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CONTRIBUTION OF GEOMATICS TO THE SUSTAINABLE MANAGEMENT OF WETLANDS IN GABON: CASE OF THE BAS OGOOUÉ RAMSAR SITE

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Abstract. In Gabon, we note the presence of several socio-economic activities on Ramsar sites whose different impacts are difficult to determine due in particular to the lack of reliable data. The Lower Ogooué Ramsar Site appears as a pilot space for the development of a methodology for the sustainable management of these ecosystems. Indeed, this site, the largest in the country and with a rich biodiversity, adjoins several industrial operations and other human settlements (cities and villages) in the province of Middle-Ogooué located in the center of Gabon. This study deals with the integrated management of Ramsar sites using geomatics tools. Also, the analysis of the functions, services and values of the wetland of the Lower Ogooué site, makes it possible to draw up a zoning plan which integrates development and conservation issues. This zoning plan has three large concentric zones dedicated to conservation, the uses of the populations and industrial activities. Similarly, taking it into account by the rulers should allow a participatory management mode of the site in order to involve all the actors, including the local communities, in the achievement of the sustainable development objectives of the study area.
Keywords: Gabon, Lower Ogooué, Geomatics, Ramsar Site, Participatory management, Sustainable development.

1. I NTRODUCTION

Formerly considered unhealthy and dangerous environments, the year 1960 is the starting point for all questions related to current environmental issues (Zaccai and Orban, 2017). Indeed, it is during this period, thanks to work that scientists sound the alarm about the rate of disappearance of biotopes in wetlands (Fournier et al, 2007). A disappearance due, in part, to a lack of knowledge of their important functions, of the valuable goods and services they provide. This finding subsequently led to the awakening of international awareness to adopt measures for the integrated management of the environment and species (Millennium Ecosystem Assessment, 2005).

The idea of establishing a convention on wetlands took shape at the International Conference of the MAR (for MARshes, MARais , MARismas) program in 1962, which focused on the drainage of marshes and other wetlands in Europe, d on the one hand, and the decline in numbers of birds, an immediate result of this phenomenon, on the other hand (Matthews, 1993). The text of the convention on wetlands was adopted nine years later, on February 2, 1971 in Ramsar, Iran. It is the first international convention concerning the conservation and sustainable use of natural resources (The Ramsar Convention, 2016).

Wetlands are rich and diversified environments, whose multiple functions and values have only recently been recognized (Fustec and Lefeuvre, 2000). They have experienced a sharp decline worldwide for several decades and are now all more or less threatened and/or degraded, due to human pressure exerted on these ecosystems (Turner, 1992), but also due to climate change (Murdoch *et al.*, 2000). The current influence and evolution of wetlands, particularly in highly anthropized landscapes, currently represent a major environmental challenge, both in terms of water resources and biodiversity or the state of the atmosphere (Rapinel, 2012).

For some years, GIS and remote sensing space techniques have been used to study changes in water stocks in large river basins on time scales ranging from a few months to several. Entering into force in Gabon in 1987, the Ramsar Convention currently has nine sites, the majority of which are superimposed on national parks, from which they benefit from management tools and resources (Mboumbou Makanga, 2022). The largest of them, Bas-Ogooué (No. 1851), does not overlap with any national park and does not benefit from any management plan in application. The purpose of this work is to synergize a set of geographical tools to guide the first management plan for a Ramsar site in Gabon.

2. METHODS

2.1. Location of the study area

The Bas Ogooué Ramsar site (No. 1851) covers an official area of 1,370,000 hectares. It has in constellation, within a radius of less than 70km, the Lopé National Park, to the northeast, the Waka National Park to the southeast, the National Park and Ramsar site of (small) Loango (No. 352) to the southwest and the presidential reserve and Ramsar site of Wonga Wongué (No. 351) to the northwest.

On its own, it represents almost 50% of all the sites inscribed by Gabon. It is located in the center-west of the country, in the coastal sedimentary basin, straddling the provinces of Ogooué-Maritime and Moyen-Ogooué. The site extends from the approaches to the Ogooué delta, in the west, to Ndjolé, in the east, and encompasses the entire area known as the "region of the Ogooué and lakes".

It enjoys dual status as an area of international importance, as it is also recognized as an «Important *Bird Area*» (IBA, No. GA006). It is a critical area for the conservation and safeguarding of bird colonies found in the various lakes located south of the site and on the sandbanks of the Ogooué. This site is home to a significant number of endangered species (IUCN Red List) such as the whalers' tern (*Sternula balaenarum)*, a migrant from southern African nesting areas; but also protected species (Act No. 016/2001) such as the manatee (*Trichechus)* and the hippopotamus (*Hippopotamus amphibius)*.

