Mahakary channel, upstream to lake Aloatra (cliché : M. Mietton).

Lake Alaotra (Madagascar) is not about to disappear.

Hydrological and sediment dynamics of an environmentally and socio-economically vital wetland.

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Résumé/Abstract

Le lac Alaotra est le plus grand lac de Madagascar (456 km² à la cote moyenne de 751,20 m). Il est entouré de marécages et de périmètres irrigués de grande valeur économique formant le principal « grenier à riz » du pays. Cette cuvette a dans le même temps une valeur patrimoniale, écologique, puisqu'elle constitue une zone humide protégée par la convention de Ramsar (1971), abritant un certain nombre d'espèces endémiques menacées. En réalité le « lac » n'est qu'un vaste plan d'eau peu profond qui semble condamné à une disparition par sédimentation. Le bassin environnant est en effet affecté par une érosion très forte, dont les marques (« lavaka » ou « evana ») peuvent être facilement repérées dans le paysage. Si le lac Alaotra est une forme transitoire destinée à disparaître, la question demeure quant à la vitesse du phénomène. Malgré les cris d'alarme répétés dans les médias malgaches et aussi quelques affirmations scientifiques, l'envasement du lac n'est pas évident. Dans une première approche, une analyse critique des arguments soutenant l'hypothèse d'une sédimentation rapide dans le lac est établie. Dans un second temps, des données nouvellement collectées mettent en lumière les processus limitant effectivement la sédimentation. De l'amont vers l'aval, ce sont les débordements dans la plaine lacustre lors des crues accompagnées d'épandages sableux, l'effet d'écran protecteur joué par la végétation aquatique (« zetra ») dans les marais, la remise en suspension des particules fines par le vent et les vagues lors des épisodes de type cyclonique et leur décharge à l'exutoire, enfin un phénomène de subsidence très probable. Contrairement à une idée reçue, une sédimentation significative dans le lac lui-même n'est donc pas démontrée. En conclusion, des options de planification locales sont discutées. La priorité doit être impérativement donnée à l'aménagement des amonts, dont la protection conditionne concomitamment celle des grands périmètres rizicoles ainsi que celle du lac lui-même.

Lake Alaotra is the largest lake in Madagascar (456 km²). It is surrounded by marshland and irrigated perimeters of great economic value forming the "main rice granary" of the country. The basin also has an heritage and ecological value as a wetland protected by the Ramsar Convention (1971) and is home to a number of threatened endemic species. In reality the "lake" is just a vast shallow pool that seems doomed to silt up as the surrounding basin is affected by very strong erosion, the marks of which can be seen in the landscape («lavaka» or «tevana»). If Lake Alaotra is a transitional form destined to disappear, the question remains of how fast this will happen. In spite of repeated cries of alarm in the Malagasy media and also a few scientific affirmations, the silting up of the lake is not obvious. In a first approach, a critical analysis of arguments backing the hypothesis of rapid sedimentation in the lake is addressed. Subsequently, new data collected highlight the processes that effectively limit sedimentation, ranked from upstream to downstream these are: sand deposits by the overflows into the lacustrine plain, buffering by the aquatic vegetation in the marshes, resuspension of fine particles by wind and waves and their discharge related to currents and a probable subsidence. Significant sedimentation in the lake itself has not been shown, quite the opposite. Finally, local planning options are discussed. Priority must be given to improved land management in the catchment which affects both the large rice perimeters and the lake itself.

Mots-clés/ Key words

Madagascar, Alaotra, lac, sédimentation, vent, courant, matières en suspension, transport de fond, crues, subsidence, périmètre rizicole, aménagement de bassin versant.

Madagascar, Alaotra, lake, sedimentation, wind, current, suspended loads, bottom transport, floods, subsidence, rice perimeter, catchment management.

Introduction

There is no known meaning of Alaotra in Malagasy language. Maybe it comes from Malaysia or the Philippines and then it would mean "sea"; or maybe from Borneo (Dayak language) and then it would mean "shore" (Anonymous, 1938). Indeed, Lake Alaotra is the largest lake in the "Grande Ile" (456 km² when the average water level reaches 751.20 m AMSL[1], 160 km² at 750 m), sited on the eastern slopes of Madagascar, 200 km north-east of Antananarivo in a remarkable north-south fault trough (Laville *et al.*, 1998 ; Mietton *et al.*, 2014). At elevation 750 m, the lake itself measures 40 km in length with an average width (area/length) of 4.4 km and maximum width of 8.6 km (Hakanson, 1981; Hutchinson, 1957). However, it is very shallow (greatest depth 3.25 m). It is more like a large pool whose silting up seems all the more inevitable as the surrounding drainage basin is marked by strong erosion with extraordinary and widespread gullies called "lavaka" (or "tevana") from the Malagasy (or Sihanaka) word for "hole" that are very noticeable in the landscape and the dynamics of which has operated for thousand years; the phenomena is generally old (Bourgeat 1972; Mietton *et al*. 2007) but also locally very recent (Erismann, 2007). The repeated flooding of the rice fields caused by the elevation of beds and the failure of protective embankments tend to show the scale of the sediment conveyance by the watercourses, the names of which are sometimes evocative (Lohafasika: "river of sand", Sahamaloto:

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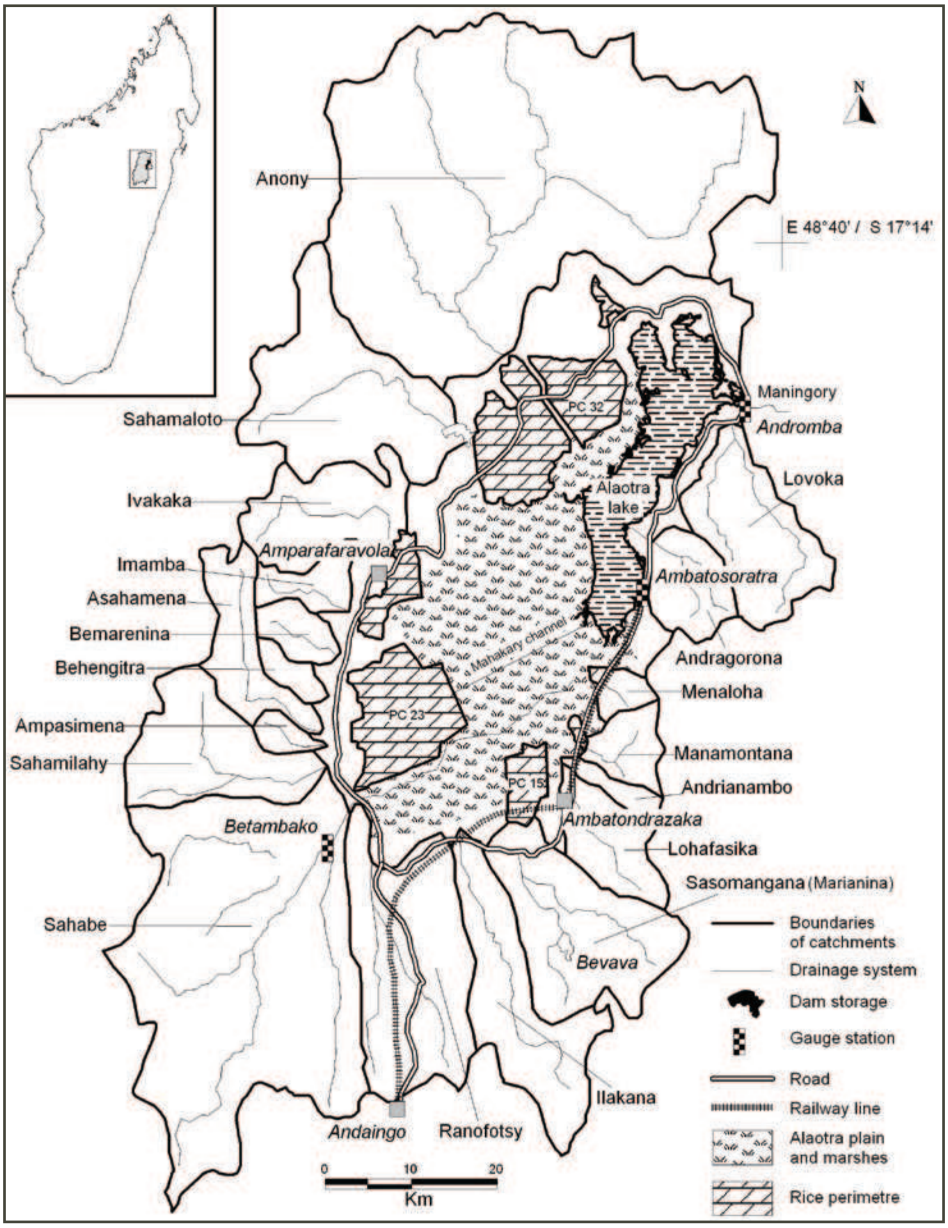

