin. All information indicates these are the most extensive and important nursery grounds in the whole basin. Flooding these lakes will likely multiply the benefits of a SWR. In my study, I did not consider the dampening of the SWR wave as it moves downstream. There is a need for a hydraulic model of the SFR that would enable managers to predict the SWR needed to flood the Bahia floodplains.

5.6.3. What is the pattern of impoundment and how much impounded water will be released?

Although TMR inflow usually increases in October with the onset of the rainy season, the reservoir showed mean positive water accumulation only after November. That happens because TMR is used to avoid a downstream flood greater than the maximum allowed discharge. Therefore, its operating rule foresees the onset of reservoir filling in the second half of December (ONS 2002a).

The volume of water impounded by TMR during the fish spawning season had great year to year variation. For a long-term SWR, the released volume can be greater than the impounded volume until January. Moreover, it can be a large percentage of the live storage, especially in November and December. Because TMR impounds water during the entire spawning season, SWR is more feasible during the second half of the spawning season.

Two consecutive SWRs may be necessary to allow fish reared in floodplain lakes to return to the river and recruit into the riverine population. Biological data are needed to determine when a second SWR is appropriate and a hydraulic model is needed to determine the magnitude of SWR that is needed. During most years, TMR impounds enough water for two short-term SWRs in the same spawning season, but not for two long-term SWRs. For long-term SWRs, it will likely only be possible to have one per spawning season.

Change in the TMR operating rule should be evaluated in order to guarantee enough water for SWR. Such a change would mean filling the reservoir earlier or at a faster pace than predicted by the operating rule. If that is possible, a SWR might bring a secondary benefit to the local fishery. Godinho (1994) suggested that one reason for the low fish yield in TMR is the low offspring survival because of a mismatch between fish spawning and water level. Filling up TMR early might increase offspring survival as occurred in Cajuru Reservoir located upstream of TMR (Alves 1995).

5.6.4. What is the lost revenue to the power plant associated with SWR?

Lost revenue due to a SWR, which I estimated ranged from US$ 0.493 million to US$ 8.056 million, is important to any decision regarding use of SWR as a fisheries management mitigation. Lost revenue did not show remarkable differences among months because mean hydraulic head did not vary greatly (range, 48.7–54.9 m). Lost revenue for a SWR in March, the month with the highest hydraulic head, would be 13% greater than in November, the month with the lowest hydraulic head. This means that lost revenue would be mostly determined by power rate, maximum discharge, and SWR duration.

5.6.5. What is the relationship between SWR and fisheries value?

Even though *R* might be large at first glance, particularly for the combination of a long-term SWR and greater power rate, the economic benefits of SWR may surpass *R*. I estimate that commercial fishery annual income had declined from US$ 6.078 million to US$ 1.610 million because of fisheries collapse.

The US$ 4.468 million decrease in the annual fishers' income is, at the present time, the best possible forecast of the income increase that might result from a SWR. In this case, my premise is that SWR will be able to increase fishery yield back to the levels of late 1980s. Compared to *R*, the forecast is greater than all except for that of the 7- and 8-day SWR at \$ = US\$ 30.00, and for SWR ≥ 5 days at \$ = US\$ 42.00.

Previous estimates of fishery income do not accurately reflect the actual income because they do not incorporate the entire value of the fisheries. For instance, they do not include the income of the commercial fishery in Bahia or the income of the recreational fishing and fisheries tourism industries. The calculations also did not consider the non-monetary benefits of the subsistence fishery that occurs along the whole river. What the estimates really show is that SWR must be seen as an investment in the river's fisheries resource and the people who earn a living from the river and that a SWR is not just lost revenue of an electricity generating plant. This investment can improve the quality of life for the families of thousands of commercial fishers that have suffered impoverishment and social exclusion after the fishery collapse in the 1990s (Valencio *et al.* 2003).

Table 5.1. Spearman correlation matrix of egg density, water level at three gauging stations (Pirapora, TM = Três Marias, and Abaeté), conductivity (Cond), turbidity (Turb), and temperature (Temp) in the São Francisco River. Gauging station distance to the ichthyoplankton sampling site is given. Abaeté gauging was located in the Abaeté River and the two other gauges were in the São Francisco River. Mean daily values were used to calculate correlation coefficient for egg density, conductivity, turbidity, and temperature. All coefficients with $P \leq 0.001$ except NS, which was not significative.

Variable	Pirapora	TM	Abaeté	Cond	Turb	Temp
Egg	0,40	NS	0,42	-0,46	0,43	-0,50
Pirapora (25 km)		0,28	0,53	-0,56	0,52	-0,70
TM (150 km)			-0,27	NS	NS	NS
Abaeté (152 km)				-0,65	0,60	-0,64
Cond					-0,83	0,68
Turb						-0,64

Table 5.2. Spearman correlation matrix of egg density, water level at four gauging stations (Guacuí, VP = Várzea das Palmas, Licinio, and Paraúna), pH, conductivity (Cond), turbidity (Turb), and temperature (Temp) in the Velhas River. Gauging station distance to the ichthyoplankton sampling site is given. Paraúna gauging station was located in the Paraúna River and all others were in the Velhas River. Mean daily values were used to calculate correlation coefficient for egg density, conductivity, turbidity, and temperature. All coefficients with $P < 0.0001$.

