

## **Water Resources Dynamics and Vulnerability in Rusizi National Park (Burundi) from 1984 to 2015, in the Context of Climate Change and Global Warming**

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### **Authors' contributions**

*This work was carried out in collaboration between all authors. Authors NE, SB and AT designed the study, performed the statistical analysis, wrote the protocol and wrote the first draft of the manuscript. Authors NFX and UT managed the analyses of the study. Authors UG and MF managed the literature searches. All authors read and approved the final manuscript.*

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### **ABSTRACT**

The study of water resources' dynamics and vulnerability in Rusizi national Park aimed to achieve the following objectives: (1) to identify, characterize and map water bodies, (2) to analyze and explain their periodical evolutions and (3) to analyze the spatial transformation processes affecting them. It is a contribution to the knowledge of the Park's water resources for the development of monitoring systems and the sustainability of their functions as strategic ecosystems. It is based on the diachronic analysis of land cover from multi-date Landsat images of years 1984, 1990 and 2011 (TM), 2000 (ETM<sup>+</sup>) and 2015 (OLI-TIRS), landscape ecology tools and socio-economic and climate data. Supervised classification of images allowed the identification of 9 to 10 land cover classes including water bodies, according to years. A total number of 17 water bodies were detected from 1984 to 2015. During this period, regularly detected and dried up water bodies

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represent 18.2% and 54.6% respectively. The rates of water bodies' drying up were 69.2% in 2000 and 64.2% in 2015. Water bodies are experiencing a great deterioration in number, size and stability. The Park's water coverage has decreased from 3.56% in 1984 to 2.43% in 2015. This corresponds to a decline of 31.2%. The water bodies' stability, which was 75.70% between 1984 and 1990, represents only 42.78% between 1984 and 2015. The stability of individual water bodies is decreasing as well while low spatial connectivities are being observed between some close water bodies. The spatial transformation processes carrying these dynamics are patch enlargement, patch creation, patch attrition and patch dissection, depending on the period. Global warming, rainfall variability and farming activities like land drainage and irrigation are the most important threats to water resources.

**Keywords:** *Rusizi national park; water bodies; water resources; water vulnerability; spatial transformation process; spatial connectivity; climate change.*

## 1. INTRODUCTION

The Rusizi National Park is known to be the only protected area in Burundi that has an international status as a Ramsar site. It is also the most threatened protected area and the most unstable [1]. Its conservation status has indeed changed three times since its creation in 1980. The human pressures that the protected area is facing bring continuous biodiversity degradation of which real processes and magnitude are still unknown [2-5]. The Rusizi national Park is a Ramsar site close to Bujumbura, the capital city of Burundi. It is known to be the most threatened and unstable protected area in Burundi which is facing important and continuous habitats and biodiversity degradation. The greatest threats consist of land cover and habitat modifications [1]. The water bodies, which are strategic habitats and play a key role in the functioning of the protected area, are subject to strong exploitation pressures that are stimulated and aggravated by the deterioration of climatic conditions [6]. The population growth and the development of agro-pastoral activities at the immediate periphery of the park are causing significant stresses on the water bodies especially during dry periods and seasons [4,7]. The location of the Park in a semi arid area exposes water bodies to additional climate constraints due to global warming [8]. Indeed, recurrent rainfall deficits and important socio-economic uses aggravate the degradation of water bodies. However, the evolution of the Park's water resources still remain poorly known given the fact that most of the studies on the protected area are always focused on flora [9,3], vegetation [10] and fauna [9]. This study first analyzes and compares the evolution of water bodies under different conservation status of the site, namely the statuses of the Reserve (1984-

1990, 2000-2011) and the park (1990-2000, 2011-2015). It then assesses their overall evolution over the period 1984-2015. The study has three objectives which are specifically: (1) to identify and characterize water bodies, (2) to analyze and explain their evolution and (3) to analyze the spatial transformation processes affecting them. It contributes to the knowledge of the water resource of the Park for development of monitoring systems and the sustainability of the functions of the « water bodies » as an ecosystem [11].

## 2. STUDY AREA

The Rusizi national Park is located in the western part of Burundi, in the extension zone of the capital city Bujumbura. It is bounded in the west by the Democratic Republic of Congo, in the north by Cibitoke Province, in the east by National Road 5 and in the south by Lake Tanganyika. As shown in Figs. 1A and 1B below, it is located between Gihanga and Mutimbuzi districts and covers an area of 10 673 ha composed of the Delta Sector (1,363 ha), the Palmeraie Sector (6,647 ha), the northern buffer zone (2,102 ha), the southern buffer zone (118 ha) and the Great Rusizi Corridor (443 ha) which connects the two separated sectors. The plain of Imbo which encloses the Park is the driest, the warmest and the lowest natural region of the country [4]. It is characterized by an altitude varying between 775 m and 1000m with a semi-arid tropical climate, an mean annual rainfall of 779 mm [12], a mean monthly temperature of 23°C to 24.5°C and a great rainfall variability which is marked by longer and longer dry seasons [6]. Since 2002, the Delta Sector has been classified as a Ramsar site under number 1180. This status was extended to the entire Park in 2013 thanks to its many wetlands and

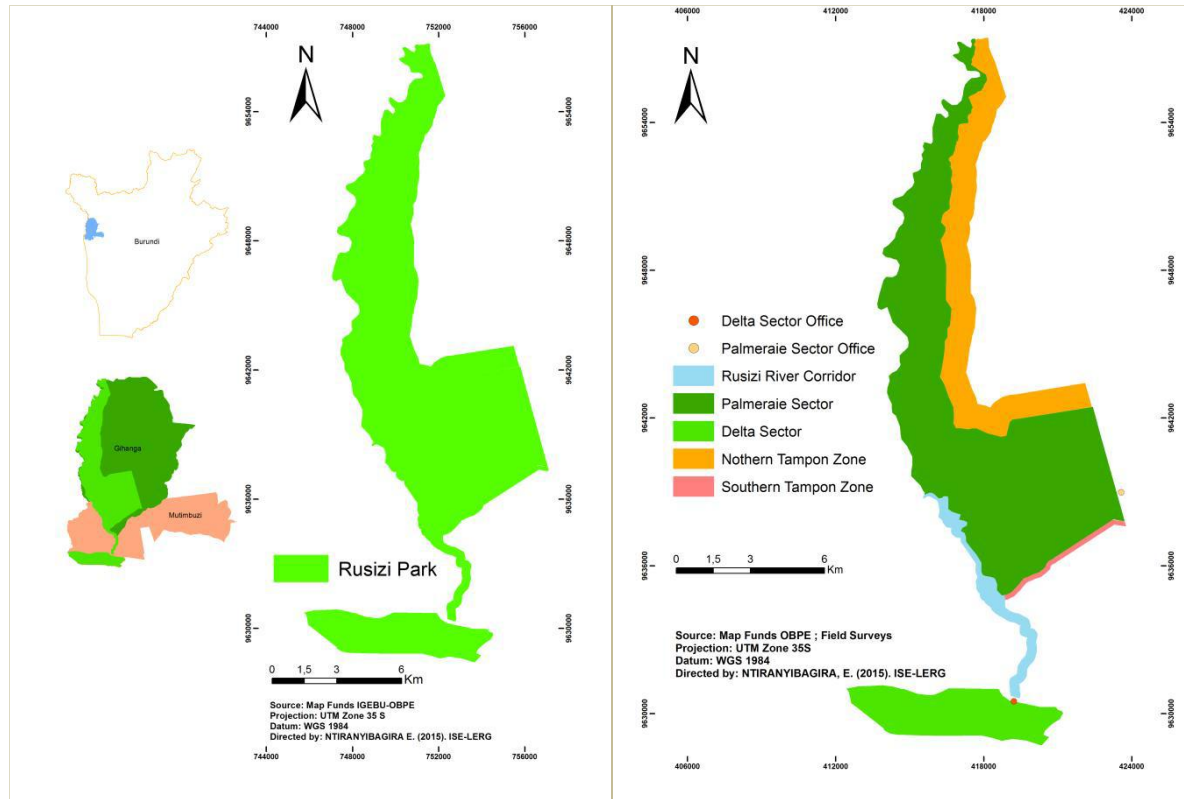


Fig. 1A. Rusizi Park location

Fig. 1B. Rusizi Park physical configuration

their interests for local and migratory freshwater birds [3,1]. The current issues of the park conservation are precisely linked to its international status of wetland and Ramsar site serving as a transit and wintering site for freshwater birds migratory along the migration routes of Africa and Eurasia [3].

### 3. METHODOLOGY AND STUDY DATA

The methodology adopted first consisted of a diachronic analysis of land cover using multi-date Landsat images and a GIS database. The relevance of the approach has been proved by numerous studies [13-17]. It then relied on field surveys, semi-structured interviews on socio-economic uses with different stakeholders and climate data for the validation and the explanation of the results of the image analysis. Water bodies were analyzed at two hierarchical levels. Firstly, they were considered as a "land cover class" which specifically evolves as an ecosystem component of the protected area [18,5]. Secondly, they were dismembered as "separated hydrological entities" that evolve individually and exhibit possible spatial connectivity under the influence of external factors. Given the fact that water bodies are defined differently according to organizations and authors, with reference to physical and socio-economic criteria [19-23], water body is defined in the study as "any hydrological body having at least 0.09 ha" reference made to the spatial resolution of the Landsat images used (30m); whatever their other spatial characteristics and socio-economic uses.

#### 3.1 Images Data and Processing

For the study, multi-dates, ortho-rectified and geo-referenced Landsat images of 30 m main spatial resolution were used. These are Landsat Thematic Mapper (TM) images from 1984, 1990 and 2011, Landsat Enhanced Thematic Mapper Plus (ETM<sup>+</sup>) from year 2000 and Landsat Operational Land Imager and Thermal Infrared Sensor (OLI-TIRS) from year 2015 covering 173-062 Path and Row scene. Each Landsat image corresponds to significant landmarks in the conservation history of the protected area and expresses reference states for the comparison of successive evolutions. The 1984 image is the first clear image of the study area since the creation of the Rusizi Reserve in 1980. The images of 1990, 2000 and 2011 mark successive

passages from Reserve status to that of Park and the status of Park to that of Reserve. The 2015 image was chosen to assess the effects of the 2011 status change on the quality of conservation, four years later. The images used were acquired at the beginning of the dry season for maximum differentiation of the land cover classes [24], especially herbaceous and woody and a minimization of the negative effect of the vegetation cover on the detection of water bodies. The images were processed and analyzed using the Envi 4.5 software. After cutting the images on the study area, a 5-4-3 colored composition in the short infrared (1.550-1.750  $\mu\text{m}$ ), near-infrared (0.730-0.900  $\mu\text{m}$ ) and red (0.630-0.690  $\mu\text{m}$ ) was applied to the 1984, 1990, 2000 and 2011 images for better discrimination of land cover units and easy detection of changes [25,24]. For the 2015 image, the 6-5-4 colored composition was carried out in the short infrared (1.560-1.660  $\mu\text{m}$ ), near-infrared (0.845-0.885  $\mu\text{m}$ ) and red (0.630-0.680  $\mu\text{m}$ ). The classification of the images was done in a supervised way, according to the maximum likelihood algorithm which calculates the probability of belonging of the pixels to a precise class of land cover based on the postulate that the signature spectrum of the pixels is representative of their class of belonging [26,27]. The quality of the classification was assessed using confusion matrices and parameters such as overall accuracy and Kappa coefficient [28,16]. The field validation of images classification was performed using Ground Control Point samples for the most recent image. Firstly, it was based on land cover and vegetation maps from previous studies [10,3,4]. Secondly, it was done using semi-directive interviews with older staff and oldest rangers of the two guard sectors (Fig. 1B) for the other images. As a result of the classification of images, 9 to 10 land cover different classes were identified according to years: (1) *Hyphaene benguellensis* forest, (2) Dense forest relics, (3) Wooded savannah, (4) Shrub savannah, (5) Grassy savannah, (6) Aquatic vegetation, (7) Water bodies, (8) Bare soils, (9) Cultivated areas, (10) Built areas and (11) Burned areas. After the validation, the classifications of images were homogenized by the application of a Kernel 3x3 majority filter and automatically vectorized in Envi 4.5 software before being exported to ArcGIS 10.1 and projected into the WGS 1984, UTM, Zone 35S for cartographic analysis.