figure 1: *Lake Alaotra drainage basins and the main irrigated farming areas.*

“muddy, dirty river”, Ranofotsy: “white water” in malagasy language means “flood” in sihanaka dialect!). The disappearance of lake Alaotra has therefore been predicted many times by the media and even by scientists (Moreau 1977; Bakoariniaina *et al*. 2006).

The interest shown by the various stakeholders in the Alaotra region is doubly legitimate insofar as the basin is of great economic value (the hydro-agricultural perimeters around the lake form the country’s major “rice granary”, or at least form the largest extent (30,000 ha) of irrigated agriculture (Droy, 1998), and is also of heritage and ecological value as it is a wetland protected by the Ramsar Convention. The pairing of these interests with the sedimentation dynamics of the lake justifies the re-examination of its spatial evolution. Indeed, this was studied by the engineer R. Longuefosse in the 1920s (Longuefosse, 1923) and more recently by Moreau (1977), Pidgeon (1996) and Ferry *et al.* (2009). The collection of much more accurate data on winds, waves, lake currents velocities, resuspension of fine silty particles and their discharge via the outlet, on the nature of the materials on the bottom of the lake and lastly on basin subsidence, make it possible to address these issues from a fresh angle.

Although Lake Alaotra is clearly a transitional form, behaving like a very shallow lake (Touchart, 2000), and thus destined to disappear, the question of the time scale at which this will happen remains highly relevant.

I- Context

At the regional scale, the waterbody is set in a basin (the “Alaotra basin” or “sihanaka basin”) fed by more than twenty rivers that approach it in a radial pattern; the largest are the Anony in the north and the Sahabe in the south **(figure 1)**. At an elevation of 775 m, the basin forms approximately 25% of the total catchment area at the outlet of the lake (6,855 km^2). The outlet is at the Andromba sill (17°24’10’’S - 48°38’20’’E), in the northeastern section of the basin, into the Maningory river.

The basin consists of the lake itself (456 km^2, approximately 525 million m^3 at the elevation of 751.20 m), the adjoining marshland (approximately 320 km^2), marshy savannah (210 km^2) and the surrounding rice fields and outlying plains (820 km^2) **(photo 1)**.

The region has a tropical climate, with a two-season precipitation regime, but temperate from the point of view of the temperatures : a hot rainy season from November to April and a cool season from May to October that is described as “dry” but that in fact accounts for 7 to 22% of total annual rainfall. Rainfall in the drainage basin of the lake averages 900 to 1250 mm per year with a maximum monthly of more than 250 mm in January. The relatively small rainfall is explained by the dynamics of the easterly winds of the föhn type that blow down the basin after losing most of their humidity on the east-facing slopes. The average annual temperature at Ambatondrazaka is 20.6°C (average of daily minima in July: 11.1°C; average of daily maxima in January: 28.4°C).

The hydrometric data used in this study on water elevation in Lake Alaotra are those of the hydrometric stations at Ambatosoratra on the east bank of the lake and at Andromba (Figure 1) at the outlet towards the east coast via the river Maningory, where the median module is 71.2 $m^3.s^{-1}$ (Chaperon *et al.*, 1993). These stations were monitored by ORSTOM (Danloux, 1980; Ferry, 1989) for a relatively long period: 16 years from 1976 to 1997. The water level in the lake begins to rise in December, with the highest point reached in March. This hydrological pattern corresponds to the climate pattern but with a marked time-lag of two to three months. Extreme annual levels were subjected to statistical adjustment using a normal law (Ferry *et al.*, 1999). In the period 1948-49 to 1996-97, the maximum reported would thus be 755.14 m and the minimum observed was 749.80 m on 25 November 1981, i.e. a maximum amplitude of 5.34 m. The water level in Lake Alaotra is subject to considerable daily and hourly variations (see below).

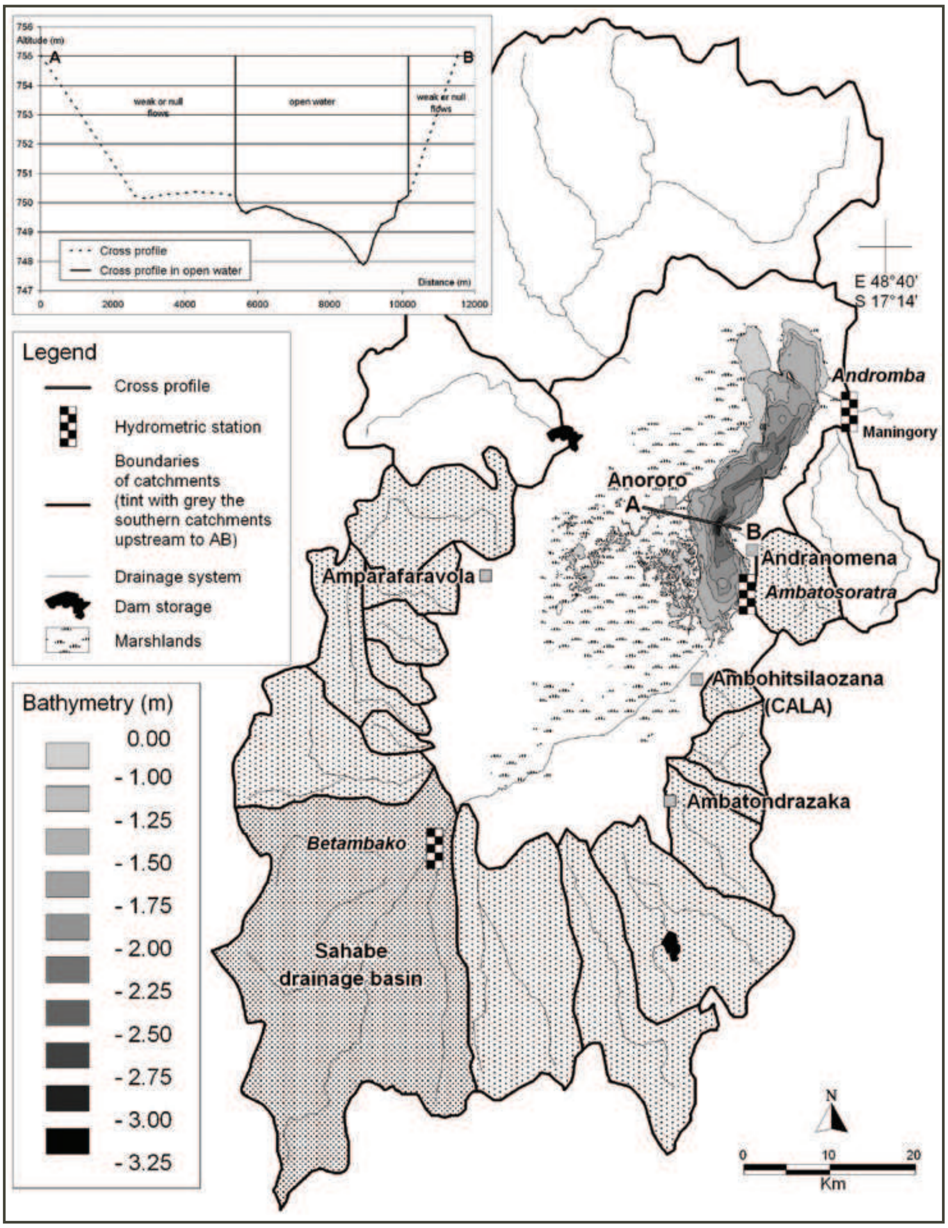

figure 2: Bathymetry of the lake and localization of the section of studies current velocities.