Variable	Guacuí	VP	Licinio	Paraúna	Cond	Turb	Temp
Egg	0,51	0,50	0,49	0,54	-0,38	0,39	-0,50
Guacuí (-3 km)		0,94	0,87	0,76	-0,79	0,79	-0,86
VP (65 km)			0,91	0,82	-0,78	0,82	-0,83
Licinio (281 km)				0,74	-0,76	0,74	-0,78
Paraúna (292 km)					-0,53	0,62	-0,66
Cond						-0,76	0,75
Turb							-0,68

Table 5.3. Strongest cross-correlation between daily mean density of the ichthyoplankton life stage and water level at gauging stations in the São Francisco and Velhas basins. The day of the strongest coefficient of correlation is shown within parenthesis. Distance downstream to the ichthyoplankton sampling site is presented for each gauging station. All gauging station in the mainstem except those marked with asterisk which were in the first biggest tributary upstream of the ichthyoplankton sampling site.

Gauging station and distance	Early life stage			
	Egg	Yolk-sac	Preflexion	Flexion
	São Francisco			
Pirapora (25 km)	0.28 (0)	0.28 (1)	0.32 (2)	0.45 (3)
Três Marias (150 km)	0.19 (0)	0.18 (0)	0.02 (3)	-0.28 (1)
Abaeté (152 km)*	0.18 (0)	0.28 (0)	0.42 (2)	0.38 (3)
	Velhas			
Guacuí (-3 km)	0.42 (0)	0.30 (0)	0.38 (2)	0.23 (7)
Várzea das Palmas (65 km)	0.37 (0)	0.26 (0)	0.37 (2)	0.12 (6)
Paraúna (281 km)*	0.33 (0)	0.22 (1)	0.38 (3)	0.17 (7)
Licinio (292 km)	0.31 (0)	0.19 (0)	0.42 (1)	0.09 (5)
Raul Soares (499 km)	0.32 (0)	0.17 (1)	0.41 (3)	0.14 (7)

Table 5.4. The volume of water released from Três Marias Reservoir during supplemental water released (SWR) of various durations.

SWR duration (days)	Volume of water released (km^3)
2	0.380
3	0.682
4	0.984
5	1.286
6	1.588
7	1.890
8	2.192

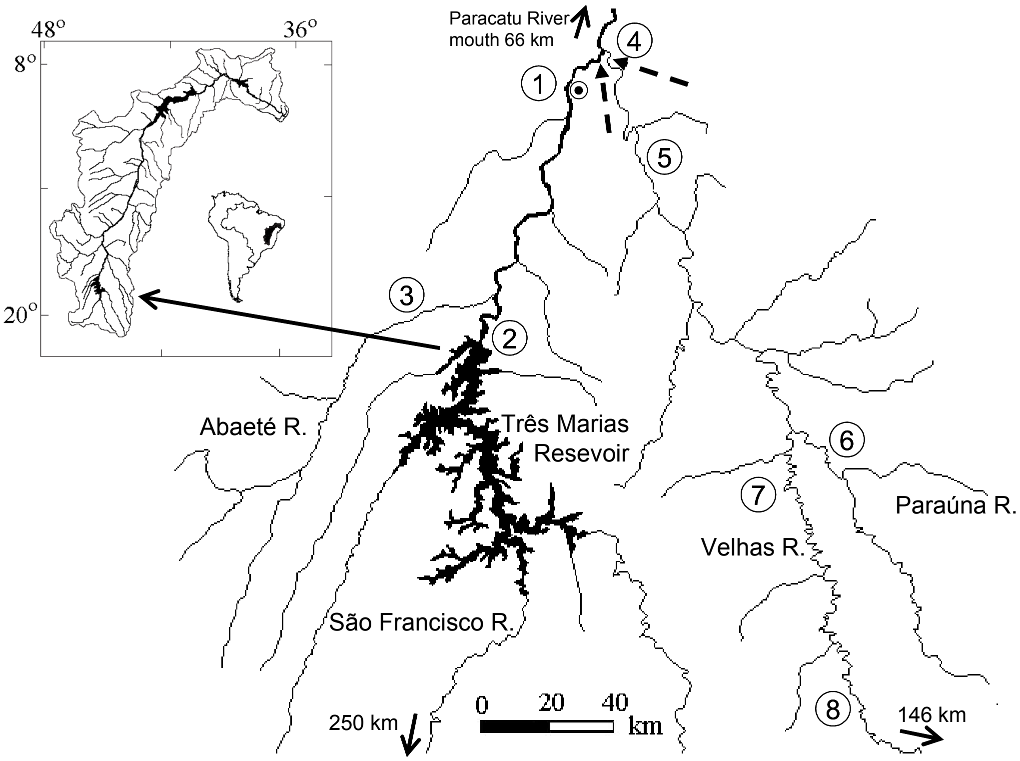


Figure 5.1. Map of the São Francisco and Velhas rivers upstream of the ichthyoplankton sampling sites (dashed arrows). Locations of gauging stations are indicate by numbers (1 = Pirapora, 2 = Três Marias, 3 = Abaeté, 4 = Guacuí, 5 = Várzea das Palmas, 6 = Paraúna, 7 = Licinio, 8 = Raul Soares) and location of Pirapora city by⦿. Distance to the headwater is shown for São Francisco and Velhas rivers. Insert shows the entire basin and its location in the South America.

