

Chapter 5.1

Description of the Mandena Aquatic Ecosystem

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Abstract

QMM plans to mine ilmenite ore near a chain of estuarine lagoons close to Tolagnaro in southeastern Madagascar. The majority of the incomes of about one hundred local families come from catching fish and crustaceans in these lagoons. The current catch level by fishermen of the lagoons is about 33 tons per year. The mining plant operation will require 72000 m³ of freshwater per day. A dam will be built at the outlet of this freshwater aquatic system to stop the inflow of saltwater. The lagoons are currently under a fluctuating salinity regime, with a range from 0 to 35.7 ppt. The water depth in most areas is 2 to 3 m, the water is nutrient poor, and the abundance of most aquatic species is low. In their current natural state, the lagoons offer poor habitat conditions for both freshwater and marine fish species, which show slow growth rates as a result. Nutrients are occasionally washed out of the lagoons when high flow conditions in the rivers after heavy rains break the sand bar, which usually separates the lagoons from the sea. After the dam is built, the lagoons will become strictly freshwater and the loss of nutrients to the sea will be much slower. A higher retention of nutrients, together with partial water-level control in the lagoon should improve fish habitat for cichlids, especially those of the genus *Ptychochromis*, which are endemic to Madagascar. About 50 species of fish are known from the lagoons, and about half of these are expected to inhabit the site after it becomes strictly freshwater. Euryhaline species, which currently migrate into the lagoons, will congregate below the dam. A lock in the dam will allow the passage of diadromous fish in and out of the lagoon.

Résumé

Description de l'écosystème aquatique de Mandena. La compagnie minière QMM exploitera un gisement d'ilménite à Tolagnaro au sud-est de Madagascar à proximité d'un complexe lagunaire de type estuarien. Une centaine de familles de pêcheurs tire une grande partie de leurs revenus des captures de poissons et crustacés dans ces lagunes. Les captures effectuées par les populations de pêcheurs riveraines dans le complexe lagunaire sont d'environ 33 tonnes par an. L'exploitation minière nécessitera l'utilisation de 72000 m³ d'eau douce par jour. La construction d'un seuil-déversoir est prévue à la sortie du système lagunaire pour empêcher la remontée de l'eau salée. Le complexe lagunaire est une zone à salinité instable de 0 à 35,7‰, dont la profondeur la plus fréquente varie de 2 à 3 m, faible en éléments nutritifs et avec des abondances spécifiques réduites. Ce milieu peut être qualifié de peu productif. Dans le système lagunaire actuel, ni les espèces de poissons d'eau douce, ni les espèces de poissons d'eau saumâtre ou salée ne rencontrent des conditions de croissance optimales. Le complexe lagunaire actuellement saumâtre deviendra strictement dulcicole après la construction du seuil. Le seuil déversoir permettra de réduire de façon significative le lessivage des éléments nutritifs que subit actuellement le complexe lagunaire lors des ouvertures sporadiques

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et brutales du cordon littoral. Les ciclidés et tout particulièrement *Ptychochromis* spp., poissons endémiques de Madagascar, bénéficieront de la nouvelle situation. Sur la cinquantaine d'espèces euryhalines de poissons actuellement présentes dans les plans d'eau plus de la moitié pourrait continuer à coloniser les lagunes devenues strictement dulci-coles. Ces espèces euryhalines de poissons remontant actuellement la rivière Anony, seront concentrées en aval du seuil. Une écluse aménagée dans le seuil-déversoir permettra le passage des poissons aussi bien vers l'amont que vers l'aval.

Introduction

QIT Madagascar Minerals (QMM) is prepared to commence the mining of an ilmenite layer along the southeastern coast of Madagascar, near Tolagnaro (Fig. 1). There are a number of lakes and rivers in this zone in addition to the main water bodies near the future mining plant, which comprise 500 to 1046 ha, depending on seasonal variations in water levels (Table 1).

The mining operations will require freshwater to be pumped from the lagoons. In order to keep Lake Ambavarano, Lake Besaroy, and the Mandromondromotra River free from saltwater intrusion, a dam will be built in the estuary of the Anony River. In the current natural state of this aquatic system, Lake Lanirano is freshwater and the Anony River discharges into the sea. Intermediate conditions occur in Lake Besaroy and Lake Ambavarano, where water changes from fresh to brackish depending on the location of the salt wedge. Building a dam and spillway will change all the lakes and rivers upstream to strictly freshwater conditions.

Local fishermen get 86% of their income from fish and shellfish caught in the lagoons and sold in local or regional markets (CSSA 2001). Continued studies of the lagoons and their fisheries resources started in 1990. Most estuaries and fluvial lagoons provide sufficient fisheries due to fish migration. However, this does not seem to be the case for the chain of lagoons in Mandena, where productivity seems to be low because of a steady loss of nutrients to the sea.

Studies have been done with the objective of describing the current state of the aquatic system, and anticipating what changes will occur after the construction of the dam/spillway. These aspects have subsequently been integrated into an optimization plan, with the intent, in part, of improving the economic conditions for fishermen and their families.

Methods

Abiotic parameters

Biotic and abiotic parameters of the Mandena aquatic systems were surveyed in the year 2000. Data have been collected for physical and biological diagnoses of the Mandena lagoons twice during the year 2000: during the wet season in May and June, and during the dry season in September and October.

A total of 54 depth transects were made on the Mandena aquatic systems (Fig. 1) with a Raytheon DE-719B echo sounder, an Odom Digitrace DT-2H-MS precision sounder, a Sokkia SET4BII station, a triple beam reflector, and a Garmin 12XL GPS with the Surfer software. The number of transects made on each of the following five water bodies are as follows: Lake Ambavarano: 7 transects; Anony River: 6

Table 1. Average and high water surface area of the lagoons and connecting rivers (Réville *et al.* 2004).

Water bodies	Area (ha)		
	Average water level	High water level	Flood plain
Anony River	73	119	46
Mandromondromotra River ¹	19	112	93
Lake Ambavarano	257	283	26
Lake Besaroy (Besaroya)	76	185	109
Andalambemboalavo River ²	50	179	129
Lake Lanirano	99	168	69
Total	574	1046	472

¹Area estimated for the first 3 km from the lake.

²The area of the main channel is 29 ha at average water level. The area of secondary channels is about 21 ha. This is the stretch of meandering river between Lake Lanirano and Lake Besaroy.

