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Low sedimentation in the Sélingué dam reservoir (Mali-Guinea). Evidence of the stability of south Sudanese savannah at the scale of a large drainage basin very little affected by man

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Abstract

Hydromorphogenic dynamics in West African drainage basins are complex phenomena that can be understood and measured through the study of sedimentation processes in reservoirs. By plotting a new topographic map of the reservoir, this study shows the limited sedimentation of Sélingué reservoir (Mali) in contrast with estimates prior to the building of the dam. Used together with studies on the specific degradation of large drainage basins and sediment transport, this study sheds new light on the hydrodynamic mechanics of a given bioclimatic environment. Specifically, for a drainage basin remarkable for its homogeneity of land use and vegetation, the study highlights the prime importance of the role of vegetation and human occupation in these hydromorphogenic processes. A new assessment of the storage capacity of the reservoir is made in the light of these findings.

Keywords

Bathymetric profile, sedimentation, reservoir, specific degradation, South-sudanese climate, dense dry forest, savannah, population density, Sélingué reservoir, Sankarani watershed, Mali, Guinea

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1 Introduction

With anthropogenic pressure, world population of 9 thousand million by 2050 and demand for water increasing by 2 to 3% per year in the coming decades (International Commission on Large Dams, 2015), storage dams have been and still are a response for covering the everyday requirements of populations. These dams are aimed mainly at the production of hydroelectricity and water for irrigation and domestic purposes. Storage dams include the 'large dam' category; these are at least 15 m high. The most complete database (International Commission on Large Dams, 2015) reports the existence worldwide of 58,266 dams with theoretical total storage capacity of 15,956 km^3. These are the largest impoundments that account for the largest part of water storage in the world. Thus the 633 very large reservoirs listed by Vörösmarty et al. (1997) with capacity of at least 0.5 km^3 (i.e. 500 million m^3) alone form 60% of artificial water storage in the world.

From a geographic angle, sub-Saharan Africa displays specific features as regards large dams. Firstly, in the face of tropical or subtropical climatic uncertainty marked by very irregular distribution of precipitation, storage dams make water supply more regular. This irregular rainfall pattern that is marked on an intra-annual level is also strong on an inter-annual scale: in West Africa in particular, the second half of the 20th century was marked by periods of severe climatic drought (Paturel et al., 2011). Secondly, as a result of the substantial increase in population and agricultural, domestic and energy requirements in developing countries, storage dams are seen as a potential vector for socioeconomic development. Finally, large African storage dams are generally younger—at 40 years against 50 years at the world scale (Wisser et al., 2013)—and have greater capacity at an average of two to seven times that on other continents, with northern Asia being the only exception (Vörösmarty et al., 1997).

The building of large dams reached a peak in the 1960s and 1970s, with annual total capacity of 150 km^3 built each year, before decreasing and stabilising at 15 km^3 in the 2000s (Wisser et al., 2013). The decrease in funding is explained by the calling into question of large dams for reasons of their durability and the negative externalities involved. Indeed, environmental (Mulholland & Elwood, 1982; McAllister et al., 2001; Vörösmarty et al., 2003; Parekh, 2004; Amegashie et al., 2011; Wisser et al., 2013), social and cultural (World Commission on Dams, 2000; Cremin, 2009) concerns and also economic preoccupations (Manatunge et al., 2009; Barbier et al., 2009; Richter et al., 2010) emerged in the 1990s and remain today in research and public debate (Alhassan, 2009; Moore et al., 2010).

However, the calling into question of the durability of storage dams is not only for reasons of these negative externalities but also and above all because their lifetimes are governed and limited by sedimentation (Palmieri et al., 2001), the subject of the present study. Indeed, storage dams control large portions of drainage basins at the world scale and thus intercept a non-negligible proportion of sediments shifted by erosion (Syvitski et al., 2005; Walling, 2006). The proportion remains difficult to measure as there are many uncertainties (Walling, 2012). However, according to Vörösmarty et al. (1997) from 16% to 25% of suspended matter in the world is thought to be intercepted by storage dams. This interception results in annual losses of theoretical reservoir capacity that are the subject of vary variable estimates at the world scale. The best known is that provided by the World Commission on Dams (2000) that mentions annual losses of between 0.5% and 1%. The estimates given by the sediment transfer model developed by Wisser et al. (2013) mention smaller values: applied to 6,399 large reservoirs with total theoretical capacity of 5,990 km^3, the model gives annual average losses of 0.64% per reservoir, but the figure is 0.13% when the average is weighted by the capacity of each reservoir. Subsequently, according to Wisser et al. (2013), 5% of theoretical reservoir capacity has been lost by sedimentation at the world scale; this is increased to as much as 10% by other authors (White, 2001).

These estimates at a world scale must be refined for very varied local conditions and therefore require case studies for individual sites. Reservoir sedimentation analyses and, more broadly, analysis of the rhythm of sedimentation in the large drainage basins were grouped for the whole of

Africa by Vanmaercke et al. (2014). These data are still comparatively rare today for sub-Saharan Africa, with the exception of Burkina Faso and Mali but for small drainage basins (Mietton, 1986; Droux et al., 2003). The assessments should be improved using the substantial technical progress made in analysis of reservoirs sedimentation.

2 The research question

This is the context of the research described in this article on the sedimentation dynamics of the Sélingué dam reservoir in south-west Mali. The reservoir on the Sankarani, a right bank tributary of the Guinean and Malian upper Niger (Figure 1) was filled in 1982. Study of the reservoir is aimed at replying to several questions at different scales.

(1) In a synchronic approach, the first step is the making of an accurate assessment of the water storage capacity of the reservoir taking the long-term sedimentation dynamics into account in order to provide firm and precise information for resource management by the stakeholders concerned, as the latter have no recent estimate of sedimentation. For this, it was found necessary to update the 1964 data compiled by Italconsult, the Italian consulting engineers who drafted the design of Sélingué dam, completed in 1973 by United Nations data. The update is particularly necessary as the maximum water level of the reservoir was increased from 348.5 m to 349 m in 1998 to increase storage capacity (Touré, 2004).

(2) It is then necessary to use a diachronic approach in order to confirm or refute the sedimentation rates calculated by Italconsult (1964) and then by the United Nations (1973). These figures put forward the hypothesis of sedimentation of the storage basin to level 337.5 m in 57 years, that is to say annual sediment deposit of 1,500,000 m³ in the reservoir (United Nations, 1973).