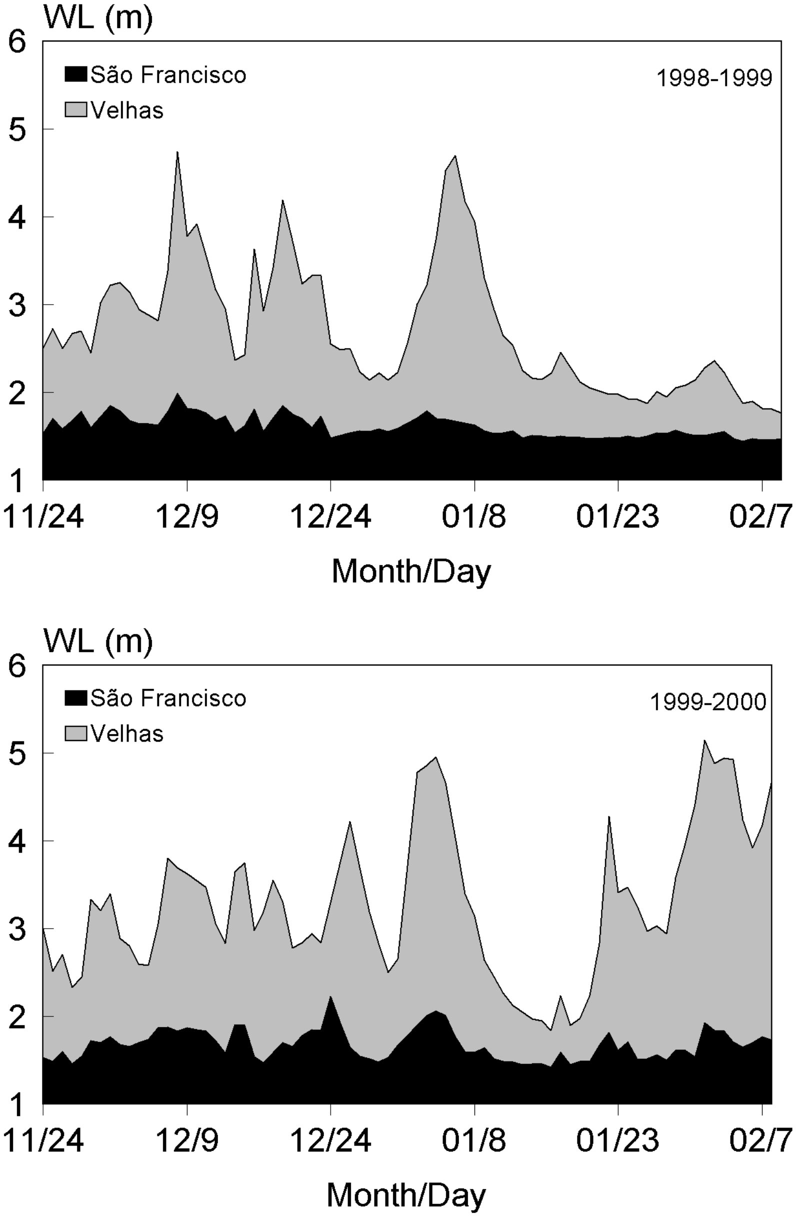


Figure 5.2. Daily water level (WL) in the São Francisco and Velhas rivers from late November to early February during two consecutive spawning seasons (1998–1999 and 1999–2000).