### 3.2 Water Bodies Detection and Designation

For the purpose of water bodies' detection, 4 situations were predefined, with reference to the detection status: (1) water bodies qualified as "inexistent" as long as they are not detected yet; (2) water bodies considered as "dried or disappeared" when they are not detected after an earlier identification; (3) water bodies said to be "appearing" at their first detection and (4) water bodies qualified as "reappearing" when they are detected again after previous disappearance [12]. The frequency and the regularity of water bodies' detections were used as indicators of their "permanence" or "seasonality". In terms of designations, all the identified water bodies were called "ponds" because of their large areas and shallow depths due to the depressions occupied [4] which differentiate them from small ponds and lakes [20], with the exception of the Rusizi River and Kumukaratusi and Kumuhasa lagoons of which qualifications were kept same as those existing in the available scientific literature [3,4].

### 3.3 Water Bodies Mapping and Cartographic Analysis

The annual and interannual land cover maps used for cartographic analysis and extraction of geospatial statistics related to the "class of water bodies" were produced using ArcGIS 10.1 software, from the exported data of the classifications of images. The cartographic analysis of the "individual water bodies" was made using separated polygons of the water bodies before their merge in a unique class of water bodies for the global analysis of land cover dynamics. The annual water bodies' maps were delivered and extracted from the annual land cover maps. The overlay of annual land cover maps made it possible to generate periodical changes that are affecting the "class of water bodies" as a whole in the global dynamics of land cover. The superposition of annual water bodies' maps allowed the production of maps of changes which are affecting separate water bodies in terms of spatial connectivity. Theoretically, the change detections between land cover classes, including water bodies and the individual water bodies as well are based on a codification of the considered entities and a comparison of the codes between two specific dates [29]. The entity changes from one date to another are thus

identified from code changes for homologous vectors that are described using transition matrices obtained from the statistical analysis data of each map [30-32]. The analysis of the transition matrices helped to identify «stable areas» and «zones of spatial change» which are either modifications or conversions, depending on the nature of the spatial changes [33,34]. The stability of water bodies between 2 specific dates  $t_1$  and  $t_2$  was defined at three levels [12]. First, the "absolute stability" or the "stability" stricto sensu which is the proportion of stable water surfaces in the total area of the Park. Second, the "intrinsic stability" defined as the ratio between the absolute stability and the water coverage rate of the Park and third the "weighted stability" which is the ratio between "the equivalent water coverage rate" and "the actual water coverage rate" of the Park. By definition, the equivalent water coverage rate is the proportion of the absolute stability of water bodies in the global stability of the Park. The weighted stability was designed as a measure of the relative stability of the water bodies' class or ecosystem compared to its weighted importance in the Park's surface and overall stability. The analysis of spatial changes affecting the class of water bodies as well as the individual water bodies were realized using the mean rate of annual spatial expansion  $T_a$  (%/year) defined by the formula:  $T_a = 100 * \frac{S_2 - S_1}{S_1(t_2 - t_1)}$  where  $S_1$  and  $S_2$  are the areas related to years  $t_1$  and  $t_2$  [35]. The differential sensitivity of individual water bodies or their resilience to climatic conditions and socio-economic stresses was determined by the "relative rate of annual spatial expansion"  $T_{ar}$  (%/year/ha) [12] defined by the relation:  $T_{ar} = \frac{T_a}{S_1}$  [12] where  $S_1$  is the area (ha) at the date  $t_1$ . In the end, the net periodic balances in water bodies evolutions as a class result from the comparison between the conversions of certain land cover classes into water bodies (floods, submersion) which are gains of water bodies areas and the conversions of water bodies into other land cover classes (drying up, drainages, vegetal colonization) which make losses of water bodies' areas.

### 3.4 Spatial Structure Indices and Transformation Processes

The spatial structure indices are important factors that explain the evolution of landscape ecosystems and ecological processes [36,37].

The main spatial parameters describing the configuration of a landscape are the number ( $n$ ), the area ( $a$ ) and the perimeter ( $p$ ) of patches of landscape units [38,39]. These parameters characterize the spatial transformation processes (STP) that are responsible for the changes defined and described by the «Decision Tree Algorithm» which is used in landscape ecology [40,39]. The comparison of the values of these parameters at two dates  $t_0$  ( $n_{t_0}, a_{t_0}, p_{t_0}$ ) and  $t_1$  ( $n_{t_1}, a_{t_1}, p_{t_1}$ ) makes it possible to determine the types of STP involved. In theory, 10 STP are possible as defined and presented in Fig. 2 [40,39,41]. In the study, patches are the polygons of the class of « water bodies» as they appeared from the raw export results of the image classifications in ArcGIS 10.1. The input values used in the

«Decision Tree» for the determination of the periodical STP are the coupled interannual homologous values ( $n_{1990}/n_{1984}, a_{1990}/a_{1984}, p_{1990}/p_{1984}$ ), ( $n_{2000}/n_{1990}, a_{2000}/a_{1990}, p_{2000}/p_{1990}$ ), ( $n_{2011}/n_{2000}, a_{2011}/a_{2000}, p_{2011}/p_{2000}$ ), ( $n_{2015}/n_{2011}, a_{2015}/a_{2011}, p_{2015}/p_{2011}$ ) and ( $n_{2015}/n_{1984}, a_{2015}/a_{1984}, p_{2015}/p_{1984}$ ) which have been calculated and compared each other. As there is still no scientific consensus on the threshold value ( $T_{obs} = a_{t_1}/a_{t_0}$ ) to be considered to differentiate patch fragmentation from patch dissection, even if patch fragmentation is known to correspond to values  $T_{obs} \ll 1$  [39], a threshold of  $T_s = 0,5$  was used [41]. When  $T_{obs} \leq 0,5$ , then we concluded this is the patch fragmentation process. In the contrary  $T_{obs} > 0,5$ , patch dissection was considered.

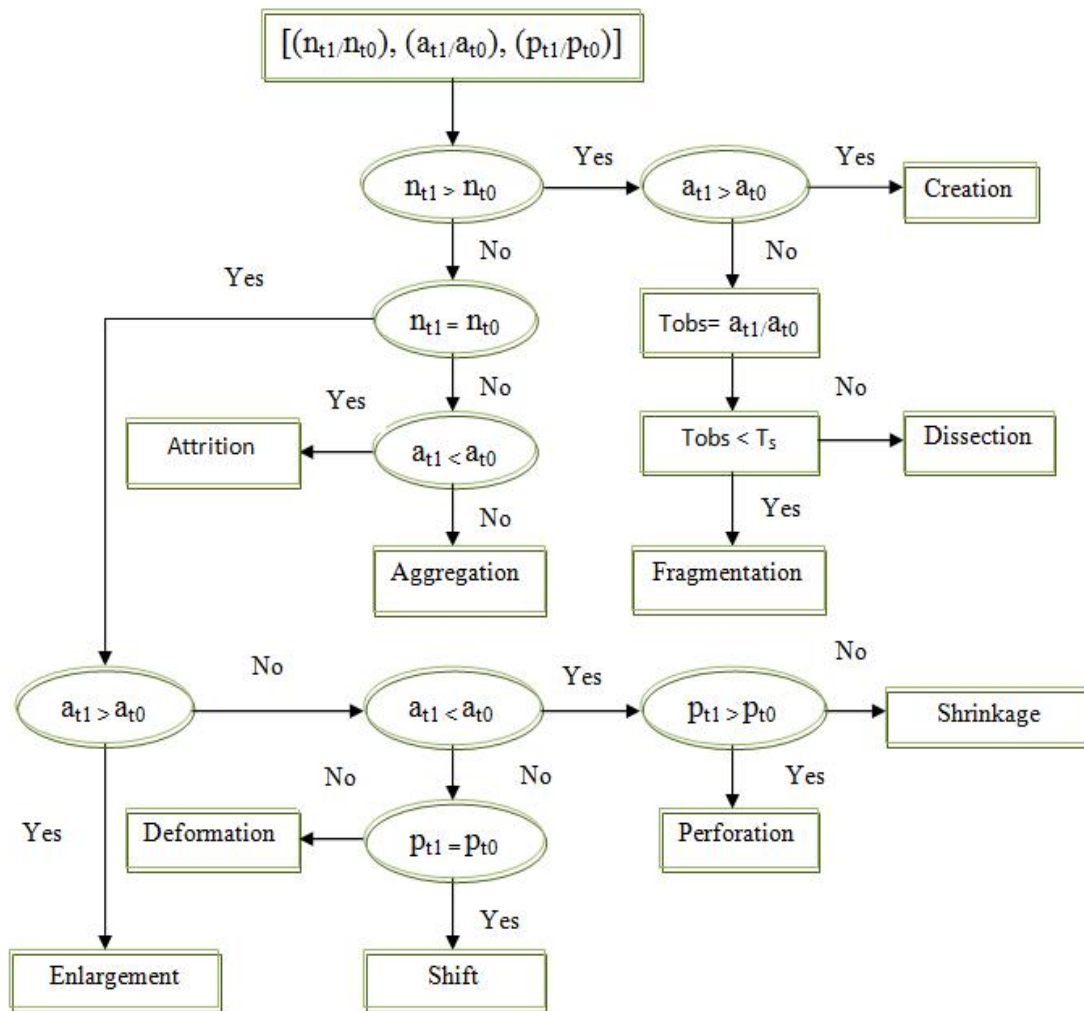


Fig. 2. Decision Tree Algorithm for the determination of STP [39, 41]

