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Effects of climate variability and uncontrolled urbanization on the spatial dynamics of lakes in the niayes area of senegal: case of thiourour, warouwaye, wouye and mbeubeuss lakes

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Abstract
The purpose of this contribution is to study the dynamics of coastal lakes on the Great Coast of Senegal in a context of climate variability and change, as in the case of Thiourour Warouwaye, Wouye and Mbeubeuss. Diachronic mapping using aerial photographs and satellite images (Landsat and Google Earth Pro images) has made it possible to assess the extent and nature of land cover changes over four dates (1989, 1999, 2009 and 2019). The results show, over the first sequence of observations (1988 and 1999), a tendency for water bodies to decline by less than 26.7 ha for Thiourour Warouwaye and Wouye lakes, unlike Mbeubeuss lake, where the water body has increased by 47.9 ha. On the second sequence of observations (1999 and 2019), an extension is noted on the building and water bodies that increased from 41.6 ha to 51.4 ha on the different lakes (only the water body of Lake Wourouwaye has regressed). Lake systems therefore regenerate after a regressive trend observed in the first sequence in a highly anthropized environment today, thus reducing their ability to perform their ecosystem functions..

Keywords: Vernal keratoconjunctivitis, tacrolimus, immunomodulators, olopatadine

1. Introduction

Lakes are major repositories of biodiversity and provide multiple ecosystem services (Politi *et al.*, 2012) [50]. They are vital resources for aquatic wildlife and human needs. Any change in their environmental quality and water renewal rate has far-reaching ecological and societal consequences (Vincent, 2009) [59]. Lakes are widely recognized as key indicators of environmental change. They exhibit remarkable variability over time in their morphometric, physical, chemical and biological characteristics (Omondi *et al.*, 2014) [44]. These variations are mainly induced by climate change and human activities in their watershed. The lakes are strongly influenced by regional and global climate change in the short and long term (Nzoiwu *et al.*, 2017) [42]. Their water level varies according to the precipitation/evaporation ratio, groundwater supply, water abstraction rate and other factors. Therefore, as sensitive indicators of change, they are able to integrate the effects of human activities in their watershed and additional disturbances due to global warming (Magnuson *et al.*, 1997) [37]. The global climate has changed considerably, from a climate system dominated by natural influences to one dominated by human activities (Bronnimann *et al.*, 2007). The global average surface temperature increased by about 0.6°C during the 20th century (IPCC, 2001), and current global circulation models predict an increase in air temperature of several degrees by the end of the 21st century, combined with large changes in regional precipitation distribution and intensity (Vincent, 2009) [59]. This awareness has led to questions about the relative effects of changes in climate conditions on natural ecosystems. The two main hydrometeorological variables affecting the lake ecosystem are precipitation and air temperature (Magnuson *et al.*, 1997). Changes in air temperature and precipitation have direct effects on the physical, chemical and biological characteristics of lakes. Studies have shown that climate change can affect water temperature, surface water elevation and lake structure (Carpenter *et al.*, 1992), increase eutrophication by modifying internal and external nutrient loading, evaporation rates and further decrease dissolved oxygen supply, leading to increased biological oxygen demand (Rooney and Kalff, 2002). These abiotic changes would be accompanied by a general change in the biotic characterization of lakes. In addition, lakes are important links in the Earth's hydrological cycle and studies have shown that predicted climate change could alter the hydrological and physical characteristics of lakes (Magnuson *et al.*, 1997). Hydrological systems are potentially highly sensitive to climate change (Arnell *et al.*, 1996) and can affect many aspects of lake and river ecosystems, such as hydrological flows into and out of lakes, net basin water supply and lake water levels. In the long term, the volume and extent of lakes have changed several times due to climate variability (Lozan *et al.*, 2001) and uncontrolled urbanization. Thus, Ayoade (1975) also pointed out that an accurate assessment of water resources in any region requires knowledge not only of the magnitude of precipitation and its spatial and temporal distribution, but also of the nature and magnitude of water losses through evaporation. This change in precipitation and temperature that accompanies climate change has the potential to change lake connectivity with biological implications (e.g. for migratory fish species), changes in lake volume, surface and depth, and other related limnological properties (Nzoiwu *et al.*, 2017) [42]. Changes in water balance due to climate change can make the lake ecosystem vulnerable to climate change, whereas these changes are likely to affect species composition (Lehtonen, 1996). Aquatic macrophyte communities located in the coastal zone of lakes (Yem *et al.*, 2011) have shown that as the surface area of lakes decreases, the ratio between coastal and pelagic habitat increases. Studies have shown that variations in lake surface area, due to human water abstraction or climate change, are responsible for variations in fisheries abundance, diversity and richness of fish fauna in lakes (Inyang, 1995), species richness and food chain length increase with lake size (Rechee *et al.*, 2005). The effects on climate have been aggravated by the increasing need to irrigate agricultural land, ensure municipal water supplies, industrial uses, power generation, etc. (Nzoiwu *et al.*, 2017) [42]. In all scenarios, the ability of African countries to cope with the potential effects of climate variable change on the freshwater ecosystem should be seriously challenged and potentially overtaken by the magnitude of these impacts. In West Africa, and more particularly in the Sahel regions, which are often referred to as arid or semi-arid, lakes perform important environmental functions (Sène *et al.*, 2006). Senegal is a Sahelian country located in the western part of the African continent (Economic Community of West African States *et al.*, 2006). It is subdivided into six eco-geographical zones (Fig. 1), each of which contains several coastal, continental and artificial wetlands. The Niayes eco-geographical zone (Fig. 1) extends along the Grande Côte to the heart of the Cape Verde peninsula over an area of 8,883 km². It contains wetlands that are precisely called "Niayes". Their importance for Senegal is linked to their membership in both the coastal and continental domains (Diop, 2006). At present, the decline of wetlands continues worldwide, both in quantity and quality (Ramsar Convention Secretariat, 2015a). To address this, the Ramsar Convention's fourth strategic plan for 2016-2024 proposes to address the drivers of wetland degradation and loss (Ramsar Convention Secretariat, 2015b). Among these drivers is the uncontrolled development of cities through urbanization, which modifies essential functions of wetlands (Boko, 2009). In Senegal, several studies have been carried out on the state of wetlands at the regional and national levels. However, few of them on small lakes and address them specifically and at local scales (Diop *et al.*, 2018). Nevertheless, studies on land use change indicate a gradual degradation of Senegal's wetlands, similar to those in West Africa as a whole (Dia, 2003). The fourth national report on the implementation of the Convention on Biological Diversity (CBD) highlights that Senegal's wetlands have a regressive dynamic (ISE and DPN, 2010). Senegal's new National Wetland Management Policy (NWMP) document, the most recent inventory, shows significant and largely conversion-related developments (Ministry of Environment and Sustainable Development of Senegal, 2015). The study of the Niayes wetlands in the Dakar region is particularly interesting. The complexity of these wetlands is linked to their location in urban areas, their biodiversity, which is still rich, and their contribution to improving the living conditions of urban dwellers. They are ideal for studying land use dynamics due to natural (water, vegetation, etc.) and human (urbanization) influences. The use of mapping through geomatics is a relevant approach to highlight land use dynamics. The latter can be defined as the evolution of land use classes, either towards a stage of degradation or improvement, or towards a more or less stable state of equilibrium (Diop *et al.*, 2018). When this dynamic is studied through the use of aerial photographs or satellite images, it becomes an important element in describing and quantifying changes in the time and space of a land use unit (Centre de suivi écologique *et al.*, 2012). The purpose of this paper is therefore to assess the effect of variations in climate elements (temperature, precipitation and evaporation) and urban growth on Mbeubeuss and Malika lakes over a 40-year period and to recommend measures to address environmental risks.