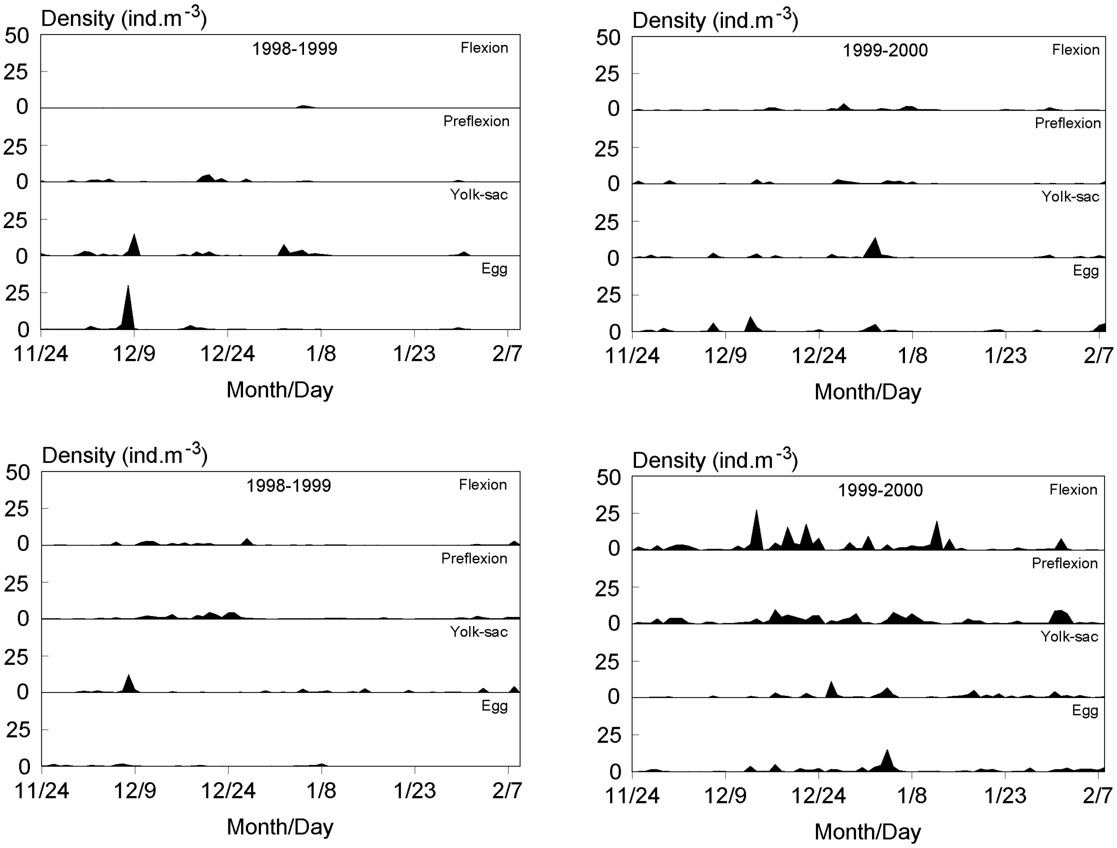


Figure 5.3. Daily mean density of ichthyoplankton life stages in the São Francisco (top panel) and Velhas (bottom panel) rivers during two consecutives spawning seasons (1998–1999 and 1999–2000).

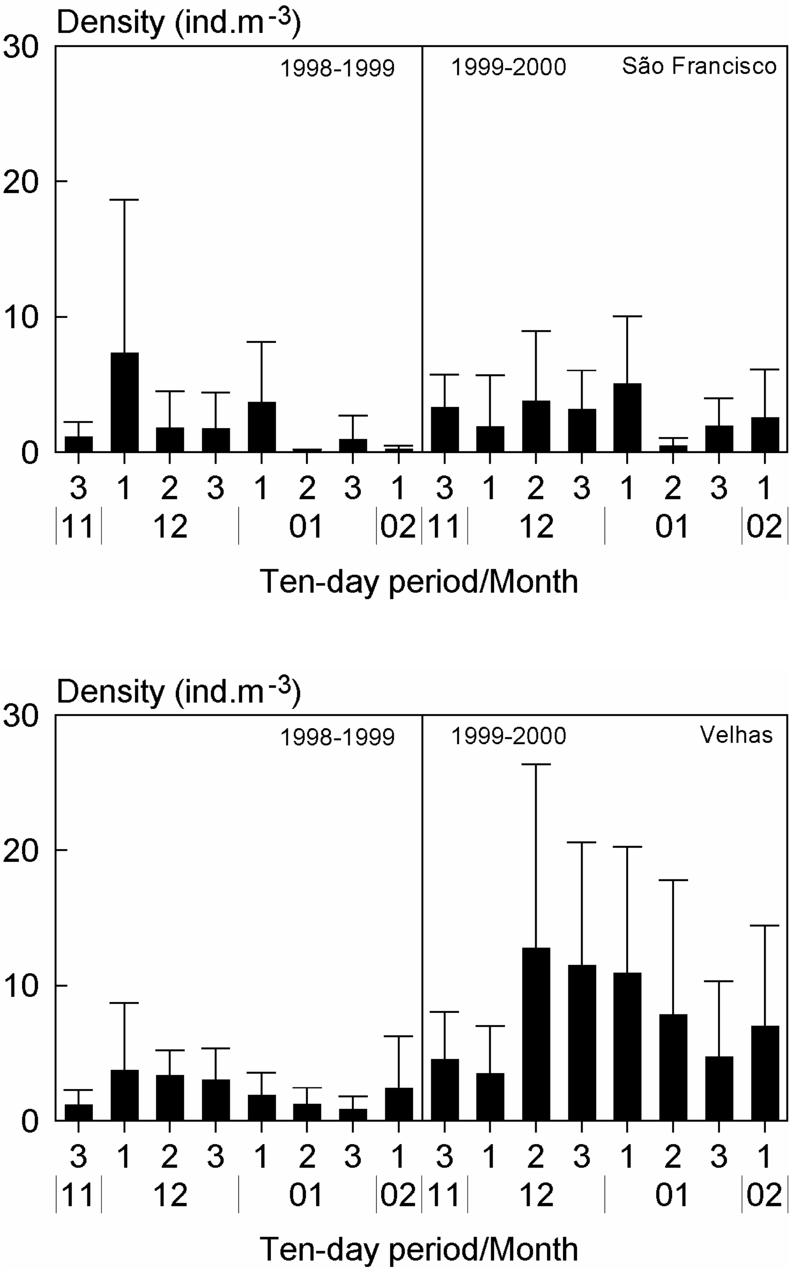


Figure 5.4. Mean and one standard deviation of total ichthyoplankton density in the São Francisco and Velhas rivers from late November to early February during two consecutive spawning seasons (1998–1999 and 1999–2000). Ten-day period comprises: 1 (day 1–10), 2 (day 11–20), and 3 (day 21–31).