II- Methods and data

We will start by describing the lake's bathymetry and the characteristics of the materials at its bottom. Then we present solid discharges data into and out of the lake. Indeed, a sediment balance can provide us with the rate of filling up, if we assume tectonic stability. Finally, we present data on lake currents and winds that result in its turbidity and the resuspension and movement of particles.

A- Bathymetry and sedimentological analyses of materials at the bottom of the lake

The first accurate bathymetric map of the lake was plotted using three series of bathymetric observations performed by ORSTOM from 1994 to 1997 (August 1994, April 1997 and May-June 1997) (Ferry *et al.*, 1999; Ferry *et al.*, 2009). The map **(figure 2)** can be considered as very satisfactory up to elevation 755 m, but with imprecision in the marsh zones and the small lakes within the marshland (especially the south-western marshes). The open water area is bordered by a marshy zone of more or less floating peat and Cyperaceae. An elevation/area curve was plotted by planimetric measurement of the total areas bounded by each contour-line taken in succession at 25 cm intervals to 750.25 m **(figure 2)**; the elevation/volume curve was plotted by integrating the latter **(figure 3)**.

The examination of the elevation/area curve shows that mean relative depth of Lake Alaotra is more representative than maximum relative depth (which would underestimate the shallowness because of a localized small depression). Mean depth is 1.15 m.

Mean relative depth $D_r = \frac{D\sqrt{\pi}}{2\sqrt{S}}$ is 0.00477%.

In comparison, Lake Balaton, regarded as the archetype of the great shallow lake, has a mean relative depth of 0.012 % (Papon et Touchart, 2003).

The lake bottom is very flat and generally muddy. Some cores were taken on January 2010, in the

photo 1: The lake Alaotra (seen in the direction of north) and its mountainous eastern edge. Foreground: marshes and marshy savannah on the left, rice fields in the right (photo : M. Mietton).

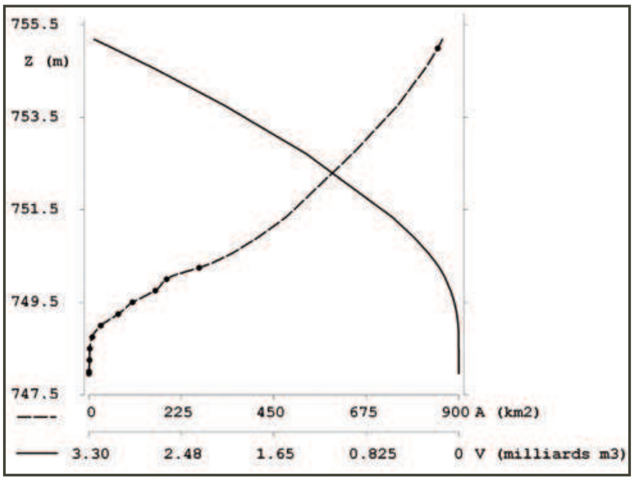

figure 3: *Elevation-area-volume curves of Lake Alaotra.*

southern part of the lake, west of Andreba (13°17'15"S; 48°29'07"E), under 1.5 m of water. The first were taken on the surface sediment of the bottom, the second in a depth of 0.30 m. The results of the sediment analysis are nearly the same for the two kinds of cores; 35-40% of organic matter, about 50% of clay, about 5% of small (20-49 microns) and subangular quartz, and some micas and heavy minerals (green hornblende, rutile, staurodite). The deposit resembles peat, with a lot of microscopic vegetal fragments and some fine pulverulent minerals.

B- Solid loads carried by watercourses

Suspended loads.

The measurements of suspended loads in the watercourses (Dosseur et Ibiza, 1981 and 1982) comprise several hundred samples collected by ORSTOM on the Anony, at the Ambohiboanjo spillway every day at 7 a.m. from 15 November 1976 to 31 August 1978. During marked floods successive samples were taken on the same day. Suspended loads varied from a few tens of grams to a few hundred grams per m^3 from November to April and generally a few tens of grams from May to October. The maximum was 7129 g/m^3 on 20 April 1978 with a gauge height of 1.41 m; the load was 3711 g/m^3 at the absolute maximum gauge height of 2.58 m on 24 February 1977. As hydrograms are available for these dates, total daily suspended loads transported can be approximated at some 60 000 metric tons on 24 February 1977 (i.e. 33 000 m^3 with a density of 1.8 ton per m^3) and 30 000 tons on 20 April 1978 (i.e. 17 000 m^3). At the outlet, in the Maningory river, suspended loads varied from a few tens of grams to a few hundred grams per m^3 (March 2010, Ql >110 $m^3.s^{-1}$).

Bottom transport and silting of storage dams

Bottom transport was estimated by comparing longitudinal profiles at close time intervals (1989, 1991 and 1993) on the rivers Lohafasika and Harave (Petitjean, 1994). The data show a scale of at least 100 000 m^3 per year at the outlet of a catchment with an area of some 238 km^2.

These are a much better indicator of solid transport, including bottom transport, and make it possible to evaluate specific degradation per year and per km^2 with better allowance made for discontinuities of transport in space and time. Diachronic measurements of reservoir capacity were performed at two sites: the Sahamaloto reservoir (Ferry, 1985) and the Bevava reservoir (Ferry et Garreta, 1987; Mietton *et al*., 2006).

The 2005 measurements made at Bevava using 950 echo-sounding points in a 2.1 km^2 reservoir can be compared to a reliable curve of capacity as plotted by ORSTOM in 1987 (Ferry et Garreta, 1987).

However, erosion intensity should be appraised in a more nuanced way. Measurements of the capacity of Sahamaloto reservoir show that no significant filling occurred between the two ORSTOM studies conducted in 1975 and 1985 (Ferry, 1985). It is also difficult to unreservedly accept the substantial sedimentation figure at the same site over a 20-year period from 1956 to 1975, because the values of the initial capacity curve should be used with great caution (operating method unknown for lack of records, uncertain setting of the curve). The difference in sedimentation between the Bevava dam south-east of Lake Alaotra and that of the Sahamaloto dam to the west could be partially linked with the rapid decrease in rainfall and climatic aggressiveness to westward, and also with the steeper slopes to the east.

C- Currents, winds and waves

Current velocity

For argument's sake we select the current speeds in the part of Lake Alaotra connected with the discharge of the Sahabe River, which drains the second biggest basin within the lake watershed. The selected section (AB) connects the Andranomena's Cape on the eastern shore to Anororo village in the western marshy plain **(figure 2)**. The section allows an evaluation of the discharge by tributaries in the southern part of Lake Alaotra with a rather good accuracy. Furthermore, the section coincides with a strait of the lake, where the depth is one of the greatest in the water body. Regarding the run-off in the western marshy plain as insignificant (very shallow sheet of water with abundant aquatic vegetation), we consider the only curve H/S (H: altitude of the lake; S: wetted area) for studying current speed **(figure 3)**. Using the hydrological data collected at the Betambako's station on the Sahabe River **(figure 2)** we present results of the calculation for two very different hydrological years: 1977-1978 and 1985-1986. Within a range of 14 near-complete years of data collection between 1976 and 1997 on the Maningory River at Andromba's station, the mean discharge of the year 1977-1978 is the lowest (23.9 $m^3.s^{-1}$), whereas the mean discharge of the year 1985-1986 is the third highest (82.1 $m^3.s^{-1}$). Mean daily speed (VJ) coincides with the quotient between daily discharge at the station and mean daily wetted area of the cross profile. The mean daily speeds present the same fluctuations for the two years of study: the highest speeds happen in the beginning of the rainy season, when the lake level is the lowest; the speeds decrease with the increase of the lake level.

