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Geostatistical analysis of rainfall variability on the plateau of Allada in South Benin

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ABSTRACT
The goal of this survey is to contribute to a better understanding of the distribution of the rainfall on the plateau of Allada in Benin. The plateau of Allada is the garner ofCotonou and vicinities. The food production is over 62% rainfed.Then, it imports to analyze the way how rains are spatially distributed on the area in order to deduct the potential rainfall. To achieve this goal, rainfall data of 28 stations have been used. Three sub-periods have been identified: 1996-2000, 2001-2005 and 2006-2010. The distribution of rainfall has been established with Thiessen and kriging methods. On average, 1117mm of rain fell on the study area per year. But three tendencies were shown: the less rainy zones, the fairly rainy zones, and the greatly rainy zones. All the rainfall zones knew an increase of the precipitations except Abomey-Calavi and Niaouli. But the variations are not significant. While analyzing the spatial structure for the kriging of precipitations, it was revealed a power model of variogram. The direction of the rainfall gradient is oriented southeast - northwest during the three sub-periods. Abomey-Calavi recorded the weakest precipitations. The strongest values are interchanged between Toffo and Sékou, Ouidah-North and Ouidah-City.
***Keywords*-**Rainfall gradient, South Benin, spatial structure, variogram.

I. INTRODUCTION

The plateau of Allada, largest plateau of South Benin, covers 2036 km^2 (Fig.1). It hosts a population of 717,813 inhabitants in 2013 with a density of 352 inhabitants per square kilometer (INSAE, 2015) [1]. It is located in the sub-equatorial area below the parallel 6°60'where there is a unimodal rainfall regime. It is an area whose agricultural sector is characterized by its vulnerability to climate hazards (Agbossou et *al*., 2012 [2]; Agossou et *al*., 2012 [3]; Allé et *al*., 2013 [4]). Climatic variations are a reality and farmers are aware. These variations occur, according to them, the lack of or insufficient rainfall, its delays, bad distribution (Adjahossou et *al*., 2014 [5]). Meanwhile, this regionis known as food products attic of the largest city of Benin (Cotonou) and around. The food production is 62% rainfed (Alléet *al*., 2013 [4]). Its increase is a key issue to help ensure food and nutritional security of the population (Sultan et *al.*, 2012 [6]). The issue is particularly important given that cereal imports have not allowed to achieve food security and have led to the impoverishment of populations (Goujon, 2010 [7];Ahomadikpohou, 2015 [8]). Understanding the spatial distribution of the limiting factor (which is rainfall) contributes to the realization of this issue.

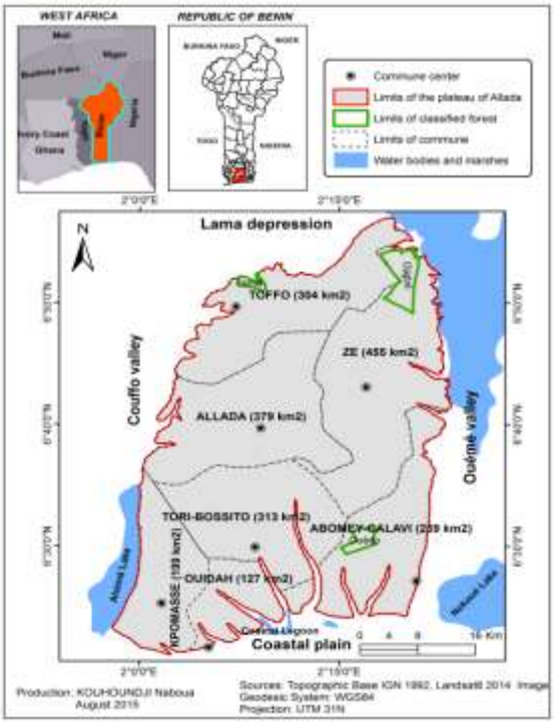

Figure 1: Study area

This is to analyze, through a GIS tool (geostatistics), the spatial discrimination of precipitation from rainfall stations that cover the study area.