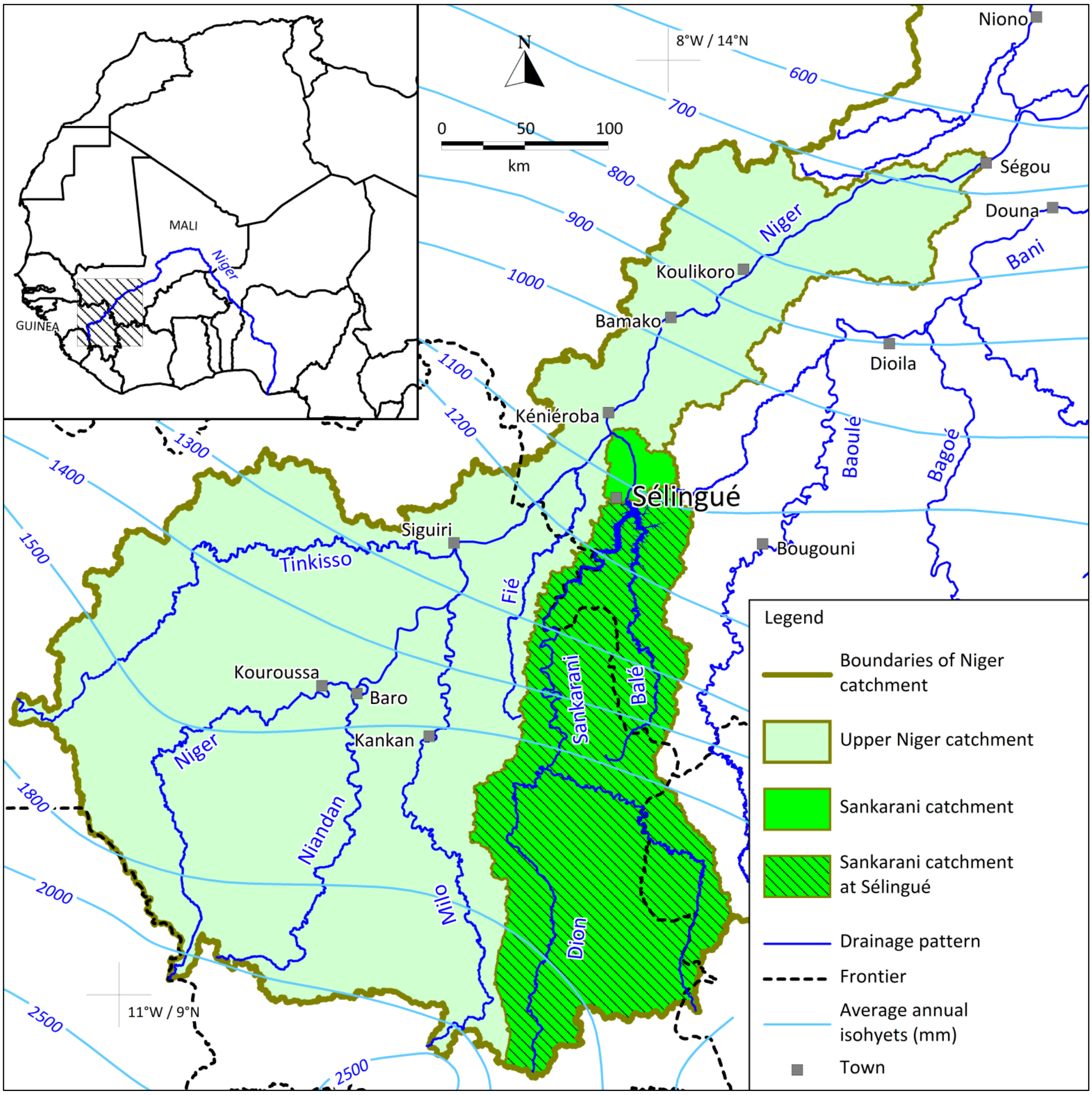
    Here, the study is for the various managers of the reservoir such as EDM (Energie du Mali) and DNH-Mali (Direction Nationale de l'Hydraulique du Mali) and also the ODRS (Office de Développement Rural de Sélingué) and the Niger Board, all of whom are members of the Reservoir Management Board that is focused on four main objectives: production of hydroelectricity, irrigation, navigation improvement on the Niger by helping during low water periods and the fishing development. There is not necessarily synergy between the four objectives. On the contrary, they can lead to conflicts of interest between stakeholders in the dam (Kupper et al. 2000), calling for more detailed knowledge of the functioning of the reservoir and its capacity, with the latter depending in turn on the rate of sedimentation.

(3) In a more fundamental way, evaluation of the sedimentation of the Sélingué reservoir is to be seen as an indicator of the specific degradation of the drainage basin of the Sankarani and the Balé, its main tributary, giving better knowledge of the factors governing sedimentation dynamics. The drainage basin of the Sankarani is all the more interesting as a subject for study as the plant cover is homogeneous, consisting of nine-tenths tree savannah and dense dry forest. It is therefore representative—in a large catchment—of the sedimentation rate in a given bioclimatic environment, in this case south-Sudanian savannah.

3 Geographic context of the study zone

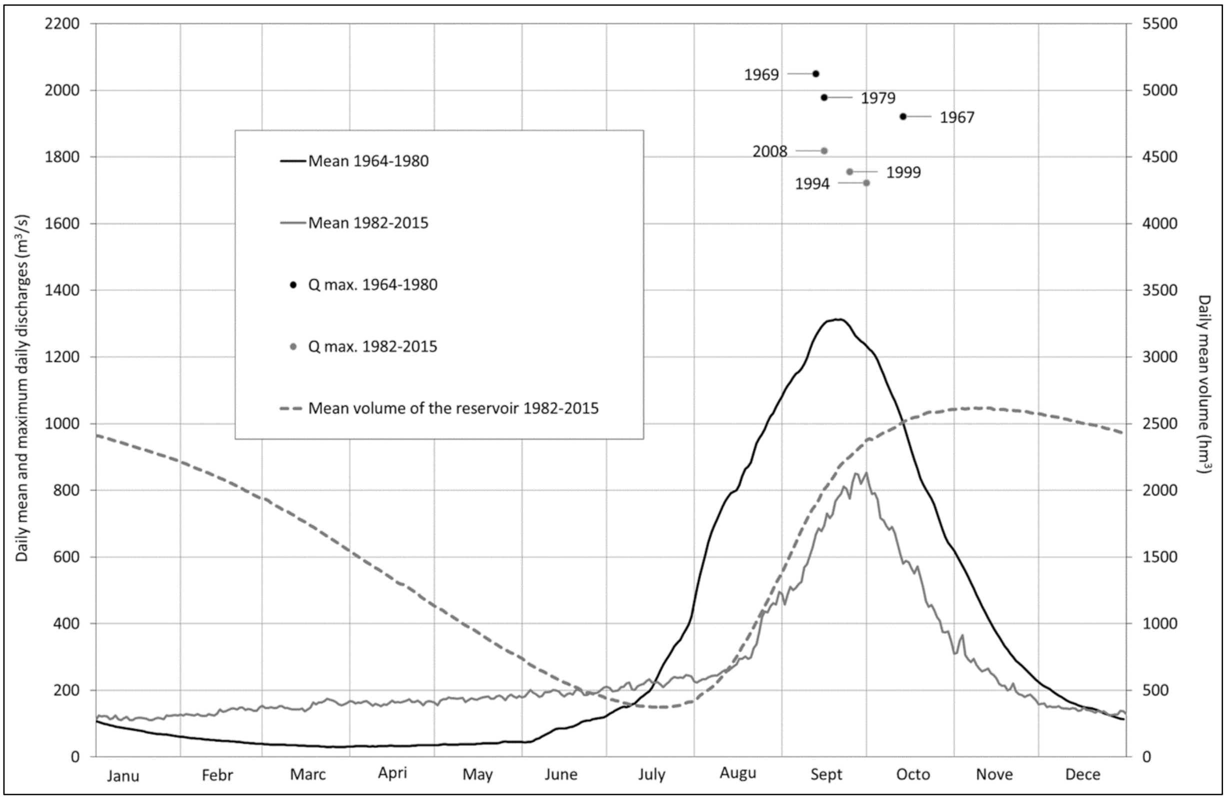
Sélingué dam is on the Sankarani, a right bank tributary of the Niger, some 150 km south-west of the city of Bamako (Figure 1). Today, it is the only large dam in the upstream part of the Guinean and Malian upper Niger basin, although many other projects are being examined (Mahe et al., 2011). The drainage basin of the Sankarani totals 32,140 km^2, that is to say 25% of the Guinean and Malian upper Niger basin. At its maximum operating level (349 m), the dam creates a reservoir about 100 km long with an area of 460 km^2 and capacity of 2.7 thousand million m³. Maximum depth is 22 m at the upstream toe of the dam (IRD, 2008; Laval, 2008).

Figure 1: Location of the Sankarani drainage basin and Sélingué dam (after Ferry et al., 2012b) and average inter-annual precipitation (after L'Hôte & Mahé, 1996).



The Sankarani catchment is in a region with a tropical climate marked by a dry season from October to May and a rainy season with most of the annual precipitation, totalling an average of 1370 mm during the period 1951-1989 in this south-Sudanian zone; the catchment is between the 1100 mm isohyet in the Sélingué region and the 2000 mm isohyet in the extreme south. This tropical pattern is seen through the contrasted hydrological regime, with high water (average daily discharges greater than 800 m^3/s) from mid-August to mid-September, and a long, very marked low water period from November to mid-July. During the 1964-1980 situation (preceding the construction of the dam), the low water period features discharges frequently smaller than 200 m^3/s. The Sankarani gauging station is 1 km downstream from the dam and the effect of the latter has obviously been seen since 1982 as a result of several factors: constant turbine operation, flood routing (at least before the filling of the storage basin) and low water back-up. Filling of the storage basin leads up to a of the flood start a month later than before, between mid-July and mid-August (Figure 2).