### 3.5 Climatic Conditions Analysis

The analysis of climatic conditions was focused on rainfall and temperatures for the period 1981-2015. The reference data were collected at Bujumbura International Airport meteorological station which is close to the study area. The analysis of the rainfall variability and trends was carried out by means of the rainfall time series breakdown Test which allowed the computation of annual rainfall indices [42,43,44]. The rainfall indices of Nicholson ( $U_i$ ) were determined by the formula:  $U_i = \frac{X_i - X}{\sigma}$  where  $X_i$  is the annual rainfall of year  $i$ ,  $X$  the inter-annual rainfall mean and  $\sigma$  the standard deviation. They were used to determine years with rainfall excesses or deficits [45,46]. Positive values correspond to rainfall excesses and negative ones to rainfall deficits. According to the rainfall index  $U_i$  values the rainfall status of a given year is determined as follows: (1)  $U_i > 2.00$  (extremely wet), (2)  $1.50 < U_i < 1.99$  (wet), (3)  $1.00 < U_i < 1.49$  (moderately wet), (4)  $-0.99 < U_i < 0.99$  (normal), (5)  $-1.49 < U_i < -1.00$  (moderately dry), (6)  $-1.99 < U_i < -1.50$  (dry) and (7)  $U_i < -2.00$  (extremely dry) [47,46]. The analysis of the interannual rainfall was completed by: (1) the comparison between “cumulative rainfall of the rainy seasons” of the study years and the “interannual rainfall average” and (2) the comparison between the «annual rainfall average» of the study periods and “interannual rainfall average”. For each study year, the “cumulative rainfall of the rainy season” is the sum of the monthly rainfall from the beginning of the rainy season in September of the previous year to the end of the rainy season in May which also corresponds to the date of acquisition of the first image in 1984. For the determination of the influence of rainfall levels on the spatial parameters of water bodies (number, area, perimeter), a rank correlation analysis of Spearman was performed thanks to the formula:

$$r_s = 1 - \frac{6 \sum_{i=1}^N d_i^2}{N^3 - N} \text{ where } r_s \text{ is the Spearman's}$$

correlation coefficient,  $d$  the difference of hierarchical ranks in values between rainfall and a considered parameter and  $N$  the number of observations which is 5 here, reference made to the number of study years. The correlation analysis was only focused on «closed water bodies» or “rain fed water bodies» excluding the Rusizi River which benefits from significant external water inputs, regardless of local rainfall. The analysis of temperatures was focused on the general trend curve compared to the inter-annual average for the considered period.

## 4. RESULTS

### 4.1 Accuracy of Image Classification

The classifications of images related to years of study are more than 85% correct for general accuracy and more than 83% correct for Kappa coefficient (Table 1). Detailed analysis of the Confusion Matrices shows a good level of discrimination between different land cover classes. Reference made to water bodies, they are one of the most well classified land cover classes, with an overall accuracy of 89.33%; 95.95%; 98.08%; 86.76% and 94.76% for years 1984, 1990, 2000, 2011 and 2015 respectively.

### 4.2 Successive States of Water Bodies' Coverage

Between 1984 and 2015, 17 water bodies were identified throughout the Park. In 1984, 1990, 2000, 2011 and 2015, 11, 13, 4, 14 and 7 water bodies were counted. They were covering 377.83 ha; 465.15 ha; 273.44 ha; 334.16 ha and 259.80 ha of the Park and representing 3.54%; 4.36%; 2.56%; 3.13% and 2.43% of its area respectively (Table 2). The Rusizi River, which gave its name to the Park, is the main component of the water bodies. It represents 76.37%; 58.24%; 86.86%; 83.74% and 81.84% in area, over the 5 years of study (Table 2). Considering spatial location, water bodies are unequally distributed.

**Table 1. Precision and quality parameters of the Image Classification**

Images characteristics	Date of acquisition	Overall precision (%)	Kappa coefficient
Landsat 5 MSS-TM 1984	26/05/1984	89.90	0.88
Landsat 4 MSS-TM 1990	03/06/1990	85.54	0.83
Landsat 7 ETM+ 2000	15/06/2000	91.02	0.89
Landsat 5 MSS-TM 2011	23/07/2011	88.86	0.87
LDCM OLI-TIRS 2015	18/07/2015	89.72	0.88

They are concentrated along Rusizi River and Delta sector, which is known for its complex hydrological interactions with Lake Tanganyika (Fig. 3A). Water bodies that have been systematically detected since 1984 represent 11.76%, those which were continuously detected after their appearance in 1990 or before their disappearance in 2015, 11.76%, sporadic ones (52.94%) and detected once (23.52%) (Table 2). This means that permanent water bodies represent 23.52% against 76.46% for temporary ones.

Due to the highly elongated shape of the Rusizi Park materialized by an asymmetric coefficient of 2.64 (Ntiranyibagira, 2017), to the great number of water bodies and to the small detection size (0.09 ha) which do not allow the use of a great scale, water bodies map is not sufficiently readable to the standard dimensions that are scientifically recommended. Despite this technical constraint, the map below illustrates and compares clearly enough water bodies for years 1984 and 2015 (Fig. 3A).

### 4.3 Spatial Changes in the Water Bodies' Class

Between 1984 and 1990, water bodies expanded by 23.11% from 377.83 ha to 465.15 ha at an annual rate  $T_a$  of 3.85%. The stability of the water bodies represents 2.68% of the Park (Table 3) and covers an area of 286.03 ha which corresponds to an intrinsic stability of 75.70% and a weighted stability of 125.3% (Fig. 3). The largest losses of water bodies' areas are related to the conversions of water bodies into aquatic vegetation (0.47%) and grassy savannah (0.24%) while the most remarkable gains result from the conversions of grassy savannah (0.82%), aquatic vegetation (0.31%) and *Hyphaene* forest (0.28%) into water bodies (Table 3). These surface transfers give a net positive balance of 96.86 ha (Fig. 4).

Between 1990 and 2000, water bodies have decreased by 41.21%, falling down from 465.15 ha to 273.44 ha at an annual rate  $T_a$  of (-4.12%). The absolute stability of water bodies represents

**Table 2. Names, detection status and areas of water bodies from 1984 to 2015**

Name of water body	Detection status and area (ha)				
	1984	1990	2000	2011	2015
1. Rusizi River	288.55	270.93	237.53	279.86	212.64
2. Kumukaratusi Lagoon	26.64	19.8	12.06	0.18	Dried up
3. Kumuhasa Lagoon	37.08	22.14	19.62	14.85	9.63
4. Western Gatumba Ponds	non-existent	<b>18.81*</b>	Dried up	<b>6.87**</b>	Dried up
5. Eastern Gatumba Ponds	non-existent	<b>113.04*</b>	4.23	15.75	31.5
6. Mukarava Ponds	4.32	1.44	Dried up	Dried up	<b>0.09**</b>
7. Mukarava-Up Ponds	non-existent	non-existent	non-existent	non-existent	<b>0.63*</b>
8. Kimirabasore Pond	7.29	2.25	Dried up	<b>5.40**</b>	3.78
9. Kidirigiri Pond	non-existent	<b>0.45*</b>	Dried up	Dried	Dried up
10. Urwotankware Pond	0.90	0.72	Dried up	<b>0.45**</b>	Dried up
11. Mariba Pond	4.95	7.74	Dried up	<b>0.36**</b>	Dried up
12. Kivunde Pond	1.80	2.88	Dried up	<b>2.88**</b>	Dried up
13. Kibururu Pond	1.35	0.45	Dried up	<b>1.17**</b>	Dried up
14. Kameme Pond	4.68	4.50	Dried up	<b>1.80**</b>	1.53
15. Kideheri Pond	0.27	Dried up	Dried up	<b>0.90**</b>	Dried up
16. Kitagabwa Pond	non-existent	non-existent	non-existent	<b>3.51*</b>	Dried up
17. Kijojo Pond	non-existent	non-existent	non-existent	<b>0.18*</b>	Dried up
<b>Total number of water bodies</b>	<b>11</b>	<b>13</b>	<b>4</b>	<b>14</b>	<b>7</b>
<b>Total area (ha)</b>	<b>377.83</b>	<b>465.15</b>	<b>273.44</b>	<b>334.16</b>	<b>259.8</b>
<b>Water coverage (%)</b>	<b>3.54</b>	<b>4.36</b>	<b>2.56</b>	<b>3.13</b>	<b>2.43</b>
<b>Rusizi River (%)</b>	<b>76.37</b>	<b>58.24</b>	<b>86.86</b>	<b>83.74</b>	<b>81.84</b>

\*: Water body appearance \*\*: Water body reappearance



2.22% of the Park (Table 4) and covers an area of 237.03 ha which corresponds to an intrinsic stability of 50.96% and a weighted stability of 221.9% (Fig. 3). The notable losses of water bodies' areas result from their conversions into cultivated areas (0.71%), grassy savannah

(0.52%), built areas (0.41%) and aquatic vegetation (0.32%) while the area gains are marginal (Table 4). Those surface transfers led to a net negative balance of 191.72 ha (Fig. 4), given that a great number of water bodies dried up (Table 1).