The maximum speed, as calculated from the discharge of the Sahabe River only, is 11,7 mm.s^{-1} for the hydrological year 1977-1978 and 7,1 mm.s^{-1} for 1985-1986. These low speeds would probably increase and reach 2 to 4 cm.s^{-1} if we would consider the runoff from the entire watershed of the southern part of the lake (the catchment area of the Sahabe River represents only one third of entire surface). Those speeds can easily transport the finest particles in suspension towards the outlet.

Lake Alaotra is basically a "wide river" and discharge out of the lake is then possible. **Figure 4** emphasizes the relationship between maximum speeds and lowest levels, especially at the beginning of the rainy season.

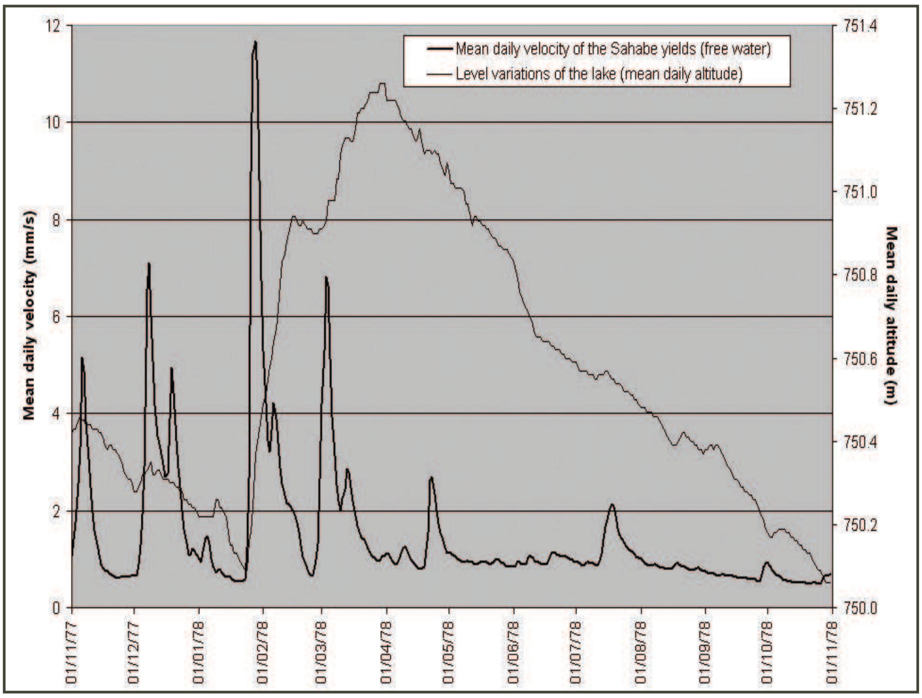

figure 4: *Mean daily velocity of the Sahabe yields and level variations of the lake.*

Winds and waves

Two kinds of wind data are available. Some (from January 2006 to October 2008) come from continuous records on an automatic meteorological station, situated in the south-east of Ambatondrazaka (Mietton, 2005). It records maximum instantaneous horizontal wind speed, the associated direction and time, and total wind per hour and per day. Other data (January 1997) derive from the Ambatondrazaka airfield and provide eight 3-hourly records of maximum wind per day (00 UT, 03 UT etc…) and associated directions.

The detailed analysis of the dataset shows that:

The cumulative wind is mostly from the south and south-east.

The maximum instantaneous winds are most frequently from the south and south-east too, especially during the dry season (from July to October).

During the rainy season (January, February, March), wind can blow from the north and north-east.

Over the close to three years of records, the maximum instantaneous speeds recorded are about 23 m.s^{-1}. This occurred during hurricane Ivan (17th February 2008, direction N 200° E). The next day the speed was about 22 m.s^{-1} (direction N 110 ° E).

Whatever the wind direction may be, the maximum effective length (Le) gives the potential wave action for the straight line of the wind upon the lake at each point. The north-eastern lake basin is marked by high values of maximum effective lengths (more than 20 km everywhere). The outlet itself is on a site of 22.5 km and draws a lake region with a Le of between 20 and 25 km. The maximum effective length of the whole lake is 31.7 km and is located at only 7.2 km to the north of the outlet. According to Stevenson's empiric formula (Stevenson, 1852), the potential maximum wave height in Lake Alaotra is therefore 1.87 m. Taking the bathymetry of the lake into account, this is only a theoretical number, but it shows the major influence of the wind on the mixing and the resuspension in all the parts of the water body. Effective lengths from southerly winds exceed 12 km in the northern lake basin **(figure 5)**, but effective fetch is a finer notion which integrates oscillations of wind on both sides of a given main direction.

For the prediction of wind waves we selected 200° (SSW), which is the direction of the maximum wind speed of 23 m.s^{-1} during hurricane Ivan.

According to Hakanson's formula,

$$Lf = \frac{\sum xi.\cos\gamma i}{\sum \cos\gamma i}.S'$$

Lf is the effective fetch, x the distance, γ the angle, i each direction (-42° to +42°), S' the scale constant. Here are the angles calculated for a reference (0°) of 200° (206° is equal to 6°). We worked on a scale of 1:153,846, so that S' = 1,54. Considering that the straight line joining the outlet and the cape on the opposite shore is the conventional beginning of the northern lake basin, we calculated the effective length in the middle of this segment. Lf = 12.8 km. We regard this value as the reference in the entry (isoline 0.50 m depth) of the shallow basin. Values are higher to the north.

According to Norrman's formula (Norrman, 1964), if the effective fetch is 12.8 km and wind speed 21 m.s^{-1}, wave height is 1.78 m (if extrapolated to 23 m.s^{-1}, height is 1.90 m). In fact wind speeds of about 6 or 7 m.s^{-1} are sufficient to create waves of 0.40 m height, if Lf=12.8 km. Such winds generate breakers down to (40x1.3) cm depth, which mobilize the lake bottom in the entire northern lake basin. Wind speeds about 6 m.s^{-1} with