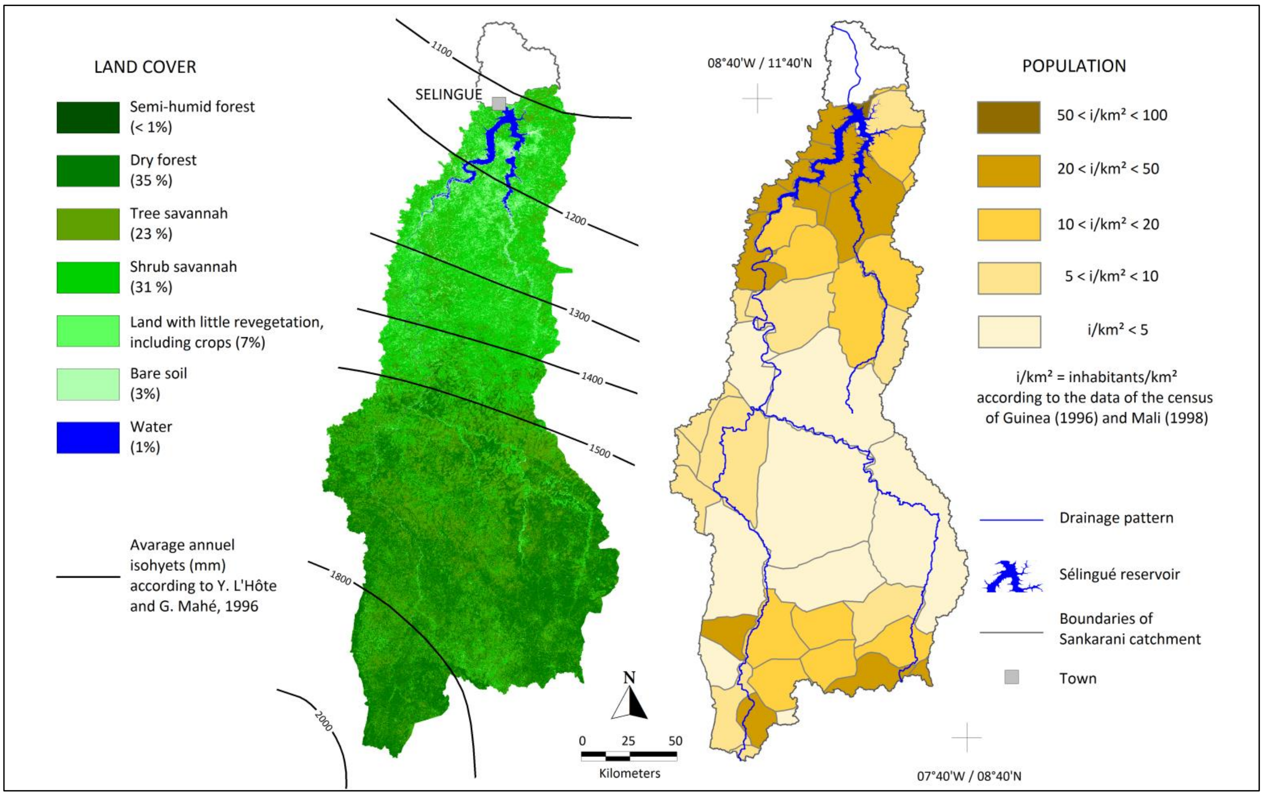
Figure 2: Daily mean discharges and examples of maximum daily discharges at Sélingué before (natural regime) and after construction of the dam. Daily mean volume of the reservoir (hm^3).



At the scale of the catchment, of which the Sélingué reservoir is the outfall, the density of plant cover increases rapidly from north to south. It consists mainly of Sudanian shrub and tree savannah, wooded savannah or dense south Sudanian dry forest and, in the extreme south, Sudano-Guinean forest (Figure 3). The Sankari and Balé catchments are in the lower and mid-Precambrian craton (DNGM, 1987), with little-marked relief consisting mainly of buttes and hills.

The Sankarani catchment is very sparsely populated, with average density of 11 persons per km². The population is concentrated mainly on the shore of the lake, with occupations being fishing, extensive livestock farming and flood recession agriculture. However, the latter occupation is a potential cause of damage in the immediate neighbourhood of the reservoir.

Figure 3: Plant cover and average inter-annual precipitation in the Sankarani drainage basin (after the data of D. Ruelland et al., 2008, L'Hôte & Mahé, 1996, and population censuses in Guinea (1996) and Mali (1998).



4 Methodology

A reminder of the different methods for measuring the silting of reservoirs is followed by a description of the methodology chosen here, with details of the choice of bathymetric soundings, their density and also their limits.

4.1 The bathymetric data gathering

Existing work on the measurement of sedimentation in reservoirs is based on very varied methods, including the following.

(1) Topographical survey of reservoirs (Haregeweyn et al., 2012), consisting of plotting a bathymetric map of the reservoir on a given date and comparing this with a previous map to use the difference to calculate the volume of sediment deposited over a known period of time.

(2) Study of the sediment load at the reservoir intake and discharge using gauging stations. This has the disadvantage of measuring only material in suspension and not the bottom load (Jansson, 1988). These measurements are also more or less discontinuous in time and may not be effective during the most effective transport by floods. In our study, measurement assumes inflow gauging not only on a single watercourse but on two (the Balé and the Sankarani, with the latter in frontier position!)

(3) Study using remote sensing determines the surface area of water on two dates with the same filling level (Goel et al., 2002) and deducing the progress of sedimentation.

(4) Making sample pits distributed uniformly over the bottom of the reservoir; the filling of the pits and the sediment composition are measured between two dates (Ermias et al., 2006).

The methods can be used together. For example, Roca (2012) combined bathymetric soundings and gauging stations for a study at Tarbela dam in Pakistan. The results found using one or other method can then be extrapolated to other reservoirs that are not observed directly using *ad hoc* methods, as was done by Wisser *et al.* (2013) and Minear & Kondolg (2009).

The first method was chosen for the present study as it is very well documented was described very early on by Eakin (1936) but has benefited from important recent technological advances. Manual soundings have been replaced by sophisticated technical techniques based on echo sounding to plot real bathymetric profiles (Dunbar et al., 1999). This is more accurate and less random than the gauging of solids in suspension as the bottom load is also taken into account, making it possible to consider sedimentation measurement over a long period, thus incorporating discontinuities in sediment movements and significant inter-annual variations of the specific rate of degradation (Vanmaercke et al., 2012). Finally, unlike remote sensing, it can be used to examine the lowest parts under water—those that are the most useful for assessment of sedimentation.

Bathymetric recordings were made at Sélingué using apparatus of the 'Acoustic Doppler Current Profiler' (ADCP) Work Horse and Rio Grande type used as echo sounders and fitted on inflatable boats with outboard motors. An ADCP connected to a microcomputer both transmits and receives waves. The ultrasonic waves transmitted ('pings') are reflected either by the bottom or by particles in suspension in the water and return to the receiver at different frequencies. The different frequencies are used to determine the depth of the bottom and particles and also to measure their rate of movement together with that of the boat (in relation to the bottom). The ADCP is also fitted with a compass and can thus record depths according to movement (bathymetric profile) using the Win River® program.

The start and finish of each bathymetric profile were georeferenced using a Garmin 60 GPS. The validity of the depths recorded was checked frequently using manual point measurements (release of a buoy during profile recording and then depth measurements using a graduated gauge). These data were completed in poorly navigable areas by point measurements with a staff gauge and using more than 3,000 points on the bank; observations were also georeferenced using a Garmin 60 GPS. Finally, the depth of the water in the reservoir given by the gauge at the limnimeter was attributed to all the bathymetric information gathered.