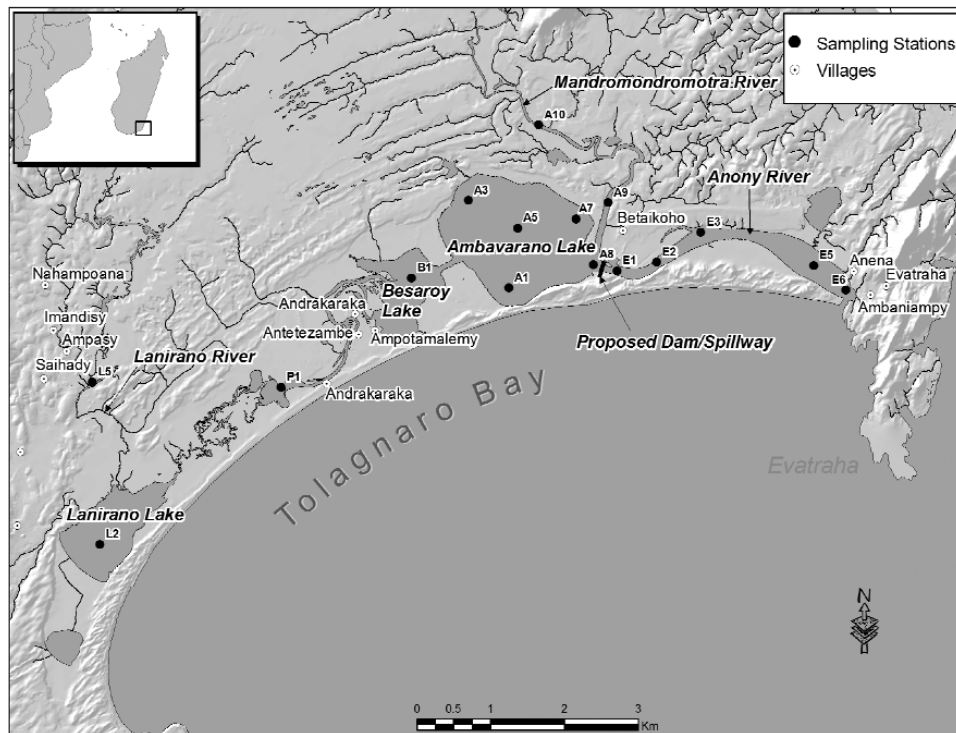


Figure 1. The Mandena lagoons with principal sampling stations.

transects, with the last one downstream at the expected location of the dam; Lake Lanirano: 14 transects; Lake Besaroy: 15 transects; and Mandromondromotra River: one lengthwise transect, in the center of the river, and 12 transects across the river from the outlet and moving upstream. The first nine were at every 100 m, and the last three at every 500 m.

Water level data were collected with recorders from March to September of 2000 on the Anandrano, Mandromondromotra, and Anony Rivers. River flow was estimated at least once every month, and at shorter intervals in high flow conditions. Height of the water table was measured every month in a network of wells. Periods when the sand bar blocked the estuary were noted.

Some chemical data were collected in the field with an YSI 57 dissolved oxygen probe, a Beckman RS-5-3 salinity probe, a Secchi disk, and a pH meter. Samples were analyzed in the laboratory for total suspended solids and nutrients (dissolved nitrogen and phosphorus). Five freshwater stations were chosen for chemical data collection, which were located from the upstream section of Lanirano River to the

inlet of Lake Besaroy, and in the upper part of Mandromondromotra River. Sampling was done from March to October of 2000.

Samples were collected at 17 stations in the brackish part of the system, from Lake Besaroy to the outlet of the Anony River, and in the lower part of the Mandromondromotra River. Changes in salinity and dissolved nutrients were monitored during the rainy season in May at three stations in the estuary. Values for these parameters are averages. Salinity and nutrients were also monitored at ten marsh stations, mostly in the freshwater part of the system (Fig. 1).

Biological characteristics

Vertical tows were made with plankton nets at 19 stations. The net ring was 0.5 m in diameter. Two mesh sizes were used: 250 μ and 64 μ . Two stations were in freshwater while the others were in brackish habitat from the outlet of the Anony River to Lake Besaroy, and in the lower section of the Mandromondromotra River. Benthos samples were

collected at 40 stations with a Ponar dredge sample size of 0.05 m² in three separate years: 1992, 2001, and 2003. Organisms in the samples were extracted on 500 µ sieves, fixed with buffered formalin, and dyed with eosin B. Benthos identification was done in the laboratory. Ponar dredge samples taken at 40 stations in 1989 and 2000 provided data on aquatic plants and algae.

Fish and fisheries

Data on fish in the ecosystems were collected from three different sources. Gillnets used for sampling were 99 m long and 2 m high. They had three 33 m long sections with 2, 3, and 4.5 cm mesh. They were made of three kg-test nylon monofilament. These nets were set at each station for 24 hour periods. Four separate gillnet fishing sessions were made in 2005 during 40 days of fieldwork — two during the rainy season (June to August), and two during the dry season (October and November). Thus, the total fishing time at each gillnet station was 96 hours.

Nine gillnet stations were located upstream of the planned dam, and one downstream. They were distributed as follows: Lake Lanirano: 3 stations, Lake Besaroy: 2 stations, Lake Ambavarano: 3 stations, Mandromondromotra River: 1 station, and Anony River: 1 station. The gillnet catch was sorted by species. Weight, up to 20 kg, and length of each specimen were recorded. Stomach contents analysis was done on the largest fish. Fish samples were also collected in the estuary in 1989 and 2000.

A weigh station was set up in which passing women transporting fish were asked about the market value of their various catches, and these prices were paired with fish of the corresponding weight obtained in the gillnet catches. The survey covers the catch made in more than 2000 fisherman days during 2005. Data on fishing activities

were collected through surveys and interviews with local fishermen. From 2001 to 2004, 15 meetings were held with the different fishing communities. Additional data were collected from fishermen living near the lagoons.

Results

Abiotic parameters

Lake Besaroy is the shallowest part of the aquatic ecosystem, with a depth of 2.5 m across much of this zone. The maximum depth in Lake Ambavarano and the Anony River, up to station E1, does not exceed 3.0 to 3.5 m. The deepest parts of the whole system were in the channels connecting the lakes and rivers, with depths of 5 m being recorded between Lake Besaroy and Lake Ambavarano, and in the Anony River. The average depth of the Mandromondromotra River was 3.6 m, and the maximum was 8 m in the eastern section of the river close to a bedrock outcrop (Table 2).

Heavy rains generate significant changes in average water flow in Lanirano River (Fig. 2) and sudden rises in the water level. For example, a 1.3 m rise was recorded there in 15 days between June and July 2000, while the Anony River increased by only 0.4 m during the same period. High water conditions due to rainfall may occur within a short period of time.

In reduced flow conditions during the dry season, a sand bar emerges at the outlet of the Anony River limiting, and sometimes blocking, the flow of freshwater into the sea. Under these conditions, some mixing still occurs in the estuary and the water remains brackish upstream from the sand bar. During the dry season, the salt wedge in the Mandromondromotra River goes further upstream.

The sand barrier is built by the action of waves and currents traveling along the coast. Sand particles

Table 2. Depth of different parts of the Mandena aquatic ecosystem (Water Management Consultants 2001); N.D.: not determined.