2. Study area

The "Big Niaye of Dakar" is part of the Niayes eco-geographical area located in the Dakar region, where Senegal's capital is located. It is bounded to the north and south by the Atlantic Ocean, to the west by the Hann Forest and Zoological Park and the Khar Yalla district, to the east by Thiaroye Gare, the Diacksao and Tivaouane districts (Direction des espaces verts urbains *et al.*, 2004). It covers an area of 4,800 hectares and includes several wetlands: the Grande Niaye de Pikine, the Niayes de Hann Maristes-Patte d'Oie, the Niayes de Thiaroye and part of the forested area of the northern coast. Niayes are interdune depressions in which the water table of the quaternary sands is exposed or sub-affected (Dasylva and Cosandey, 2010; Ndao, 2012). The water table, known as the "Thiaroye table", extends along the coast from Thiaroye to Saint-Louis over a width of about ten kilometres (Chaoui, 1996). It is based on an impermeable substratum made up of clays and marls from the lower Eocene (Agence nationale de la recherche scientifique appliquée, 2012). The surface water contained in depressions, which causes ponds (or lakes) to form, comes mainly from a groundwater flow of infiltrated water (Peeters, 1998).

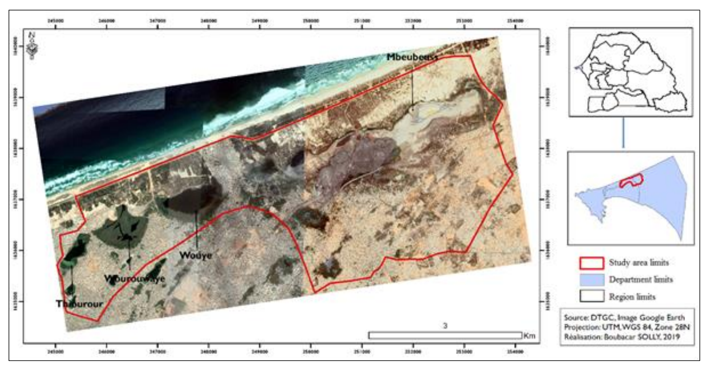

Fig 1: Location of lakes in the Dakar region

Between Saint Louis and Dakar, there is a string of freshwater lakes spread over a distance of about 300 kilometres. The lakes studied are among them (Fig. 1). Many lakes are located on this transect, including Thiourour Lake, Warouwaye Lake, Wouye Lake, Mbeubeuss Lake, Retba Lake (pink lake), Tanma Lake and Mbawane Lake. Among these lakes, Malika (Thiourour, Warouwaye and Wouye lakes) and Mbeubeuss (Sène *et al.*, 2018) are studied. Their genesis and evolution are linked to climatic and marine oscillations observed during the recent quaternary period (Dasylva and Cosandey, 2010). These lakes were reported to have developed during the Noachottan transgression (7000 to 4200 years BP) during which the sea entered the interior of the dunes to form a lagoon that communicated with the sea (Ndao, 2012). The closure of the lagoon during the subcurrent period (1700 years BP) isolated this unit, which now evolves like lakes fed mainly by rainfall and the water table of the quaternary sands. The lakes lie between the departments of Pikine and Guédiawaye in the Dakar region, more precisely in the district communes of Wakhinane Nimzatt, Yeumbeul Nord, Malika and Keur Massar (Sène *et al.*, 2018). They are housed in interdune depressions and constitute one of the landscape units of the Niayes wetland.