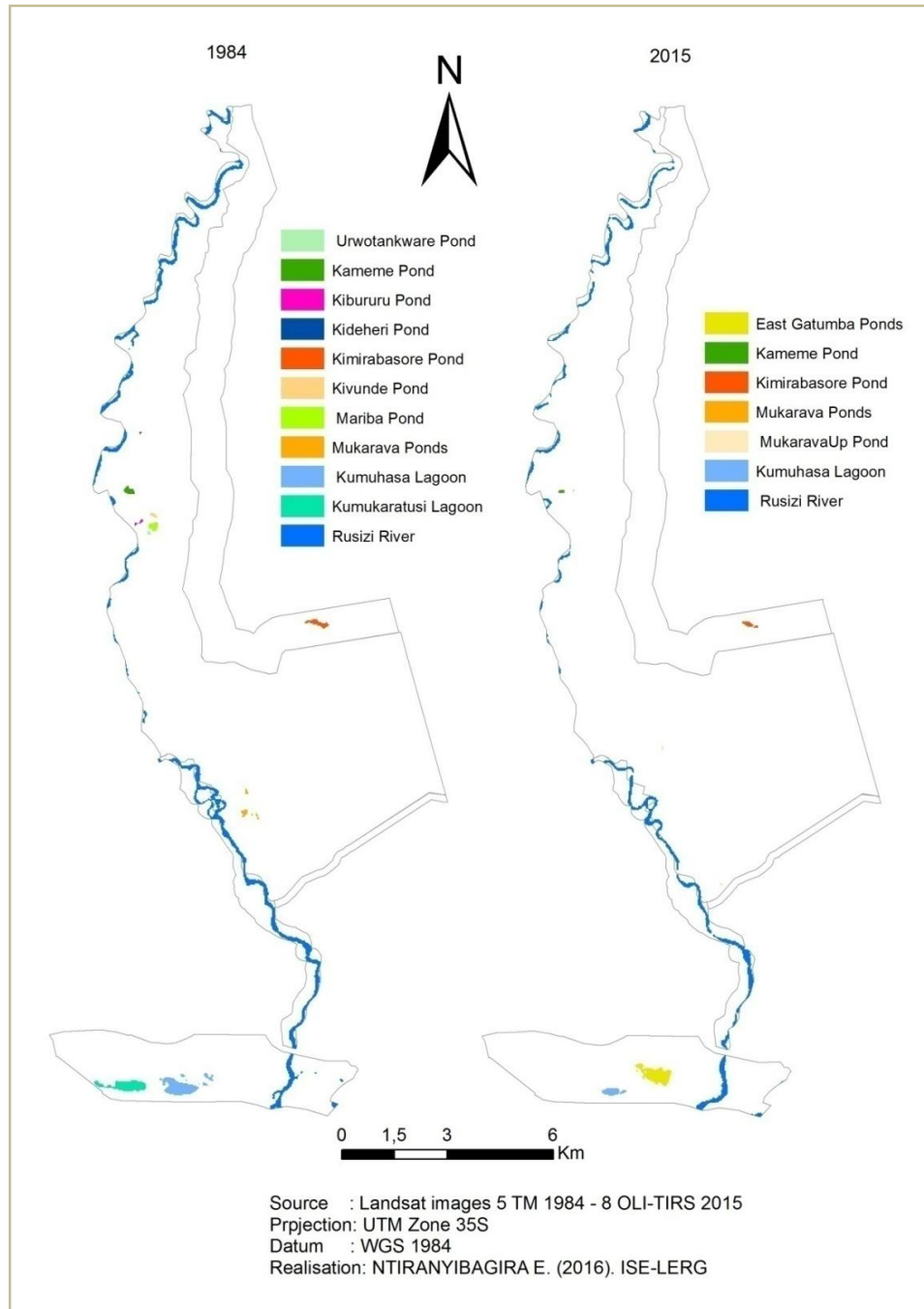


Fig. 3A. Compared evolution of water bodies between 1984 and 2015

**Table 3. Land cover transition matrix between 1984 and 1990 (%)**

		Year 1990										
Class		A	B	C	D	E	F	G	H	I	J	Total
Year 1984	A	<b>2.68</b>	0.24	0.01	0.04	-	-	0.47	0.01	-	-	3.45
	B	0.82	6.34	2.08	0.16	0.03	-	0.88	0.44	0.04	0.01	10.80
	C	0.02	1.52	9.03	0.93	-	-	0.93	0.45	0.02	0.00	12.90
	D	0.28	0.35	0.31	33.62	0.09	2.25	0.42	1.35	0.08	4.98	43.73
	E	0.00	0.07	0.03	0.10	0.00	0.00	0.02	0.01	-	-	0.23
	F	-	-	-	1.07	0.04	2.65	-	0.01	-	0.35	4.12
	G	0.31	0.33	0.58	0.13	0.00	-	3.45	0.01	-	0.01	4.82
	H	0.12	1.76	2.19	5.87	0.01	0.00	0.97	1.64	0.07	0.06	12.69
	I	-	0.13	0.02	-	-	-	-	0.00	0.09	-	0.24
	J	0.13	0.03	0.06	3.25	0.06	1.01	0.15	0.17	0.01	2.17	7.04
	Total	4.36	10.77	14.31	45.17	0.23	5.91	7.29	4.09	0.31	758	100

A: Water bodies B: Grassy savannah C: *Hyphaene benguellensis* Forest D: Wooded savannah E: Burned areas F: Bare soils G: Aquatic vegetation H: Cultivated areas I: Dense forest J: Built areas

**Table 4. Land cover transition matrix between 1990 and 2000 (%)**

		Year 2000										
Class		A	B	C	D*	E	F	G	H	I	J	Total
Year 1990	A	<b>2.22</b>	0.52	0.06	0.09	0.01	0.01	0.32	0.71	-	0.41	4.35
	B	0.18	4.30	1.24	0.63	0.78	0.03	0.39	3.12	0.00	0.11	10.78
	C	0.01	1.52	4.43	0.15	0.60	0.00	4.23	3.23	0.00	0.14	14.31
	D	0.02	0.10	0.72	2.23*	6.60	4.57	1.85	26.94	-	2.12	45.15
	E	0.00	0.00	-	0.00	0.05	0.13	0.01	0.01	-	0.02	0.22
	F	-	-	-	0.07	0.41	4.77	0.01	0.55	-	0.11	5.92
	G	0.08	0.74	1.02	0.27	0.12	0.02	3.21	1.64	-	0.19	7.29
	H	0.00	0.04	0.07	0.96	0.36	0.38	0.09	1.97	0.00	0.18	4.05
	I	-	0.00	-	0.03	0.03	0.06	0.00	0.08	*	0.02	0.22
	J	0.05	0.02	0.01	0.27	1.01	1.61	0.03	3.29	-	1.38	7.67
	Total	2.56	7.24	7.55	2.47	9.97	11.58	10.14	41.54	0.00	4.68	100

A: Water body B: Grassy savannah C: *Hyphaene benguellensis* Forest D\*: Wooded savannah E: Burned areas F: Bare soils G: Aquatic vegetation H: Cultivated areas I: Dense forest J: Built areas I\*: No sign of dense forest even on the images of 1990 and 2000, D\*: Wooded savannah became shrubby in 2000

Between 2000 and 2011, water bodies expanded by 22.21% increasing from 273.44 ha to 334.16 ha at an annual rate  $T_a$  of 2.02%. The stability of water bodies represents 2.09% of the Park (Table 5) and covers an area of 223.09 ha which corresponds to an intrinsic stability of 81.59% and a weighted stability of 234.1% (Fig. 3). The most significant gains in water bodies' areas came from the conversions of grassy savannah (0.35%), cultivated areas (0.30%) and aquatic vegetation (0.23%) while the largest losses came from the conversions of water bodies into grassy savannah (0.22%) (Table 5). Finally, the surface transfers involving water bodies resulted in a net positive balance of 60.71 ha (Fig. 4) which is dominated by a great number of water bodies' reappearances (Table 1).

From 2011 to 2015, water bodies decreased by 22.25% dropping from 334.16 ha to 259.80 ha at an annual rate  $T_a$  of (-5.56%). The stability of water bodies accounts for 2.05% of the Park (Table 6) and covers an area of 218.89 ha which corresponds to an intrinsic stability of 65.51% and a weighted stability of 156.4% (Fig. 3). The most significant losses of water bodies' areas came from the conversions of water bodies into cultivated areas (0.34%), burned areas (0.27%) and grassy savannah (0.20%) while the largest gains resulted from the conversion of aquatic vegetation (0.22%) into water bodies (Table 6). These surface transfers led to a net negative balance of 74.34 ha (Fig. 4) dominated by a great number of drying up water bodies (Table 1).

**Table 5. Land cover transition matrix between 2000 and 2011 (%)**

		Year 2011										
Year 2000	Classes	A	B	C	D*	E	F	G	H	I	J	Total
	A	2.09	0.22	0.08	0.00	0.00	-	0.14	0.00	-	0.02	2.55
B	0.35	3.33	2.04	0.12	0.22	-	0.16	1.00	-	0.04	7.26	
C	0.05	0.49	5.05	0.21	0.15	0.02	0.79	0.76	-	0.04	7.56	
D*	0.04	0.29	0.11	1.77	0.10	0.23	0.00	1.83	-	0.34	4.71	
E	0.01	0.06	0.11	3.51	0.62	0.23	0.01	3.01	-	2.40	9.96	
F	0.00	0.03	0.01	4.71	0.38	3.09	-	0.52	-	2.84	11.58	
G	0.23	0.40	4.68	0.27	0.50	0.03	2.60	1.34	-	0.10	10.15	
H	0.30	1.59	4.65	14.87	1.68	0.68	0.28	15.34	-	2.15	41.54	
I	-	-	-	0.00	-	-	-	0.00	**	0.00	0.00	
J	0.05	0.45	0.13	1.37	0.14	0.52	0.02	0.80	-	1.21	4.69	
Total	3.12	6.86	16.86	26.83	3.79	4.80	4.00	24.60	-	9.14	100	

A: water bodies B: Grassy savannah C: Hyphaene forest D\*: shrubby savannah E: Burnt areas  
F: Bare soils G: Aquatic vegetation H: cultivated areas I\*\*: Dense forest disappeared J: Built areas

**Table 6. Land cover transition matrix between 2011 and 2015 (%)**

		Year 2015										
Year 2011	Classes	A	B	C	D*	E	F	G	H	I	J	Total
	A	2.05	0.20	0.04	0.00	0.27	-	0.13	0.34	-	0.09	3.12
B	0.06	4.29	0.15	0.15	0.11	0.09	0.30	1.64	-	0.09	6.88	
C	0.05	1.65	8.67	0.50	1.73	0.00	1.65	2.58	-	0.01	16.84	
D*	0.01	0.30	0.01	12.59	3.17	0.90	0.02	8.88	-	0.97	26.85	
E	0.02	0.26	0.67	0.37	1.50	0.17	0.17	0.47	-	0.16	3.79	
F	0.00	0.00	-	1.62	0.26	1.17	0.00	1.31	-	0.44	4.80	
G	0.22	0.26	0.83	0.01	0.36	-	2.25	0.08	-	-	4.01	
H	0.01	2.25	0.25	6.56	6.88	0.07	0.39	8.10	-	0.09	24.60	
I	-	-	-	-	-	-	-	-	**	-	-	
J	0.02	0.17	0.02	4.03	1.05	0.79	0.00	1.98	-	1.08	9.14	
Total	2.44	9.38	10.64	25.83	15.33	3.19	4.91	25.38	-	2.93	100	

A: Water bodies B: Grassy savannah C: Hyphaene forest D\*: Shrubby savannah E: Burned areas  
F: Bare soils G: Aquatic vegetation H: Cultivated areas I\*\*: Dense forest disappearance J: Built areas

**Table 7. Land cover transition matrix between 1984 and 2015 (%)**

		Year 2015										
Year 1984	Class	A	B	C	D*	E	F	G	H	I	J	Total
	A	1.51	0.63	0.22	0.02	0.24	0.00	0.31	0.53	-	0.06	3.52
B	0.38	5.88	0.86	0.14	0.59	0.02	1.09	1.81	-	0.03	10.80	
C	0.03	0.80	7.29	0.66	1.57	-	0.91	1.64	-	0.01	12.91	
D	0.02	0.21	0.22	17.92	8.96	0.97	0.07	13.93	-	1.42	43.72	
E	0.00	0.05	0.00	0.03	0.02	-	0.01	0.11	-	-	0.22	
F	0.00	0.00	-	1.66	0.03	1.36	-	0.73	-	0.33	4.11	
G	0.31	0.53	0.77	0.15	0.66	0.01	2.01	0.35	-	0.02	4.81	
H	0.14	1.12	1.26	1.98	2.77	0.04	0.48	4.58	-	0.32	12.69	
I	0.01	0.09	0.00	-	0.01	-	0.02	0.02	**	-	0.15	
J	0.03	0.07	0.00	3.27	0.48	0.80	0.01	1.64	-	0.73	7.03	
Total	2.43	9.38	10.62	25.83	15.33	3.20	4.91	25.34	-	2.92	100	