Twenty-nine days in the field resulted in 427 bathymetric recordings with 732 km of cross sections (approximately every 500 m) and longitudinal sections (Figure 4) and the collection of 4163 GPS points, 3015 of which are point measurements of depth.

After verification, the bathymetric observations collected in the field (recordings and point measurements) were converted into the same body of altimetric references and put into form for import into a geographic information system (GIS, Mapinfo® program). The GIS table thus has 681,476 altimetric points drawn mainly from the bathymetric recordings made using ADCPs. The contour of the lake at 349 m was drawn from a 2008 Google Earth® image. On this basis, the contours of the reservoir level between 328 m and 348 m were plotted by linear interpolation between the altimetric points drawn from the bathymetric observations. The density of the observations did not allow automatic plotting with a geostatistical program and the plotting of the curves was sometimes an interpretation. The topographical map of the reservoir is shown in Figure 5. This figure showing the topography of the reservoir today was compared with the topographical maps of the impoundment plotted in 1964 by Italconsult.

Figure 4: Location of the profiles plotted by IRD in 2008 (IRD, 2008).

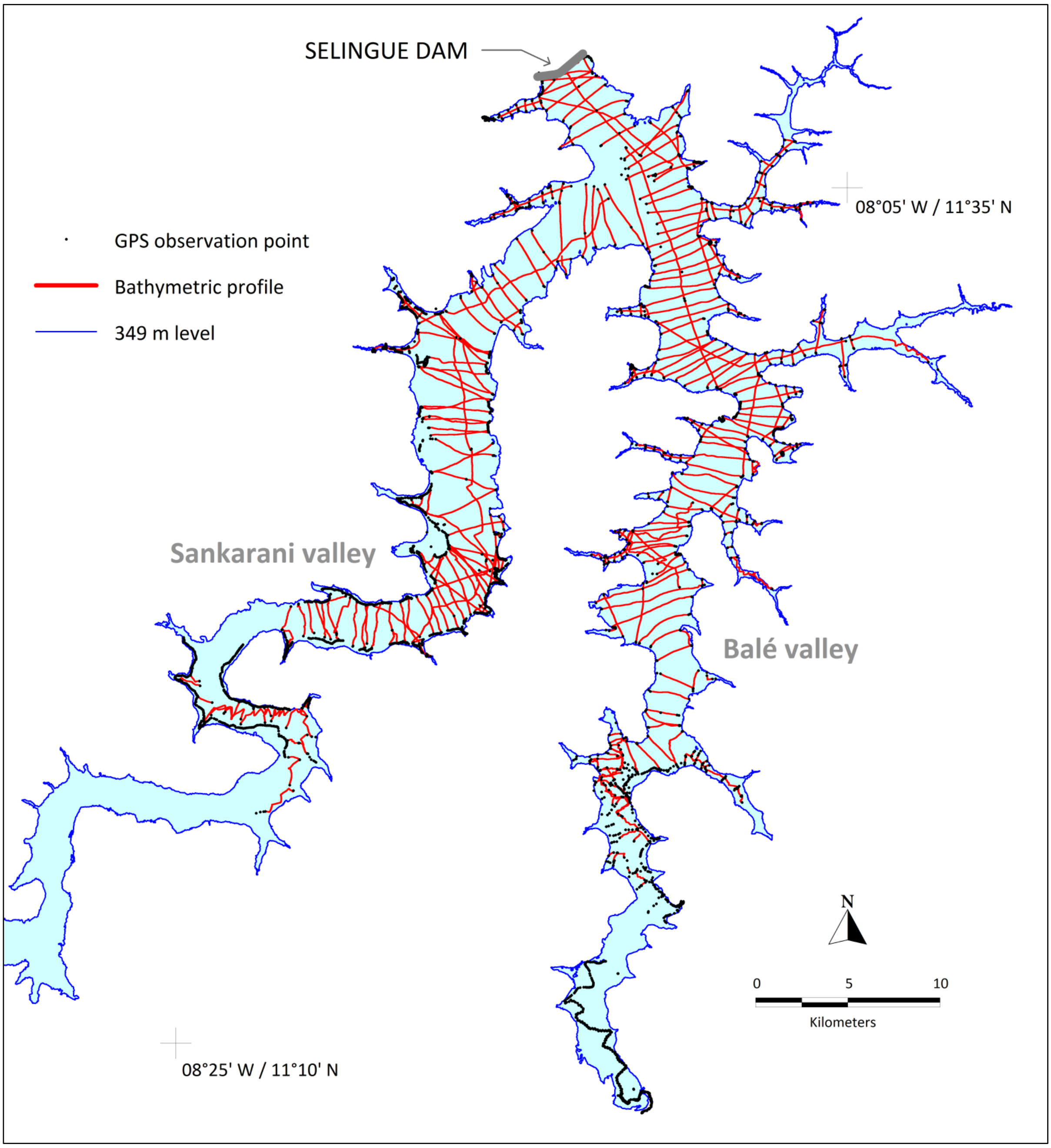
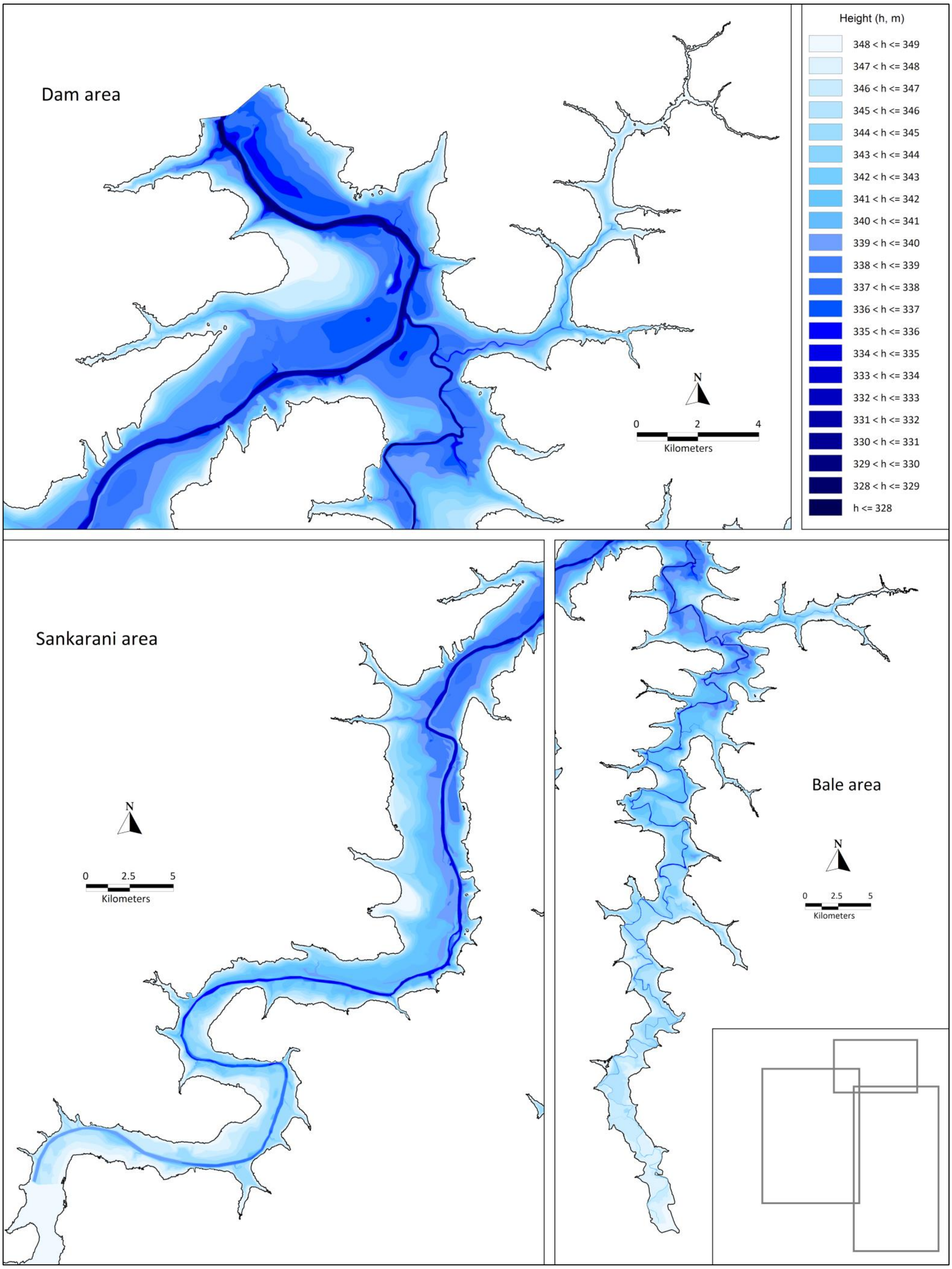


Figure 5: Topometry of Sélingué reservoir (IRD, 2008).