II. DATA AND METHODS

2.1 DATA

The data used consist of ten rainfall stations (obtained from the Agency for the Safety of Air Navigation in Africa and Madagascar -Cotonou) covering the study area. To better analyze the spatial structure of rainfall, we took into account other surrounding stations of southern and central Benin. There are eighteen. Based on the work of Le Barbé et *al*. (2002) [9], Balme et *al*. (2006) [10], Ali and Lebel (2008) [11] and Sané et *al*. (2008) [12] on climate disruptions in West Africa from the beginning of the 1970s, we chose the sub-period after 1990 (more precisely 1995) for a recent analysis of changes. Furthermore, in order to analyze the precipitation for small step time, we have chosen five-year terms. Thus, the sub-periods of precipitation are considered: 1996-2000 (P1), 2001-2005 (P2) and 2006-2010 (P3). This choice is justified by the fact that on the same area, Allé et *al*. (2013) [13] studied the rain on the steps of 20 years. Contrary to10 or 30 years step time, five-year terms allow for a short-term picture of rainfall variations. Agricultural production depends on it.

2.2 METHODS

Thiessen method was used for the segmentation of the study area into rainfall zones. Differences between sub-periods of precipitation have been evaluated by the parametric Student test. In the case where the conditions of normality of data and homogeneity of variances are not checked, the alternative nonparametric Wilcoxon was used. All this was done under the R3.1.3 software.

To better appreciate the distribution per point of precipitation, the data have been geostatistically analyzed (kriging method). Surfer 11.0 software was used to carry out the distribution maps based on the analysis of the appropriate variogram model. The experimental variogram (Abramowitzand Stegun, 1972 [14]) was calculated by (1):

$$\gamma(h) = \frac{1}{2N(h)} \sum_{(i,j)\in S(h)} (Zi - Zj)^2 (1)$$

with:

$\gamma(h) \equiv observedvariogramforadistanceh$

$N(h) \equiv numberofcuplesofobservations$
$separatedbyadistanceh$

$ZiandZj \equiv rainfallatiandjstations$

The variogram model used is evaluated by the Nash criterion (Nash and Sutcliffe, 1970 [15]) whose formula is (2):

$$Nash = 1 - \frac{\sum_1^n (Yi^{obs} - Yi^{mod})^2}{\sum_1^n (Yi^{obs} - Y^{moy})^2} (2)$$

with:

$Yi^{obs} \equiv collectedrainfall$

$Yi^{mod} \equiv estimatedrainfall$

$Y^{moy} \equiv meanofcollectedrainfall$

The ordinary kriging method is used to estimate precipitation values at unknown points. This is an unbiased estimator widely used in hydrometry. This method takes into account the influence (weight) of the stations surrounding the unknown location. Any precipitation value Z at a location x is estimated by (3):

$$Z_x = \sum \lambda_i Z_i \ (3)$$

Where$Z_x \equiv estimatedrainfall$;

$Z_i \equiv observedrainfall$;

$\lambda_i \equiv weightofknownrainfall$

The $\lambda_i$are calculated through the resolution of the kriging system (4):

$$\begin{cases} K_0\lambda_o = k_0 \\ \sigma_{k_0}^2 = \sigma_x^2 - \lambda_o' k_0 (4) \\ \sum_{i=0}^n \lambda_o = 1 \end{cases}$$

with

$K_0 \equiv covariancematrixofall$
$couplesofpoints$

$k_0 \equiv covariancematrixofallcouples$
$ofpointscontainingZ_x$

$\sigma_{k_0}^2 \equiv estimationvarianceofordianrykriging$

$\sigma_x^2 \equiv varianceofestimanedvalues$

$\lambda_o' \equiv transposeofthematrix\lambda_o$

The first equation of the system (4) can be developed like (5):

$$\underbrace{\begin{bmatrix} \sigma^2 & Cov(Z_1,Z_2) & \bullet & Cov(Z_1,Z_n) & 1 \\ Cov(Z_2,Z_1) & \sigma^2 & \bullet & Cov(Z_2,Z_n) & 1 \\ \bullet & \bullet & \bullet & \bullet & \bullet \\ Cov(Z_n,Z_1) & Cov(Z_n,Z_2) & \bullet & \sigma^2 & 1 \\ 1 & 1 & \bullet & 1 & 0 \end{bmatrix}}_{K_o} \underbrace{\begin{bmatrix} \lambda_1 \\ \lambda_2 \\ \bullet \\ \lambda_n \\ \mu \end{bmatrix}}_{\lambda_o} = \underbrace{\begin{bmatrix} Cov(Z_1,Z_x) \\ Cov(Z_2,Z_x) \\ \bullet \\ Cov(Z_n,Z_x) \\ 1 \end{bmatrix}}_{k_o} (5)$$