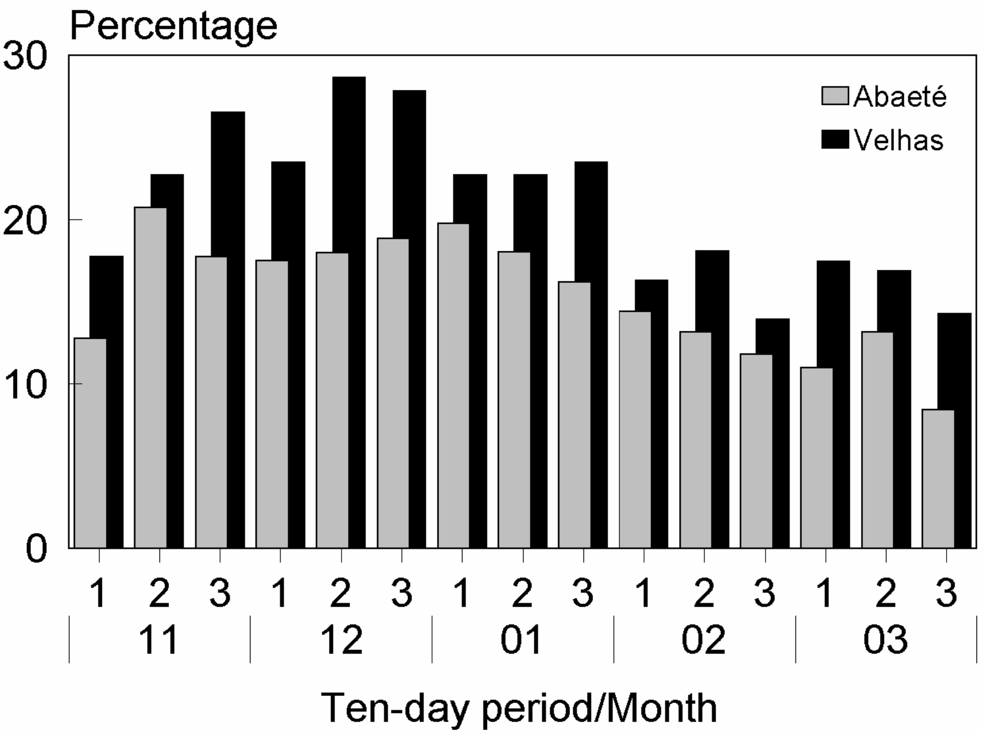


Figure 5.5. Percentage of days with flood (water level at any day at least 20 cm greater than the day before) from November to March in the Abaeté and Velhas rivers. Ten-day period comprises: 1 (day 1–10), 2 (day 11–20), and 3 (day 21–31). Historical data series cover 1963–2003 for the Abaeté River and 1938–2003 for the Velhas River.