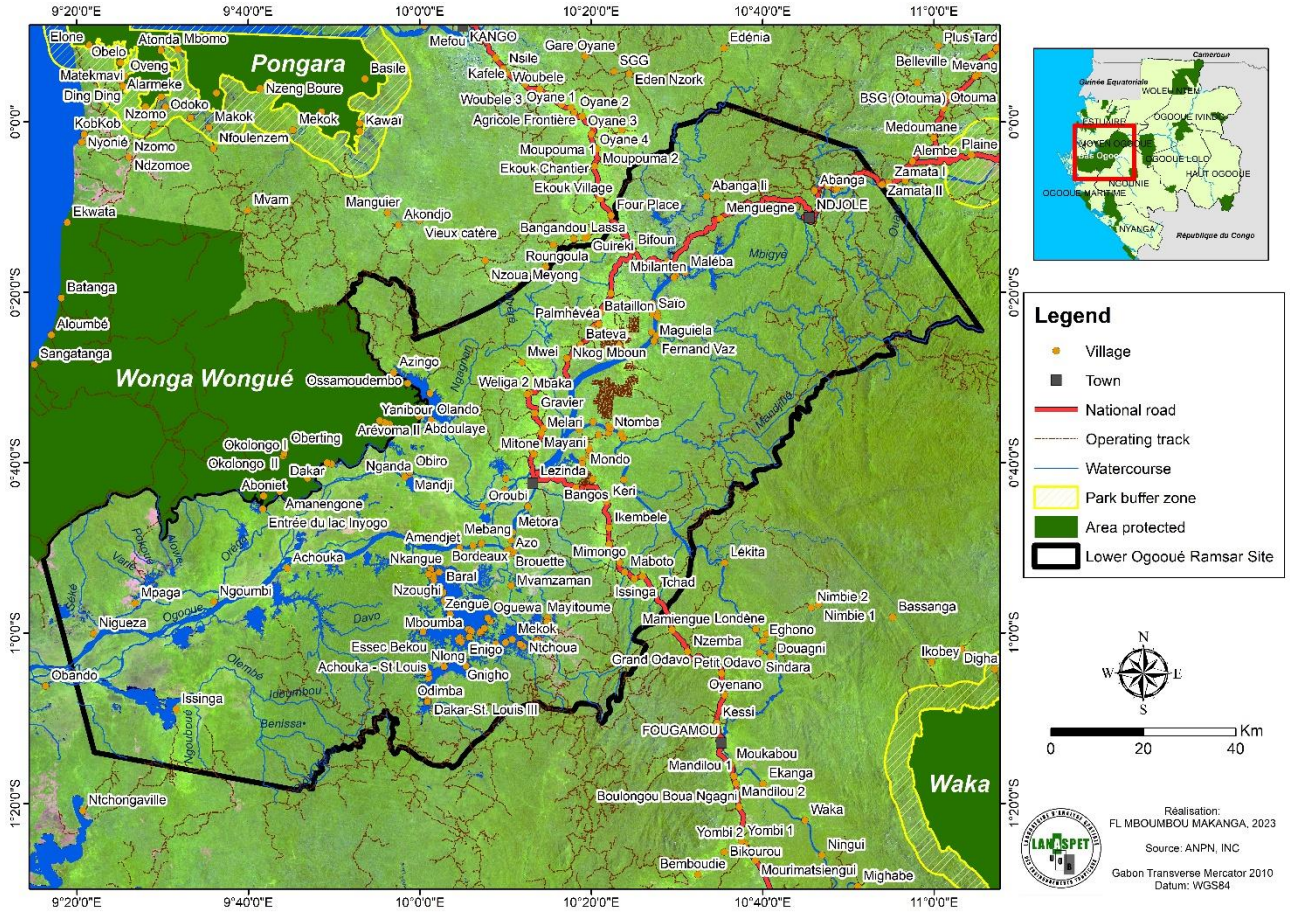

Figure 1: Location of the Bas-Ogooué Ramsar Site

The omnipresence of water on this site makes it a veritable hydrological reservoir, certainly the most important in the country. Nevertheless, if half of the area is occupied by bodies of water, rivers, streams and

lakes, the rest bears luxuriant vegetation, with a varied landscape and species. The populations of diversified animal and plant species contribute to the maintenance of its biological diversity, due to the interactions existing between them.

2.2. Methodology

The data used is of two types: pre-existing data and data acquired directly from the field. All of this data made it possible to draw up a zoning plan for the Bas Ogooué Ramsar site in two main stages: the delimitation of the wetland and the delimitation of the conservation zones based on the study of the functions of the wetlands (Figure 2, below).

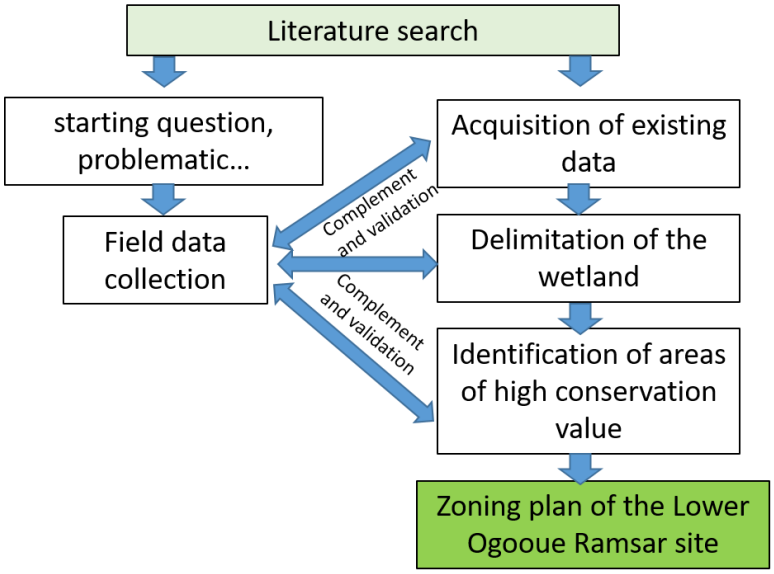

Figure 2: Methodological flowchart

a. Delimitation of the wetland and hydrogeomorphological units

The delimitation of the wetland of the Bas Ogooué Ramsar site is the result of a crossing of layers from data from various sources. It is based on the method of Rapinel (2012) which is based on the combination of a set of layers to generate the potential wetland which integrates both functional areas and those which have lost their wet character through backfilling, concreting of surfaces etc.
This method makes it possible to identify the wetland in its entire extent, before gradually bringing it back to the current wetland which includes permanent and temporary wetlands. The layers leading to this delimitation are:

- The alluvial type layers from the geological map which give an initial envelope of potential wetlands (Schnebelen N. and Laroche B., 2013)
- The TWI index which offers undeniable potential for the detection of wetlands (Verin M., 2021). It is calculated from the ALOS PALSAR Terrain Corrected image, according to the formula:

$$TWI = ln\left(\frac{SCA}{\tan\beta}\right)$$

Where SCA is the specific drainage area and β the slope angle

- The land cover map which allows to refine the results concerning the wetlands, by taking into account the wetland habitats, initially. Subsequently, the layer representing the building was used to subtract the potentially concreted areas. A second wetland envelope corresponding to the effective wetland according to Mérot and *al* (2006) is thus obtained. This effective wetland will be the mask for all other analyzes in the wetland.

As for the hydrogeomorphological units, they allow a spatialization approach for a functional approach to wetlands. It divides the wetland into four compartments: water surfaces, depressions, embankments and ridges. The delimitation and characterization of the HGMU were carried out using TanDem X data. This data seems sufficiently precise to identify the topographic variations within the wetlands both at the fine scale (1/5,000th) and medium (1/ 25,000th).

b. Determination of the functions and zoning of the Bas Ogooué Ramsar site

Four wetland functions have been inventoried over the entire effective wetland. These are the functions of stream flow maintenance, flood reduction, denitrification and fish and widlife habitat. The intensity of these functions was measured from the hydrogeomorphological units and 18 other descriptors using the multi-criteria analysis method (table 1 below).

The descriptors are in reality the elements of the environment which can act negatively or positively on the studied function. The influence of each descriptor is scored out of five: "zero" representing the absence of impact, "one" a weak or bad influence and "five" a very strong influence or a very good contribution to the function. High value wetlands and core areas are inferred from wetland functions, services and values.

Table 1: Descriptors used in the analysis of functions and areas of high conservation value

Results	**Descriptors**
Functions of support for low water level, flood reduction, denitrification and fish and widlife habitat.	1- Presence/absence of drainage ditches, 2- density of the drainage network, 3- ratio of length of the wetland to contact length of the slope, 4- length between the wetland and the slope by linear type, 5- density of wooded features, 6- road connectivity, 7- micro-topography, 8- Topographic Wetness Index (TWI), 9- vegetation roughness, 10- density of water surfaces and lowland wetland systems. funds, 11- vegetation transpiration, 12- irrigation, 13- hydromorphic vegetation density, 14- productivity indicator, 15- grassland management method, 17- occupation composition soils and types of vegetation, 18- the duration of flooding
High conservation value wetlands	1- Stream flow maintenance function, 2- flood clipping function, 3- denitrification function, 4- fish and wildlife habitat function, 5- wetland values (remarkable flora and fauna), 8- services rendered by the wetlands (carbon storage, anthropogenic activities etc.)

The zoning plan was drawn up according to the recommendations of the Ramsar Convention Secretariat (The Ramsar Convention, 2010). Among the zonings it proposes, we have opted for that of biosphere reserves, given the complexity of land use in the site. Thus the zoning plan takes into account three zones: The central zone which corresponds to the conservation zones, the buffer zone which serves as a transition zone with the industrial activities relegated to the peripheral zone, which constitutes the third zone.