A: Water bodies B: Grassy savannah C: Hyphaene forest D: Wooded savannah D\*: Shrubby savannah E: Burned areas  
F: Bare soils G: Aquatic vegetation H: Cultivated areas I\*\*: Dense forest disappearance J: Built areas

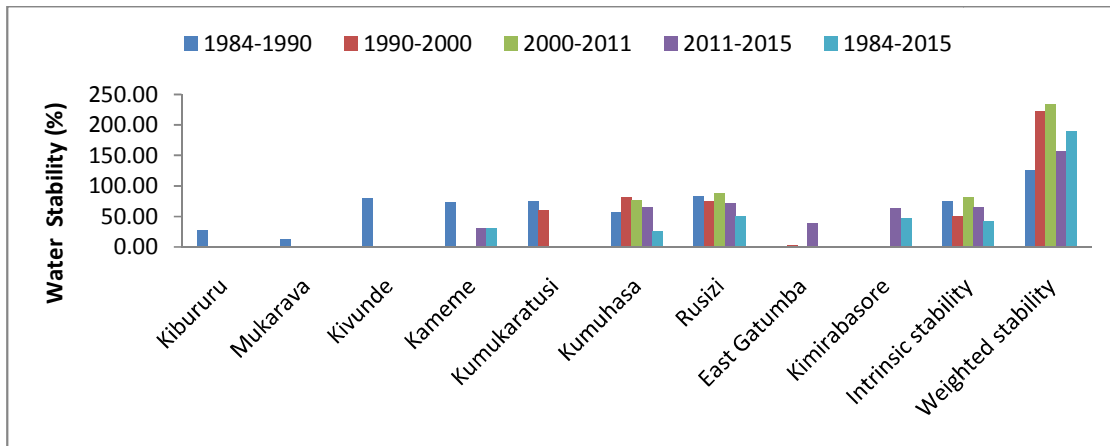


Fig. 3. Evolution of the water bodies' stability between 1984 and 2015

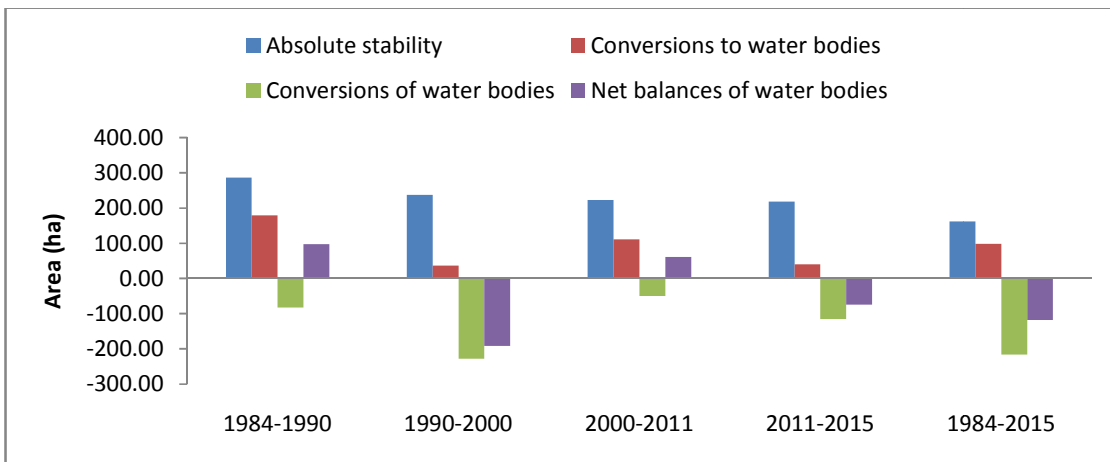


Fig. 4. Overall assessment of the evolution of the water bodies' class

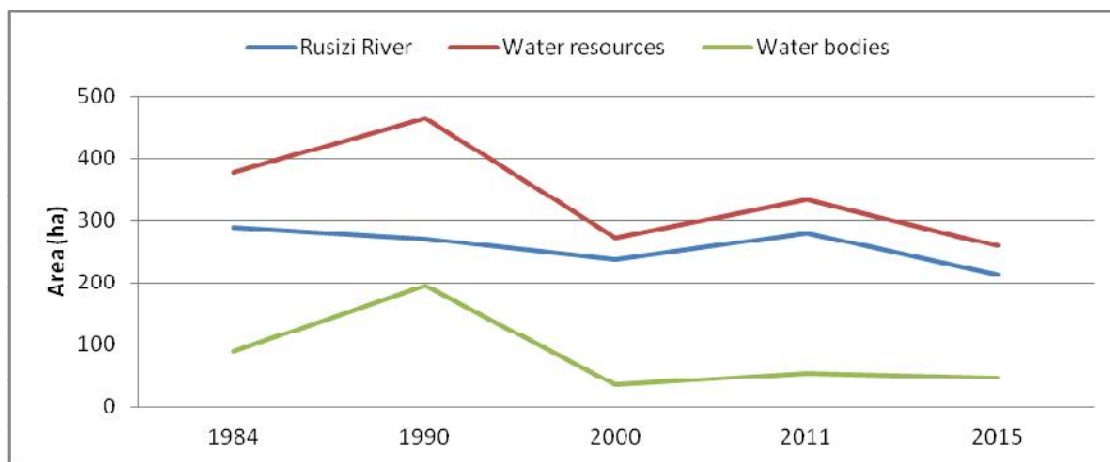


Fig. 5. Overall evolution of the Rusizi Park's water resources from 1984 to 2015

During the whole period of study 1984-2015, water bodies decreased by 31.24% falling down from 377.83 ha to 259.80 ha at an annual rate  $T_a$  of (-1.01%). This evolution follows a decreasing exponential equation  $y = 462.12e^{-0.108x}$  with a correlation coefficient  $R^2 = 0.5113$  (Fig. 5). The stability of water bodies represents 1.51% of the Park (Table 7) and an area of 161.81 ha which corresponds to an intrinsic stability of 42.83% and a weighted stability of 190.3% (Fig. 3). The largest losses in water bodies' areas came from their conversions into grassy savannah (0.63%), cultivated areas (0.53%), aquatic vegetation (0.31%), burned areas (0.24%) and *Hyphaene* forest (0.22%) while the most notable gains

came from the conversions of grassy savannah (0.38%) and aquatic vegetation (0.31%) into water bodies (Table 7). The surface transfers resulted in a net negative balance of 118.0 ha (Fig. 4).

#### 4.4 Spatial Changes in Individual Water Bodies

The analysis of the dynamics of individual water bodies detected at least twice between 1984 and 2015 shows the existence of contrasting periodic evolutions as indicated in Figs. 6 and 7 presented below.

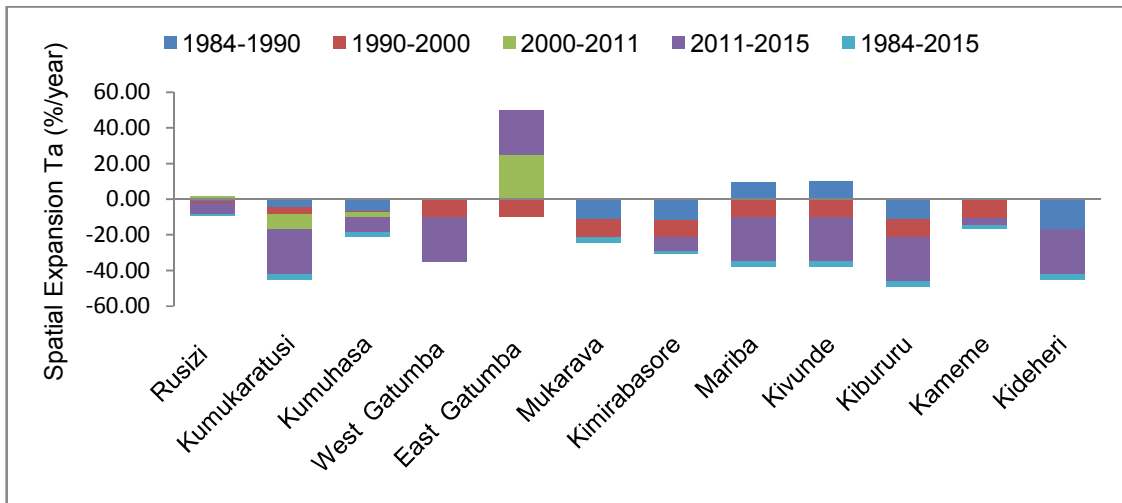


Fig. 6. Evolution of the spatial expansion of water bodies from 1984 to 2015

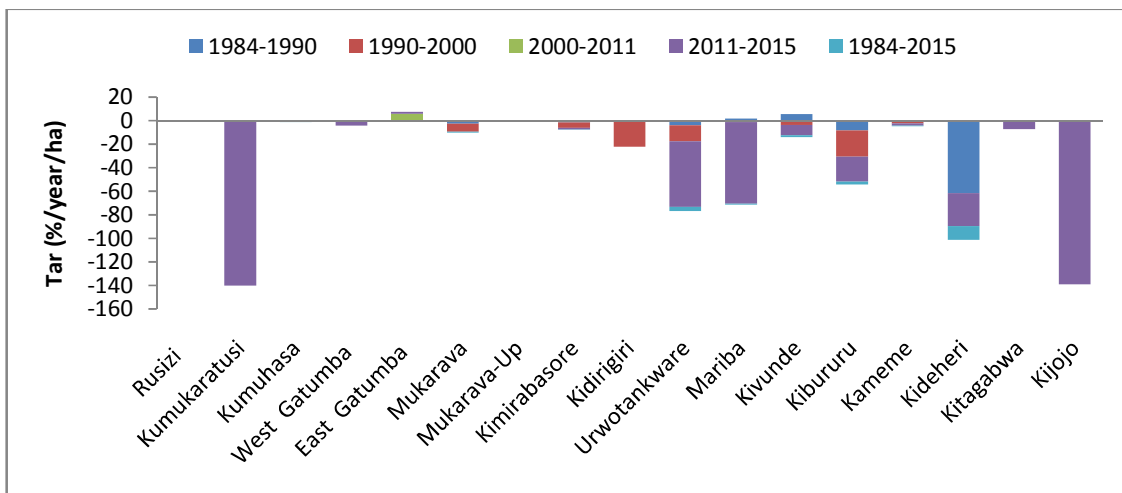


Fig. 7. Periodic evolution of the relative annual expansion rate of water bodies

Between 1984 and 1990, water bodies' spatial expansion, partial drying up and total drying up represent 18.2%; 72.7% and 9.1% respectively. Only Mariba and Kivunde ponds spread while all other water bodies were drying up. The water bodies which experienced relative quicker evolutions are Kideheri pond (61.73%/year/ha), Kibururu pond (-8.23%/year/ha) and Kivunde pond (5.56%/year/ha) (Fig. 7). The Rusizi River, Kivunde pond, Kumukaratusi lagoon, Kameme pond and Kumuhasa lagoon were the most stable water bodies, with 82.13%, 80%, 74.32%, 73.08% and 56.07% intrinsic stabilities (Fig. 3).