4.2 Methodological limits and strong points

The approximations in the design by Italsoft should be remembered first of all. To start with, the margin for error in the method used to plot the 1964 topographical map—stereoscopic interpretation of aerial photographs—is not negligible. In addition, neither the number of altitude measurements made in situ nor the way in which the thickness of the canopy are specified in the document accompanying the Italconsult maps. As the aerial photographs of the time are not available it is not possible to determine the characteristics of the forest and savannah cover at the time. However, the frequency of dead trees that sometimes rise to more than 10 m about the surface of the water is an indication of the presence of tree cover (gallery forest) prior to the filling of the reservoir. The second critical point is that the Italconsult map does not show contour lines above 347 m, whereas the maximum storage level has been 349 m since 1998. Finally, the extrapolation of the rate of sedimentation in Sélingué reservoir performed by the United Nations in 1973, as a complement to Italconsult's 1964 results, was drawn up using only 10 measurements of suspended matter using samples collected upstream of Sélingué reservoir and also data collected by Nedeco on the Niandan (Figure 1) at Baro in 1959 (in a different drainage basin and some 200 kilometres from Sélingué dam).

Difficulties were also encountered in the present study in both the data collection campaigns and in the processing of this data. Indeed, from a technical point of view various obstacles may have affected bathymetry locally: dead trees under the water that are sometimes invisible and extremely dangerous for the apparatus, fishermen's nets, floating plants (bourgou), insecurity resulting from the military authorities forbidding the taking of measurements on the Guinean bank of the lake. In addition, obtaining bathymetric profiles was limited by the water level in the reservoir (lower than 348 m from February onwards). As a result the plotting of the 347, 348 and 349 m contours is less accurate.

Conversely, the very fine resolution of this study for such a vast reservoir can be highlighted. Indeed, the point density is remarkable when seen against the size of the reservoir (15 bathymetric points per hectare in the reservoir covering 460 km^2). The international literature rarely gives information about the point density attained (De Araújo et al., 2006; Soler-López, 2001). To the best of our knowledge, the only work using a higher point density has been for small reservoirs: for example, 71 points per hectare in the very detailed study by Haregeweyn et al. (2012) concerning a 51-hectare reservoir (1000 times smaller than Sélingué) in Ethiopia; 7 to 23 points per hectare for reservoirs of 35 to 105 hectares in Ghana in the study by in Adwubi et al. (2009).

5 Results

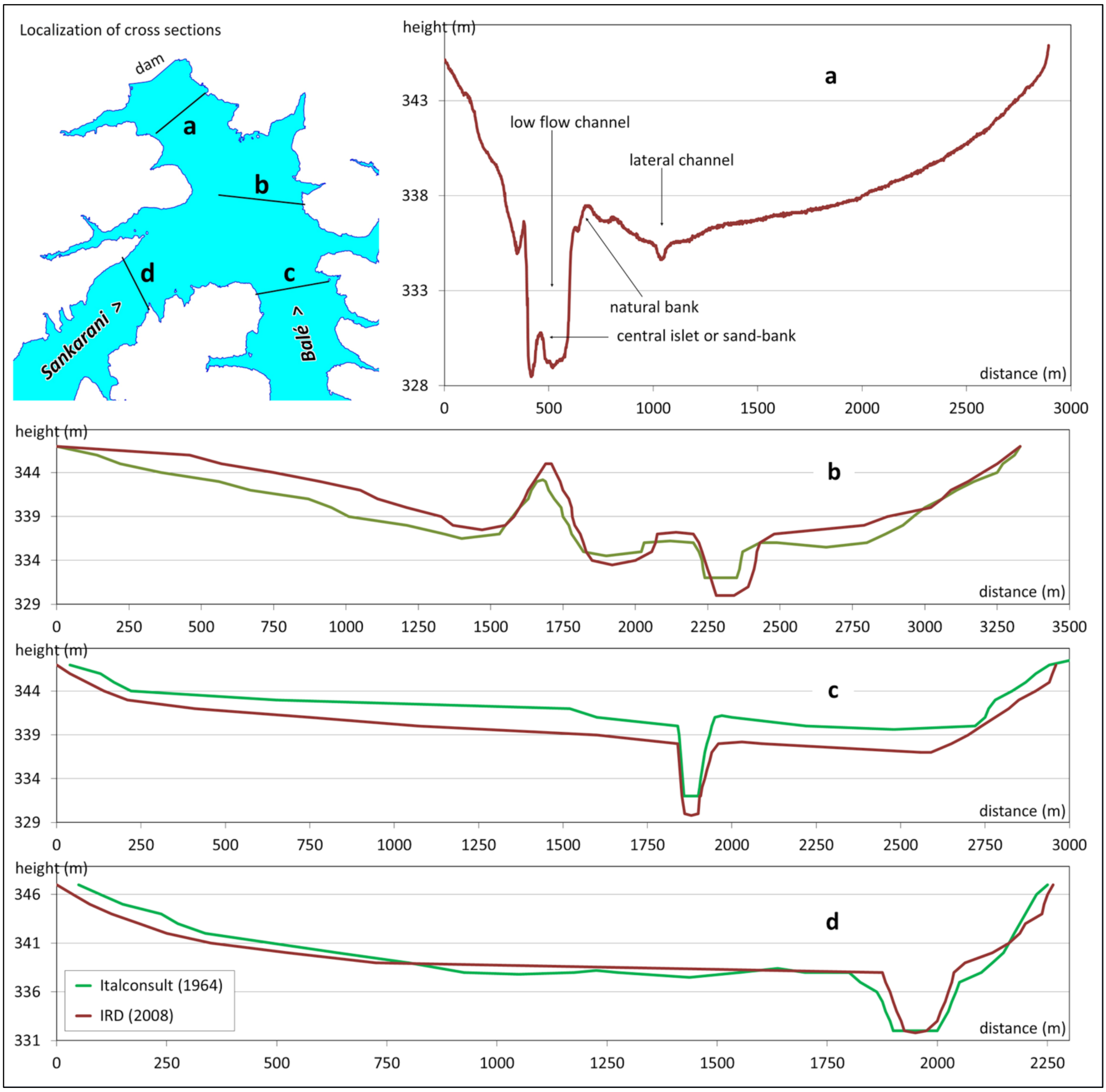
First of all, it is noted that the hydraulic management of the dam has no effect on silting of the storage basin as there is no bottom dewatering outlet.

5.1 Practically no silting of the reservoir

Examination of the four cross sections in the central part of the reservoir (Figure 6-a and Figure 6-b) and in the two main branches (Balé, Figure 6-c and Sankarani, Figure 6-d) does not reveal any significant silting of the reservoir, especially in the deepest zones where any sedimentation phenomenon would be more likely to occur.

More generally, the topographical profiles plotted using the bathymetric recordings made in 2008 and shown in Figure 6-a show that the original forms are perfectly conserved. Alluvial plains, low flow channels with steep banks with islands or sandbanks, riverbanks, secondary channels and small tributaries can be seen clearly. It is noted that former gallery forest was detected in certain areas. These features alone lead to suggesting that there has been no significant silting of the storage basin since it was filled in 1982.