3. RESULTS AND DISCUSSION

3.1. Delimitation of wetlands and HGMUs

The extent of effective wetlands is estimated at 509,836 ha, a total much lower than the predominantly non-humid zones. In fact, the wetland represents only 37% of the entire Ramsar site (Figure 3, below).

The hydrogeomorphological units are divided into four classes: riverine and depression, slopes, franges and mineral flats (figure 4, below). The riverine and depression zones, which constitute the lowest zones of the site, represent the majority class and occupy 59% of the wetland.

Figure 4 below indicates that the spatial configuration of these hydrogeomorphological units is typical of alluvial valleys. There is indeed a wide central alluvial plain, bordered by so-called slope zones, which in turn are overhung by peaks (so-called mineral flat).

The analysis of the hydrogeomorphological units predicts that the functions will be more intense in the central zone of the wetland, given the vast extent of the depression. The presence of the ridges and embankments at the ends confirm the reality of the map on the ground, which indicates that these wetlands are bordered, for the most part, by dry land forests.

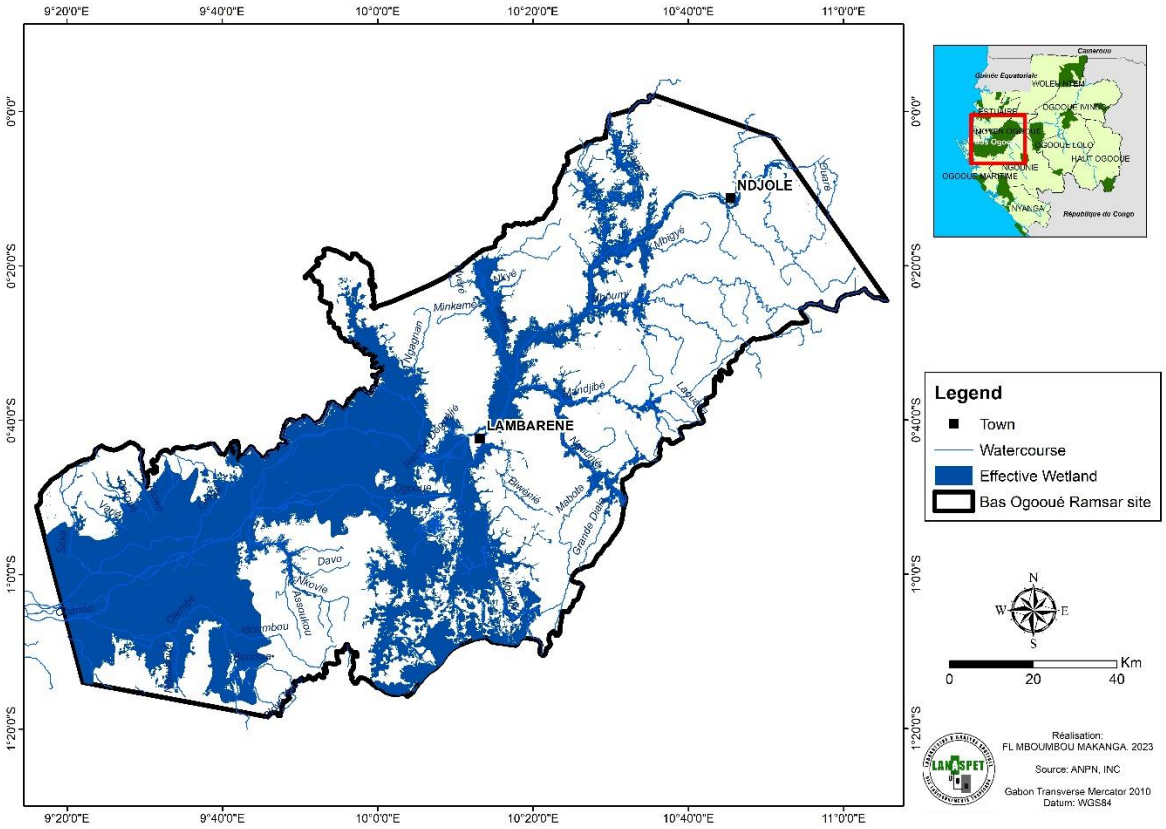

Figure 3. Delimitation of wetlands in the Bas Ogooué Ramsar site

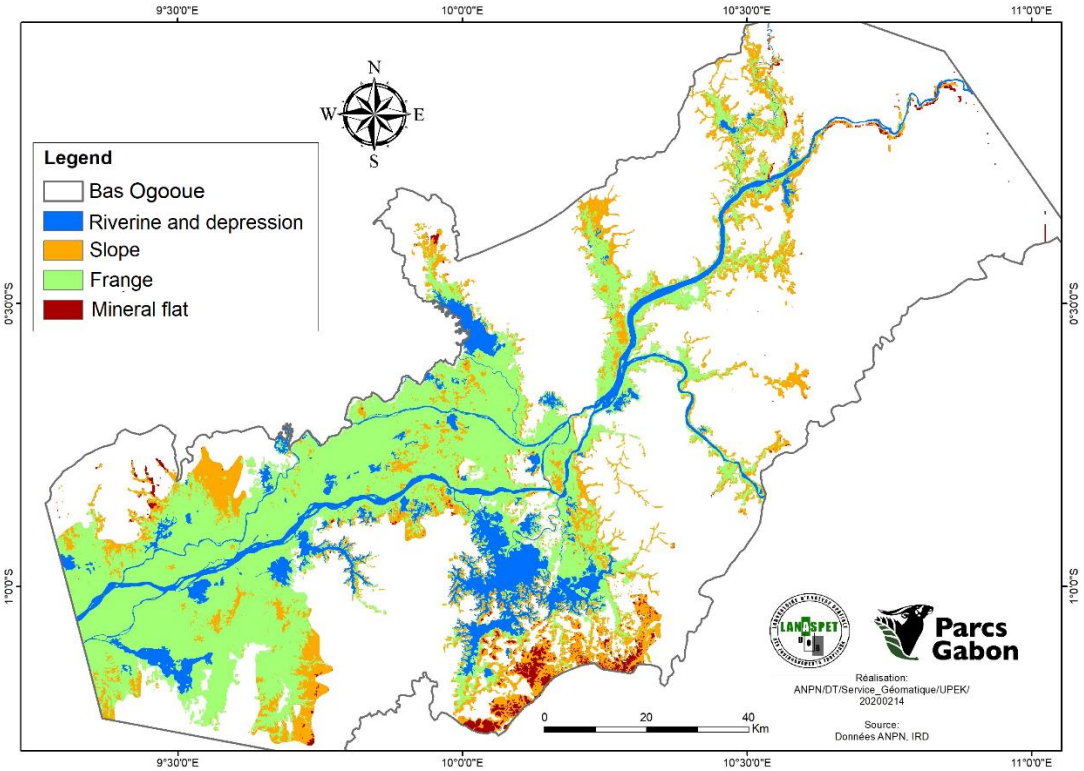

Figure 4 Spatial configuration of HGMUs in the wetland of the Bas Ogooué Ramsar site

3.2. Application to ecological functions

Using the analysis of 18 descriptors, we identified four ecological functions: stream flow maintenance, flood reduction, potential denitrification and fish and widlife habitat. Divided into two types, linear and surface,

the descriptors were deduced from the cartographic databases at our disposal, as well as by automatic processing of remote sensing data.