From 1990 to 2000, all water bodies have experienced dewatering. Partial and total dewatering reached 30.8% and 69.2% respectively. The water bodies that have evolved fast are respectively Kibururu pond (-22.22%/year/ha), Kidirigiri pond (-22.22%/year/ha) and Urwotankware pond (-13.89%/year/ha) (Fig. 7). The most stable water bodies are Kumuhasa lagoon (80.49%), Rusizi River (75.23%) and Kumukaratusi lagoon (60.91%) (Fig. 3). Between 2000 and 2011, water bodies' spatial extension and partial dewatering represent respectively 50% and 50%. The continuous dewatering of the two iconic lagoons of the Rusizi Park led to near disappearance of Kumukaratusi lagoon in 2011 and to its total disappearance in 2015. Eastern Gatumba ponds were the most rapidly evolving water body at a *Tar* of 5.85%/year/ha (Fig. 7). The most stable water bodies were Rusizi River (87.59%) and Kumuhasa lagoon (75.69%) (Fig. 3). From 2011 to 2015, the spatial extension, partial dewatering and total dewatering rates represented 7.1%; 28.6% and 64.3% respectively. Only Eastern Gatumba ponds widened while all other water bodies were drying up. This period experienced the fastest rates of evolution of water bodies, namely Kijojo pond (-138.89%/year/ha), Kumukaratusi lagoon (-138.89%/year/ha) and Mariba ponds (-69.44%/year/ha), Urwotankware pond (-55.56%/year/ha) and Kideheri pond (-27.78%/year/ha) (Fig. 7). Rusizi River, Kumuhasa lagoon, and Kimirabasore pond were the most stable water bodies, with respective stabilities of 71.17%, 64.85% and 63.33% (Fig. 3). During the entire period of study 1984-2015, partial and total dewatering rates represent 45.4% and 54.6% meaning that all the water bodies are drying up, at different rates. Only Rusizi River, Kumuhasa lagoon and Kameme, Mukarava and Kimirabasore ponds which represent 29.4% of the total number of water

bodies were identified both in 1984 and in 2015. Rusizi River and Kumuhasa lagoon were the most stable water bodies, with 50.99% and 25.97% of respective stabilities (Fig. 3). Water bodies' appearances and reappearances were the most important in 1990 and in 2011, with 50% and 88.9% of the cases reported respectively. Therefore, according to the detection status and criteria, permanent water bodies are Rusizi River, Kumukaratusi and Kumuhasa lagoons and Eastern Gatumba, Mukarava, Kimirabasore, Urwotankware, Mariba, Kivunde, Kibururu and Kameme ponds. They represent 64.70% of the total number of water bodies and are the most interesting for priority planning and management.

#### 4.5 Spatial Connectivity between Neighboring Water Bodies

The periods 1984-1990 and 1984-2015 have experienced spatial connectivity between specific water bodies belonging to two geographical entities: (1) the "Mariba-Kivunde-Kibururu-Urwotankware" ponds hydrologic group in the Palmeraie sector (Fig. 8) and the (2) "Eastern Gatumba – Western Gatumba - Kumuhasa-Kumukaratusi" ponds and lagoons hydrologic group in the Delta sector (Fig. 9).

Between 1984-1990, 4 spatial connectivities affecting 0.71% of the total area of water bodies were observed (Table 8): (1) Kidirigiri pond, which appeared in 1990, occupies part of the space left by Kimirabasore pond in drying, (2) Mariba pond has spread over part of the abandoned zone of Kibururu pond drying up, (3) Urwotankware pond occupies an area under the former Mariba pond and (4) Mukarava ponds gained an area abandoned by the withdrawal of Rusizi River. These hydrological modifications represent 0.12%; 0.21%; 0.19% and 0.19% in percentages (Table 8) and 0.45 ha; 0.79 ha; 0.72 ha and 0.72 ha in areas, respectively. Between 1984 and 2015, only 1 spatial modification was recorded in water bodies. It is related to Eastern Gatumba ponds appeared in 1990 which overflow part of the withdrawal zone of Kumuhasa lagoon in drying (Fig. 9). It represents 0.05% in percentage and 0.19 ha in area (Table 9). The distance between water bodies in spatial connectivity is varying considerably. They reach 0.07 km, 0.12 km and 0.69 km distances in case of Kibururu-Mariba, Mariba-Urwotankware and East Gatumba - Kumuhasa connectivities respectively (Figs. 8, 9).

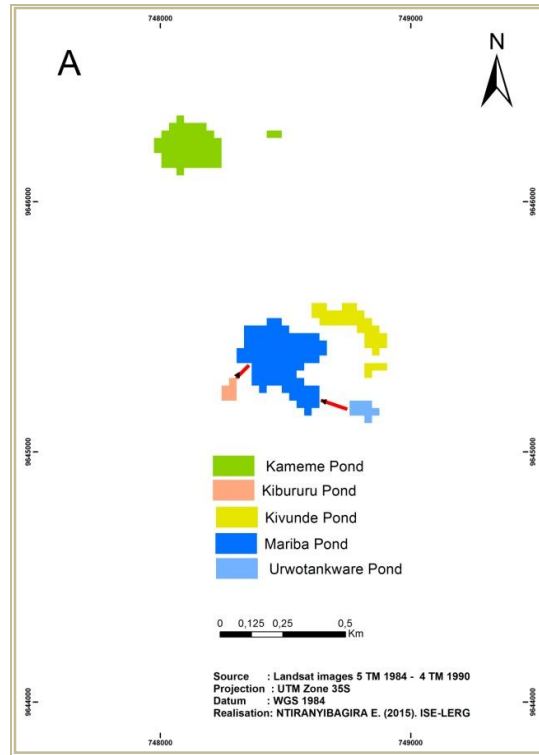


Fig. 8. Water bodies' connectivities (1984-1990)

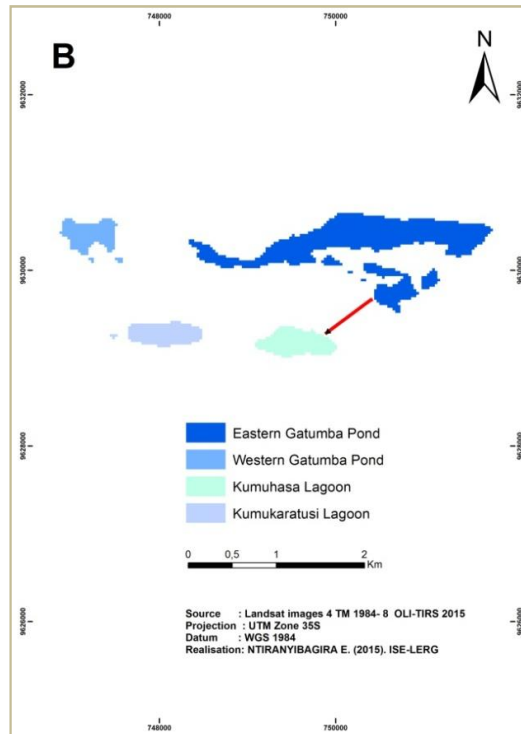


Fig. 9. Water bodies' connectivities (1984-2015)

**Table 8. Water bodies transition matrix between 1984 and 1990 (%)**

		Year 1990													
		RZ	KK	KH	MK	KR	RT	MR	KV	KB	KM	KG	WG	EG	%ST
Year 1984	RZ	62.72	0	0	<b>0.19</b>	0	0	0	0	0	0	0	0	0	76.37
	KK	0	5.24	0	0	0	0	0	0	0	0	0	0	0	7.05
	KH	0	0	5.50	0	0	0	0	0	0	0	0	0	0	9.81
	MK	0	0	0	0.14	0	0	0	0	0	0	0	0	0	1.14
	KR	0	0	0	0	0	0	0	0	0	0	<b>0.12</b>	0	0	1.93
	RT	0	0	0	0	0	0	0	0	0	0	0	0	0	0.24
	MR	0	0	0	0	0	<b>0.19</b>	0	0	0	0	0	0	0	1.31
	KV	0	0	0	0	0	0	0	0.38	0	0	0	0	0	0.48
	KB	0	0	0	0	0	0	<b>0.21</b>	0	0.10	0	0	0	0	0.36
	KM	0	0	0	0	0	0	0	0	0	0.91	0	0	0	1.24
	KD	0	0	0	0	0	0	0	0	0	0	0	0	0	0.07
	%ST	58.25	4.26	4.76	0.31	0.48	0.15	1.66	0.62	0.10	0.97	0.10	4.04	24.30	100

RZ: Rusizi, KK: Kumukaratusi, KH: Kumuhasa, MK: Mukarava, KR: Kimirabasore, RT: Urwotankware, MR: Mariba, KV: Kivunde, KB: Kibururu, KM : Kameme, KD : Kideheri, KG : Kidirigiri, WG : West Gatumba, EG : East Gatumba, ST: Total surface of water bodies(%)

**Table 9. Water bodies transition matrix between 1984 and 2015**

		Year 2015							
		RZ	KH	MK	KR	KM	MKU	GE	%ST
Year 1984	RZ	38.94	0	0	0	0	0	0	76.37
	KK	0	0	0	0	0	0	0	7.05
	KH	0	2.55	0	0	0	0	<b>0.05</b>	9.81
	MK	0	0	0	0	0	0	0	1.14
	KR	0	0	0	0.91	0	0	0	1.93
	RT	0	0	0	0	0	0	0	0.24
	MR	0	0	0	0	0	0	0	1.31
	KV	0	0	0	0	0	0	0	0.48
	KB	0	0	0	0	0	0	0	0.36
	KM	0	0	0	0	0.38	0	0	1.24
	KD	0	0	0	0	0	0	0	0.07
	%ST	81.85	3.71	0.03	1.45	0.59	0.24	12.12	100

MKU: Mukarava-Up. Other water bodies' codes remain those used in Table 8



#### 4.6 Spatial Structure Indices and STPs

The computation of the spatial structure indices affecting water bodies as a specific land cover class made it possible to identify 4 of the 10 STPs described theoretically in Fig. 2. These are patch creation, patch enlargement, patch dissection and patch attrition, depending on the period (Table 10). Patch enlargement was observed between 1984 and 1990 ( $n_{1990} = n_{1984}$  and  $a_{1990} > a_{1984}$ ) while patch creation was recorded between 2000 and 2011 ( $n_{2011} > n_{2000}$  and  $a_{2011} > a_{2000}$ ). Between 1990 and 2000 and from 2011 to 2015, patch attrition was noted [ $(n_{2000} < n_{1990}$  and  $a_{2000} < a_{1990}$ , with  $T_{obs} = 0.59 > T_s = 0.5$ );  $(n_{2015} < n_{2011}$  and  $a_{2015} < a_{2011}$ , with  $T_{obs} = 0.78 > T_s = 0.5$ )]. For the continuous period of study 1984-2015, it is the patch dissection that was observed ( $n_{2015} > n_{1984}$  and  $a_{2015} < a_{1984}$ , with  $T_{obs}=0.69 > T_s = 0.5$ ).