Water body	Maximum depth (m)	Average depth (m)	Increase of water level (m) in high water condition
Anony River	5.0	N.D.	0.4
Mandromondromotra River	8.0	2.0	N.D.
Lake Ambavarano	3.0 to 3.5	2.0	N.D.
Lake Besaroy	2.5	2.0	N.D.
Andalambemboalavo River	5.0	N.D.	N.D.
Lake Lanirano	4.5	3.0	1.3

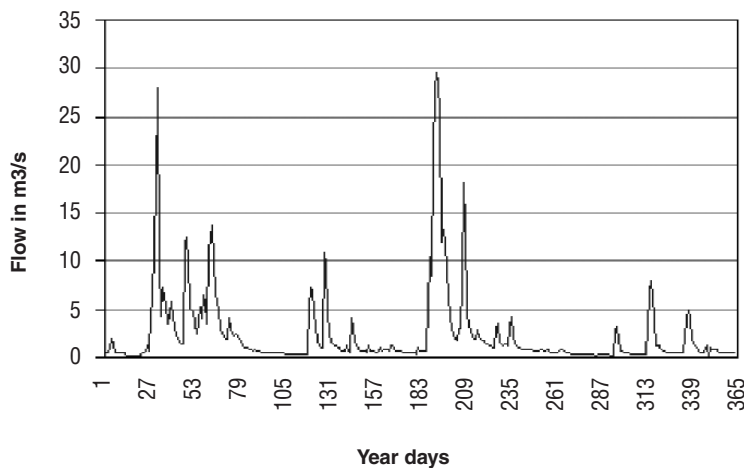


Figure 2. Changes in average water flow in Lanirano River in 2001.

Table 3. Range values of some physical and chemical parameters in sections of the Mandena aquatic ecosystem (CSSA 2001).

Parameter	Lakes and Rivers			Estuary				Marshes
	Andalam-bemboalavo River	Mandromon-dromotra River, upstream part	Lake Lanirano	Lake Besaroy	Lake Ambavarano	Mandromon-dromotra River, downstream part	Anony River	Stations MC-1 to MC-7
Salinity (%)	0.0-0.8	0.0-0.4	0.0-0.8	0.7-18.4	2.2-30.7	0.30-29.8	8.9-35.7	0.04-1.6
Temperature (°C)	22.9-23.8	22.9-23.2	22.8-23.7	22.7-26.8	21.3-28.2	21.3-27.8	22.2-27.7	20.0-25.0
Dissolved oxygen (mg/l)	5.4-8.2	5.4-8.8	7.6-9.8	6.6-8.9	3.4-9.8	2.2-9.4	6.6-10.0	0.9-9.0
Secchi reading (m)	0.5-1.9	0.9-1.0	0.8-1.0	1.1-1.5	0.5-2.6	1.1-2.6	1.0-3.1	N.D.
Depth at sampling site (m)	1.5-2.9	1.0-1.9	1.0-3.0	2.8-2.9	1.3-2.8	2.0-3.0	1.0-3.1	N.D.
pH	6.2-7.4	6.7-6.9	7.4-7.9	7.4-7.9	7.6-8.3	6.0-8.2	7.6-8.8	4.1-6.7
Nutrients	Low	Low	Low	Low	Low	Low	Low	Low
Suspended particles (mg/l)	< 6	<	<	<	< 16	< 5	< 110	< 89
Total organic carbon (%)	< 2.5	< 0.4	< 8.4	3.2-3.9	< 5.3	0.3-4.8	< 4.3	N.D.

settle in the estuary because the river flow is not strong enough to break through the barrier, especially for the period of two to six weeks during the dry season (July to November) when river flow drops below 2 m³/second. Complete blocking of the outlet by the sand bar also occurs at times during the year, but usually for shorter periods.

Generally, fresh and brackish water temperatures show greater fluctuations than that of the neighboring seawater. Both freshwater and seawater are warmer during the rainy season. The temperatures of surface water and wells are very similar during the dry season (Table 3).

Higher values of dissolved oxygen were recorded at the outlet of the lagoon system. Maximum

dissolved oxygen was 10 mg/l in the Anony River, with values decreasing as the distance of the stations from the estuary increased. A maximum of 8.2 mg/l was measured in Lake Lanirano (Table 3). Freshwater was slightly acidic (pH 6.2) and seawater basic (pH 8.8). The range of total suspended particle values goes from undetectable to 110 mg/l, and volatile total particles from undetectable to 6 mg/l. Secchi disk could be seen down to the bottom of all lakes and rivers all year long.

Salinity in the Anony River changed with depth, and the higher salt content was measured near the bottom. During a tide cycle, salinity fluctuated between 6 and 10 ppt in the first meter below the surface, and between 32 and 34 ppt in the first meter

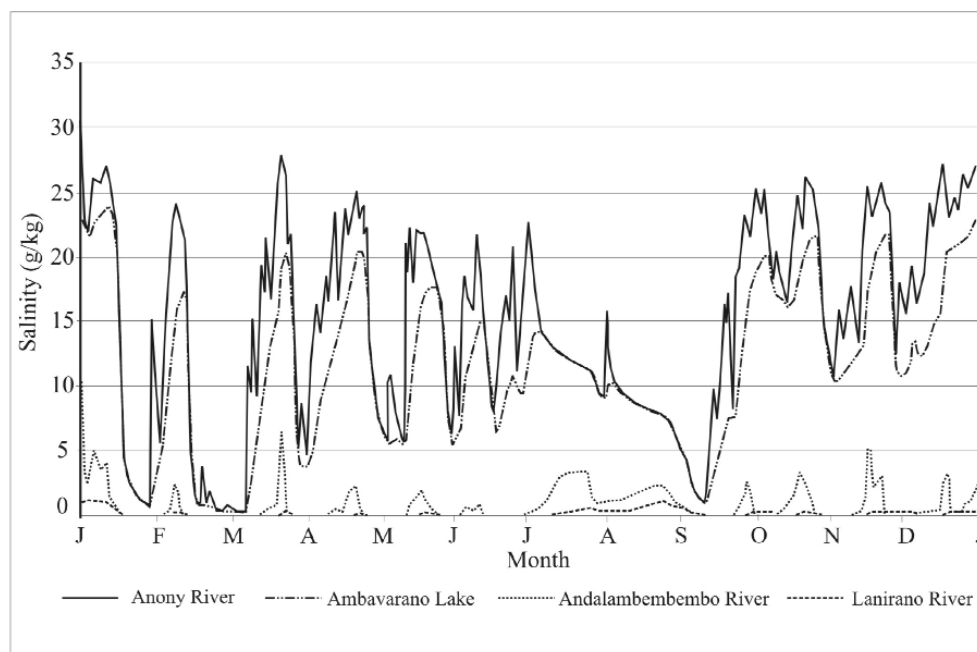


Figure 3. Salinity regimes in different parts of the Mandena system during 2000 (Water Management Consultants 2001).

above the bottom at depths of 3.5 m and 2.5 m. At stations where the water depth was 1 m, salinity fluctuated between 9 and 18 ppt in the first 50 cm from the surface, and between 15 and 35 ppt in the first 50 cm above the bottom. Salinity was much lower in the Anony River when the outlet was blocked by the sand bar. Lake Ambavarano showed marked changes in salinity in relation to freshwater flow from the rivers. Salt contents were lower and fluctuated less in Lake Ambavarano and the Andalambemboalavo River (Fig. 3).

Nutrient contents of water in the Mandena aquatic ecosystem were below the limit of detection (0.04 mg/l for nitrates/nitrites and 0.009 mg/l for orthophosphates) during the rainy season. Both of these nutrients were at slightly higher levels during the dry season, which was probably due to the closing of the outlet by the sand barrier, and retention of nutrients usually washed out to sea. Detectable levels of orthophosphates were measured during the rainy season in the Andalambemboalavo River (maximum value: 0.070 mg/l), Lake Besaroy and the Mandromondromotra River (maximum value in both places: 0.050 mg/l), and the Anony River (maximum

value: 0.027 mg/l). Orthophosphates remained under the limit of detection in the marshes all year long. Nitrites were also below the limit of detection at all sampling stations in the system during the rainy season, but they increased during the dry season up to a maximum value of 0.070 mg/l in Lake Lanirano and 0.090 mg/l in Lake Ambavarano. In the brackish part of the lagoon system and in the seawater of Mandena Bay, nitrate concentrations were low, but within the normal range of values during both the dry and rainy seasons. The highest nitrate concentrations were 0.90 mg/l in Lake Ambavarano and 0.13 mg/l in the Anony River.