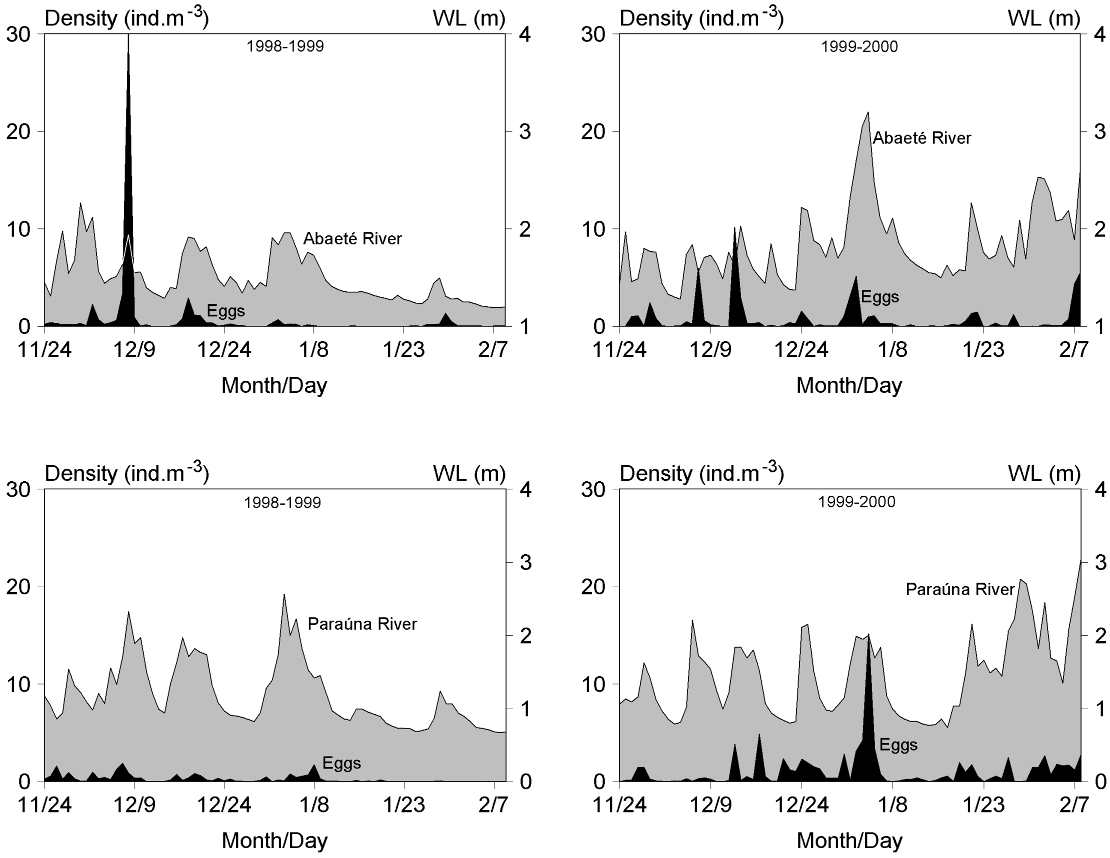


Figure 5.6. Daily mean egg densities in the São Francisco (top panels) and Velhas (bottom panels) rivers near their junction and the daily water level (WL) in the biggest upstream tributary from late November to early February during two consecutive spawning seasons (1998–1999 and 1999–2000).

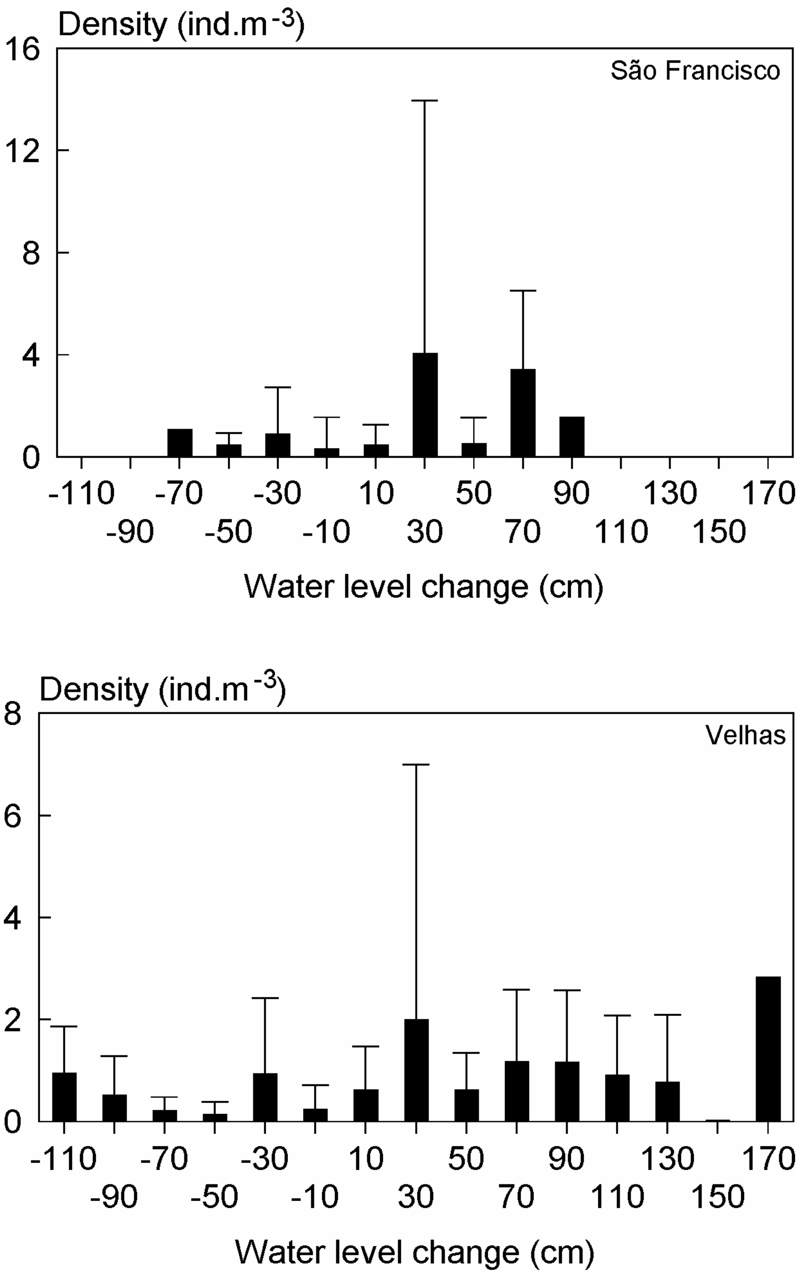


Figure 5.7. Mean and one standard deviation of egg densities in the São Francisco and Velhas rivers near their junction. Water level change is the 24-hour variation in the biggest upstream tributary.