Surfer 11.0 software was used for thedifferent calculations. Spatial analysis maps are performed with the same software after ArcGIS 10.2 software which was used to generate shape files (.shp). Thiessen segmentation is performed using also ArcGIS10.2.

III. RESULTS AND DISCUSSION

The processing of data generated three types of results: Evolutionof precipitations in the rainfall zones, spatial structure of precipitations and spatio-temporal distribution of rainfall.

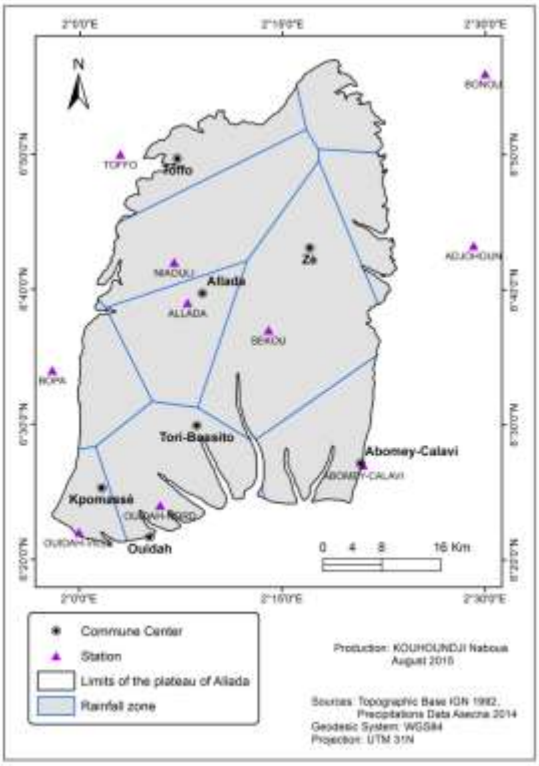

Figure 2: Study area into rainfall zones

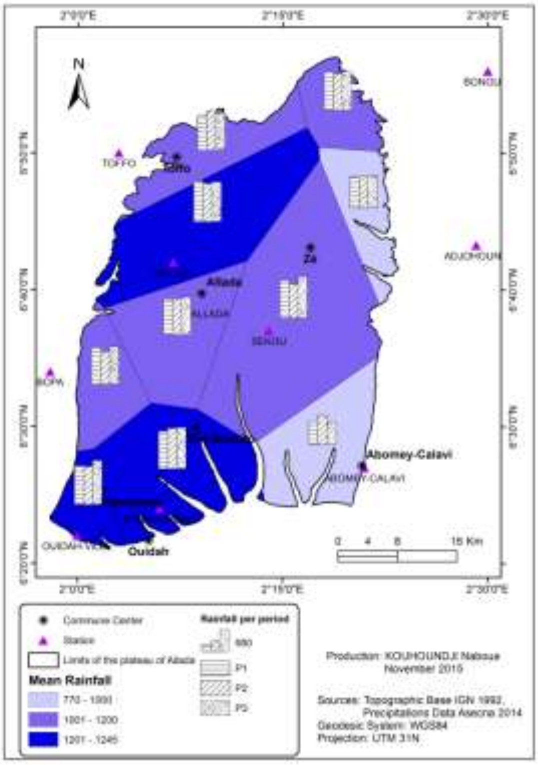

Figure 3: Mean and periodic rainfalls

3.1. EVOLUTION OF PRECIPITATIONS IN THE RAINFALL ZONES

3.1.1. DELIMITATION OF RAINFALL ZONES AND REGIONALIZATION OF PRECIPITATIONS

The segmentation method of Thiessen identified 10 rainfall stations that influence the study area (Fig.2). These segments define homogeneous rainfall zones. The areas covered by each of the zones vary from 208 to 1018 km^2 with an average of 658 (+/-283) km^2. These values show the surface disparity of rainfall zones. The resulting spatial resolution is 51 km. This resolution is very loose in accordance with the standards of the World Meteorological Organization (WMO), which advocates 30-5 km (WMO, 2012 [16]). This observation is identical to that of Akponikpè and Lawin (2010) [17] intheir work on the evaluation of observation systems and research on climate change in Benin.