Productivity of the marshes was sustained by a steady input of nutrients from the land (Binet *et al.* 1995). Turnover of these substances in the Mandena lagoon ecosystem seemed to be high, and nutrients were quickly washed out to sea. Marshes did not seem to contribute significantly to the input of nutrients, which seem to be absorbed by plants as soon as they reach the aquatic environment, thus leaving only small residual concentrations in the water. Overall, data collected on nutrients suggested that the Mandena system has a low productivity.

Biological characteristics

Across the year of sampling, diatoms comprised nearly half of the phytoplankton, followed in numbers by green and blue algae. Among diatoms, centric and pinnate species were equally abundant. Phytoplankton densities in Lake Lanirano were double those in the Andalambemboalavo River.

The number of species (70) and the specific diversity index (H' index value: 1.48) were higher during the dry season than during the rainy season (50 species, index value: H' index value: 1.33-1.39). However, overall phytoplankton abundance was higher in the rainy season (1527-3702 cells/l) than in the dry season (833-1603 cells/l). The dominance index was low (less than 0.1) in the system during all seasons.

The specific diversity of phytoplankton in the Mandena system was in the range of values estimated for estuaries (Lae 1992), but somewhat lower than along the seacoast. Index values for data collected in the system changed over time, for example these values ranged from 0.22 to 0.73 in 1989, and from 1.39 to 1.46 in 2000. The explanation for these differences might be that the 1989 data were collected after heavy rainfall. Phytoplankton may have been washed out of Lake Lanirano, while the blue-green *Spirogyra* algae and the green *Staurastrum* algae were highly abundant. However, the diversity index of phytoplankton was much lower in 1989 (0.22) than in 2000 (1.46).

Diatom species account for 60 to 70% of the phytoplankton in the estuary. Percentages of green and blue algae are in the range of 12 to 19%. The total number of species in this part of the system was 192. Phytoplankton abundance from Lake Ambavarano to the outlet of the Anony River was higher during the rainy season than during the dry season. For example, abundance and specific diversity are quite similar in the Mandromondromotra River (6475 cells/l; index value: 1.66) and in the Anony River (6778 cells/l; index value: 1.69) during the rainy season, while during the dry season these values were notably lower in the upstream part of the Anony River (2922 cells/l; index value: 1.66). Generally, there is a gradient of increasing phytoplankton diversity along the system (from Lake Ambavarano to the Anony River outlet) across the year. However, higher diversity values in any part of the system occur during the dry season. Dominance index for phytoplankton species is low in the estuary (less than 0.01).

Comparison of samples collected in 1989 and 2000 show that groups of phytoplankton species are similar. Diatoms are the most abundant, a well documented characteristic of tropical estuaries (Day 1981). Similar diversity and abundance values were found in Lake Ambavarano in both years. However, slightly higher diversity and much higher abundance values were found in 2000 in the Anony River (134-6475 cells/l), compared to the year 1989 (17-1660 cells/l).

Some points should be noted for phytoplankton in the Mandena system: 1) Abundance of green algae of the genus *Staurastrum* and blue-green algae of the genus *Spirogyra* generally decreased across the gradient from freshwater to seawater; 2) No dinoflagellate alga was found in freshwater. These algae occurred in the brackish estuary and in increasing abundance from there to the sea; 3) Abundance of diatom algae and dominance of centric diatoms increased from freshwater to seawater; 4) Phytoplankton densities were generally higher during the rainy season; 5) Species diversity was lower during the rainy season, which might be related to the increased freshwater flow and the breaking of the sand bar at the system outlet; 6) Phytoplankton abundance was dependent on the location within the system. Variations in abundance occurred seasonally, within the system and within each of its water bodies; and 7) Species dominance remained low in all circumstances.

In the Mandena system, the dominant zooplankton group was rotifers, which made up 58% of all organisms in the samples. Other important groups, in decreasing rank by abundance, were adult copepods (15 to 22%), polychaete larvae (3 to 11%), and copepod larvae (5 to 9%). Zooplankton abundance was three times higher in Lake Lanirano (336-848 ind./l) than in the Andalambemboalavo River (181-301 ind./l) during both seasons. Zooplankton showed the same seasonal trend as phytoplankton, and the highest diversity and species numbers were reached during the dry season (16 species; H' index value: 1.02) as compared to lower values during the rainy season (10 species; H' index value: 0.82). The highest zooplankton abundance occurred during the rainy season with numbers per liter being about two times the values estimated during the dry season. The same trend was apparent in Lake Lanirano (rainy season high of 848 ind./l; dry season low of 301 ind./l) and in the Andalambemboalavo River (rainy season high

of 336 ind./l; dry season low of 181 ind./l). Freshwater samples collected during the rainy season had higher species diversity in 2000 (H' index value: 0.74-0.82) than in 1989 (0). This might be due to heavy rainfall and high flow conditions at the time the samples were collected in 1989. Species diversity values for samples collected during the dry season were slightly lower in 1989 (H' index value: 0.83) than in 2000 (H' index value: 0.94-1.02).

Estuary zooplankton was dominated by adult copepods (50 to 55% of organisms) with a smaller proportion of copepod larvae (21 to 34%) and polychaete larvae (6 to 7%). Foraminifers are found in samples from the estuary. The highest zooplankton abundance (10443 ind./l) was at a station near the outlet of Lake Ambavarano. Most organisms in this sample were copepods. Decapods larvae (crabs, shrimp, and spiny lobsters) were

found in samples from Lake Besaroy (16 ind./l) and from the downstream section of the Mandromondromotra River (6 ind./l).

Estuary zooplankton showed the same general trends as freshwater zooplankton for abundance, species number, and specific diversity index. The highest abundance (3427 ind./l), the lowest species number (52), and the lowest diversity (H' index value: 0.12-0.86) were reached during the rainy season as compared to the dry season (690 ind./l; 61 species; H' index value: 0.77-1.17). During the rainy season, zooplankton abundance was about five times higher than during the dry season. Species dominance index was higher during the rainy season, with values in the range of 0.12 to 0.86 as compared to 0.07 to 0.21 during the dry season. During the rainy season, a few species dominated, thus resulting in high species dominance index values.

Table 4. Most abundant taxa of phytoplankton and zooplankton at 19 sampling stations in the Mandena aquatic ecosystem (CSSA 2001).