Figure 6: Diachronic comparison of profiles of the Sélingué impoundment (IRD, 2008).



The superposition of three cross sections plotted from Italconsult (1964) and IRD (2008) maps of identical areas (Figure 6-b, Figure 6-c and Figure 6-d) also reveal the permanence of pre-existing forms. Superposition also reveals different results according to the cross section; in (b) the level of the lateral parts was higher in 2008 than in 1964, indicating accumulation of sediment; in (c) the levels are lower overall in 2008, a feature that is difficult to explain; in (d) there is little difference between the 1964 and 2008 cross sections. It is noted that the lowest elevations of the low-water channel are always less than those of 2008 in the three profiles. The inaccuracy of the topographical plotting of 1964 probably results from the limits of photointerpretation as the part under water was not sounded and there was substantial vegetation on the banks. In addition, the distortions of the 1964 topographical maps and the deformations resulting from the type of support (paper) observed when they were set geographically lead to supposing that the positions of the profiles are slightly different, giving possible differences in altimetry. Finally, as is seen below, the probable difference of about 0.60 m between the 1964 and 2008 altimetric references can only give a qualitative dimension to the comparative analysis of the profiles. In spite of these few inaccuracies, the continued presence of relief and in particular the fact that the former channels have not been filled with sediment rules out the hypothesis of significant sedimentation in the reservoir.

Analysis of the depth-area (D/A) and depth-volume (D/V) curve of the reservoir (Figure 7) by Italconsult (1964), EDM[1] (undated) and IRD (2008) supports the preceding results. However, the partial information provided in the Italconsult study report and by EDM make this analysis somewhat delicate. The latter is based first on five curves plotted on different dates (Table 1 and Figure 7).

Table 1: Inventory of depth/area and depth/volume curves available.

Depth-area curves			Year	Range of elevation (m)
	(2)	Italconsult	1964	336-347
	(4)	IRD	2008	327-349
Depth-volume curves				
	(5)	Italconsult	1964	336-347
	(6)	EDM	current	340-349
	(7)	IRD	2008	327-349

The D/A curves of Italconsult (2) and IRD (4)—the latter after smoothing—were plotted from the 1964 and 2008 topographical maps. It is noted that in all cases the areas given by the IRD curves are larger than those of the Italconsult curve from 338 m. Italconsult's overestimation of the elevation of the lowest levels (low-water channel, thick vegetation on banks and thalwegs) should be seen in relation to the plotting of the topographical map by photo-interpretation. The D/V curves (5 and 7) deduced from the data above, show smaller volumes in 1964 than in 2008; the same applies to the EDM curve (6), which is clearly difficult to accept.

When the values of the D/V curve of Italconsult (5) are attributed to the values of the D/V curve of EDM (6) for levels of 340 m or lower, the two curves overlap perfectly (5 and 8). EDM's D/V curve (6) used for the operation of the reservoir is therefore identical to that of Italconsult but only covers the useful capacity of the reservoir (altitude >340 m). As for the initial D/V curve (5), the volumes of the new D/V 'Italconsult + EDM' curve (8) are much smaller than those of the 2008 IRD D/V curve (7).

Assuming that there has been no significant sedimentation in the reservoir since 1982 (date of filling), the 'Italconsult + EDM' curve (8) can be recalculated using the IRD 2008 D/V curve at 336 m as the volume. The D/V curve recalculated in this way (9) is very close to the IRD 2008 D/V curve (7) from 336 m to 340 m but is lower at above 340 m. When an altimetric correction of -0.60 m is applied to the 'Italconsult + EDM + IRD' D/V curve (9) above 340 m, the resulting D/V curve (10) is practically identical to the 2008 IRD D/V curve (7). No explanation has been found for the difference, which may be simply the result of an error in the retranscription of the basic data or, as happens fairly frequently in diachronic topometric analyses, a change in the altimetry references between 1964 and 2008 and more precisely between 1964 and the installation of the limnimetric gauge on the dam. This was probably done in 1981/1982, before the reservoir was filled[2].

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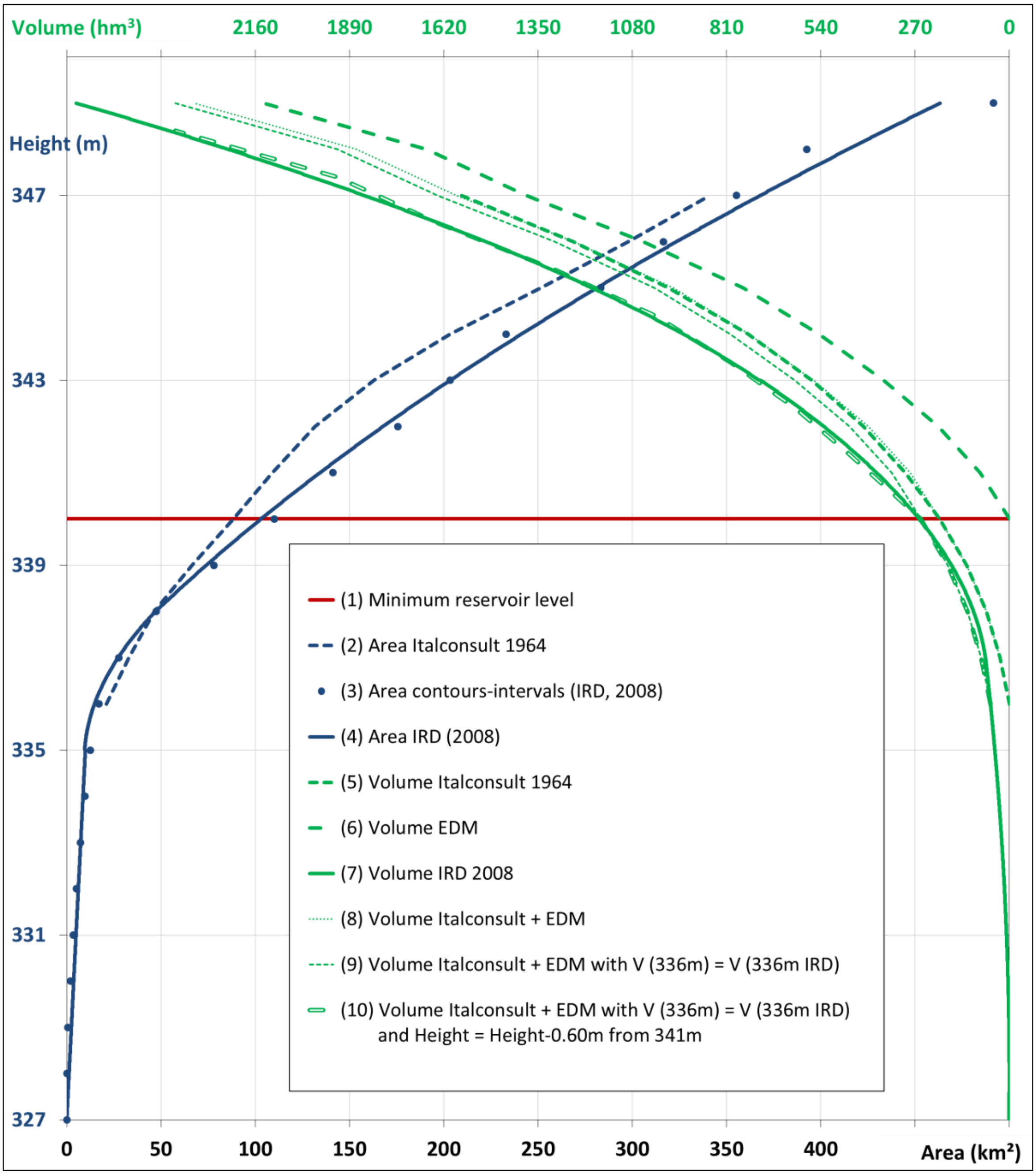
[1] The curve currently used by EDM (Electricité Du Mali).

[2] Depths recorded at the limnimetric station at the dam do not display any erratic features since 1982.