3. Data and methods

3.1. Satellite data acquisition

Two types of geospatial images are used for land use and lake mapping. These are Google Earth Pro and Landsat images (Table 1). A time difference of 10 years has been taken into account depending on their availability. Envi 5.1 software is used for pre-processing Landsat images. The Arc Gis 10.5 software was used for mapping.

Table 1: Satellite and aerial images used

Type of image	Date	Sensor	Spatial resolution
Landsat 4	10/03/1988	TM	30 m
Landsat 7	04/11/1999	ETM+	30 m to 15 m
Google Earth Pro	11/03/2009		3 m
Google Earth Pro	29/01/2018 - 07/04/2019		3 m

The mapping method is based on five steps: georeferencing, strip combination for Landsat images, photo-interpretation, digitization and validation. Geo-referencing consisted in bringing the images back to the same geometry. The aim is to provide common geographical coordinates for the different images. This step is necessary to overlay multi-date and multisensor images (Ducrot, 2005). The geo-referencing method by direct integration from Google Earth is used. It required prior definition of the geographical coordinate system (UTM, WGS 84, Zone 28N) on Arc Gis and finding the same remarkable points on both the images used and Google Earth. In the interest of good georeferencing, we have ensured that the residual error is less than 0.5 m. Following the georeferencing, we made a colored composition in natural color for Landsat images. This combines the red, green and blue bands (3-2-1) in the RGB channels respectively. Since the Landsat 7 image has a panchromatic band captured in the 0.50-0.90 µm wavelengths with a resolution of 15m, this has been merged with the colour composition to reduce the resolution of this image to 15m. The different combinations made it possible to identify the units to be mapped, particularly the lakes. These units, coded from 1 to 6 (Table 2), are then digitized on the screen. The results were validated using soil control points and previous studies conducted in the region.

Table 2: Codes, Units and Description of Cartographic Units

Code	Class	Description
1.1	Mbeubeuss Lake	Name given to the lake near the outlet
1.2	Wouye Lake	Name given to the different lakes of Malika
1.3	Wourouwaye Lake	
1.4	Thiourour Lake	
2	Water	Other lakes or water bodies
3.1	Concentrated frame	Populated areas (significant urbanization)
3.2	Frame dispersed	Populated areas (less urbanization)
3.3	Other buildings	Populated area in the landfill, in aquatic vegetation and in the floodplain (non aedificandi area)
4	Discharge	Large garbage can in Dakar (Mbeubeuss landfill)
5	Aquatic vegetation	Vegetation around lakes and water
6	Others	Mosaic of floodable surfaces, other vegetation, bare soils, market garden surfaces

3.2. Climate data

In Dakar, the rainfall observation network consists of stations including a synoptic. Among these, only the station of Dakar-Yoff was selected. This station located at 14°7' North latitude and 17°5' West longitude is located near the north coast, in Dakar. The choice of this station was made based on the significant number of years of observations and the absence of gaps. The sample size criterion is based on the recommendations of the World Meteorological Organization, which recommends the use of a minimum observation period of 30 years for any study on climate change (WMO, 1994). The temperature and precipitation data series were collected from the Agence Nationale de l'Aviation Civile et de la Météorologie (ANACIM). The evolution of all temperature and precipitation variables is evaluated using statistical tests. While the Mann-Kendall test can detect possible gradual changes in the series of extreme variables (Kendall, 1975), the Pettitt test (1979) is a non-parametric test to detect a break in the series. Based on temperature and precipitation data, the standardized precipitation and evapotranspiration index (SPEI) was calculated and used to monitor and quantify drought in the Dakar region. The SPEI is considered an improved drought index, particularly suitable for analysing the effect of global warming on drought conditions (Beguería *et al.*, 2015). The calculation of the SPEI in this study follows the method mentioned in the study by Vicente-Serrano *et al (*2010). For this study, the monthly SPEI was calculated from 1950 to 2018 at 5 time scales (1, 3, 6, 12 and 24 months) for the Dakar region.