Concerning the flood clipping function, the majority of wetlands (50%) have an average interest and 49% have a low interest. Only 1% has a strong interest in this function. These are therefore the marshes of Ebel, Azingo, Alombiè as well as the tributaries of the Onangué and Anengué lakes which have a high potential for flood reduction. However, within the previously mentioned sectors, certain HGMUs sometimes corresponding to bulges, have a lower flood curtailment potential. Indeed, open water areas, as well as those close to artificial surfaces, record the lowest values.

The stram flow maintenance, meanwhile, is relatively average for all the wetlands, with 24% of the surface area of the wetlands being of very low interest. However, some hydrogeomorphological units are of greater interest, particularly in the alluvial plains of the Great Lakes and the Ogooué, south of Lambaréné. The intensity of the function varies from "medium" to "very strong" in the alluvial plain zones, while it is "weak" in the slope zones and very weak in the highest zones. The areas with very high intensity are those of Alombiè, Azingo, Oguémoué, Evaro, Ezanga and Onangué lakes.

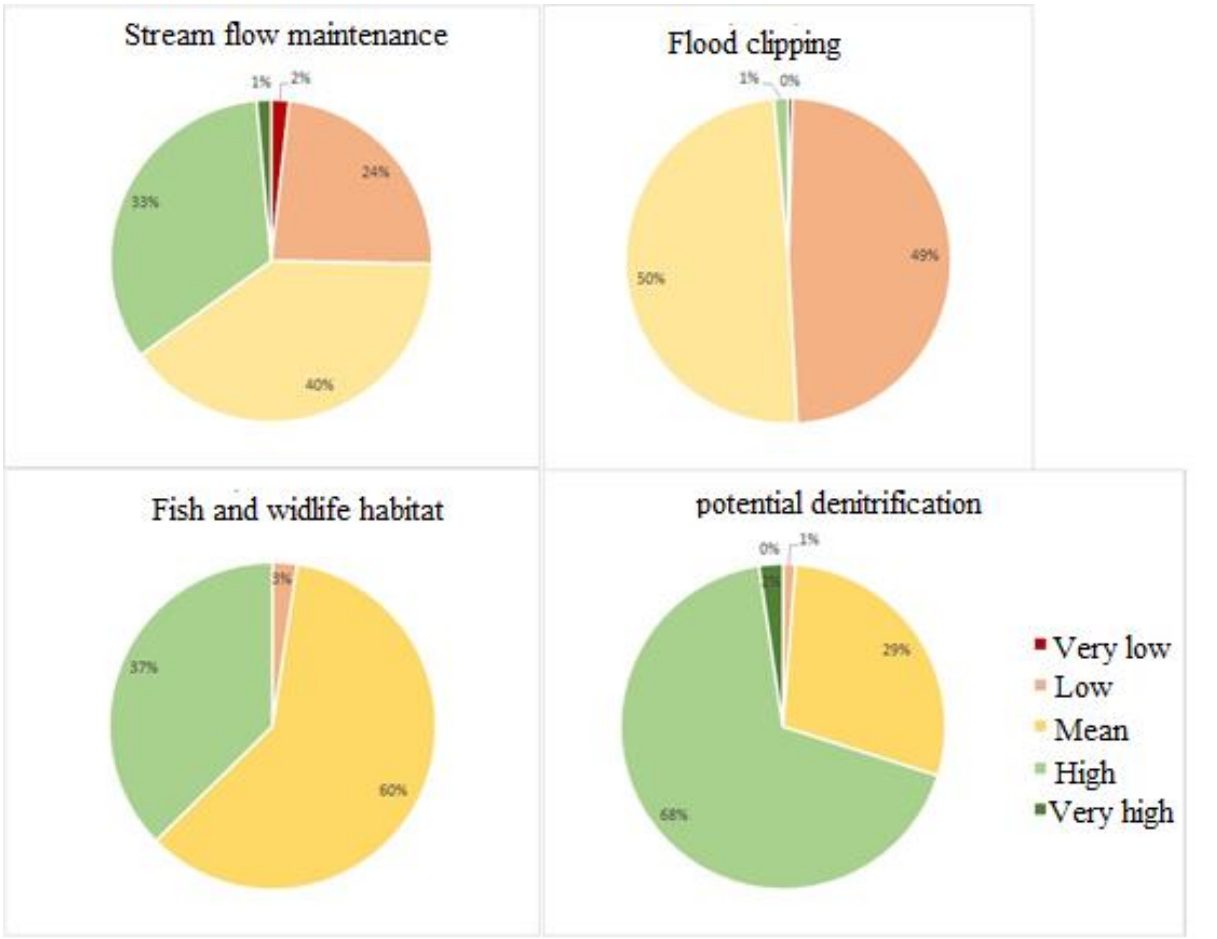

Figure 5. Distribution of classes of functional interest of wetlands in Bas Ogooué

The denitrification potential is globally strong to very strong over all the wetlands. More than half of the surface area of wetlands (68%) is of high interest. Almost no sector has low interest, and only 29% have medium interest. Generally speaking, alluvial valleys have a fairly strong functional potential with respect to polluting flows, while the situation in the meanders is more contrasted.

Fish and wildlife habitat for wetland species is essentially medium (60%). It is however strong for the marshes of Denguelié, Ebel, Ogooué, as well as the regions of the great lakes (except Azingo). Other sectors such as upstream of the Mbiné River seem to be of great interest for this function. The spatial evaluation of the fish and widlife habitat of the wetland, based on remote sensing data, shows significant disparities. The central marsh areas as well as the small alluvial valleys have significant functional potential for biodiversity. Conversely, certain areas of the slope, adjoining the non-wet zone, have a low potential for this function.

3.3. Definition of core or so-called conservation areas

According to UNESCO (2021), a core area is a designated portion of territory that has a strictly protected area contributing to the conservation of landscapes, ecosystems, species and genetic variation.

Overall, the site has an average ecological value distributed, mainly in the alluvial valley, in which are scattered the large areas of high conservation value around which the central or conservation areas have been digitized. Apart from these eight areas, two others have been added based on our field surveys. These are the wetland of the Mbiné River, reputed to be home to a large concentration of hippopotamuses, and that north of Lake Azingo recognized as a spawning ground and reputed to be a favorable habitat for the manatee.