Type of habitat	Lakes and Rivers		Estuary	
	Rain	Dry	Rain	Dry
Phytoplankton				
Cyanophytes	15%	20%	12%	19%
Chlorophytes	33%	36%	12%	17%
Xanthophytes	6%	1%	1%	1%
Coccolithophoricea			1%	1%
Dinoflagellates			4%	5%
Centric diatoms	23%	17%	27%	27%
Pennate diatoms	24%	27%	44%	30%
Zooplankton				
Protozoa	-	-	0%	1%
Foraminiferans	-	-	4%	4%
Radiolaria	-	2%	-	0.4%
Acantharia	-	-	0%	-
Rotifera	59%	58%	2%	4%
Branchiopods				
Cladocera	-	-	1%	1%
Ostracods	-	3%	1%	0.4%
Copepods	22%	15%	50%	56%
Mollusks	-	-	-	-
Doliolides	-	-	-	-
Chaetognatha	-	-	0%	1%
Thecosoma	-	-	-	-
Appendicularia	-	-	1%	-
Spiculates	-	10%	-	1%
Larvae :				
Copepods	5%	9%	34%	22%
Polychaetes	11%	3%	6%	7%
Decapods	-	-	-	0.3%
Shrimps	-	-	-	-
Other larvae	3%	-	-	4%

Data collected in 1989 and 2000 showed copepods as the dominant group. However, gastropod larvae were not found in 2000 samples although adult gastropods were the most abundant benthic organism. More species and a higher diversity index were found in samples collected in 2000 than in those collected in 1989. In 1989, crab larvae were more abundant during the dry season than during the rainy season, whereas, in 2000, crab larvae were found only in samples collected during the dry season.

Copepods were found in all samples collected in the Mandena systems, as both larvae and adults. In all parts of the system, zooplankton abundance was higher and both diversity and species number were lower during the rainy season. This is similar to the trend shown by phytoplankton. As a rule, the number of species and the diversity increase from freshwater to seawater at any period of the year (CSSA 1992).

In 1989, crab and spiny lobster larvae were found in the estuary during the dry season as well as the rainy season. In 2000, decapods larvae were found only in samples collected during the dry season, which suggests that reproduction occurs mainly during the dry season. Shrimp larvae were found during both seasons in 2000, but they were more numerous during the rainy season. Most shrimp larvae were collected in seawater around the Evatraha, Ehoala, and Tolagnaro peninsulas. In 1989, shrimp larvae were found in both the estuary and the sea. They were in higher abundance during the rainy season, as in 2000 (Table 4).

Benthos species were more abundant in rivers than in Lake Lanirano. Only two species of polychaete worms of the genus *Pectinaria* were found in the rivers in densities of 680 to 900 ind./m². In Lake Lanirano, the predominant benthos species were gastropods of the genus *Amaea* (160 ind./m²) and bivalves of the genus *Modiolus* (60 ind./m²). Benthos densities were lower in both the rivers and Lake Lanirano during the dry season. No benthic organism was found in the Mandromondromotra River during the dry season.

Species composition was different from one location to the other. For instance, the only species in the benthos samples from the Andalambemboalavo River was the bivalve *Tellina* sp. (20 ind./m²), whereas nematode worms were found in Lake Lanirano (20 ind./m²). Diversity and abundance of benthos organisms were lower in freshwater than in the sea.

Specific diversity and abundance of benthos were lower in samples collected in 2000 than in those of 1989 (CSSA 1992). Species composition seems to have changed also. For instance, worms were common in both sampling years, but no bivalve was found in samples of 1989, and no chironomid larvae were found in the 2000 samples. Benthos taxa were much more abundant and diverse (species number and diversity index) in the estuary than in freshwater habitat. Generally, both the abundance and diversity of the benthic community of the estuary decreased during the dry season.

The most important groups of benthic organisms, sorted by rank of decreasing abundance, were gastropods (60 to 72%), bivalve shellfish (12 to 19%), and worms (14 to 19%, with about 87% of polychaete among this group). During the rainy season, the highest number of benthic species (11) and highest overall density (2540 ind./m²) were found in Lake Ambavarano. Most of this benthos was *Mitra* sp. and *Terebra* sp. gastropods. During the dry season, the highest abundance (1580 ind./m²) and species number (8) were in stations on the Anony River. Gastropods were predominant there.

During the dry season, the highest diversity index (1.02), species number (13), and density of benthos (1640 ind./m²) were in the upstream section of the Anony River. Gastropods were predominant (nine species) in these stations also. Dominance index values generally increased during the dry season, when one or two species of gastropods outnumbered most other benthic taxa.

In 1989, dominance of the benthic community shifted from polychaete worms during the rainy season to bivalve shellfish during the dry season. In 2000, densities of benthic organisms were about half the values estimated in 1989, and gastropods were dominant during both seasons (60% during the rainy season, 72% during the dry season). Worms and bivalve shellfish were in nearly the same proportions (12 to 19%). The changes in the benthic community over time are not likely to result from changes in the habitat such as bottom sediments. The increase in gastropod abundance seems to be part of some long-term changes in the community, which are still unexplained. The diversity index of the benthic community in 2000 (0.46) was about half the value estimated during year 1989 (0.82) (Table 5).

Physical parameters of estuary habitat, especially the marked changes in water level and salinity, are usually detrimental to most life forms (Day 1981). This is true for the Mandena aquatic ecosystem. Physical parameters changed among places within the estuary and over time at any given site. There were some indications that the benthic community of Mandena had changed towards a lower species diversity and abundance since 1989, however, current data are not conclusive about this point.

The most common rooted aquatic plants in Lake Lanirano are *Myriophyllum* sp. and *Chara* sp. Downstream from the lake, there are stands of *Cyperus* sp., *Typha angustifolia*, *Scirpus pterolepsis*, *Halodule uninervis*, and *Halophila johnsonii*. In Lake Besaroy and Lake Ambavarano, there are populations of *Chara* sp., *Cyperus* sp., *Halophila johnsonii*, *Hydrocotyle* sp., *Rhizoclonium* sp., and *Enteromorpha* sp. In Lake Ambavarano, standing biomass of *Halophila johnsonii*

has been estimated to reach up to 1.3 g/0.05 m³ in some places. Common plants at the outlet of the Anony River were *Halophila johnsonii*, and *Enteromorpha* sp. Along the shores of the estuary, especially the south shore, *Rhizoclonium* sp. are the dominant plant species. *Cladophora frascatii* can be seen from Lake Ambavarano to the outlet of the Anony River. In saltwater habitat, typical marine plants such as *Cladophora frascatii* and *Enteromorpha* sp. are common. In the whole Mandena system, algae are more abundant during the dry season.

Fisheries resources and fishing activity

A total of 164 specimens were caught in the gillnet samples, belonging to 18 species of fish, and three species of crustaceans (Table 6). Fourteen of the fish species are euryhaline, or tolerant to a wide range of salinity and the four others are freshwater species.

Table 5. Specific benthos richness in the Mandena aquatic ecosystem (CSSA 2001).

Water body	Andalambemoalavo River	Lake Lanirano	Lake Besaroy	Lake Ambavarano
Specific richness	3	9	16	35
SDI	N.D.	0,4826	0,92608	0,80714
H	N.D.	1,1418	0,3035	9,61322

SDI = Species dominance index

H = Species diversity index

N.D. Unavailable

Table 6. Gillnet fish samples taken in the Mandena aquatic ecosystem (Randrianasolonjanahary 2005).