4. Results and Discussion

4.1. Analysis of climate data

The overall trend is the annual variation in temperatures at Dakar-Yoff station. The coefficient of variation is slightly higher on minimum (TN) and average (TM) temperatures with 0.03 than on maximum (TX) temperatures with 0.02. These three variables TM, TX and TN increased slightly from 1960 to 2018. In line with global variation (IPCC, 2007), this warming appears to have been greater for minimum temperatures (at 0.52°C/year) than for maximum temperatures (at 0.25°C/year), although the difference between the two is very small (0.27). The standard deviation is 0.65°C over the global average and indicates the low interannual variability in relation to warming over the period. The average temperature in Dakar has therefore risen from a minimum of 23.4°C (in 1976) to a maximum of 26.2°C (in 2010) over a total of 69 years. During 2010, the "hottest" year of the series, the maximum temperature reached 29.3°C and the minimum temperature 23.1°C. As for 1976, the "coldest" year in the series, the maximum temperature did not exceed 26.5°C and the minimum only 20.3°C. Annual precipitation totals range from 897 mm in 1951 to 114 mm in 1972. The difference between the maximum and minimum of the series is 783 mm. Rainfall is therefore highly variable with a coefficient of variation of 0.42. However, rainfall in the dry season is more random and variable with CV = 1.62 than in the rainy season where CV = 0.42. Like temperatures, there is a significant trend towards a decrease in precipitation over the 1950-2018 period. The annual averages of temperature and precipitation are standardized by the average of the period 1950-2018. The result is a series of annual temperature and precipitation anomalies, both negative and positive (Fig. 2). For the annual average temperatures, we distinguish a first part where the standardized temperature indices are mainly negative (the minimum being -2.35°C in 1976) and a second part where they are mainly positive (the maximum being 2.01°C in 2010). In addition, the negative indices appear to be lower than the average than the positive indices, which would be higher and higher at the end of the series, reflecting a non-homogeneity in global warming. The Fig. 3 allows to retain the year 1976 as exceptionally "cold" with a TM of 23.4°C, while the average value of the TM series is 24.6°C and 2010 as an exceptionally "hot" year in which the TX is 29.3°C compared to an average value of 27.7°C. In relation to precipitation, the standardised precipitation indices for the 1950-2018 period are not clearly distributed over time as they are for average temperatures. They change sign from one year to the next and the maximum number of successive years of the same sign rarely reaches a full decade, despite a significant trend in rainfall patterns in Dakar. Nevertheless, the three decades 1970, 80 and 90 represent the most deficit period of the series. On the Fig. 3, the year 1972 appears to be exceptionally "dry" with an index of -1.76 and the year 1951 as exceptionally "rainy" with an index of 2.40.

Fig 2: Standardized indices of average temperatures and precipitation in Dakar over the period 1950-2018

Table 3 shows the results of the Pettitt and Mann-Kendall tests on annual scale temperatures and precipitation recorded at the Dakar-Yoff station from 1950 to 2018.

Table 3: Results of the Pettitt and Mann-Kendall tests on annual temperatures and precipitation recorded at the Dakar-Yoff station from 1950 to 2016

Mann-Kendall test					Pettitt test				
Descriptors	P (mm)	TX	TN	TM	Descriptors	P (mm)	TX	TN	TM
Trend	O	O	O	O	Breakdown	O	O	O	O
Direction of the trend	decrease	rise	rise	rise	p of the test	< 0,0001	< 0,0001	< 0,0001	< 0,0001
τ of Kendall	-0,15	0,25	0,52	0,39	Date of termination	1969	1994	1996	1994
S	-375	407	842	680	Mean before breakage	600,6	27,4	21,2	24,3
p of the test	0,05	0,005	< 0,0001	< 0,0001	Mean after breakage	373,8	28,2	22,2	25,2
Slope	-2,44	0,01	0,03	0,02	Change in %	-37,8	3,0	4,9	3,5

O (yes) = presence of a trend or break; N (No) = absence of a trend or break τ = Kendall's Tau; S = statistical S; test p = one-sided p-value; TX = Maximum temperatures; TN = Minimum temperatures; TM = Mean temperatures; P (mm) = Precipitation

On the minimum, maximum and average temperatures, the two tests (Pettitt and Mann-Kendall) show the presence of a break and/or trend. The Pettitt test indicates 1994 as the break date for TX and 1996 for TN. These ruptures are confirmed by the Mann-Kendall test which shows positive Kendall τ with 0.25 for TX, 0.52 for TN and 0.39 for TM. Thus the trend is upward and more significant on TN than on TX. To quantify the temperature variation across the break date, we divided the time series into two sub-periods: 1950-1994 and 1995-2018. The comparison of the two sub-periods shows the existence of a 3% surplus between 1995 - 2018, compared to 1950-1994, for TX, i.e. an increase of 0.8°C, 3.5% for TM, i.e. an increase of 0.9°C and 4.9% for TN, i.e. an increase of 1°C. For precipitation, the Pettitt and Mann-Kendall tests indicate a break in 1969 and a significant downward trend of the order of -0.15 mm/year. The evolution of the standardized precipitation indices shows a decrease in values, particularly from the 1970s onwards, illustrating the Sen slope, which is negative at -2.44. On both sides of the rupture date, the variation in precipitation is in the order of -37.8% between 1950-1969 and 1970-2018

4.2 Mapping and analysis of land use and lake development in 1988, 1999, 2009 and 2019

4.2.1. Changes in land use

To analyse the changes in land use in 1988, 1999, 2009 and 2019 in the study area, five main classes are used (Table 4 and Fig. 3): water bodies (consisting of lake and pond water); the building surface (in all its components); aquatic vegetation, the discharge (of Mbeubeuss) and the "other" class consisting of floodable areas, shrub steppe, bare soil and crop areas.