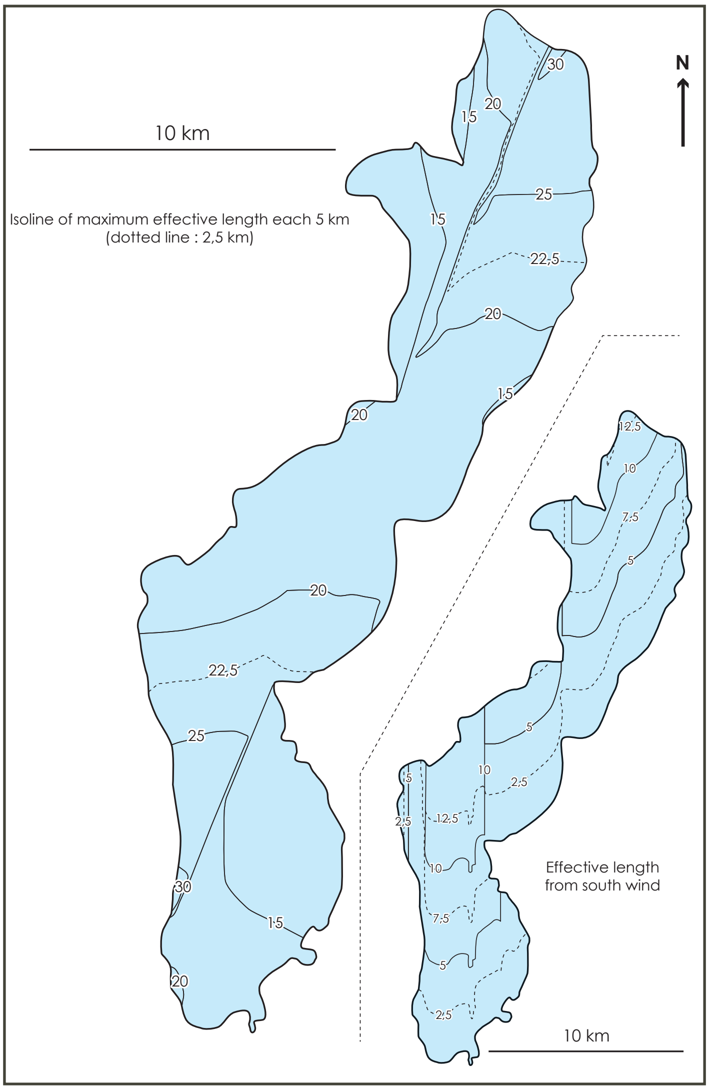

figure 5: *Maximum lengths and south wind effective lengths in Lake Alaotra.*

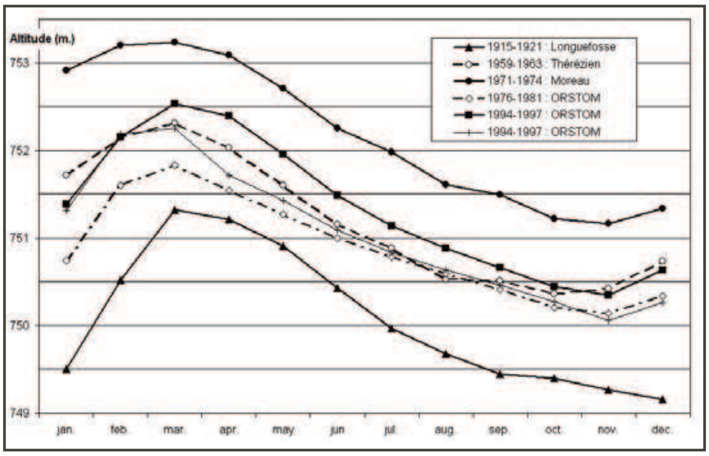

figure 6: *Monthly water level variations in Lake Alaotra (six reporting periods).*

such fetches may transport particles of up to 1 mm in diameter in a two-meter water column. Furthermore, according to Hakanson's ETA (erosion-transportation-accumulation) diagram (Hakanson et Jansson, 1983) the erosion regime for superficial bottom sediment durably prevails, if effective fetch is more than 3.9 km and depth less than 2.5 m. Owing to the bathymetry and the lake area, conditions are therefore favourable to erosion in most parts of the lake and to the export of particles through the outlet.

III- Results and Discussion

As shown previously, the "lake" is just a vast shallow pool that seems doomed to silt up as the surrounding basin is affected by very strong erosion. The disappearance of Lake Alaotra has therefore been predicted many times by the media and even by scientists, whose results are presented below together with our counterarguments.

A- Arguments used to predict a rapid filling and disappearance of the lake

Lake water annual levels and sedimentation (Moreau, 1977)

J. Moreau tried to demonstrate the inevitable filling of the lake by drawing a parallel between the variations of the water level for three reporting periods: 1915-1921 (data compiled from Longuefosse (1923)), 1959-1963 (data compiled from Thérézien (1963)) et 1971-1974 **(figure 6)**. In one half-century, the mean level of the lake would thus have risen by at least two meters, which, according to Moreau would be explained by the deposits at the bottom. This approach is highly questionable as an elevation of the bed of the lake cannot cause the water level to rise physically unless the outlet is raised to the same extent. Such a rise in outlet level seems difficult to imagine at the outlet sill upstream of Menasaka rapids because it is a rocky outflow sill. In any case it has not been demonstrated. In addition the water level curves of Moreau and of Longuefosse raise questions concerning topometric settings.

Examination of the **figure 6** leads to several objections:

- first, a rise in the open water level of some 1 m between 1959-63 and 1971-74 would have caused major disruptions in the downstream part of the rice fields. No such observations have been documented.
- second, if the water level of the lake rose until 1971-1974, how can a subsequent fall in the level be interpreted? Such a difference does not exist between the curve of Thérézien (1958-1963) and the curves of the ORSTOM, which have been drawn up for three periods (1976-1981, 1982-1987, 1994-1997) posterior to the curve of Moreau (Figure 6). The positioning of the "Moreau curve" must therefore clearly correspond to a difference of topometric setting.
- finally, including the Longuefosse curve in the parallel positioning would imply an increase of 1 m to 1.50 m at the outlet (and possibly also in the lake) between 1915-1921 and 1959-1963, that is to say in 40 years. But how can it be explained that nothing would then have happened in terms of sedimentation during the next 30 years?

To summarise (Ferry *et al.*, 2009):

- either heavy sedimentation occurs in the lake and at the outlet which would have formed a deposit 1 to 3 m thick between 1915-1921 and 1959-1963. However, this would require an explanation for the change in dynamics around 1960, whereas most of the hydroagricultural development works and the reduction of the marshland area occurred later than this;
- or, as in the present authors' opinion, significant sedimentation in the lake has not been demonstrated.

Satellite imagery and filling up of the lake (Bakoariniaina *et al*., 2006)

The authors of this study are right to emphasize the significant erosion within the watershed of Lake Alaotra. Nevertheless, we would like to raise a few issues:

Despite of the alarming title of the Bakoariniaina *et al.*, paper (2006), which forecasts an imminent disappearance of the lake, it is a study about sedimentation in a mix of short and long time scales. If considering the plio-quaternary period, everybody agrees with the authors on the gradual filling-up of the lake basin. But over the last decades this has not been demonstrated convincingly. Bakoariniaina *et al*., 2006 themselves quote other research (Brenon, 1949, Aldegheri, 1972, Pidgeon, 1996) that has shown that the shape of the lake did not change significantly. The authors indicate a 5 km² decrease of the lake area during the last 30 years, i.e. about 1 % of the lake area at mean water level. The margin of error at the scale of the Landsat 7 ETM+ used cancels out such an accuracy.

Remote sensing with a medium resolution provides an admissible demonstration only if there is a strict association between the image of the lake area and the lake level at the same moment.

The imagery used shows the situation at the end of the rainy season, when the lake level is the highest. The authors do admit a potential error of interpretation regarding the marsh area, especially because the lake plain was submerged in March by hurricane Eline. Both lake and plain were strongly colored in red at the time due to suspended matter.

Thus the remote-sensing examination of the evolution of Lake Alaotra is not convincing. The disappearance of the lake in the short term is not demonstrated in spite of the authors' cry of alarm when they rightly stress the importance of erosion in the drainage basin.

Several limiting factors can be put forward to explain the continued survival of the lake in spite of the high erosion in the catchment and the suspended and bedload solids transported by the inflowing rivers.

B- Arguments for the absence of filling and for the continued existence of the lake

Using a hypothetical evaluation of the rate of filling of the Alaotra lake itself (525 million m^3) from the average specific degradation of the entire mountainous drainage basin (approximately 5,500 km^2) estimated at between 1000 and 1500 tonnes/km^2/year and mud with a density of 1.2 tonne/m^3, and supposing that all this material is deposited in open water, filling up would be completed in 50 to 100 years and should therefore be clearly visible at the human generation scale. This is not the case.

Three main factors may explain the absence of filling up of the lake:

- high sediment loads in the inflowing rivers frequently correspond to overflows into the lacustrine plain and as marshes and wetlands act like a filter very little of this sediment actually ends up in the lake itself.
- resuspension and export of fine particles is frequent as winds, waves and currents disturb a very shallow lake with a highly unstable bottom
- subsidence probably is higher than was thought previously (Ferry *et al*., 2009).

In addition, the development of hydraulic and agricultural infrastructure may have counter-intuitive impacts that need to be considered in catchment-wide planning.

Potential impacts of hydro-agricultural infrastructure

The Sahamaloto and Bevava dams, the irrigation canals and the rice fields themselves trap sediment, while road and railway embankments form obstacles or at least slow down movement.