The 10 stations influencing the sector are part of 14 chosen by Allé et *al*. (2013) [4] in their study on the evolution of intra-seasonal descriptors of rainy seasons in South Benin between 1951 and 2010. They chose these 14 stationsconsidering the homogeneity of recorded rainfallvariances.

The average precipitation throughout the study area during the study period (1996-2010) is 1117mm per year. This value conceals disparities. Eastern rainfall zones recorded the lowest rainfall values (less than 1000mm / year) (Fig. 3). Those wereAdjohoun and Abomey-Calavi. The majority of western zones are moderately watered (1000 - 1200mm / year) except Niaouli. That one was part of the wettest zonesincludingOuidah-north and Ouidah-city (rainfall more than 1200mm / year) (Fig. 3). This presentation on trends in precipitation from 1996 to 2010 smooths sub-periods P1, P2 and P3.

3.1.2. CHANGES IN PRECIPITATIONS THROUGHOUT SUB-PERIODS

Fifty percent (50%) of rainfall zones experienced a decrease in total rainfall means between P1 and P2 (Fig. 4). Those wereBonou, Bopa, Niaouli, Ouidah-city and Sekou. But the magnitudes of the declines vary widely. While Bopa and Sekou decreased each down to 11%, Bonou and Niaouli recorded respectively 4% and 6% decrease (Fig. 5).That decrease in rainfall amounts impacted negatively food crops especially maize (*Zea mays*) and cowpea (*Vignaunguiculata*). As examples, in the Niaoulizone, maizedecreased in yield of 8% while in Sékou, the decline was 15%. Cowpea, meanwhile, had 9% and 17% decrease in yield respectively in the twozones. The zones that experienced a perceptible increase were 30%. Those were Abomey-Calavi, Toffoand Ouidah-north. They have known respectively 25, 14 and 8% increase (Fig. 5).

From P2 to P3, all the rainfall zones experienced an increase in precipitation (though they were of different magnitudes) except Abomey-calavi and Toffo (Fig. 5). Those two zoneswere respectively southeast and northwest of the study area. So, they described the southeast - northwest axis (Fig. 3).

Overall throughout the study period (P1 to P3), all the rainfall zones have experienced increased precipitation with the exception of Abomey-calavi and Niaouli (Fig. 5). Note that Niaouli is on the southeast - northwest axis previously described by P2 to P3 rainfall (Fig. 3). It should be checked whether the differences of precipitations fromP1 to P3 were statistically significant.

According to the normality test of Shapiro-Wilk at a confidence level of 95%, precipitations of P1 and P3 are not normally distributed, while those of P2 are (Table 1). Indeed, the probabilities obtained for P1 and P3 is less than 0.05 and that for P3 is greater than 0.05 (Table 1). It follows that the Wilcoxon test can be used to assess the significance of the mean differences of precipitations of sub-periods.