Table 4: Area in hectares and as a percentage of land use in 1988, 1999, 2009 and 2019

Main classes	1988		1999		2009		2019	
	ha	%	ha	%	ha	%	ha	%
Water bodies	130,7	5,9	152	6,9	71	3,2	86,2	3,9
Frame	600,8	27,2	768,9	34,9	640	29,0	999,9	45,3
Discharge	76,2	3,5	88	4,0	124,1	5,6	141,8	6,4
Aquatic vegetation	179,2	8,1	148,4	6,7	156,5	7,1	179,6	8,1
Others	1219,4	55,3	1049	47,5	1214,7	55,1	798,8	36,2
Total Total	2206,3	100	2206,3	100	2206,3	100	2206,3	100

In 1988, surface water covered 130.7 ha (5.9% of the total area of the study area) and aquatic vegetation represented 179.2 ha (8.1% of the total area). The areas occupied by shrub steppe, bare soil and cultivation areas largely dominate the perimeter covering 1219.4 ha (55.3% of the total area). The building, on the other hand, occupied 600.8 ha (20.26% of the total surface area) and the landfill the smallest surface area with 76.2 ha (3.5% of the total surface area). For 1999, the water bodies widened slightly in surface area and accounted for 152 ha (or 6.9% of the total surface area), as did buildings with 768.9 ha (or 34.9% of the total surface area) and landfills with 88 ha (or 4.0% of the total surface area), due to the ever-increasing urban growth. On the other hand, the areas occupied by shrub steppe, bare soils and largely dominant crop areas decreased to 1049 ha (47.5% of the total area). The same is true for aquatic vegetation, for which the occupied area has decreased to 148.4 ha (6.7% of the total area). For 2009, the water bodies shrank to 71 ha (3.2% of the total surface area), as did the buildings, which declined to 640 ha (29.0% of the total surface area). The area occupied by shrub steppe, bare soil and cropping areas increased to 1214.7 ha (55.1% of the total area). An increase in the surface area is also noted on the aquatic vegetation side with 156.5 ha (or 7.1% of the total surface area) and the landfill with 124.1 ha (or 5.6% of the total surface area), due to the increase in the population. Finally, for the year 2019, land use is thus distributed: water bodies increased with 86.2 ha (3.9% of the total area); the surface of aquatic vegetation agreed with 179.6 ha (8.1% of the total area); shrub steppe, bare soil and crop areas declined sharply with 798.8 ha (36.2% of the total area); the building developed further with 999.9 ha (45.3% of the total surface area); the landfill also increased significantly on the surface with 141.8 ha (6.4% of the total surface area).

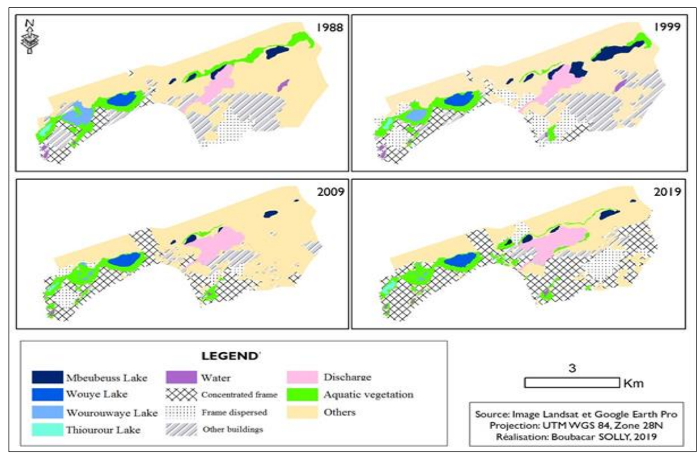

Fig 3: Changes in land and lake use in 1988, 1999, 2009 and 2019

4.2.2. Changes in water bodies

The land use map on the four dates indicates a global change in the morphology of lakes Mbeubeuss, Thiourour, and more specifically Lake Wourouwaye (Fig. 4). In general, these changes are highly dependent on the quantities of precipitated water during the wet season. For Lake Mbeubeuss, its evolution also depends on the evolution of the outlet. This landfill is the largest garbage dump in the Dakar region since 1970. The quantity of garbage dumped per day is about 900 tons, according to the African Institute for Urban Management (Ndao, 2012). Thiourour Lake has seen relatively fewer changes, from 7.9 ha in 1988 to 6.3 ha in 1999, 4.1 ha in 2009 and 10.1 ha in 2019. Wourouwaye lake, on the other hand, is the most affected by the changes. From a large lake in 1988 (46.5 ha), it is only present in 2019 in the form of relics divided into several pieces (with only

6.2 ha). This significant decrease in the surface area of this lake could be explained by the silting up and the advance of the urban front on its surface. Wouye lake is the least affected by the changes noted. Its surface area, which stood at 31.1 ha in 1988, remained stable in 1999, before falling slightly in 2009 to 34.5 ha and in 2019 to 35.1 ha. The high coverage of aquatic vegetation all around gives it a stable situation.