However, hydraulic and hydro-agricultural operations can also favor movements of sediment into the lake. Embanking (at least when there is no overflowing) and canalizing rivers (such as the 1984 excavation of a rectilinear channel in the Marianina valley), increases flow rates and the proportion of alluvial material reaching the lake basin. The development of irrigation plots at the expense of marshland has had and still has the same effect. Large-scale hydraulic works have been carried out since 1961 to enable the population to develop marshland, in particular to the west of the lake, and replace it by irrigated rice fields. The marshes totaled 55,000 ha in 1961 (Thérézien, 1963), only 30,000 ha in 1976 (Moreau, in Burgis et Symoens, 1987) and about 20,000 ha in 1994 (Mutschler, 2003). Increased sedimentation could also result from the extension of drainage channels southward. For example, channels D3 and D8 in PC 15 could thus soon flow into the Sahabe, with the unfortunate result of enhancing conveyance of the load of suspended solids and of agricultural pollutants into the lake **(photo 2)**.

Factors limiting sedimentation

Floods, overflows and deposits

Atmospheric disturbances and hurricanes, which occur nearly every year, commonly cause an increase in the water level in the rivers. Even during non-exceptional rainfall (e;g. hurricane Hubert, 6-10 March 2010) the resulting floods break dams, because of generally very gentle longitudinal grades and because of the uplift of stream beds due to high erosion and deposit in the rivers. Such floods damage hydro-agricultural perimeters and leave

photo 2: *Aerial view of confluence between Sahabe river and the new rectilinear drainage channel D3 (marshlands on the right, rice fields on the left, rice perimeter PC 15 in the background) (Photo: P. Grandjean).*

deposits on rice-fields **(figure 7)**. Overflows usually happen upstream of the plain, but occasionally also downstream when the drains are waterlogged and filled in with sediments **(photo 3)**. It seems impossible to fight these dynamics or even to control them, as it would require very considerable and non-sustainable expense to regularly clear drains, dredge channels, raise dams, strengthen embankments, etc. Another solution would consist in the restoration of shifting river characteristics, the establishment of settling basins or the re-establishment of areas where floods would spread out naturally. Fluvial shifting existed before the building of agricultural perimeters. In any case, at the present time and also formerly, solid load is not (yet?) likely to enter the lake, even during substantial floods. As such the low vegetation cover on the slopes in the catchment area is not in contradiction with the low sedimentation rate in the lake.

The buffer role played by the aquatic vegetation of marshland

Marshland ("zetra" in Malagasy language) covers an area larger than the lake itself and is as much as 15 kilometers wide, providing an essential slowing effect on inflowing watercourses in the south (Sahabe, Ranofotsy, Ilakana and Sasomangana) and west (with the exception of Sahamaloto). The Anony in the north is the only large drainage basin from which water flows into the lake to have a narrower marshland. At its mouth in the lake, the Anony displays a slightly curved delta-like shape. On the east coast of the lake, where there are no marshes, inflow is limited by the fact that only one small drainage basin (Andragorono) discharges into the lake and, logically, a micro-delta is present.

Among the forty-five (45) aquatic species belonging to twenty (20) families inventoried (Andrianasetra Ranarijaona, 1999), *Cyperus madagascariensis* (Cyperaceae) or "zozoro" and *Phragmites mauritianus* Kunth (Poaeceae) or "bararata" play remarkable filtering roles. *Cyperus madagascariensis* is a tall, strong floating sedge that thus requires water at all times (to a depth of nearly 3 m) or at least a waterlogged environment. The rooting depth of the species is 0.02 to 0.55 m. *Cyperus madagascariensis* is dense and impenetrable, even under water. *Phragmites mauritianus* Kunth *(*Poaeceae) is less abundant but forms islets on Lake Alaotra itself and is found on its banks and also along drainage ditches (Mahakary) and rivers (Sahabe). This species is resilient and can withstand prolonged emergence from water. Fishermen use *Phragmites mauritianus* to make V-shaped traps in the lake or at drain and river outlets. Thus bushy rows of *Phragmites mauritianus* tend to obstruct watercourses and channels where they enter the lake. The "zetra" is also difficult to penetrate because of the surprising presence of "vodifonga", a thorny shrub, and "vankelana", a creeper-like species.

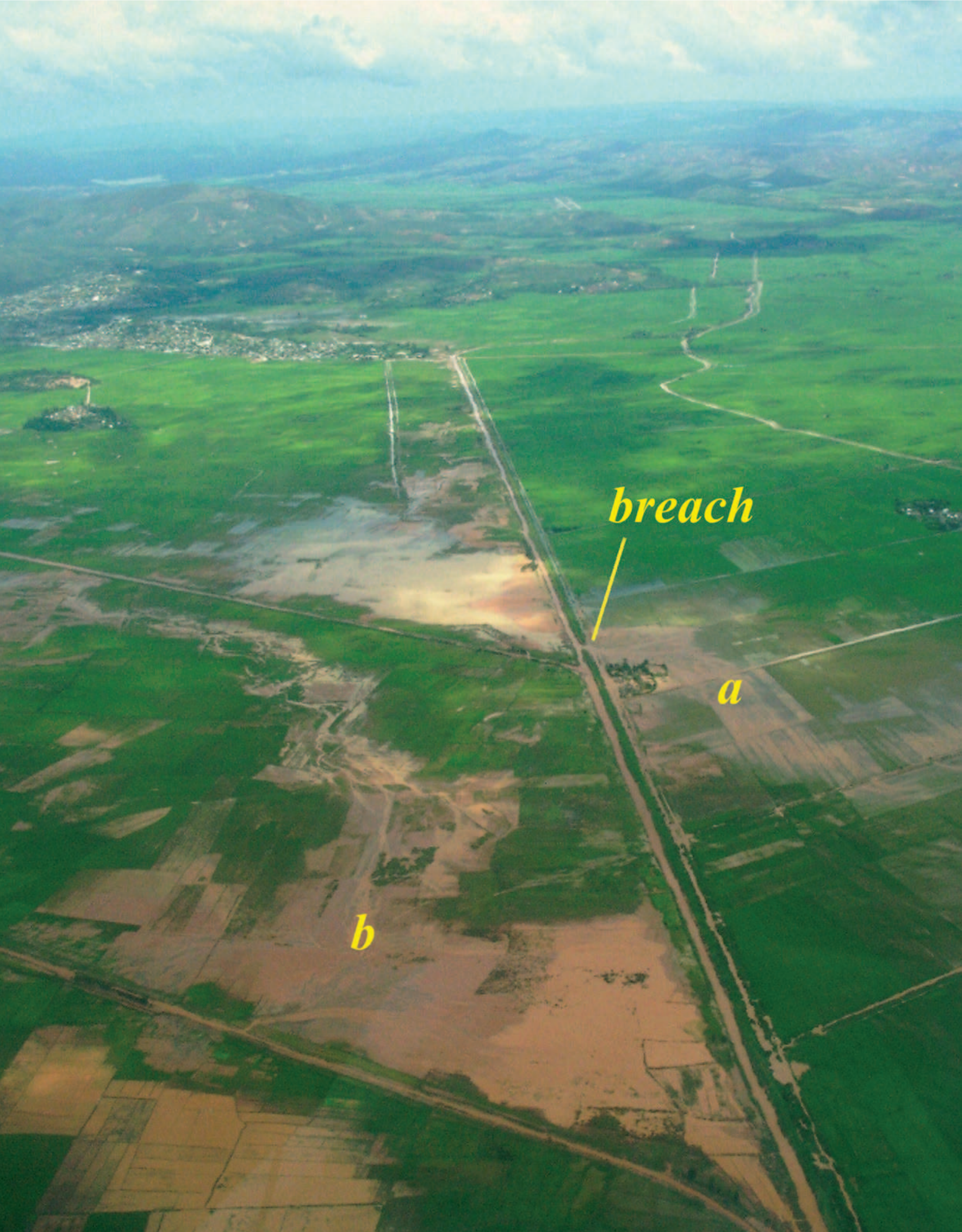

photo 3: Aerial view of deposits (a: deposits from the breach through D3 left embankment, b: deposits from river and drainage channel upstream overflows) in PC 15 (Ambalanomby) after cyclonic rainfall and overflows (March 2005). Ambatondrazaka town in the background (photo: P. Grandjean).

photo 4: Marianina Valley and Harave River (seen in the direction of north-west) : rectilinear channel and embankment (on the left side, Madagascar, cliché : P. Grandjean).