Figure 7: Depth-area and depth-volume curves for Sélingué dam plotted by Italconsult (1964), EDM (no date) and IRD (2008).



If we use the major hypothesis of a difference in altimetric references between 1964 and 2008, examination of the D/A and D/V curves reveals little or no change in storage capacity and hence no marked sedimentation.

It is stressed that confirmation of a difference in altimetric references between 1964 and 2008 would have serious consequences, as it would present management of the reservoir into question. Complementary field observations should be made, especially with regard to the setting of the limnimetric gauge in relation to the dam and the maximum water level.

5.2 Erroneous previous interpretation

The estimate of the rate of sedimentation of the storage basin made by Carlo Lotti in the 1973 United Nations report conflicts with the results described above. According to the author, the sediment accumulated in the storage basin should reach level 337.5 m 57 years after filling. This figure is the result of a simplistic calculation based on regular sediment accumulation from the heel of the dam. In reality, silting processes are much more complex and occur throughout the reservoir, even mainly in zones further upstream (as a result of the slowing effect when rivers flow into the reservoir). Using Carlo Lotti's figure of 1.5 x 106 m^3 of sediment arriving in the storage basin each year and considering that sediments accumulate in a regular manner at the heel of the dam—which is not the case, as mentioned above—the sediment level should have reached 334.78 m in 2008 (26 after the filling of the reservoir) with 39 x 106 m^3 deposited. However, the minimum reservoir level observed at the heel of the dam in 2008 was close to 327 m, equivalent to Italconsult's 1964 observation that the average level of the bottom was 328 metres. It can therefore be considered that the estimate made by Carlo Lotti in 1973 was erroneous.

6 Discussion

The weak sediment deposit dynamics in Sélingué reservoir should be seen in perspective at a larger scale and compared to those observed in other reservoirs at a global scale and at that of the south-Sudanian zone in sub-Saharan Africa in order to approach the factors that play a decisive role in our study zone.

6.1 Sedimentation rates observed in the world as a whole and in south-Sudanian Africa

At the world scale, many studies have been aimed at measuring reservoir sedimentation rates and identifying the factors involved. However, comparisons between reservoirs should be seen in perspective. In addition to the methodological differences mentioned above, it must be stressed that sedimentation rate figures can be expressed in various ways: total sediment volumes on the beds of reservoirs, specific degradation related to the size of the drainage basin or as a percentage of loss of reservoir capacity. Such evaluation of decrease in capacity is the most pertinent approach for managers and decision makers as it finally shows the useful life of the reservoir. However, the definition of useful life varies from one author to another (Lajczak, 1996; Adwubi et al., 2009; Haregeweyn et al., 2012), which makes comparisons more difficult.

In addition, reducing sedimentation to an annual percentage loss is risky as it gives the mistaken impression of linear silting whereas sedimentation varies in both space and time. In the short term, exceptional events can cause considerable variation in sediment volumes from one year to the next (Chanson, 1998; Ben Mammou & Louati, 2007; Boun Heng, 2013). Sediment rates also vary in the longer term and according to changes in climate or type of land use (Morris & Fan, 1998): as an example, the rate of sedimentation of Djorf Torba dam in Algeria doubled from 1986 to 2008 after the 1990s droughts that reduced plant cover and caused soil degradation. It is difficult to assess and quantify this variability in time. First, technical reasons make it difficult to measure sedimentation linked to an exceptional event (White, 1990), and second longterm changes are also difficult to assess for lack of long periods of observation (Chanson, 1998).

Taking these reserves into account, spatial comparisons nonetheless make it possible to assess sedimentation variability in the world's reservoirs—expressed as an annual percentage of lost capacity. As regards temperate zones, mention should be made of the work carried out in Japan on 922 storage dams and that showed annual average loss of 0.24%, with a high average of 0.42% in the Chubu region that is on tectonic lines (Sumi, 2006); this work is exceptionally exhaustive insofar as it can use the legal obligation of managers to measure sedimentation each year in reservoirs with a theoretical capacity exceeding 1 million m^3 (Kashiwai, 2005). Losses are generally greater in tropical regions. In Puerto Rico, the losses in 14 reservoirs of average capacity (1 to 56 million m^3) vary from 0.2 to 1.7% per year (Soler-López, 2001). In Java (Indonesia), a study (Boun Heng, 2013) performed on 12 medium-sized reservoirs (capacity of several tens of million m^3), losses vary from 0.58% at Lahor reservoir to 4.14% at Sengguruh reservoir.

In Africa more specifically, North Africa, Ethiopia and the Rift (Remini & Remini, 2003; Remini et al., 2009; Shahin, 1993) stand out for their high sedimentation rates. Data directly concerning capacity lost by sedimentation are scarce for other parts of Africa. However, mention should be made of the work by Adwubi et al. (2009) on four recent reservoirs in Ghana in a locally very eroded Sudanian savannah environment and whose useful life varies from 22 to 190 years (annual loss of capacity of between 0.5% and 4.5%), and the study by Sichingabula (1997) on 66 small reservoirs in southern Zambia and whose lifetimes are between 200 and 5100 years (losses of 0.02% to 0,5%). For other factors of comparison, use should be made of the data given in specific studies of degradation expressed in m^3/km^2/year or in t/ km^2/year. These show comparatively low values for sub-Saharan Africa, at least in the south-Sudanian zone. The map drawn by Jansson (1988) showing the different specific erosion measurements made at the world scale thus indicates specific erosion of generally less than 10 t/km^2/year in the south-Sudanian part of West Africa. The map is confirmed by the more recent examination by Vanmaercke et al. (2014): regional differences in Africa illustrate a range of figures from 0.2 to 15,700 t/km^2/year, with maximums in North Africa (in the Atlas region) and the African rift and low values in the drainage basins in West and Central Africa (less than 60 t/km^2/year). A figure close to 50 t/km^2/year is found at large drainage basin scale in Lake Volta in Ghana (Akrasi, 2005). Similar or small values (but based on suspended load alone) are found downstream of Sélingué dam in the 'Middle' Niger (Picouet et al., 2000).

6.2 The factors governing the practically complete absence of sedimentation in Sélingué reservoir

The factors involved in the sedimentation of a reservoir are well known: some are related to the climatic and physical features of the drainage basin and human occupation (Holeman, 1968; Walling & Webb, 1996; Morris & Fan, 1998; Balthazar et al., 2013) while others are related to the characteristics of the reservoir itself (Brune, 1953; Chanson, 1998; Lewis et al., 2013; Kashiwai, 2005).

- The morphological stability of the Sankarani drainage basin depends first of all on its small population density (average 11 persons per km^2), which is in turn linked to reasons of history (societies with less centralised power than in the Sudan-Sahel zone) and health (more numerous endemic diseases— onchocerciasis, sleeping sickness) and to different farming methods from one country to another (cotton growing is important in Mali at the same latitude as the upper Bani basin). There is no conflict between this and the fact that other south-Sudanian regions, with the exception of the Niger basin, such as Sikasso circle (Traore, 1978; Tappan & McGahuey, 2007) in Mali, are sectors in which use of land is much more marked. But even during periods of poor climatic conditions as in the 1970s and 80s, the vulnerability of these south-Sudanian zones should not be seen as being the same as that of the Sudano-Sahelian areas where there is a much more homogeneous 'overload' of people and cattle on the land.
- The corollary of this under-population is the maintaining of protective climactic vegetation. At the scale of the Sankarani drainage basin, as in the Upper Niger catchment in a more general manner, remarkable latitudinal zoning in relation to the rainfall gradient results in a succession of different plant formations that are all the more recognisable as the low population pressure has changed this fine arrangement very little. At Sudano-Guinean latitudes, the southern extremity of the basin hardly touches the semi-humid forest formations (less than 1% of the area of the basin) where inter-annual average precipitation is nearly 2 m. However, the major part of the basin displays the south-Sudanian character that is typical of dense dry forest (35%) and tree savannah (23%), that is nonetheless affected in the extreme north of the basin near the

reservoir, where it is replaced by shrub savannah (31%) that is typical of north-Sudanian landscapes.