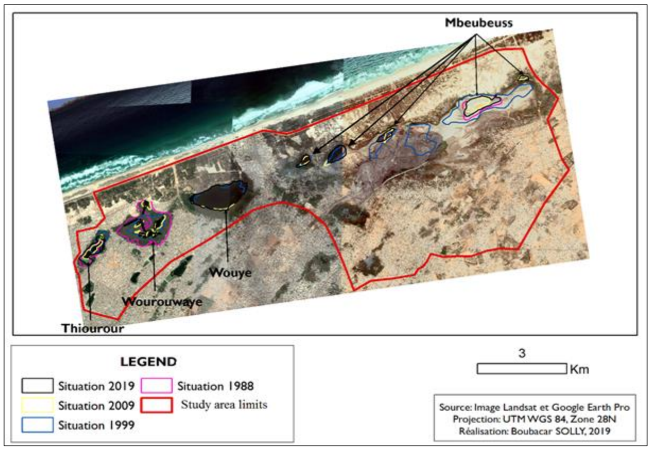

Fig 4: Changes in lakes between 1988 and 2019

The statistical results in Table 5 show that Lake Mbeubeuss has experienced a more mixed evolution. Its surface area, which was 32.6 ha in 1988, first increased sharply in 1999 with 80.5 ha, then shrank sharply in 2009 with 20 ha and finally expanded further, albeit slightly, in 2019 with 27.3 ha. The increase in its area in 1999 is related to the date of the image shooting, which corresponds to the end of the wet season. This increase also indicates that, the further away from the wet season, the more the lake dries up. However, it lost 5.3 ha of its surface area between 1988 and 2019 to the landfill. This increased from 76.2 ha to 141.8 ha between 1989 and 2019. The increase in the area occupied by the landfill is nothing more than the result of the urbanization of the Dakar region. Moreover, the results show a significant increase in the number of buildings concentrated in the mapped area, to the detriment of those scattered and those located in non aedificandi areas, especially during the 2009-2019 period. This significant extension of the building on wet depressions following the occupation of almost all the available spaces around Les Niayes since 2003 (Diop *et al*., 2018), resulted in a significant loss of floodplains, non-aquatic vegetation, bare soil and market gardening of 415.9 ha in the mapped area over the same period. According to Diop *et al* (2019), the latter are the target of non-agricultural infrastructure projects because of their strategic location between the Dakar city centre and its periphery. Thiourour Lake decreased in area by 3.8 ha between 1989 and 2009. However, between 2009 and 2019, its area increased by 6 ha. This situation is similar to wet surfaces and aquatic vegetation. It could be explained by the increase in precipitation levels in the region as early as the middle of the 1991-2000 decade (Descroix *et al*., 2015; Faye, 2019). As a result, flooding increased as early as 2005, to the point where a large proportion of the buildings installed in the areas not aedificandi in 1999 were abandoned in 2009, then covered by floodplains and aquatic vegetation. According to Diongue (2014), in 2009, 44% of the population of the city of Pikine were directly affected by the floods.

Table 5: Area in hectares of land and lake use in 1988, 1999, 2009 and 2019

Classes	Area in hectares				Evolution of the surface area between two dates			
	1988	1999	2009	2019	1988-1999	1999-2009	2009-2019	1999-2019
Mbeubeuss Lake	32,6	80,5	20	27,3	47,9	-60,5	7,3	-53,2
Wouye Lake	31,1	31,1	34,5	35,1	0	3,4	0,6	4
Wourouwaye Lake	46,5	20,5	7	6,2	-26	-13,5	-0,8	-14,3
Thiourour Lake	7,9	6,3	4,1	10,1	-1,6	-2,2	6	3,8
Water	12,6	13,6	5,4	7,5	1	-8,2	2,1	-6,1
Concentrated frame	127,9	204,1	407,3	778,9	76,2	203,2	371,6	574,8
Frame dispersed	95,2	201,3	88,8	137,8	106,1	-112,5	49	-63,5
Other buildings	377,7	363,5	143,9	83,2	-14,2	-219,6	-60,7	-280,3
Discharge	76,2	88	124,1	141,8	11,8	36,1	17,7	53,8
Aquatic vegetation	179,2	148,4	156,5	179,6	-30,8	8,1	23,1	31,2
Others	1219,4	1049	1214,7	798,8	-170,4	165,7	-415,9	-250,2
Total	2206,3	2206,3	2206,3	2206,3				

For Wourouwaye lake, it lost 40.3 ha of its area between 1988 and 2019 to aquatic vegetation. On the other hand, Lake Wouye increased its surface area by 4 ha from 31.1 ha in 1988 to 35.1 ha in 2019. Compared to other lakes, it is less affected by the changes. The area of water bodies in the area increased significantly between 1988 and 2019. The conversion of humus soils on which agriculture was practiced (especially market gardening and arboriculture) has contributed to the increase in the distribution of water bodies (Sène *et al.*, 2018). However, the first observation sequence is marked by a decrease in the surface water surface area. Much of the water in the lakes has disappeared and been replaced by aquatic vegetation or agricultural perimeters. Water bodies undergo a significant increase during the 1999-2019 sequence during which water conversions become more important. The result is a wider distribution of surface water that follows the old routes of the river system (Diop, 2005).

The evolution of the lakes is not observable and is not linear. It depends mainly on rainfall inputs according to years, but also on the date and period of the aerial or satellite images (Fig. 5).

Fig 5: Aerial view from Google earth Pro of the evolution of Lake Mbeubeuss during the transition period of the two seasons (A), during the wet period (B), and during the dry period (C

4.3. Factors in land and lake use change

The main factors in the evolution of land and lake use are to be found in the climate variability and high urbanization of Dakar.