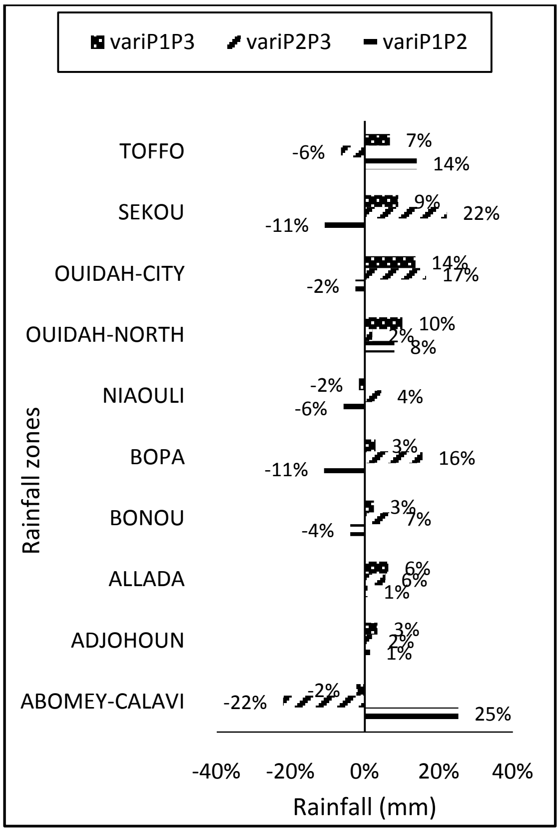

Figure 5: Precipitation variations between sub-periods

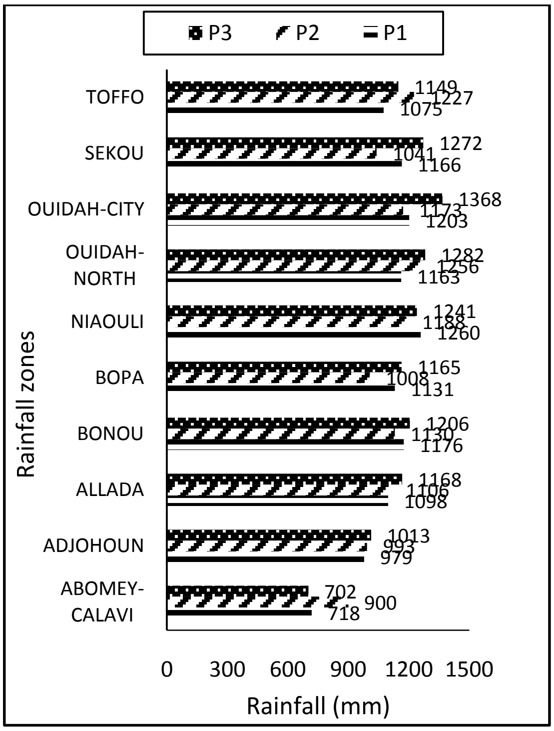

Figure 4: Mean precipitations in rainfall zones

Table 1: Normality Test of Precipitations from P1 to P3

Sub-periods	Probability (p-value)	Decision
P1	0.022< 0.05	The precipitations of the sub-period P1 are not normally distributed
P2	0.824> 0.05	The precipitations of the sub-period P2are normally distributed
P3	0.032< 0.05	The precipitations of the sub-period P3 are not normally distributed

Applying the Wilcoxon test for P1-P2, P2-P3 and P1-P3, we obtained the results summarized in Table 2.

Table 2: Significance test of mean differences of precipitations from P1 to P3

Couples ofperiods	Probability (p-value)	Decision
P1-P2	0.9118>0.05	There is no significant difference between precipitations of P1 and P2
P2-P3	0.1903>0.05	There is no significant difference between precipitations of P2 and P3
P1-P3	0.1903>0.05	There is no significant difference between precipitations of P1 and P3

All the probabilities obtained are greater than 0.05 (Table 2). It is clear from this table, with a confidence level of 95% that no difference exists between the average rainfall of sub-periods P1, P2 and P3. However, from the agronomic point of view, 10mm of rain are very important for crops, especially those who cannot tolerate a short period of dryness. The examples given in thesection 3.1.2 about maize and cowpea are illustratable. Therefore,it is necessary to analyze the spatial structure of precipitation and deduce the point distribution through the kriging method.

3.2. Spatial Structure of Rainfall

The semi-variogram was the basis for the analysis. Fig. 6 shows the evolution of the semi-variograms of the observations versus distances between rainfall stations and the simulation model (Fig. 6).