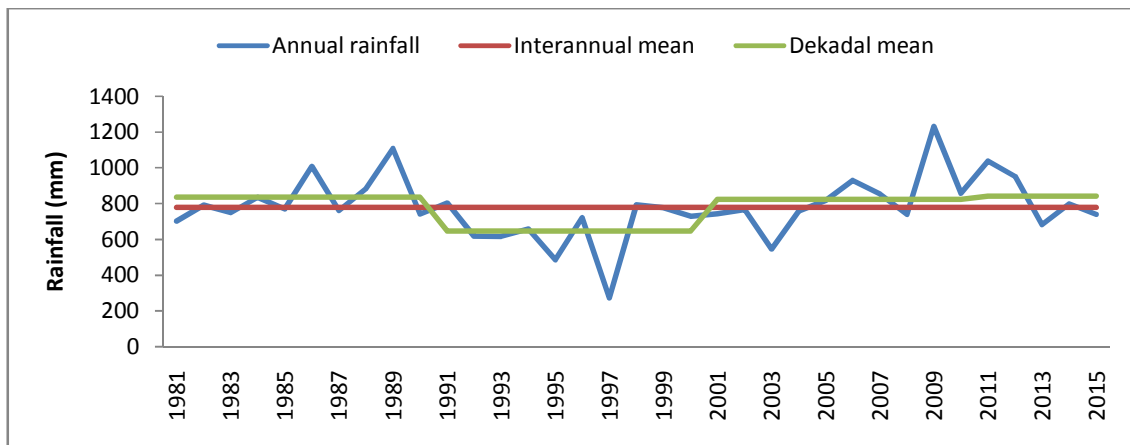
#### 4.7 Climatic Conditions

The analytic results show that annual rainfall is characterized by alternating cycles of rainfall surpluses and deficits compared to inter-annual rainfall average corresponding to 779 mm. These rainfall cycles are successively a surplus cycle (1982-1989), a deficit cycle (1990-2004), a surplus cycle (2005-2012) and a deficit cycle starting with year 2013 (Fig. 10). The annual rainfall related to years 1984, 1990, 2000, 2011 and 2015 are respectively 836 mm ; 740.3 mm ; 728.8 mm ; 1037.3 mm and 739.2 mm while their cumulative seasonal rainfall are successively 742.3 mm; 839 mm ; 727.8 mm ; 779.4 mm and

700.9 mm. The annual rainfall averages for the periods 1984-1990, 1990-2000, 2000-2011 and 2011-2015 are 872.0 mm; 647.0 mm; 833.7 mm and 841.8 mm (Fig. 10).

**Table 10. Evolution of Water bodies' STPs between 1984 and 2015**

Spatial parameters		Values of parameters	Type of STP
1984	N	29	
	a (ha)	378	
	P (km)	107	
1990	N	29	
	a (ha)	465	
	P (km)	114	
$N_{1990}/N_{1984}$		1.00	<b>Patch Enlargement</b>
$a_{1990}/a_{1984} (= t_{obs})$		1.23	
2000	N	20	
	a (ha)	273	
	P (km)	86	
$N_{2000}/N_{1990}$		0.69	<b>Patch Attrition</b>
$a_{2000}/a_{1990} (= t_{obs})$		0.59	
2011	N	35	
	a (ha)	334	
	P (km)	99	
$N_{2011}/N_{2000}$		1.75	<b>Patch creation</b>
$a_{2011}/a_{2000} (= t_{obs})$		1.22	
2015	N	31	
	a (ha)	260	
	P (km)	85	
$N_{2015}/N_{2011}$		0.89	<b>Patch Attrition</b>
$a_{2015}/a_{2011} (= t_{obs})$		0.78	
$N_{2015}/N_{1984}$		1.07	<b>Patch Dissection</b>
$a_{2015}/a_{1984} (= t_{obs})$		0.69	



**Fig. 10. Evolution of periodical rainfall levels from 1981 to 2015**

The results on rainfall indices presented in Fig. 11 indicate that the most deficit years were 1997 ( $U_i = -2.99$ ), 1995 ( $U_i = -1.74$ ) and 2003 ( $U_i = -1.38$ ). These years experienced extreme drought, a great drought and a moderate drought. The other 17 deficit years knew a slightly drought ( $-1.00 < U_i < 0$ ). The most surplus years were 2009 ( $U_i = 2.67$ ), 1989 ( $U_i = 1.94$ ), 2011 ( $U_i = 1.52$ ), 1986 ( $U_i = 1.34$ ) and 2012 ( $U_i = 1.02$ ). They are considered as extremely humid (2009), humid (1989, 2011) and moderately humid (1986, 2012). The remaining 10 surplus years are slightly humid ( $0 < U_i < 1.00$ ). Finally, the period 1981-2015 count 20 deficit years ( $U_i < 0$ ) and 15 surplus years ( $U_i > 0$ ). That gives a frequency of extremely dry years and of slightly dry years of 57%. Reference made to water bodies' periodical number, area and perimeter, the Spearman's correlation study showed a *high positive correlation* between annual rainfall and the number of water bodies ( $r_s$

= 0.9) and a *high positive correlation* between cumulative seasonal rainfall and the number of water bodies ( $r_s = 0.8$ ). It also revealed the existence of a *high positive correlation* between cumulative seasonal rainfall and the total perimeter of water bodies ( $r_s = 0.8$ ) and between cumulative seasonal rainfall and the total area of water bodies ( $r_s = 0.8$ ).

The results of temperature analysis show an annual average increase of  $0.03^\circ\text{C}$  which follows a linear regression model of equation  $y = 0.0287x + 23.989$  and a correlation coefficient  $R^2 = 0.5063$  (Fig. 12). They highlight two contrasting periods to know 1981-2000 and 2001-2015 whose temperatures are respectively below and above the general average which is  $24.5^\circ\text{C}$ . The annual averages are respectively  $24.1^\circ\text{C}$  (1984-1990);  $24.4^\circ\text{C}$  (1990-2000);  $24.8^\circ\text{C}$  (2000-2011) and  $24.7^\circ\text{C}$  (2011-2015) (Fig. 12).

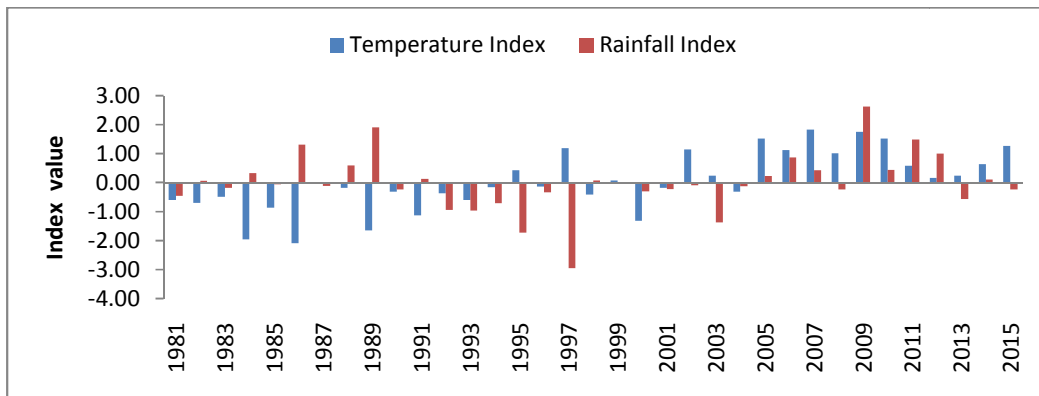


Fig. 11. Evolution of annual rainfall and temperature indices from 1981 to 2015

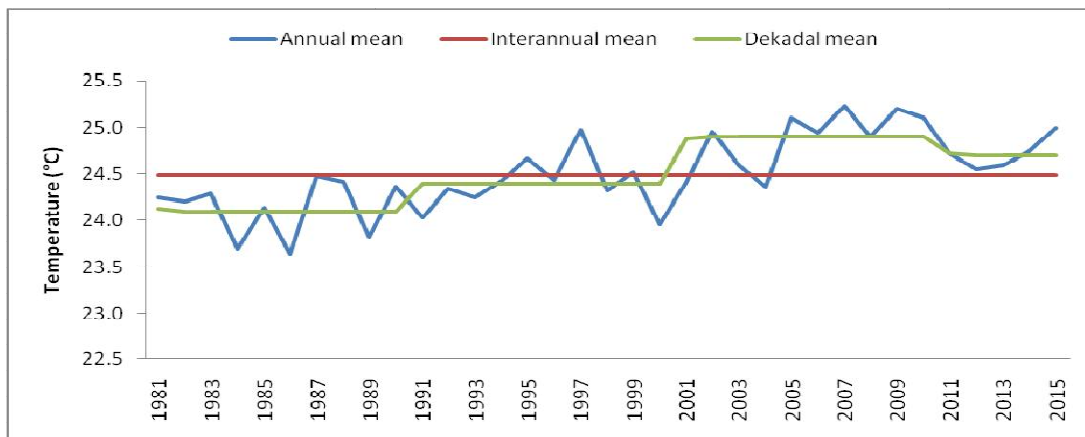


Fig. 12. Evolution of temperature levels from 1981 to 2015

## 5. DISCUSSION

### 5.1 Precision of the Classifications of Images

In comparison with the recommended thresholds for the Kappa coefficient [48,49] and the global precision [50], the accuracy of the classifications of images is statistically good. It is as much as acceptable that the number of 9 to 10 land cover classes identified on the different satellite images is high [51]. The precision is superior to 85% for global accuracy and more than 81% for Kappa Coefficient.