4.3.1. Climate variability

To analyse the impact of climate variability on Dakar lake water bodies, the standardized rainfall and evapotranspiration index (SPEI), considered an improved drought index, was used, particularly suitable for analysing the effect of global warming on drought conditions (Beguería *et al.*, 2015). Fig.s 6 and 7 explicitly show an upward trend in drought sequences in the Dakar region. The SPEI series with different time scales all indicate a tendency for Niayes to dry out. According to the SPEI values, humidity conditions were very contrasted before and after 2005. However, this drying is much more apparent at the level of the 12-month time scale, which shows a dry character almost every month of each year, particularly over the period 1990-2018. Before 1970, the study area was mainly characterized by light to severe moisture conditions (and rarely extreme as noted on the 12-month time scale: this is the case over the 1950s and 1960s). However, droughts have actually started since 1970 and are generally of a mild to moderate nature, although cases of severe to extreme droughts occur in some months on different time scales. While droughts are moderate over the period 1970-2000, they will worsen over the period 2010-2018. Table 6, which shows the average values of SPEIs with different time scales from 1950 to 2018 in the Dakar region, clearly shows that while the periods 1950-1959, 1960-1969 and 1970-1979 are wet, those from 1980 to 2018 are rather dry. While the 1950-1959 period remains the wettest on the different time scales, the 2000-2009 period remains the driest. Thus, the last period (2010-2018), although dry, is less so than the previous period (2000-2009), which attests to a decrease in drought in the Niayes area with the increase in rainfall noted over the recent period. This improvement in rainfall conditions is in line with the work of some authors (Ali and Lebel, 2009; Ozer *et al.*, 2009; Ouoba, 2013) who suggest that the Sahelian drought ended in the 1990s.

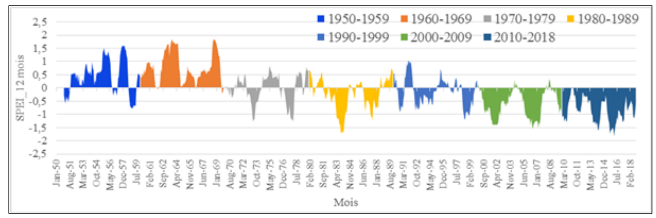

Fig 6: Monthly Evolution of spei values on the 12-month time scale from 1950 to 2018 for the dakar region

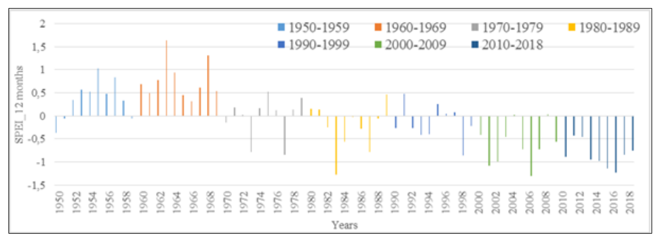

Fig 7: Annual evolution of SPEI values on the 12-month time scale from 1950 to 2018 for the Dakar region

If the standardized precipitation indices become positive over the period 2010-2018 (in line with rainfall increase), indicating important wet sequences even if the 1960s optimum has not yet been reached (Faye *et al.*, 2017; Faye, 2017; Faye, 2018), the SPEI continues to be negative. This is probably related to the reported temperature increase, with climate change (IPCC, 2013). This temperature increase improved the PET, which made the water deficit high and thus lowered the value of SPEI (Xing *et al.*, 2015). This global warming would likely lead to an intensification of the hydrological cycle (Yeh and Wu, 2018), resulting in changes in water availability and the frequency and intensity of droughts, as well as an increase in warming through water vapour feedback (Huntington, 2006).

Table 6: Average SPEI values on time scales of 1, 3, 6, 12 and 24 months from 1950 to 2018 in Senegal

Periods of time	Spei 1	Spei 3	Spei 6	Spei 12	Spei 24
1950-2018	-0,04	-0,05	-0,08	-0,08	-0,12
1950-1959	0,28	0,39	0,43	0,44	0,43
1960-1969	0,32	0,47	0,60	0,78	0,93
1970-1979	0,03	0,03	0,02	-0,02	-0,05
1980-1989	-0,10	-0,16	-0,19	-0,25	-0,34
1990-1999	-0,09	-0,12	-0,14	-0,16	-0,17
2000-2009	-0,36	-0,49	-0,55	-0,62	-0,76
2010-2018	-0,35	-0,54	-0,67	-0,81	-1,07

Overall, the persistence of droughts since the late 1960s in the Sahel has had a significant impact on water resources, causing them to dry up in some areas. This is observed on the coastal lake system, such as Tamna Lake, which has gradually dried up with droughts (Faye, 2016) and Rose Lake, which has fallen from 6.7 km² in 1954 to less than 3 km² in 2006 (ANAT, 2015). Moreover, this drying trend has even justified the use of Lake Mbeubeuss as the main or even only garbage dump in the Dakar metropolitan area (Diawara, 2009) where, currently, the body of water is once again emerging surrounded by garbage. While the evolution of Thiourourour Warouwaye and Wouye Lakes indicates a drying up, between 1989 and 1999, it showed a completely different situation between 2009 and 2019, mainly due to urbanization (Sène *et al.*, 2018).