Aquatic vegetation plays an essential general role as a buffer and filter in the sedimentation process at the edge of the lake itself and therefore governs its evolution to a considerable degree. Without this screen that is particularly effective in the face of a solid load consisting of comparatively large particles (micaceous deposits), it is clear that the inflow of solid load would be sufficient to quickly fill this shallow water-body. This screen effect might disappear suddenly in the near future as a result of the fires lit by the fishermen in the dry season; this destruction of the natural plant cover would subsequently open the way to traditional cultivation and then possibly to hydroagricultural development operations.

The resuspension of fine silty particles and their discharge via the outlet

Surface movement in such a shallow lake is not without importance with as regard to sedimentation dynamics.

The strongest agitation is the effect of waves. We have noted that different formulas and various calculations give the same result of the maximum maximorum: if wind speed is about 20 $m.s^{-1}$ during a cyclone, wave height is between 1.50 and 2.00 m. In this case the entire water volume is strongly mixed. According to the fishermen, during the more common episodes, the heights reach 0.60 to 0.80 m at the centre of the waterbody and during the cyclonic episodes the fish die in great quantity per resuspension of fine silty particles and asphyxiation. The resuspension process is at its peak effectiveness in the north of the lake close to the outlet of Maningory.

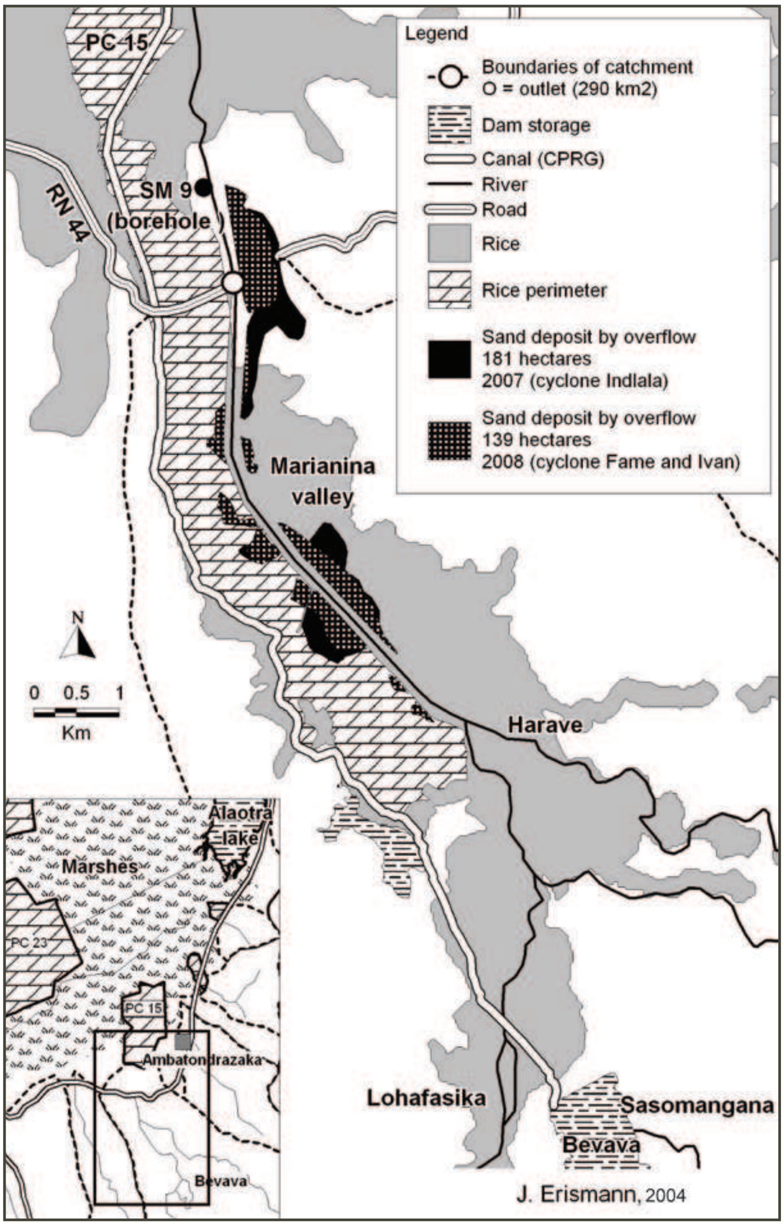

figure 7: *Overflows and alluvial deposits at the time of cyclonic risings (Examples in 2007 and 2008).*

In addition to the effect of waves, the discharge of fine sediments could be related to currents. Fairly marked rapid variations can take place in the level of Lake Alaotra. Amplitudes are irregular in time and space (at Ambatosoratra, neighboring people mention tide-like falls in water level when south-east winds are strong). Level recordings from Ambatosoratra station from 1994 to 1997 show variations with an amplitude frequently as great as 0.1 m over periods of a few hours.

These water level oscillations coincide with tilting of the surface of the water from the south to the north, increasing discharge in the River Maningory. For example during the night by 13th and 14th January 1997 a very strong wind blew from south-east or south. It is the highest average hourly windspeed recorded at Ambohitsilaozana (Cala agricultural research station south of the lake; Figure 2) in that month (18 kph at 18:00 h, SE wind) and the more precise data, i.e. maximum instantaneous windspeeds, recorded at Ambatondrazaka airfield indicate speeds of some 7.5 to 8.1 m per s during this night. The recording shows that the level decreases strongly in the south of the lake (3.45 m) and a few hours later an increase of the discharge (98 $m^3.s^{-1}$) was observed at of the outlet **(figure 8)**. The same phenomenon was observed on several occasions during two weeks with atmospheric disturbances.

In addition to the effect of waves, the discharge of fine sediments could be related to such currents, may be seiche currents (Pourriot et Meybeck 1995). But seiche currents have not been measured or even proved and the narrows or straits that enhance them are not characteristic of the morphometry of Lake Alaotra. Whatever that may be, even limited current speeds of some dm per s are enough to shift particles brought by watercourses or whose detachment from the bottom is related to mechanisms other than strictly hydrological ones (Douglas et Rippey, 2000; Smith et Sinclair, 1972; Hilton, 1985).

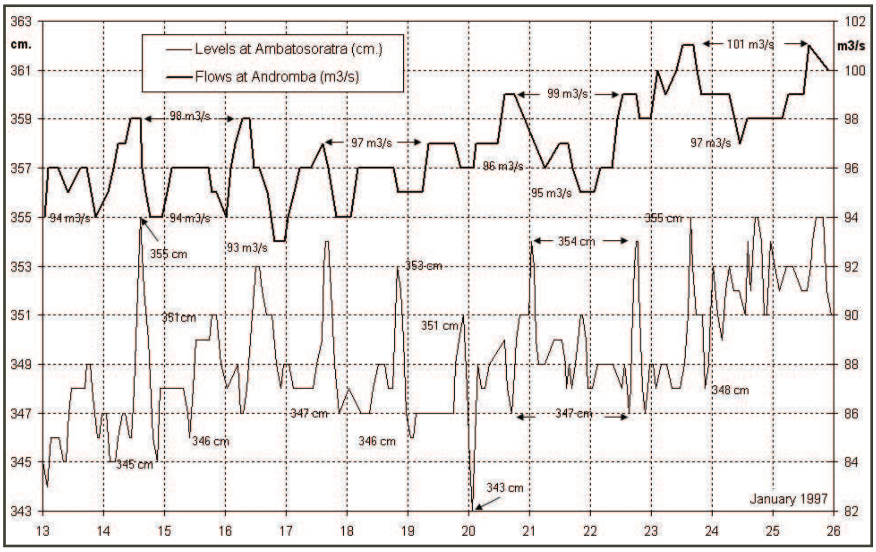

figure 8: *Rapid variations in the lake water level (at Ambatosaratra station) and discharge (at Andromba station) measured from 13 to 26 January 2007.*

The latter suffer repeated flooding, especially during cyclone rainfall as was again the case during hurricanes Ivan and Indlala in February and March 2007 (Figure 7). The protective embankments are not high enough and insufficiently compacted and never fail to be breached, especially as watercourse beds progressively fill and rise as a result of alluvial deposits. Flooding is a lasting preoccupation when it is accompanied by the soil degeneration resulting from thick deposits.