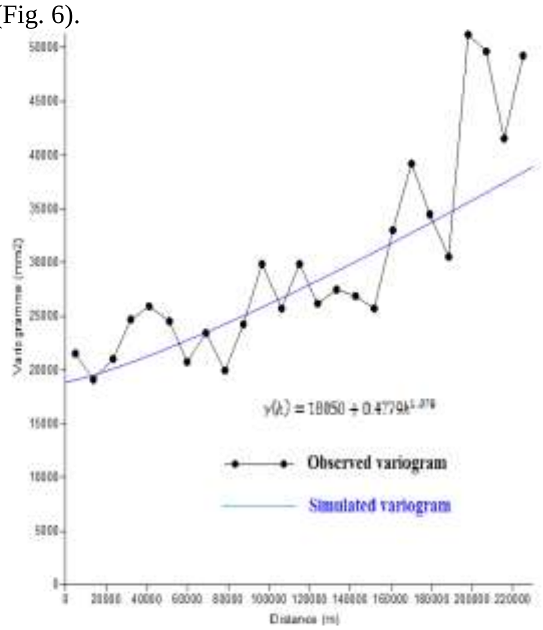

Figure 6: Observed and simulated variograms

The variogram model is power-type (Fig. 6). It admits no sill. The variance in the rainfall process on the study area tends to infinity. So, there is a spatial correlation among rainfalls recorded at the stations. The Nash coefficient calculated (0.704) confirms this status. Those rainfalls have regular trend in their spatial distribution. They can therefore be modeled as a function of X and Y coordinates of the stations. The model admits a nugget effect. That reflects the variations of the precipitations at small distances, so small scale (within 20 km) (Fig. 6). The model underestimates the variances between 20 and 50km and after 170km, while it overestimates them between 120 and 170km. The formula ofthe variogram model ɣ is as follows:

$$\gamma(h) = 18050 + 0.4779h^{1.076} \quad (6)$$

where h = distance between two points

This model is different from that obtained by Lawin et al. (2010) [18] when they studied the variability of rainfall scheme compared at regional and local scales in the upper valley of Ouémé. They had obtained an exponential model. They have used daily rainfall throughout the period 1954-2005. That model is also different from that obtained by Ly et *al.* (2011) [19] when they studied daily rainfallinterpolation at catchment scale by using several variogram models in the Ourthe and Ambleve catchments in Belgium. They found that the Gaussian model was the most frequently observed.Allé et *al.* (2013) [4], in their study of intra-seasonal descriptors in south Benin, found also an exponential model. This is related to the extent of their study area and a larger number of stations they have taken into account.

Spatial analysis allowed the productionof the maps ofrainfall distribution of sub-periods in the study area.

3.3. Spatio-temporal Distribution of Rainfall

During the period P1 (1996-2000), the spatial distribution of rainfall is shown on Fig. 7. Reading that figure, we noted an overall rainfall gradient southeast - northwest. The lowest rainfall is recorded at Abomey-Calavi while the highest is recorded at Niaouli. This observation is identical with the Thiessen method of regionalization (Fig. 3 and 4).However, the method of Thiessen is more holistic. Meanwhile it was assigning the yearly average of 720mm of rainfall for the entire zone of Abomey-Calavi, the Kriging method said that this average varies from 720 to 980mm per year. It is the same for other rainfall zones where there is a spatial variation of rainfall.