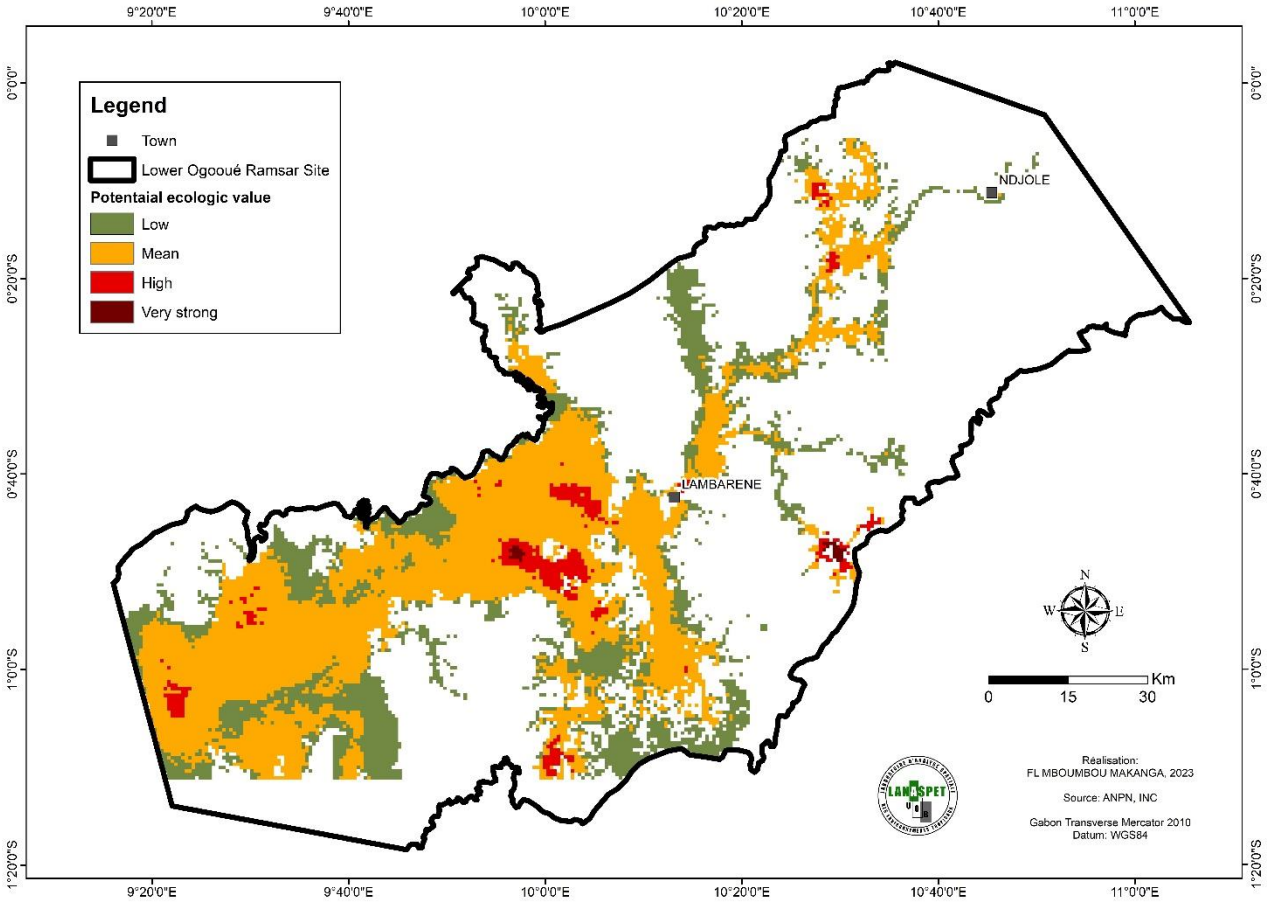

Figure 6 Distribution of HCV wetlands on the site

A total of 10 conservation areas have been delineated and represent a total area of 115,103 ha, i.e. 22.58% of the entire effective wetland and 8.44% of the Bas Ogooué Ramsar site (Table 2 and Figure 7, below).

These zones are mainly distributed in the zone of the upper delta of the Ogooué where there are six of them. In a straight line, the Oguémoué-Ezanga section seems to be a crucial area for conservation. It alone groups together 4 central zones (figure 6). Nevertheless, there are areas of large voids, in particular the northeast sector (on the side of the left bank of the Ogooué and the southwest area (in the area of Lake Ovowé). These voids are generally explained by the fact that in these regions, dry land ecosystems dominate wetlands, and the low intensity of functions in the Lake Ovowé area must be taken into account.

Table 2: Conservation area in the Bas Ogooué Ramsar site

conservation area	Area (in ha)	Share of wetland	Share of Ramsar site
Alombie	7124.63	1.40%	0.52%
Azingo	1853.18	0.36%	0.14%
Ebel Abanga	6704.23	1.32%	0.49%
Evaro	26871.84	5.27%	1.97%
Lambarene	221.28	0.04%	0.02%
Mbiné	18833	3.69%	1.38%
Ngounié downstream	6812.57	1.34%	0.50%
Obando	12342.2	2.42%	0.91%
Oguemoue	8852.29	1.74%	0.65%
Ouango	25487.73	5.00%	1.87%
Total	**115 103**	**22.58%**	8.44%