The technical alternative is simple from the hydraulic point of view (Mietton, 2007):

1. either the river is corseted by high, compacted embankments with riprap at their bases, constraining a narrow channel in which the current is accelerated. Training the watercourse in a straight line, as is the case in the Marianina valley, enhances the increase in net power and, by a flushing effect, conveys a greater solid load downstream, potentially in the end to the lake **(photo 4)**; or

2. the bed, embanked on one bank (for example, the irrigated rice in the Marianina valley is on the left bank only and the maintenance of the embankment on the right bank does not seem to be imperative) or on both, is kept as wide as possible so that the energy of the watercourse spreads and is dissipated as much as possible. Thus, the river partially recovers its original functioning in an alluvial floodplain. Controlled dissipation areas could possibly be planned upstream. The advantage of this solution is that it limits ruptures and does not carry too great a solid load into the marshes. It obviously has the disadvantage of using cropland but this is only partly true. Many of the farmers questioned considered that the soils in "baiboho", recent alluvial land with no water control, little higher than the alluvial plain, may have at least as much agronomic interest as the land in irrigated perimeters.

Still, from the point of view of regional development, choosing between these two scenarios is probably not as easy as all that. It has to be presented to and discussed by all the stakeholders, whose interests differ considerably. The management plan for the Ramsar site is currently being drafted by the Ministry of Water and Forestry and the Environment. There is of course coordination with the Ministry of Agriculture but this must integrate the agricultural and economic dimension of the "rice granary" formed by the Alaotra basin. The conservation option has been enhanced through the establishment of a 43,000 ha Protected Area covering the lake itself and the surrounding marshes, whose final status (reserve, national park, etc.) will be established in 2010. In addition to the total protection core zones in both the marshes and the lake (spawning zone), the project proposes so-called "buffer" zones or zones under joint management (fishing). The zoning operation is intended to be

Flows during floods and especially those at the beginning of the rainy season, when the water level in the lake is at its lowest, generate longitudinal south-north currents that can be observed by their color, caused by the suspended load. Lake Alaotra is then more like a broad watercourse than a lake.

Subsidence of the depression

The tectonic fault underlying Lake Alaotra is still mobile (Laville *et al.*, 1998), as is shown by the numerous small magnitude tremors recorded in the highlands of Madagascar, less than 5.2 in the Alaotra region (Professor G. Rambolamanana, Geophysics Institute Antananarivo: personal communication). The last one, of magnitude 4.5, affected this region on July 28th 2009. Subsidence is very probable.

Some peaty layers have been identified at depths of 7 and 15 m below the surface of the alluvial plain. As we don't have any indication of uplift of the eastern lake shore, those marshy deposits are probably due to a slow collapse of the lake basin. Unfortunately we do not have any data on the age of the peat layers but recent geotechnical studies of the Marianina valley (borehole SM9, Figure 7) have shown the presence of clay layers at 25 and 29 m depth. These have been dated (Age 14C) to 14770 +- 60 BP (Lyon-6768 (GrA)) and 15270 +- 60 BP (Lyon-6769 (GrA)) respectively. This would imply a sinking rate of 1.5 to 2 cm per 10 years, sufficiently fast to compensate for any sedimentation in the lake.

C- Options for catchment management

The entire Alaotra drainage basin has been classified as a Ramsar Convention wetland protection site since 2003 and the management plan is still being drafted. The area concerned (722,000 ha) covers a range of very distinct landscape units. It includes the lake of course and the surrounding marshes but also upstream areas used as grazing land or for rainfed farming and, between the two zones, large rice perimeters (PC 15, PC 23, etc.).

participative but a management structure capable of ensuring adherence to the regulations in the field and providing ecological monitoring still needs to be established. It is essential for the institutional partners to compare their positions and coordinate their actions, with priority going to taking local stakeholders' opinions into account as outlined in Borrini-Feyerabend *et al*. (2004).

These discussions could also address an old development scenario conceived by Longuefosse and mentioned repeatedly (Grontmij N.V., 1971). It consists of building a small dam on the outlet of the lake (the Maningory); the resulting rise in water level would provide a little hydroelectricity, favor fishing and bring water closer to a number of crops; however it would have the big disadvantage of hindering drainage in the rice perimeters and probably changing the conditions of sediment discharge…

Conclusion

In spite of the recurrent cries of alarm in the media in Madagascar, filling of the lake is not obvious. This is not surprising. Load transfers, at least with regard to the coarsest bottom load (sand and gravel) are like elsewhere—even more than elsewhere—regulated by a principle of discontinuity in space as a result of violent overspilling into the alluvial plains and also by storage in the marshes, even at the long time scale. These deposits are not subsequently transported any further. As for the fine particles that have reached the lake, they are resuspended during the frequent movements of the shallow waterbody and drawn to the outlet by substantial currents during floods. Reference to erosion data at the scale of the upstream drainage basins is therefore misleading, as are the very visible scars ("lavaka") in the weathered cover. It is probably one more example of "an over-dramatisation" of degradation of Madagascar, as written by C.A. Kull (2000).

We consider that if the ecological composition of the lake has been upset, the reason is not sedimentation in the open waterbody but rather changes in agricultural techniques, including the changes that these have caused in water quality, in the bordering plains or at the expense of marshland, the introduction of exotic plants and fish (Kiener, 1950), over-intensive hunting and fishing and the use of fire at the expense of the "zetra". As was noted by Pidgeon (1996), translated from French, "*… through the changes made by man, Lake Alaotra has become a wetland of limited importance for its natural elements*''.

However a more optimistic viewpoint can be based on our analyses of muds of the bottom of the lake did which did not reveal pollution by the weedkillers (2,4-D; < 0.1 mg/kg) used extensively and over long time periods in the catchment area. Perhaps this is an additional indicator of the throughflow capacity of the lake! Effectively, given the high solubility of 2,4-D and its soil/water partitioning coefficient (K_{oc}), one can assume that 2,4-D resided preferentially in the water columns during sedimentation. Only acidification of the lake might convert the hydrophilic 2,4-D into a lipophilic substance resulting in its uptake by micro- and macro-organisms. Currently measurements of the pH of the lake show neutral or alkaline waters (Burgis and Symoens, 1987; Ferry et al., 2009). Recent measurements (June 2010) confirm these values (7.2<ph<8.1).

Is the conservation of the ecological elements of the lake, or at least of the heritage value of its lacustrine landscape, a priority? If so, how can development and conservation be reconciled? The fact that it is difficult to reply to this question must not prevent the Malagasy institutions from conducting a calm debate with each other and with the users in order to make well thought-out decisions on solid scientific bases. There is not necessarily conflict between ecological concerns and those of the farming world. The sustainability of both the lake and the rice perimeters depends to a considerable degree on the policy for the protection of the upstream parts of the Alaotra drainage basin (Bergeret, 1967). Drawn from the technical arsenal of new agro-ecological practices, the strategy of introducing forage plants of the *Stylosanthes* or *Brachiaria* type should be favored. These leguminous grasses combine the qualities of appetence for cattle and resistance to fire, slow runoff and enhance the chemical and physical rehabilitation of land that is generally uncultivated today. These plants can also be intercropped with dry crops such as cassava and provide a food substitute in case of shortage of rice. This concomitance of features can make them acceptable for all stakeholders and make it possible to envisage their propagation at an effective spatial scale.

From a territorial point of view, the financial efforts made by financial backers should be focused on the upstream areas, even though the political reflex linked with the immediate concern for the legibility of actions has hitherto led to the setting of projects in the large hydro-agricultural perimeters or the lake itself.

Modern (regulating floodgate through Channel I2 : « vanne à masques ») and traditional hydraulics (aqueduct with sight holes, upstream to Harave basin, similar to the one page 56, Madagascar, Alaotra, cliché : M. Mietton).

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