Fish species	N	Average length (cm)	Average weight (g)	Stomach contents	Euryhaline species	Freshwater species
<i>Ambassis commersonii</i>	33	10	24	Annelids	X	
<i>Caranx stellatus</i>	2	16	82		X	
<i>Eleotriodes ophiocephalus</i>	11	18	120	Crab, shrimp, mud	X	
<i>Gerres punctatus</i>	9	9			X	
<i>Gobius macrorhynchus</i>	34	18	85	Plants, annelids, crab, fish, nematodes	X	
<i>Leiognathus equulus</i>	7	30	207		X	
<i>Liza macrolepis</i>	1	36	572		X	
<i>Lutjanus</i> sp.	1	17	75		X	
<i>Mugil robustus</i>	5	14	52	Mud, annelid	X	
<i>Paraplagosia bilineata</i>	4	12	15		X	
<i>Rhabdosargus sarba</i>	7	11	55	Mud, bivalve mollusk, shrimp	X	
<i>Scomberoides</i> sp.	3	23	156		X	
<i>Therapon jarbua</i>	4	13	38		X	
<i>Ptychochromis oligacanthus</i>	4	12	86	Mud, unidentified item		X
<i>Oreochromis machrochir</i>	1	20	261	Algae		X
<i>Oreochromis mossambicus</i>	1	8	18			X
<i>Yirrkala tenuis</i>	13	74	581	Shrimp, ambassid fish		X
Crustaceans	24					

Table 7. Catch per unit effort in relation to season and type of habitat in the Mandena aquatic ecosystem (Randrianasolonjanahary 2005).

By season				
Season (and month)	Number of fish	Specific richness	Fish caught per hour	Fish caught per day
Rain (June/July)	38	13	0.04	1.04
Rain (August)	31	9	0.03	0.85
Dry (October)	24	11	0.03	0.66
Dry (November)	71	17	0.08	1.94
By type of habitat				
Localization				
Lake Ambavarano	46	12	0.05	1.26
Lake Lanirano	42	7	0.05	1.15
Anony River	41	12	0.05	1.12
Mandromondromotra River	14	6	0.02	0.38
Lake Besaroy	21	4	0.02	0.57

Table 8. Some fish and shellfish reported in the Mandena aquatic ecosystem (QMM 2001).

Fish					
Latin name	Malagasy name	Latin name	Malagasy name	Latin name	Malagasy name
<i>Acanthurus triostegus</i>	hinta	<i>Gobius fusca</i>	toho	<i>Oreochromis rendalli</i>	fiambazaha
<i>Agonostomus telfairi</i>	tofoky	<i>Gobius macrorhynchus</i>	toho	<i>Paraplagusia bilineata</i>	pipapipa
<i>Ambassis commersonii</i>	ambatsy	<i>Hemiramphus far</i>	tabobo	<i>Paratilapia polleni</i>	fony
<i>Anguilla bicolor bicolor</i>	amalomaitso	<i>Kulhia rupestris</i>	fiampotsy takapoky	<i>Paretroplus polyactis</i>	han
<i>Anguilla marmorata</i>	amalombanda	<i>Leiognathus equulus</i>	malaly/malady	<i>Platycephalus indicus</i>	taindalitry/ tandaly
<i>Arothron immaculatus</i>	botana	<i>Liza macrolepis</i>	zompo	<i>Ptychochromis sp.</i>	sarao
<i>Bedotia sp.</i>	vilibemaso	<i>Liza vaigiensis</i>	tofoky	<i>Rhabdosargus sarba</i>	zanabahoho/ vahoho
<i>Belone sp.</i>	angeloky	<i>Lutjanus bohar</i>	varavara	<i>Scatophagus tetracanthus</i>	hita
<i>Caranx spp.</i>	farogna	<i>Lutjanus ehrenbergii</i>	fatola	<i>Scomberoides tol</i>	fiambazahandriaky
<i>Decapterus russelli</i>	valahara	<i>Megalops cyprinoides</i>	voivoy	<i>Signanus rivulatus</i>	halalaza
<i>Dussumieria elopsoides</i>	ampiny	<i>Mesopristes argenteus</i>		<i>Stolephorus waitei</i>	vilimena
<i>Eleotriodes ophiocephalus</i>	Toho	<i>Mesopristes elongatus</i>	vokoko	<i>Strongylura leiura</i>	angeloky/ angeloky vontolo
<i>Eleotris fusca</i>	ambotsiky	<i>Monodactylus falciformis</i>	felefela	<i>Taeniura sp.</i>	fay
<i>Gambusia affinis</i>	pirina	<i>Monodactylus argenteus</i>	takimbaky/imbaky	<i>Terapon jarbua</i>	nengy
<i>Gerres filamentosus</i>	sandrisandry	<i>Mugil cephalis</i>	zompo	<i>Tylosurus indicus</i>	angeloky
<i>Gerres acinaces</i>	matsitsoky	<i>Oreochromis mossambicus</i>	malemilo	<i>Upeneus tragula</i>	fiasomotry
<i>Glossogobius giuris</i>	damilava	<i>Oreochromis niloticus niloticus</i>	fiambazaha	<i>Valamugil robustus</i>	tofoky
				<i>Yirrkala tenuis</i>	lamera
Shellfish					
<i>Panaeus monodon</i>	kamaron /orantrozo	<i>Macrobrachium idella</i>	orambokoky	<i>Metapaneus monoceros</i>	oramena
<i>Panaeus indicus</i>	orandava	<i>Macrobrachium idae</i>	orambokoky	<i>Scylla serrata</i>	foza
<i>Panaeus japonicus</i>	orampasy	<i>Macrobrachium equidens</i>	orambokoky		
<i>Macrobrachium lar</i>	orambokoky	<i>Macrobrachium lepidactylus</i>	orambokoky		

The largest sample (71 fish) was collected in November, which also coincided with the period with the highest species diversity. In Lake Ambavarano, 46 fish of 12 species were caught, while a smaller number of fish were obtained in Lake Lanirano (42) and in the Anony River (41) (Table 7).

One of the most common fish in the Mandena system was *Ambassis commersoni*, which is a small animal that travels in schools in brackish water and estuaries. In the Mandena system, this fish was found from the freshwater of Lake Lanirano to the stratified estuarine waters of the Anony River outlet. Distribution

of Gobidae in the system was quite similar to *A. commersoni*. Although they are less abundant than *Ambassis*, gobies accounted for a larger biomass in the fisheries. The other fish species were far less abundant.

The gillnet fishing sessions of 2005 captured only four *Ptychochromis* sp., while members of this genus form a major portion of the catch for Mandena fishermen. This seems to be due to the use of gillnets for sampling and the location of the sampling stations, which were not in the typical habitat of this species. Thus, it seems that the experimental gillnet samples underestimate the abundance and availability of this fish.

Table 9. Resilience of some fish species of the Mandena aquatic ecosystem. Data derived from <http://www.fishbase.org/search.php>.

Species	Resilience	Double-time
<i>Ptychochromis grandidieri</i>	High	< 15 month
<i>Ptychochromis oligacanthus</i>	High	< 15 month
<i>Paratilapia polleni</i>	High	< 15 month
<i>Oreochromis macrochir</i>	High	< 15 month
<i>Oreochromis mossambicus</i>	Medium	1.4 to 4.4 years
<i>Oreochromis niloticus niloticus</i>	Medium	1.4 to 4.4 years
<i>Tilapia rendalli</i>	Medium	1.4 to 4.4 years

Table 10. Adaptability of most significant commercial fish species to conditions of aquatic environment.