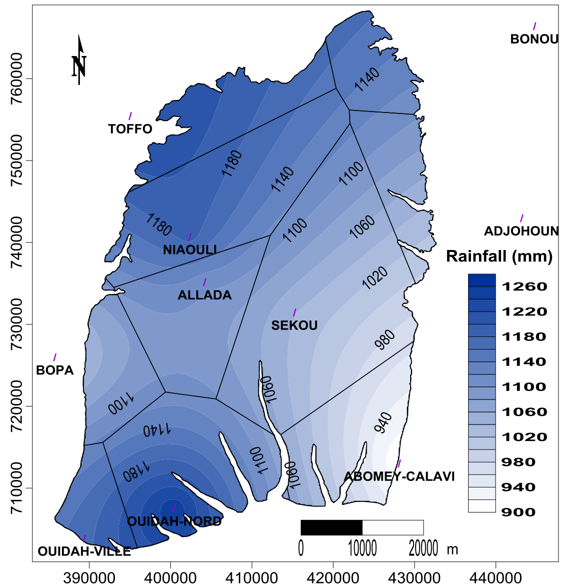

Figure 8: Precipitation distribution of P2

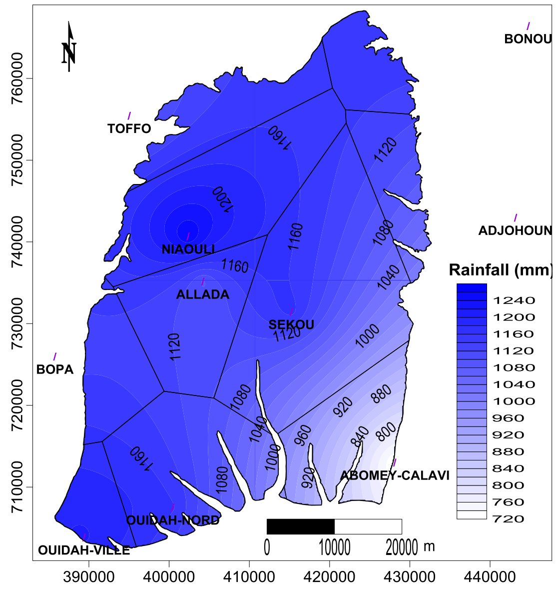

Figure 7: Precipitation distribution of P1

Figure 8 shows the spatial rainfall variations throughout the sub-period P2 (2001-2005). Overall, this sub-period was rainier than P1 (average annual precipitation of 1102mm against 1096mm for P1). The direction of the rainfall gradient was maintained (southeast - northwest) with a particularity in Ouidah-north. Abomey-Calavi was still recorded the lowest rainfall from 900 to 1000mm per year. With the Thiessen method, that zone was labeled900mm for the same period (Fig. 3 and 4). About the particularity of Ouidah-north and around, the average annual rainfall oscillatedbetween 1260 and 1140mm. That brings to observe that throughout that sub-period, there were two poles of high rainfall: Toffoin northwest and Ouidah-north insouthwest.

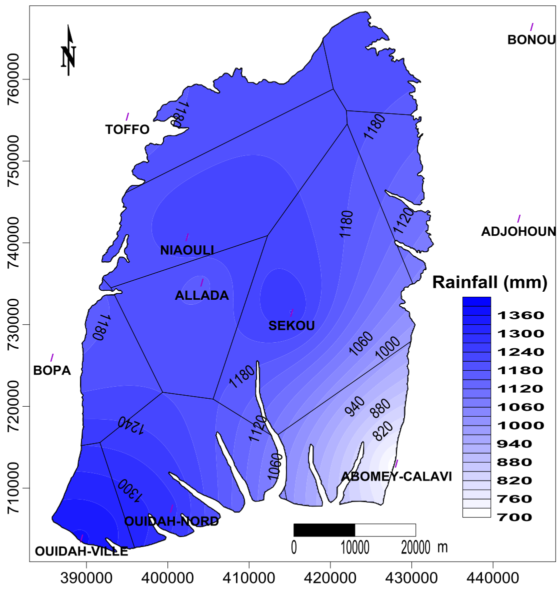

Figure 9: Precipitation distribution of P3

During the sub-period P3 (2006-2010), the same direction of rainfall gradient was maintained. But there had been a shift of the rainiest zone in the northwest (Toffo) towardsSekou, in the same direction. The wettest zone in southwest (Ouidah-north) had moved westward (Ouidah-city). Overall, this period is rainier than the two previous (1156mm per year).

Those spatial distributions of rainfall are expected to let have an idea aboutfive-year food production of the study area. But it is not obvious. The crops are sensitive to the beginning of wet seasons, their intra-annual distribution and their cessation (Allé et *al*., 2013 [13]).

IV. Conclusion

This research is a contribution to the understanding of the spatial and temporal distribution of rainfall on the plateau of Allada. It is based on precipitation data. Those data were averaged on five-year time to better appreciate the changes. Two methods were combined: the Thiessen method and kriging method. The first method smooth the spatialization of rainfall based on rainfall zones influencing the study area. The second discriminates, at 100m of spatial resolution, variations within rainfall zones. On point of view coverage with rainfall stations, spatial resolution is very loose (51km instead of 30km). Precipitation variationsalong sub-periods are not statistically significant. But they can impact agricultural production regardingthe sensitivity of cropsto water factor. In this way, it is important to foresee the impacts of these changes on the production of prime crops on the study area. This will lead to initiate sustainable management methods of the limiting factor that is agricultural water.

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