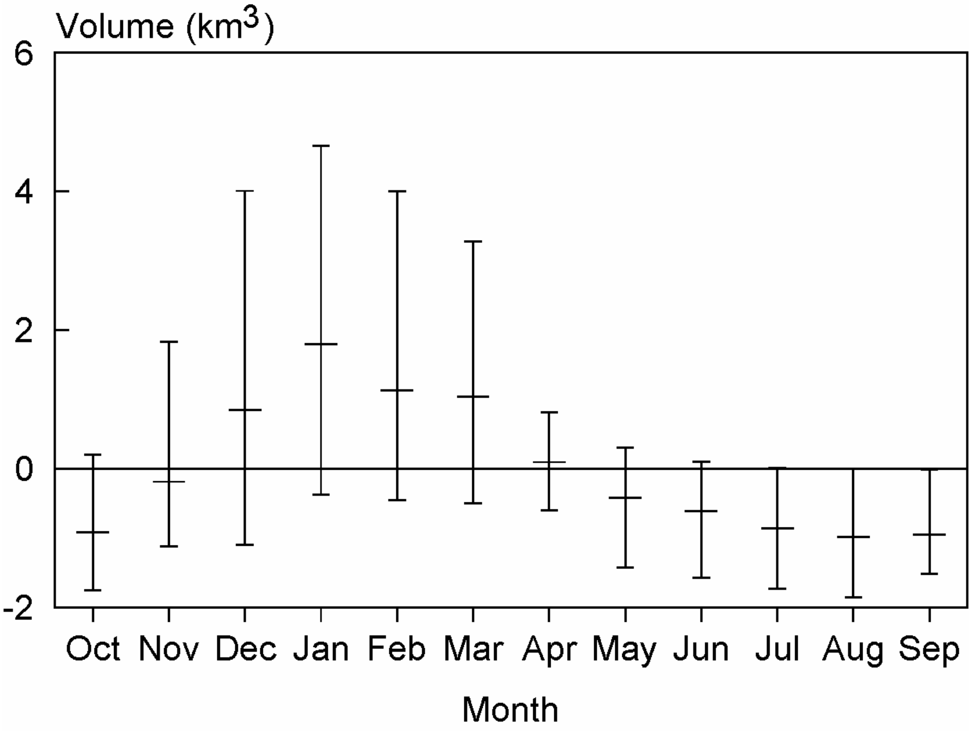


Figure 5.8. Monthly volume of water (mean and range) impounded by Três Marias Reservoir, 1976–2003.

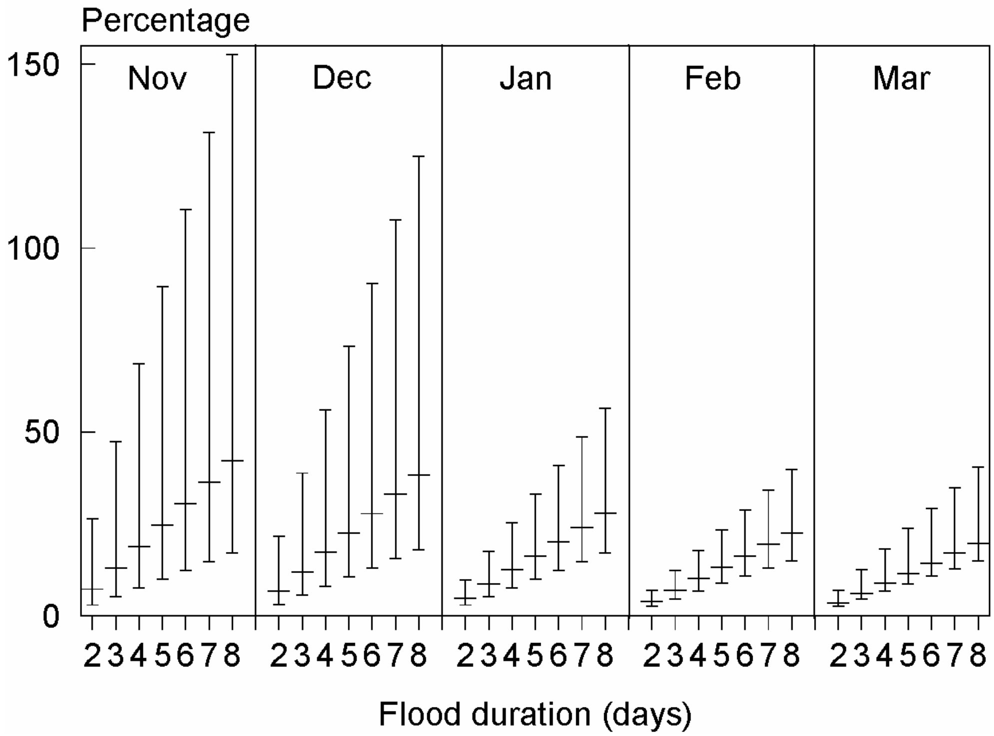


Figure 5.9. Percentage of the flood volume (mean and range) in the daily live storage of Três Marias Reservoir for flood duration of 2–8 days in November to March. Live storage data covers 1976–2003.