### 5.2 Periodical and Global Evolution of Water Resources

The analysis of the Spearman's rank correlation having shown the existence of high positive correlations between the rainfall levels and the water bodies' numbers, areas and perimeters, we conclude that the periodical evolutions of water bodies (appearance, partial dewatering, full dewatering and re-appearance) are directly and mainly related to rainfall dynamics, beyond anthropogenic pressures and socio-economic uses. The existence of high positive correlations between cumulative seasonal rainfall and water bodies' spatial parameters shows the relevance and the interest of the concept of cumulative seasonal rainfall compared to the annual rainfall concept. Those results were confirmed by previous studies which established the existing strong links between cumulative seasonal rainfall and water recharges on one hand [52] and development of vegetation on the other hand [53]. Therefore, because of their surpluses rainfalls, the periods 1984-1990 and 2000-2011 experienced favorable climatic conditions for the development of water resources. At contrary, the periods 1990-2000 and 2011-2015 were characterized by unfavorable climatic conditions due to rainfall deficits. The cyclical characteristics of annual rainfall and continuous increase in temperatures highlighted by the study (Figs. 9-10) have already been described by previous studies on the Plain of Rusizi [6]. The high frequency of dry years between 1981 and 2015 shows a general trend towards increasingly dry conditions which are aggravated by annual temperature increase of 0.03°C which gives 0.3°C per decade. The results show that permanent water bodies are actually the most extended at their first detection either in 1984 or in 1990. They are also more stable and more

resistant to dry climatic conditions and to anthropogenic pressures (Fig. 3, Tableau 8). The most important water bodies' surfaces and perimeters were obtained in period of high recharges (1990) while the weakest ones were observed in period of limited recharges (2000). During the driest years 2000 and 2015, only largest, most resistant to dry conditions and most stable water bodies were identified. Despite comparable seasonal rainfalls, year 2015 has more water bodies than year 2000 due to more previous humid period; decade 1990-2000 having been particularly dry (Fig. 10). The stability of water bodies has been declining continuously since 2000 while smallest water bodies dried up faster than big ones (Figs. 3, 6) because of higher sensitivity and vulnerability to climatic and anthropogenic stresses. This is the case of Kideheri and Kibururu ponds (1984-1990), Kibururu and Kidirigiri ponds (1990-2000) and Kijojo pond, Kumukaratusi lagoon, Mariba, Urwotankware and Kideheri ponds (2011-2015) whose surfaces were respectively and relatively weak in 1984, 1990 and 2011 (Table 2, Fig. 5). The periods 1984-1990 and 2000-2011 have experienced important water bodies' stabilities and net positive balances which are favorable to the conservation of this wetland contrary to the periods 1990-2000, 2011-2015 and 1984-2015 (Figs. 3-4). The periods 1990-2000 and 1984-2015 have been characterized by important conversions of water bodies into other land cover classes and large negative net balances (Fig. 4) because of dry conditions and high anthropogenic pressures. The high levels of weighted stabilities show that the water bodies constitute a stable ecosystem reference made to the spatial transformations that have affected the Park (Fig. 3). The results of cartographic analysis show the existence of important spatial interactions between water bodies, aquatic vegetation, grassy savannah, *Hyphaene* forest and cultivated areas. During humid periods (1984-1990, 2000-2011), these land cover classes were flooded by the overflowing of Rusizi, Kajeke and Mpanda rivers and/or the stagnation of surface waters whose flow is slow due to the low slopes of the Park [4]. In dry periods (1990-2000, 2011-2015), they develop in dewatered or dry areas that retain again some moisture. The cartographic analysis of land cover indicates that agricultural drainage and irrigation, which were particularly important during dry periods constitute the greatest anthropogenic threats to water bodies. Indeed, illegal crops are concentrated around the main water bodies

(Rusizi, Kumuhasa, Kumukaratusi, Kimirabasore, Kameme, Mariba).

Between 1984 and 1990, the development of water resources is firstly justified by excess rainfall (872 mm average) which was accompanied by the appearance of vast ponds in 1990 (Eastern Gatumba, Western Gatumba). The partial dryness of the Rusizi River and the majority of water bodies connected to it is explained by the installation of an irrigation dam on the watercourse at Kiliba Sugar Company in D.R. Congo. Despite high annual rainfalls in 1984 and in 1990, year 1990 has better water coverage (number, surface) than 1984 due to most important cumulative seasonal rainfall which was 839 mm against 742.3 mm. The year was also preceded by humid years while the year 1984 experienced previous dry years (Fig. 10). Secondly, water bodies' development is explained by the evacuation of the Park's inner populations after its creation in 1980 which contributed to reduce agro-pastoral farming pressures. From 1990 to 2000, the important reduction in water resources can be explained by the unfavorable climatic conditions characterized by rainfall deficit (647mm average) on one hand. On the other hand, it is justified by intensive agricultural and pastoral activities consuming great quantities of water resources because of a high concentration of increasing populations in and around the Park, especially due to the 1993 civil war which has produced many displaced people at Gatumba and Gihanga [4]. The agro-pastoral pressures and the retreat of water resources were accentuated by the distribution of nearly 50% of the Park for agricultural purposes at the beginning of the year 2000. The significant reduction of water in Lake Tanganyika in 1994 has especially contributed to the dryness of Kumukaratusi and Kumuhasa lagoons by breaking hydrological connectivity and interactions between the Lake and the two remarkable water bodies [9,3]. Between 2000 and 2011, the extension of water resources resulted from the excess rainfall (833.7mm average), the decline of anthropogenic pressures following progressive repatriation of the displaced people of the civil war of 1993 and the insecurity caused by the presence of armed groups in the Park until 2006. From 2011 to 2015, the significant reduction in water resources is linked to the continuous decline in rainfall since 2012 and to the intensification of illegal agro-pastoral activities. In fact, not only the change of the conservation status in 2011 failed to

evacuate the distributed and exploited land since 2000, but it has also been accompanied by fraudulent occupation from high placed and powerful land speculators [7]. During the period of study 1984-2015, the reduction of water cover and resources is caused by the unfavorable climatic conditions characterized by cyclical rainfall and continuous temperature increase on one hand (Figs. 10-12). On the other hand, it is explained by the considerable increase of peripheral and inner anthropogenic pressures because the Park depending populations have increased at an average annual rate of 10% [7]. The high dewatering rate measured (54.6%) concord with those which have been observed in most of Western European countries following land use planning and management [23]. Depending on the country, the rates vary between 50% and 90% [23]. The drying up and the disappearing of water resources are often linked to agricultural drainage in dry season for the cultivation of rice and food crops [4]. This result is confirmed by the conclusions of other studies which showed that the disappearance of small water bodies is highly linked to the changes of anthropogenic activities and land use [23]. The natural phenomenon of landing observed at a decennial scale for many water bodies of Plains and socio-economic uses explain the degradation of water resources [22]. This is the case of the studied water bodies which are mostly formed in shallow topographic depressions left behind by River Rusizi [4]. The relatively important surface of most of water bodies, their rapid drying up and their reappearance during favorable rainfall prove enough their shallow depth and their limited volumes. These arguments justify a posteriori the designation of pond given to many water bodies and show that the climatic factor is the most determinant in the evolution of water resources. The regressive trend of the Rusizi Park's water resources proved by the study has already been established for the Plain of Rusizi and Lake Tanganyika where long droughts are observed [6]. The hydrologic connectivity observed between some water bodies is a normal spatial phenomenon that often affects nearby water bodies [22]. In this case study, it appears from spatial substitutions which are induced by two phenomena: (1) the appearance of a given water body in the abandoned area or the withdrawal area of another and (2) the extension of a water body towards the withdrawal area of another one. The advanced drying of Kumuhasa and Kumukaratusi emblematic lagoons due in

particular to the connectivity break with Lake Tanganyika and Rusizi River illustrates the importance of the phenomenon in the dynamics of specific water bodies of the Park as described by Ntakimazi and Nzigidahera [9].

### **5.3 Spatial Structure Indices, Water Bodies' Dynamics and Quality of Conservation**

The spatial structure indices delivered from the cartographic analysis reflect perfectly the evolutions observed in water bodies and resources. In fact, the development of water bodies in number and surface characterizing the periods 1984-1990 and 2000-2011 is explained by the respective patch enlargement and patch creation processes that are expressed by extension, appearance and reappearance of specific water bodies. Conversely, the decline in these water bodies' parameters that marked the periods 1990-2000, 2011-2015 and 1984-2015 is linked to patch attrition and patch dissection processes which are concretized by the narrowing, the modification and the total drying up of specific water bodies. Consequently, patch enlargement and patch creation processes were accompanied by positive net balances while patch attrition and patch dissection processes led to negative net balances (Fig. 4). At a climatic plan, we notice that beneficial processes of patch enlargement and patch creation correspond to periods of excess rainfall (1984-1990, 2000-2011) while degradative processes of patch attrition and patch dissection are due to periods of rainfall deficits (1990-2000, 2011-2015). At the anthropogenic level, positive water resources' evolutions or development correspond to the reduction of socio-economic uses caused by suppression or limitation of previous human activities and vice versa. Those are common farming activities, livestock farming and fishing which are usually illegal or prohibited in protected area. These activities are indeed at the origin of anarchic and intensive exploitation of water bodies, especially in dry periods and seasons. In terms of quality of conservation, the qualitative interpretation of the STPs affecting land cover classes depends on their nature. Given the status of humid zone of the Park and the central role played by water bodies, we can conclude that the processes of patch enlargement and patch creation were favorable to the conservation during the periods 1984-1990 and 2000-2011 since they have contributed to improve the available water resources. These periods have

indeed experienced important water bodies' stabilities which reached 75.70% (1984-1990) and 81.59% (2000-2011) and numerous cases of water bodies' appearance and reappearance. At contrary, the processes of patch attrition and patch dissection have been unfavorable to the conservation during the periods 1990-2000, 2011-2015 and 1984-2015 because they have caused the reduction of available water resources. These periods have experienced low water bodies' stabilities which have not exceeded 50.96% (1990-2000), 65.51% (2011-2015) and 42.78% (1984-2015) and many cases of partial or complete water bodies' drying up. The predominance of the degradative processes of patch attrition and patch dissection demonstrates the high vulnerability of water bodies which manifest itself in a continuous decrease of spatial stability and the important natural drying rates. In the current context of global warming and the intensification of anthropogenic pressures, water bodies are extremely vulnerable. At the annual average rate of drying up observed since 1984 (-1%/year), they could dry out by 2084 if appropriate measures are not taken.

### **6. CONCLUSION**

Water bodies are important elements of the Rusizi national Park's both as a key ecosystem and a specific land cover class. They justify its wetland and Ramsar site status on which the conservation of the protected area is lying. However, they are threatened by human activities and the deterioration of climatic conditions that jeopardize their ecological functions which are of paramount importance for wildlife, bird migration and ecotourism. The study and regular monitoring of these particular ecosystems are therefore a priority for the sustainable management of this semi-arid protected area. This prospective study shows that the water resources are under a continuous decline, both in number, surface and stability. The majority of the water bodies are shallow, unstable and quickly evolving. The largest and deepest water bodies are the most stable and the most resistant to dry conditions, despite steadily declining stability. These water bodies are considered as permanent. They should be well managed as a matter of priority in the framework of the appropriate and urgent measures to be undertaken for the rational management of water resources which are subject to advanced degradation. Despite the limitations of the study which does not take into

account small water bodies of less than 0.09 ha which are ephemeral and the water bodies' qualitative degradation related to farming activities, it has the merit of providing essential baseline data for future studies and the sustainable management of the Park's water resources.

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## COMPETING INTERESTS

Authors have declared that no competing interests exist.

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