Euryhalines and holoeuryhalines species, and their expected capacity to live in freshwater habitat						
Species	Fresh water		Brackish water		Sea water	
	inland	coastal	lagoons	outlet	inshore	offshore
<i>Ambassis commersoni</i>	←					→
<i>Liza macroleptis</i>	←					→
<i>Megalops cyprinoides</i>	←					→
<i>Glossogobius giuris</i>	←					→
<i>Platygobius</i> sp.	←					→
<i>Leiognathus equulus</i>	←					→
<i>Mugil robustus</i>	←					→
<i>Scatophagus tetracanthus</i>	←					→
<i>Therapon jarbua</i>	←					→
<i>Rhabdosargus sarba</i>		←				→
<i>Caranx hippos</i>		←				→
<i>Caranx forsteri</i>		←				→
<i>Caranx sexfasciatus</i>	←					→
<i>Eleotris fusca</i>		←				→
<i>Hemirampus far</i>		←				→
<i>Gerres</i> sp.		←				→
<i>Anguilla bicolor bicolor</i>		←				→
<i>Anguilla marmorata</i>	←					→

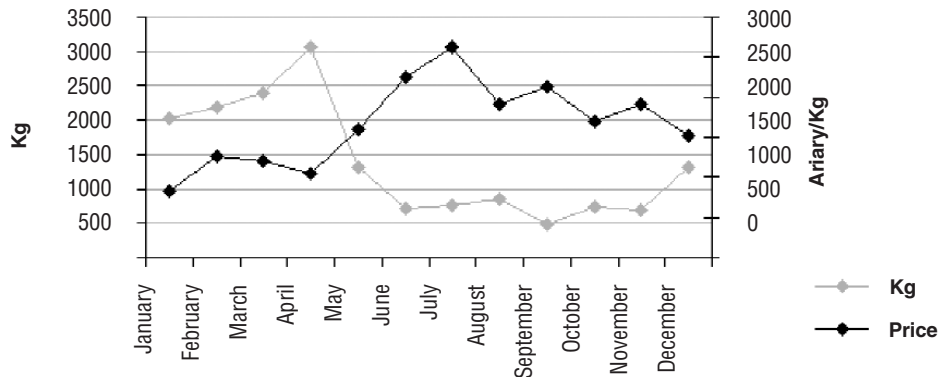


Figure 4. Fish weight and average price, Mandena system fisheries, 2005.

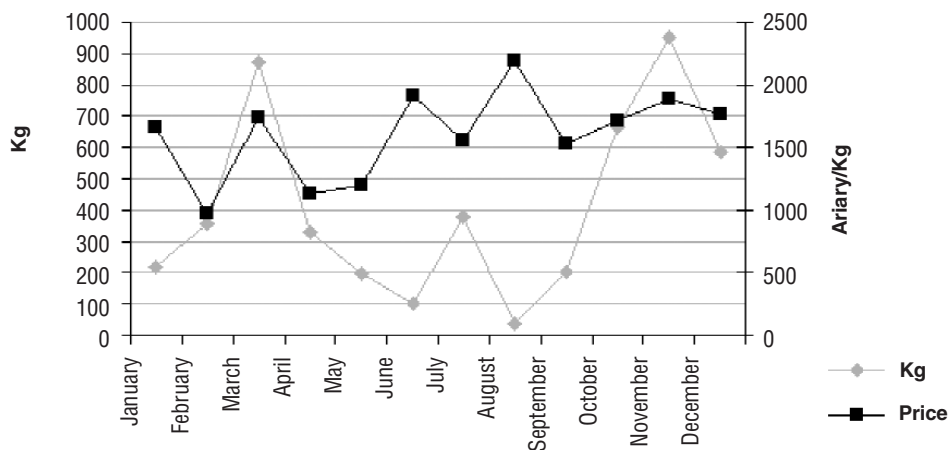


Figure 5. Shrimp weight and average price, Mandena system fisheries, 2005.

Cichlid species are typically fast growing, productive, and resilient (Table 9). Resilience is the capacity for a population to maintain its integrity when subject to disturbance (Holling 1973, Pimm 1984). In the Mandena system, resilient species are likely to take advantage of new habitat conditions expected with structures controlling freshwater flow and level. Members of the genera *Ptychochromis* and *Paratilapia* are endemic to Madagascar. Their high resilience should allow these fish to face competition by the exotic *Tilapia* species, which were introduced to Madagascar in the 1950s.

The proposed dam at the outlet of the Anony River will increase the area of freshwater habitat in the Mandena lagoons, and presumably increase nutrient levels in the system. These conditions should be beneficial to freshwater fish. Euryhaline fish species found in the Mandena system are common and showing parallels to other tropical aquatic habitats, such as the lagoons of the African coast. This group of fishes was an important part of the income of fishermen. The most commercially important groups are the Ambassidae, Gobiidae, Mugilidae, and Gerreidae, which migrate in and out of the Mandena lagoons.

Ambassis fontoynti can complete its whole life cycle in freshwater, without moving out of the system (De Rham and Nourissat 2002).

Two eel species, *Anguilla bicolor bicolor* and *A. marmorata*, are found in the Mandena system. Both are catadromous. They achieve most of their pre-reproductive growth in freshwater, and upon reaching maturity, they leave for spawning areas in the ocean. About 50 species of fish are known from the lagoons, about half of which, especially euryhaline species, are expected to inhabit these water bodies when they will be strictly freshwater habitat (Table 10).

The total catch of fish and shellfish in the Mandena lagoons in 2005 was estimated to be 32,716 kg (Table 11). The Mandena aquatic ecosystem measures about 500 ha, thus the annual fisheries productivity was 65.4 kg per ha. The most valuable fish species make up 51% of the catch in weight, and 56% of the fishermen's income. The average price of these species at the market is 1664 ariary (or \$0.74 US, exchange rate of 2240 ariary/dollar in 31 December 2005) per kilogram. The most valuable shrimp species were 15% of the total catch, and 19% of the income, for an average price of 1605 ariary (\$0.72 US) per kg. The other catch categories are crabs (13% weight, 13% income, 1436 ariary or \$0.64 US per kg), and a mix of low value fish and shrimps (20% weight, 13% income, 905 ariary or \$0.40 US per kg). The fishermen and their families eat only 1.7% of the catch. The total annual income from the fisheries for the community was estimated

to be 42 million ariary, or \$18750 US. There is considerable monthly variation in catch weight and catch value for fish (Fig. 4) and shrimp (Fig. 5).

Fishing activity

The fisheries in the Mandena lagoon system only began in recent years. Before the 1980s, it was unusual to see anybody fishing in Lake Lanirano, whereas this was a common sight by 2005. There has been a marked increase in fishing effort in the last ten years. Moreover, the use of fine-meshed shore seine in fishing gear caused an important by-catch of juvenile fish (Cima International/Sogec 2002). Fishing effort and catch in Lake Lanirano and the Andalambemboalavo River was still quite low. According to surveys conducted in 2000, only four men fished these sites for eels and freshwater fish. Fishing was much more intense in Lake Besaroy, Lake Ambavarano, and along the Anony River. Most fishermen used handcrafted gear and traditional fishing techniques. They traveled in single place dugout canoes less than 3 m long, which are easy to maneuver. They made their own gillnets in various sizes and meshes, using 3 or 8 kg test nylon monofilament. Depending on the season, they fish with gillnets of 2 to 5 cm mesh size.