Anthropogenic pressure is small in the drainage basin and it consists of very small percentages of bare (2.6%) or cultivated (7.3%) land. The population density is a little higher around the reservoir at some 20 persons per km² (Ferry et al., 2012a), but the increase around the reservoir of some 60% from 1976 to 1998 results more from the arrival of Bozo fishermen from the inner Niger delta than occupation by farmers (ODRS, 2003), and this tends to limit the impact as regards soil degradation. Furthermore, only the actual banks of the lake are suitable for farming when the water recedes during the dry season. The rare cultivated areas around the lake are flood recession fields. Only pastoral activity causes degradation of the environment around the lake because of trampling by cattle and burning off during the dry season.

- The absence of sedimentation is an important finding as its shows the quasi-stability of the environment perceived also by Ruelland et al. (2008), on the scale of a large drainage basin whose climactic cover is homogeneous. It confirms former results obtained on a much smaller scale, on experimental plots (Roose, 1980; Mietton, 1988). It is reminded that this stability is linked to the presence of a twin tree/herbaceous plant barrier, with the latter (tall and short Gramineae) certainly playing the major role as regards rain erosion and runoff. Only bush fires, and especially those late in the season, make these environments vulnerable but their effect at large drainage basin scale is fairly limited because of discontinuities in movement.

Other factors make a contribution: the longitudinal gradients are small at some 0.68 m/km, the soil is ferruginous with marked crust and releases little fine material when the hardened horizons are at the surface. However, the role that these play is only minor as their features are not such as to combat specific, markedly greater degradation in the north-Sudanian region. However, this absence of transport of solids is not linked to an absence of surface runoff on slopes. Indeed, the reservoir filling curves that are markedly identical from one year to the next show that the latter is not affected and fills fairly quickly (in about two months) during the second half of the 'winter' period (Figure 2).

The role played by natural plant cover is tremendous as its protective nature is sufficient to erase potential aggression by precipitation that becomes stronger from the Sahel to the Guinean zone, as is shown in Wischmeier's soil loss equation (USLE) (Roose, 1980).

7 Conclusion

This research shows the absence of significant sedimentation in the reservoir of Sélingué dam and the method and results are of definite interest.

First, specific erosion behaviour is shown in a drainage basin in a south-Sudanian environment. Indeed, Sélingué reservoir has the exceptional advantage of being the outfall of a drainage basin that is surprisingly homogeneous, given its area, unlike most of the large drainage basins studied at the global scale and that are much more heterogeneous (Ambroise, 1998) and subject to anthropogenic pressures and therefore little representative of a given climactic formation. The essential factors here among those affecting erosion are plant cover and its corollary, land use.

Second, 26 years after the filling of the reservoir (1982-2008) it makes it possible to update the preliminary estimates of reservoir sedimentation. The accumulation of sediment envisaged did not take place and the margins of error in the methodology used are not enough to render the result uncertain.

Finally, the work makes it possible to inform the many managers about the real, present capacity of the reservoir at different filling levels as the evaluation of sedimentation is combined with the updating of reservoir surface and volume data. This knowledge is essential for reconciling the various interests of the different managers and in particular to settle conflicts of use between irrigation and hydroelectricity.

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9 Annexes

9.1 Decimetric scale altitude(m) / surface (km^2) (IRD, 2008)

m	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
327	(0.0)									
328	1.2	1.3	1.5	1.6	1.7	1.8	2.0	2.1	2.2	2.3
329	2.4	2.6	2.7	2.8	2.9	3.1	3.2	3.3	3.4	3.6
330	3.7	3.8	3.9	4.1	4.2	4.3	4.4	4.6	4.7	4.8
331	4.9	5.0	5.2	5.3	5.4	5.5	5.7	5.8	5.9	6.0
332	6.2	6.3	6.4	6.5	6.7	6.8	6.9	7.0	7.1	7.3
333	7.4	7.5	7.6	7.8	7.9	8.0	8.1	8.3	8.4	8.5

334	8.6	8.8	8.9	9.0	9.1	9.2	9.4	9.5	9.6	9.7
335	9.9	9.7	10.0	10.3	10.7	11.2	11.8	12.4	13.1	13.9
336	14.7	15.7	16.6	17.7	18.9	20.1	21.4	22.7	24.2	25.7
337	27.2	28.9	30.6	32.4	34.3	36.2	38.3	40.3	42.5	44.7
338	47.0	49.8	52.4	55.0	57.7	60.3	63.0	65.7	68.5	71.2
339	74.0	76.8	79.6	82.5	85.4	88.3	91.2	94.1	97.1	100.0
340	103.0	106.1	109.1	112.2	115.3	118.4	121.5	124.7	127.9	131.1
341	134.3	137.5	140.8	144.1	147.4	150.7	154.1	157.4	160.8	164.3
342	167.7	171.2	174.7	178.2	181.7	185.2	188.8	192.4	196.0	199.7
343	203.3	207.0	210.7	214.5	218.2	222.0	225.8	229.6	233.4	237.3
344	241.2	245.1	249.0	252.9	256.9	260.9	264.9	269.0	273.0	277.1
345	281.2	285.3	289.5	293.6	297.8	302.0	306.3	310.5	314.8	319.1
346	323.4	327.8	332.1	336.5	340.9	345.4	349.8	354.3	358.8	363.3
347	367.9	372.4	377.0	381.6	386.3	390.9	395.6	400.3	405.0	409.7
348	414.5	419.3	424.1	428.9	433.8	438.7	443.5	448.5	453.4	458.4
349	463.3									

9.2 Decimetric scale altitude(m) / volume (hm3) (IRD, 2008)

M	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
327	(0.0)									
328	0.2	0.2	0.3	0.3	0.4	0.5	0.6	0.7	0.9	1.0
329	1.2	1.4	1.6	1.8	2.0	2.3	2.5	2.8	3.1	3.4
330	3.8	4.1	4.5	4.9	5.3	5.7	6.1	6.6	7.1	7.5
331	8.0	8.6	9.1	9.6	10.2	10.8	11.4	12.0	12.6	13.3
332	13.9	14.6	15.3	16.0	16.8	17.5	18.3	19.0	19.8	20.7
333	21.5	22.3	23.2	24.1	25.0	25.9	26.8	27.7	28.7	29.7
334	30.7	31.7	32.7	33.8	34.8	35.9	37.0	38.1	39.2	40.4
335	41.5	42.7	43.9	45.1	46.3	47.6	48.8	50.1	51.4	52.7
336	54.0	55.4	56.7	58.1	59.5	60.9	62.3	63.7	65.2	66.7
337	68.2	70.7	73.0	75.7	78.6	81.9	85.4	89.3	93.4	97.8
338	102.5	107.5	112.8	118.4	124.3	130.5	137.0	143.7	150.8	158.1
339	165.8	173.7	182.0	190.5	199.3	208.4	217.8	227.5	237.5	247.8
340	258.4	269.2	280.4	291.8	303.6	315.6	328.0	340.6	353.5	366.7
341	380.2	394.0	408.1	422.5	437.2	452.2	467.4	483.0	498.8	515.0
342	531.4	548.2	565.2	582.5	600.1	618.0	636.2	654.7	673.5	692.6
343	711.9	736.1	756.3	777.0	798.2	819.7	841.7	864.2	887.0	910.3
344	934.1	958.2	982.8	1007.9	1033.4	1059.3	1085.6	1112.4	1139.6	1167.2
345	1195.3	1223.8	1252.7	1282.1	1311.9	1342.1	1372.8	1403.9	1435.4	1467.4
346	1499.8	1532.6	1565.9	1599.6	1633.7	1668.3	1703.3	1738.7	1774.6	1810.9
347	1847.6	1884.8	1922.4	1960.4	1998.9	2037.8	2077.1	2116.9	2157.1	2197.8
348	2238.8	2280.3	2322.3	2364.6	2407.4	2450.7	2494.3	2538.4	2583.0	2627.9
349	2673.4									