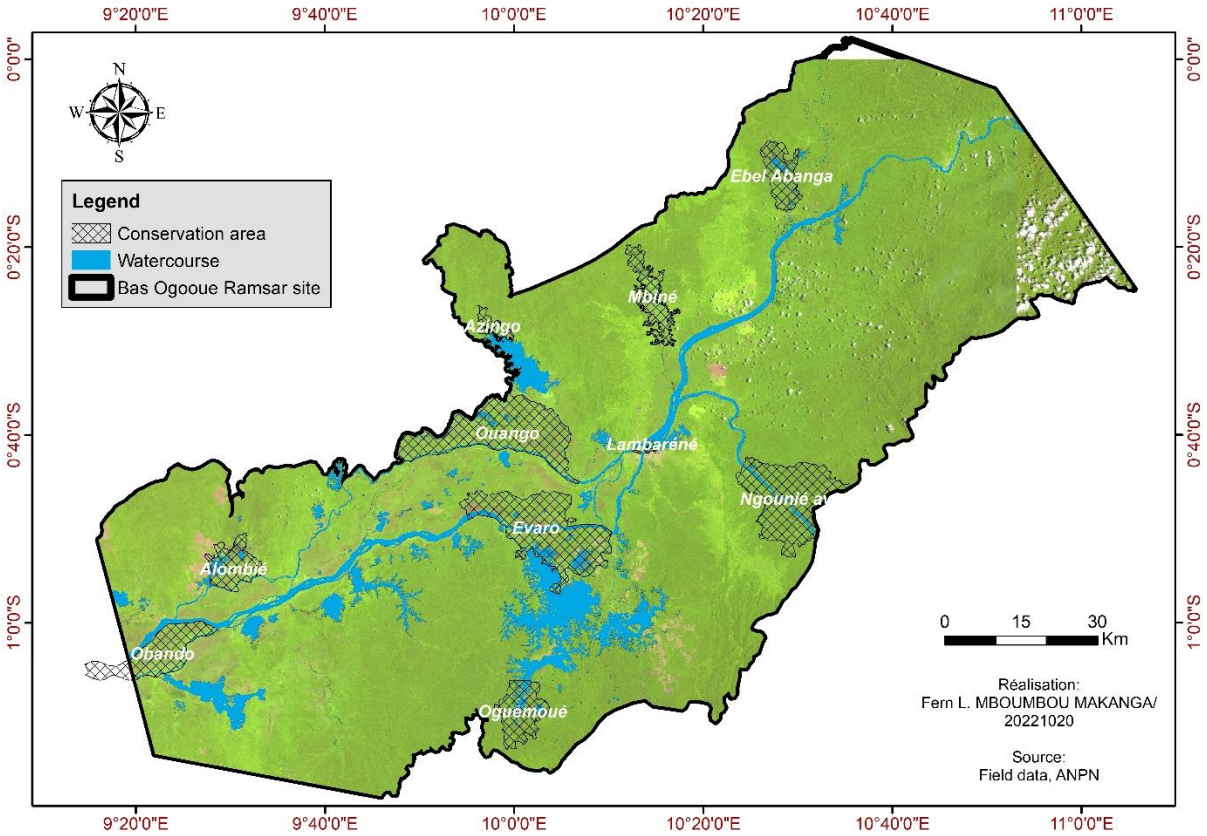

Figure 7. Distribution of conservation areas in the Bas Ogooué Ramsar site

3.4. Zoning of the Bas-Ogooué Ramsar site

The Bas Ogooué Ramsar site is not an environment empty of men, but a platform bringing together 2 towns, 166 villages, but also permits for industrial purposes granted to companies. All of the allocations for industrial purposes cover 8,479 km², or 60% of the site. It includes, in detail, forestry permits (8,164 km²), mining exploitation permits (467 km²), agro-industrial concessions (345 km²) and oil exploitation permits (approximately 88 km²).

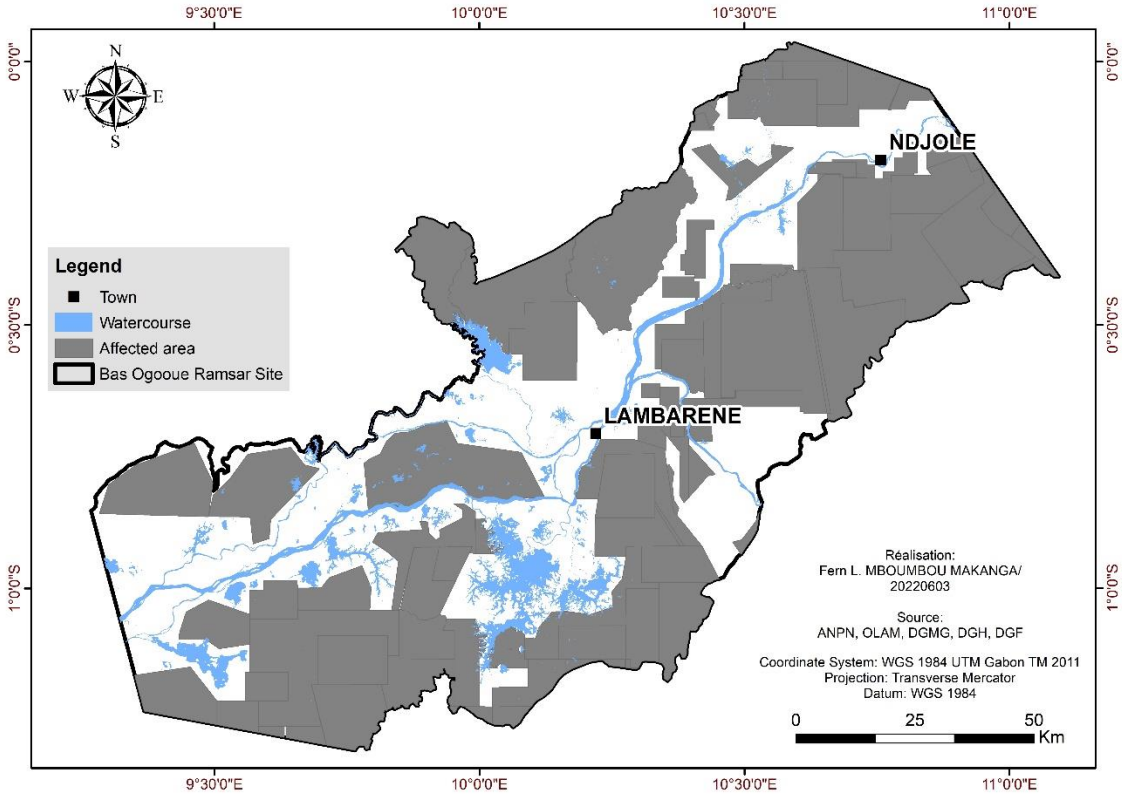

Figure 8. Areas affected in the Bas Ogooué Ramsar Site

Within the area allocated to industry, the forest concessions overlap with all the other concessions up to 900 km². In addition, data analysis proved that six assignments can be designated or categorized as inadequate. In fact, these are concessions with objectives or activities that are inappropriate or inadequate to the ecosystems of the areas of their installations. Note that all inappropriate allocations are forest concessions.

They total an area of 1,290 km² and can be grouped as follows:

- forest permits at savannah level,
- forest concessions in degraded areas,
- forest concessions where there are more wetlands.

The Bas Ogooué Ramsar site zoning plan provides for seven very distinct sub-zones spread over the entire Ramsar site (Figure 9, below). Like a concentric envelope, it develops from the center outwards. In the center, we have the current urban centers and the spaces of degraded vegetation, on which can be made projections of urban extension. Beyond the urban extension zone extends the *non aedificandi zones* made up of water and marshes.

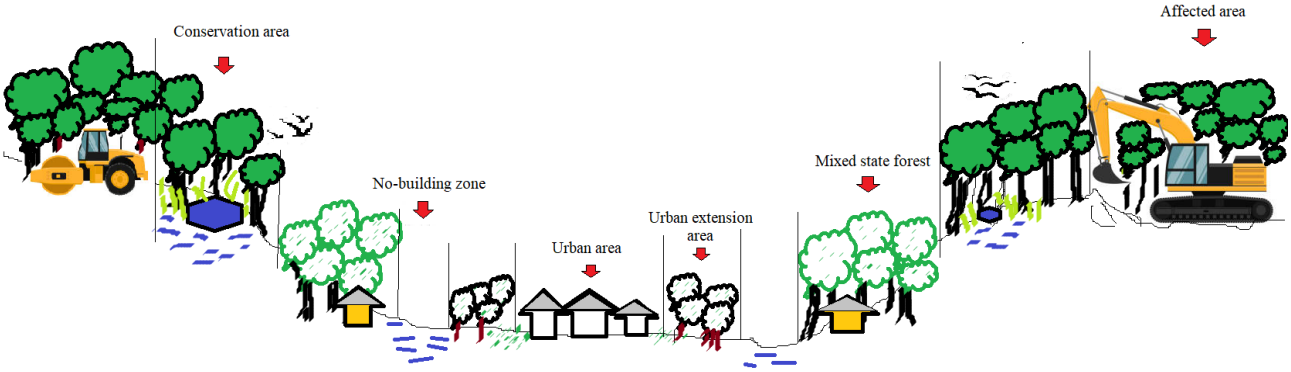

Figure 9 Zoning transect of the Bas Ogooué Ramsar site. Source: Mboumbou Makanga, 2022

Beyond these *no-building zones* are the mixed state forests which are not subject to any official allocation. Admittedly belonging to state forests, these areas are qualified as mixed because the settled populations have already been drawing their subsistence products there for a long time. These areas may at any time be subject to various assignments, but those relating to the rights of the communities should be given priority.