4.3.2. Irregular and spontaneous urbanization

The Dakar region covers an area of 550 km², or 3% of the national territory. It accounts for almost half (nearly 49%) of Senegal's urban population and concentrates most of the infrastructure (ANSD, 2010). This situation is reflected in the increasingly important extension of the suburbs on the outskirts of Dakar, a city where wetlands in particular are located (Diop *et al*., 2018). In the 1968s, the peri-urbanization of the city of Dakar towards Pikine and Guédiawaye experienced a frenetic pace. However, no provision was made in the urban master plans of 1946, 1961 and 1967 to control population growth (Ndao, 2012). This peri-urbanization coincides with the severe drought that has led to rural poverty and massive migration of rural populations to Dakar (Mbow *et al.*, 2008). During this period, the population of the Dakar region increased considerably: 374,000 inhabitants in 1961, 583,000 in 1971, 799,000 in 1976, 1,492,344 in 1988, 2,471,730 in 2000 (Dakar Urban Master Plan, Horizon 2035). The parallel dynamics between aridification and high migration have thus led to unplanned land occupation, including high occupancy of lowlands, which has sometimes impacted on the water bodies of the area Despite the persistence of drought over the current period, as indicated by the SPEIs, there has been a significant increase in the amount of water on the lakes in the last year (2019) compared to the other two years. However, this strong presence of water on some lakes is due more to the strong artificialization of the environment than to the natural recharge factors of the lakes. The municipalities surrounding the lakes (Wakhinane Nimzatt, Yeumbeul Nord and Malika) have experienced rapid and significant urbanization (Sène *et al.*, 2018). The first massive population arrivals began in the 1970s due to ecological crises and the disruption they caused to agricultural activities and the rural world (Vernière, 1973; Mbow *et al.*, 2008). This urbanization, which is irregular and spontaneous in most cases, has developed in an area dotted with depressions (niayes) and where the water table (Thiaroye table) is sub-surface to flush. The analysis of land use change in 1954, 1978, 1999 and 2014 (IAO, 2003; Mbow *et al.*, 2008) shows a rapid development of residential areas while all other land use classes, including natural vegetation and agricultural areas, have been seriously reduced. The municipalities surrounding the lakes are among the most densely populated in the Dakar region today: 28038 inhabitants/km² in Wakhinane Nimzatt and 18106.53 inhabitants/km² in Yeumbeul Nord for an average density of 5404 inhabitants/km² for the region (ANSD, 2014). While the area has virtually no sanitation network, wastewater is returned to the groundwater table (Ndao *et al.*, 2015). This lack of a sanitation network combined with the cessation of the pumping of the Thiaroye groundwater since 1950 for the supply of drinking water to the Dakar region (Ndao *et al.*, 2015) has led to the groundwater rising. The proximity of the water table to the groundwater, in addition to contributing to the maintenance of lake water bodies, exacerbates the risk of flooding, as the soil is rapidly saturated. The drainage of rainwater to the lakes and the alternative found for the management of recurrent floods recorded in the area drastically increase the volumes of water present on the lakes in recent years. Moreover, pumping the water drained from the lakes to the ocean, which is part of the drainage system to keep the water level of the lakes below 2.80 metres, is already subject to many breaches (pumping station failure, fuel supply failure (Sène *et al.*, 2018). Thiourour, Warouwaye, Wouye and Mbeubeuss lakes currently record much higher water volumes than in the past.

5. Conclusion

The Niayes are among the last wetlands in the Dakar region where natural water bodies are rare. This study, which examines the dynamics of land and lake use from 1988 to 2019, shows a natural influence (drought) and a strong anthropogenic influence linked to urbanization. Diachronic analysis of the environment in which these lakes operate between 1988 and 2019 shows that, in the first observation sequence, there is a tendency for water bodies to decline and built areas to increase due to climatic deterioration, which has greatly reduced the humidity in the area and thus allowed human settlement. The second sequence confirms the increase in the building in line with the increase in the population at the same time as that of the water bodies resulting from the recent increase in rainfall. Aquatic vegetation increased between 1999 and 2019. This increase in the first sequence is due to the replacement of existing water bodies by aquatic vegetation, while in the second sequence it is due to the multiplication of water bodies within the study area. The lake environment therefore regenerates after the negative impact of drought years. However, this regeneration is becoming problematic as human settlements have been affected by drought events and the exploitation of the quaternary sand table, which have contributed to drying out low-pressure areas and facilitating the settlement of populations in this wetland. This irregular and spontaneous urbanization did not lead to any development of the land before any human settlement. One of the consequences of this hydrological dysfunction is the recurrence of recorded floods, which have always been acute since the rainfall recovery. In addition to rainfall, which is the main factor responsible for flooding, there are other structural factors such as overcrowding and promiscuity, the absence of a sanitation network, the obstruction of natural waterways by housing and poverty. However, it seems clear that the actions that have been taken, and this in an emergency, have proved insufficient and ineffective. The flood prevention and management policy focuses on structural measures (retention basins, pumping stations, sanitation facilities with costly investments) and focuses mainly on social issues. Given that the preservation and enhancement of wetlands is a sustainable means of flood control, it would be contradictory to want to control and accentuate at the same time the destruction of natural rainwater catchment areas. This flood management, which consists in draining rainwater into the lakes, is not always beneficial for economic activities all around the lakes (market gardening, tanning, fishing). In addition to the area losses observed for certain activities such as market gardening and tanning, drained water compromises the quality of lake water.

6. References

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