The fishing techniques were set or drifting gillnets, and hook lines were used to fish for eels. Each fisherman of the Mandena system owns at least one dugout canoe and one gillnet. Gillnets are

Table 11. Summary of catch statistics, Mandena system fisheries, 2005.

Type of catch		January	February	March	April	May	June
Fish	kg	2027	2186	2386	3069	1306	722
Average price/kg	A/kg	824	1270	1196	1037	1595	2258
Fish	Ariary	1 670 900	2 776 667	2 854 967	3 181 286	2 084 406	1 630 875
Shrimp	kg	220	356	874	328	194	103
Average price/kg	A/kg	1662	972	1742	1128	1196	1909
Shrimp	Ariary	365 800	346 267	1 522 543	369 857	232 500	196 500
Crab	kg	236	638	128	457	153	87
Average price/kg	A/kg	1605	1048	1509	1106	1565	1325
Crab	Ariary	378 200	668 267	193 086	505 714	239389	114 750
Fish-Shrimp	kg	766	1176	787	615	723	461
Average price/kg	A/kg	656	656	437	725	910	1075
Fish-Shrimp	Ariary	501 959	770 933	344 100	445 629	657889	495 225
Subsistence	kg	0	150	76	36	41	23
Monthly catch weight	kg	3 249	4 506	4 251	4 505	2 418	1 396

set at dusk and fish are collected early in the morning. Some people also set gillnets during the day, and splash the water with their paddle to drive fish into the nets. Shore seines were used in most locations in the Mandena system, but they were most commonly seen in Lake Lanirano. A maximum of nine shore seines were counted in the system at any one time. The use of this type of gear seems to be integrated into local fishing practices. Mangrove crabs (*Scylla serrata*) are caught from Lake Besaroy to the Anony River with handcrafted cages. About 30 fishermen operate 520 cages for crabs. Shrimp are fished with bow-nets of various sizes or with trap-nets.

Among the 60 households living in Lanirano and the village of Andrakaraka, including its hamlets, 51 families earned their living from fishing in freshwater or, more commonly, in the estuary. Fishing was the most important economic activity in Andrakaraka, providing 86% of the village income. Fishing activity was twice as important during the rainy season than during the dry season. In most cases, all family members are involved in fishing. Fathers and sons usually do most of the fishing effort on the water, but women and younger children provide help in numerous other ways. Women carry fish to the Tanamboa market in Tolagnaro for sale. Many families depend on the fisheries resources of the Mandena system to earn their living. Fishing effort has a low efficiency because of the handcrafted gears and traditional fishing techniques.

Discussion

Ecology of the inland part of the Mandena aquatic ecosystem

Shallow lagoons and brackish water lakes such as Lake Ambavarano and Lake Besaroy are tropical estuary environments with transitional conditions from marshland to sea. Many aquatic animals in their early life stages, either larvae or juveniles, find food and shelter in this type of habitat. Most parts of the Mandena system are shallow, turbid waters. The mixing of freshwater and seawater is limited and the input of nutrients seems to be low. The estuary outlet of the system is often blocked by a sand bar when water flow from the rivers decreases during the dry season. When heavy rains reopen the outlet, nutrients seem to be washed away into the ocean.

In the tropics, marshland areas are more important in shallow estuaries than in deeper ones (Binet *et al.* 1995). In shallow estuaries, such as that at Mandena, the food web depends more on detritus feeders than on phytoplankton production, and most energy enters the food chain through benthic organisms. Life cycles of most aquatic animals are based on seasonal rainfall cycles. Fluctuations in these ecosystems make it impossible to reach a stable state (Binet *et al.* 1995). The suddenness and unpredictability of algal blooms make it difficult for consumers to settle and reach population stability. In these conditions, food chains are rather short and abundance of consumers remains low.

July	August	September	October	November	December	Total
749	855	491	735	695	1318	16 540
2616	1910	2137	1695	1924	1511	1664
1 958 270	1 631 924	1 050 133	1 245 757	1 337 000	1 992 138	23 414 322
376	35	200	664	950	585	4 885
1562	2190	1527	1717	1887	1764	1605
588 114	75 950	306 000	1 139 914	1 791 333	1031525	7 966 304
118	435	321	164	363	1061	4 159
2180	1836	1340	1562	1179	977	1436
256 857	798 250	430 000	255 529	427 667	1 036 563	5 304 270
251	225	171	218	841	347	6 580
1203	559	1115	1472	1058	991	905
302 029	125938	191 000	321 071	889 667	344 100	5 389 539
29	35	23	46	46	46	551
1 523	1 584	1 207	1 827	2 894	3 358	32 716 kg

Production of fish

Productivity is defined as the biomass generated by a population or community per unit of time. Fish productivity refers to the productivity in terms of fish or shellfish biomass, whereas “fishery productivity” focuses on an even smaller part, the proportion of fish productivity that is effectively removed by fishing (Allen 1971).

In the Mandena system, fishery productivity is severely limited by fluctuations in physical and chemical water parameters. Water level, salinity, pH, temperature, and suspended particles are parameters showing marked changes over short periods. Even the beneficial effects of floods on freshwater fish species are largely negated by variations in salinity. The current conditions for growth in the Mandena lagoons are sub-optimal for freshwater, as well as marine or brackish fish species.

The dynamics of lagoon fisheries resources has been discussed in detail by Lae (1992), who surveyed lagoons of the west coast of Africa. Fishery production has been estimated and analyzed in relation to salinity regime and fishing techniques. Large differences are found in fishery productivity, and they are explained by a number of factors. However, the role of sand dunes at the outlets of the lagoons, which seem to bolster migration of sea fish into the system, and fishing techniques are two of the most important factors in this system.

In areas where fisheries are operated collectively, using shore seines or weirs of other fixed gear, the catch may be as high 300 to 600 kg per ha per year. This has been estimated for the Ébrié Lagoon, close to Abidjan, Ivory Coast. In areas with mixed fisheries (both collective and individual), productivity in the range of 170 to 200 kg per ha per year has been reported. In areas where most fisheries are individual, values between 50 and 70 kg per ha per year are common.

Other researchers also reviewed lagoon fisheries and concluded that many factors, both internal and external to each system, might have an effect on productivity. They estimate that lagoon fisheries operated in optimal conditions might catch between 150 and 200 kg of fish per ha per year.

Characteristics of the Mandena lagoon system allow it to be classified according to factors regard-

ed as determinant in the literature. In the Mandena system, fisheries are individual and gillnets are the most common gear, with 100 m shore seine used in some periods of the year. Systems with these characteristics fall in the intermediate class and the expected optimal fisheries productivity should be somewhere in the range of 70 to 170 kg per ha per year. Yearly fisheries production of the 500 ha Mandena system have been estimated at between 35 and 85 tons (Réville *et al.* 2004). According to the fisheries survey of 2005, the actual yearly catch in the Mandena system was 32.7 t (65.4 kg per ha), at the lower limit of the expected range. The catch could probably be increased by improving fishing techniques and gear, which might be inefficient.

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