Beyond these areas extend the conservation areas to be islands to be preserved for their important ecosystem services. Finally, we have the affected zones which represent all the permits present on the site. It is important to specify that certain *no-building zones* and central zones overlap with certain forest permits. In essence, these superpositions should not generate any conflict, because the forestry law takes up the issues related to the preservation of wetlands of interest.

Thus, like the biosphere reserves, these seven management sub-zones can be grouped into three main zones:

- central wetlands corresponding to HCV wetlands;
- buffer zones corresponding to *no-building zones*, urban areas and urban extensions, community forests and mixed state forests;
- the transition zones corresponding to the affected zones.

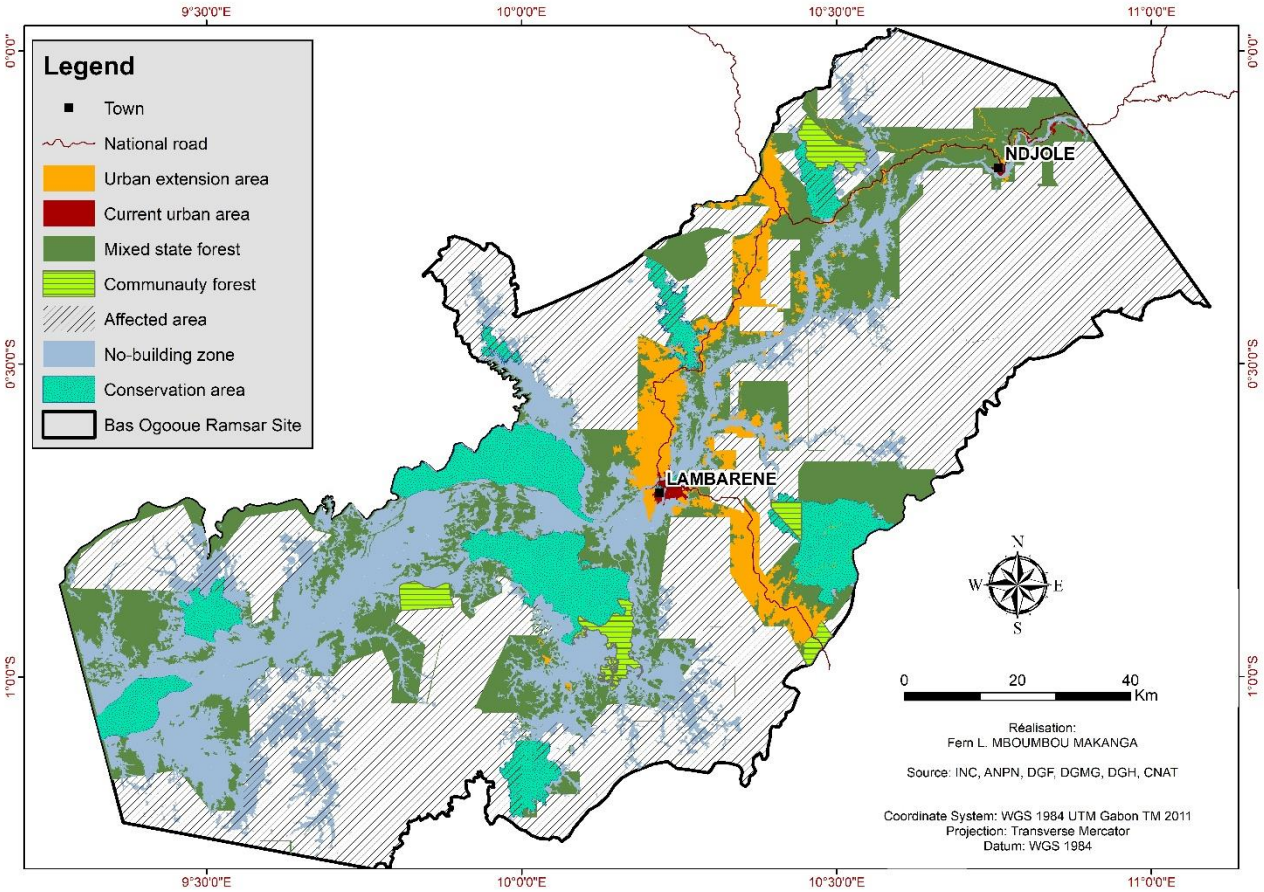

Figure 10. Zoning of the Bas Ogooué Ramsar site

3.5. Discussion

Wetlands are environments characterized by the continuous or temporary presence of water on the surface or at very shallow depths, by the majority presence of a hygrophylous phytocenosis and the permanent presence of hydromorphic soil. These are complex and polymorphic, sometimes dynamic ecosystems whose boundary mapping remains today a global challenge (Gramond and *al*, 2005).

Today, multi-spectral sensors and digital cartography are proving to be a godsend for solving the difficulties of delimitation. Indeed, several authors such as Töyrä (2002), Hakdaoui (2019) and Rapinel (2019) have shown the interest of multi-sensor, multi-scale and multi-temporal approaches in the spatial study of wetlands.

While these approaches have made it possible to correctly detect water bodies and the limits of wetlands, medium and high spatial resolution satellite images cannot provide all the information necessary for the precise definition of a wetland typology. Like all remote sensing techniques which remain subject to field visits, the delimitation results remain confined to an inventory and are intended to be a prerequisite for a more exhaustive inventory.

Various methods have been developed over the past 15 years to assess wetland functions (Adamus, 1987; World Wildlife Fund 1992, Matby, 2009). However, none have been widely used or accepted, due to a failure to meet one or more technical or programmatic requirements, which include applicability in a wide geographic area, ability to evaluate a variety of types, and of wetland functions and the ability to assess functions accurately and efficiently within the limited time and resources available.

The method used (Rapinel, 2012) is inspired by the FAAP Procedure *developed in 2009 by Maltby.* This procedure is developed in several European countries such as the EVALUWET project (The European assessment and evaluation tool supporting legislation on wetland ecosystems) which aims to develop and implement an operational system to support decision valuation of wetlands to support European policy objectives (Jansen, 2005). According to Maltby (2009), the complexity of wetlands is understood by identifying distinct functions for each hydrogeomorphological unit or HGMU. The FAP makes it possible to evaluate 12 hydrological, biogeochemical and ecological functions and takes place in three stages.

This method is above all suitable for the functional evaluation of wetlands at the scale of a site. The limits of this approach are based exclusively on the measurements taken in the field and at a time "t". The results can indeed vary over time depending on the observations, in particular on the hydrodynamics. It is, however, a suitable approach for determining functional indicators that are overwhelmingly associated with wetland compartments.