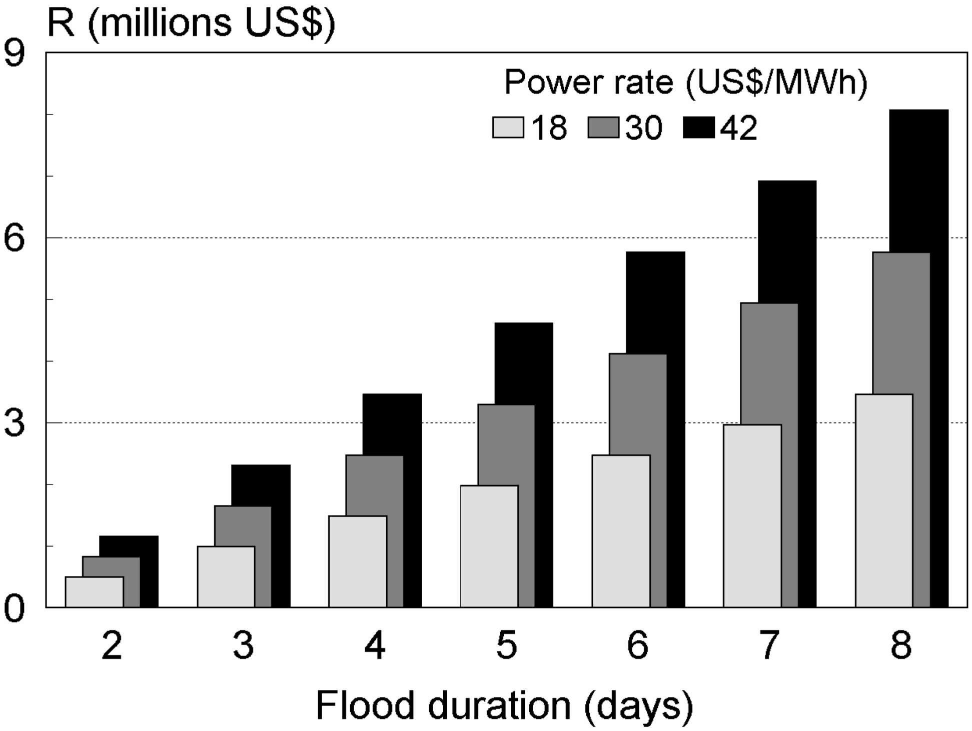


Figure 5.10. Três Marias power plant lost revenue (*R*) due to supplemental water releases for durations of 2–8 days and three power rates.

CHAPTER 6

CONCLUSIONS

In Chapter 2, I concluded that the Pontal area at the Abaeté River mouth was the dominant spawning area for curimbatá in 129 km of river mainstem downstream of TMD. Pre-spawning adults staged upstream of the Abaeté River mouth and moved back and forth during short visits to Pontal until spawning cues from a flooding Abaeté River were present. Migratory style of curimbatá was dualistic (resident and migratory) and home range was 1–127 km. Some fish homed to pre-spawning staging areas, spawning areas, and non-spawning areas. Location of spawning areas and home ranges suggest the Pontal group (which likely includes Cilga fish) is one population that occupies about 110 km. The Pontal population overlaps for a short reach with another population located downstream. Movements of late-stage TM adults suggest the TM group is a separate population, possibly with connections to populations upstream of TMD.

In Chapter 3, I concluded that surubim migration was dualistic with resident and migratory fish. Pre-spawning fish migrated at ground speeds of up to 31 km day-1. Pre-spawning migration was in early October to late December to pre-spawning staging sites located 0–11 km from the spawning ground. The most important spawning ground was in the mainstem at PR, 129 km downstream of TMD. During the spawning season (November–March), surubims made a short distance migration (spawning migration) from the pre-spawning staging site to visit (a short period stay, mostly $\leq$ 2 days) the PR spawning ground. Surubim visited the PR spawning ground multiple times (spawning-site homing) generally during floods. After a visit, some surubims returned to the same pre-spawning staging site (pre-spawning staging-site homing). Most post-spawning surubims left the spawning ground, but some stayed until the next spawning season (dualistic migratory pattern). Migration of post-spawning fish (non-spawning migration), which occurred from early January to early March, were up- or downstream with fish swimming at ground speeds up to 29 km day-1. Dualistic migration also occurred during the non-spawning season resulting in small (< 5 km, 63% of tracked fish) and large (> 60 km, 26%) home ranges. A few surubims returned the following spawning season to spawn at the same site (spawning-site homing). Construction of planned dams downstream from TMD will greatly reduce surubim abundance, the most valuable commercial and recreational São Francisco River fish. Fish passage structures for surubim at TMD should not be developed as this time because upstream passage for bottom-oriented fish and downstream passage are not adequately addressed. The permanent prohibition of fishing at PR should be enacted during floods to reduce conflict between law enforcement and fishers, and to maximize the cost-benefits of law enforcement.

In Chapter 4, I concluded that movements and thermal fluctuations experienced by curimbatás and surubims showed they are eurythermal species with a broad short-term temperature variation tolerance. The behavioral drive to move to a functional habitat was stronger than the preference for warmer water. I also concluded that water discharged from dams that is < 5°C cooler than ambient river water will not disrupt migrations of surubim and curimbatá. This information provides guidance on the level of acceptable thermal change for Brazilian fishes that live in rivers with similar short- and long-term thermal amplitudes.

In Chapter 5, I concluded that there was a clear positive relationship between fish spawning, as indicated by egg and larval fish densities, and water level in the SFR. While the relationship between water level and the area of floodplain that results from a flood and the subsequent fish recruitment is not known, I concluded the best date for release is when there is a natural flood, which naturally triggers fish spawning and the SWR will add to the natural flood and cover the greatest floodplain area. The released volume will range from 0.302 km^3 to 2.192 km^3, depending on SWR duration. The TMR usually impounded enough water for SWR only in the second half of the fish spawning season (January–March). Lost revenue at TMR depended on release volume and ranged from US$ 0.493 million to US$ 3.452 million for the actual power rate. However, SWR could increase commercial fisheries income an estimated US$ 4.468 million. I forecast that SWR can bring fisheries benefits that surpass the lost revenue.

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