However, cartography and remote sensing techniques, even the finest, always require, at a minimum, assisted corrections, at maximum, and *in situ verifications.* Also this study would have been more complete, if we had been able to carry out physico-chemical analyzes of the waters, in particular to attest to the chemical composition of the black waters, but also to provide information on the physico-chemical quality of the potential pressure points.

The results obtained concerning the central wetlands are similar to two other existing works (Vande Weghe and Stevart, 2017), highlighting areas of ecological interest. In fact, wetlands with high conservation value extend for the most part over areas designated as the most important for mammals. In addition, the areas of high conservation value near lakes Onangué, Oguémoué and Evaro include one of the two nature reserves proposed by the IUCN in 1990 (figure 12, below).

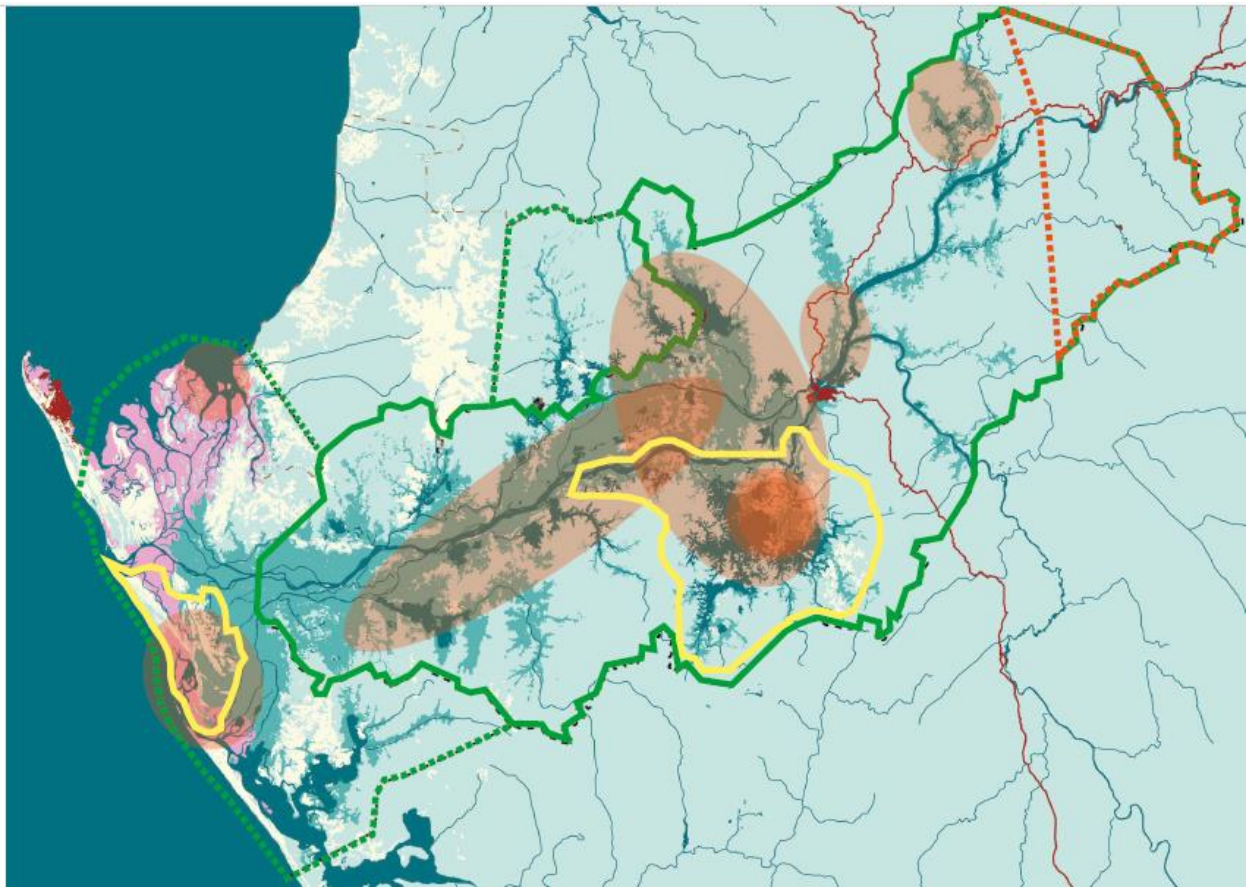

Figure 11: Important area for mammals (in pink) and the two reserves proposed by the IUCN in 1990 (in Vande Weghe JP and Stévart T., 2017)

Admittedly, the state of conservation of this inner delta is still very good and human populations are few, unlike the Nile and Niger deltas. These two points make the Ogooué delta a unique site in Africa, and even in the world (DGEPN and ANPN, 2020). Nevertheless, the towns of Lambaréné and Ndjolé are gradually opening up to economic development marked by the consolidation of the process of industrialization of the wood sector, prospects for the installation of companies to work in the field of mining and oil, like Maboumine and Maurel & Prom.

The analysis of land cover shows the predominance of water. Present both on the surface and underground, water is the identity vector of several spaces, both natural and natural anthropized: left bank, right bank, South Lake, ... The positioning of the towns of Ndjolé and Lambaréné, in edge of the Ogooué, illustrates this permanent dialogue between man and nature. Even today, the question of water control arises within the two cities between various operations, agro-industry, and waste management. The choice to plan urban sprawl engages a policy of intensification of the city, on spaces likely to be wetlands. The zoning plan proposed in this work is intended to be a tool for organizing this dialogue between city and nature.

4. CONCLUSION

The Bas Ogooué Ramsar Site is the largest wetland of international importance in Gabon. Located mainly in the province of Moyen-Ogooué, the Bas Ogooué Ramsar site has 60,809 inhabitants residing mainly in the towns of Lambaréné, Ndjolé and 166 villages spread over 10 cantons. With regard to industrial activities, 60% of it is covered by various allocations, mainly forestry. These various actors are today at the origin of a progressive deterioration of natural ecosystems.

However, the Bas Ogooué Ramsar site remains, all the same, a wetland of international importance, managed by the Water and Forest administration. Given the presence of many actors,–of their divergent interests, even worrying, the various assignments and uses should be taken into account in the process of sustainable management of the site, especially that the latter does not have any management plan in force.

In recent years, Geomatics has tended to impose itself in most studies in physical geography. This study is not to be outdone, since it manages to demonstrate the potential of collection, processing and spatial analysis tools to create usable cartographic supports for the zoning of a Ramsar site.

In addition to the information provided by land use and the hydrological network, the multi-scalar method has made it possible to delimit wetlands at a higher level, by integrating geomorphological, geological and spatio-temporal dynamic elements. This information makes it possible to delimit the geographical area, in its broadest sense, or the theoretical wetland.

Using the functions, values and services provided by the study area. A total of nine central or high conservation value wetlands have been delineated and represent a total area of 1,539 km², or 30.19% of all wetlands on the site and 8.8 % of the entire Site.

Overall, the zoning plan for the Bas Ogooué Ramsar site is made up of three main zones: the central zones, which correspond to the conservation zones, the buffer zones correspond to all the other surrounding wetlands and the transition zones correspond to those subject to industrial assignment. They are at the limits of the site and constitute a first envelope of the core. Operators should adopt, as far as possible, the most environmentally friendly methods of exploitation.

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