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Review Article

Dynamism of the Flood Zones of the City of San Pedro (South-west of côte d'ivoire): Contribution of Remote Sensing and GIS

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Abstract *- To provide a solution to the flood problem in the locality of San Pedro, it is important to control the evolution of flood zones by taking into account natural and anthropogenic factors through flood risk maps. A field survey made it possible to compare the results of the GIS with the realities on the ground. The flood risk maps were produced taking into account the city's flood vulnerability and flood hazard maps for the different years (1980, 2000 and 2020). Using Saaty's AHP method, parameter weights are calculated and superimposed to obtain the flood risk map. For the field survey, it was done by probabilistic spatial sampling. The results showed that over the past four (4) decades, the city's high-flood risk areas have tripled. As the city's urbanization increases in San Pedro, the risk of flooding increases.*

Keywords *- Wetland, Flood risk, AHP, Problem, Sampling.*

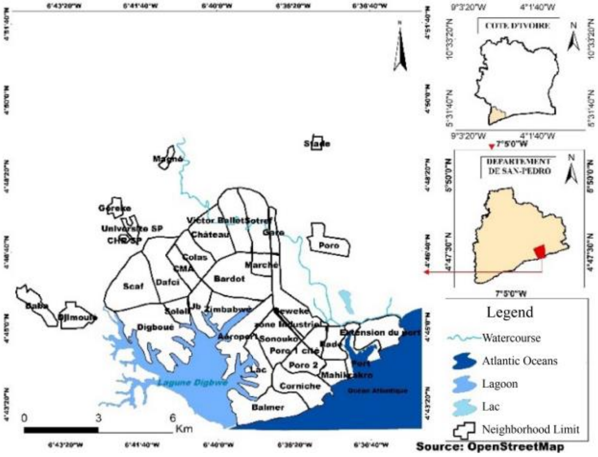
1. Introduction

According to Article 1 of the 1971 Ramsar Convention, « wetlands are areas of marshes, peatlands, or natural or artificial waters, permanent or temporary, where the water is stagnant or flowing, fresh, brackish or salty, including bodies of marine water whose depth at low tide does not exceed six meters. (22) The current influence and evolution of wetlands in highly anthropized landscapes currently represent a major environmental challenge. The poor spatial dynamism of its wetlands leads to several consequences, such as the degradation of ecosystems and flooding. (16). Of all these disasters caused by the mismanagement of wetlands, floods represent the natural phenomenon whose recurrence is widespread on the surface of the globe. (14) In Ivory Coast, floods, as everywhere in Africa, cause a lot of loss of human, material and moral life. According to the report of the State of Ivory Coast through the study on natural disasters in Ivory Coast, the only city of Abidjan 2018 during the floods that occurred on June 18 and 19, 2018 in the city of Abidjan killed 18 people and caused damage to economic and social infrastructure in at least five urban communes in Abidjan. (15) The city of San Pedro, like the Ivory Coast and the world, is confronted with this reality in general and the problem of flooding in particular. The second economic pole of Ivory Coast after the city of Abidjan due to the presence of a port and many industrial units, the city of San-Pedro contains wetlands generally occupied by human activities because of the lack of space in this locality. During the rainy seasons, floods occur in most of the city with material damage and even the exordium of population. Populations occupy areas at risk of flooding and erosion. (5) Flood zones are increasing over the years and floods are becoming more and more frequent. Several previous works, such as (5), (8) and (20), have listed the vulnerable places in the city and the areas vulnerable to flooding. It is necessary to look at the causes of the recurrence of flooding in the city of San Pedro in order to better define the areas at real risk of flooding and better understand the problem of flooding in the city. Not to mention the fact that the city has evolved since then and that the limits of the city have also evolved and extend to the village of Baba.

The objective of this study is to evaluate the dynamism of the flood zones of the city of San Pedro during the last forty years and its correlation with the floods that have become recurrent, taking into account the different natural and anthropogenic factors, to solve this environmental problem in this locality. It is important to control the evolution of these flood zones in time and space. Knowledge of the evolution in time and space of flood zones, synthesized and treated thanks to a Geographic Information System, helps to understand the dynamism of flood zones and, in turn, to solve the problem of flooding. Thus, remote sensing and GIS are privileged tools.

2. Study Area

The locality of San-Pedro is located in the southwest of Côte d'Ivoire, between latitudes 4°15'N, 5°30'N and longitudes 6°15 W, 7°20 W. The city covers an area of 662.21 km². (6) It is bounded by the Gulf of Guinea (Atlantic Ocean) to the south and the departments of Tabou, Soubré and Sassandra to the west, north and east, respectively. The general population census of the San Pedro region carried out in 2021, counted 390654 inhabitants or a population density of 590 inhabitants /km². (11)



Source: OpenStreetMap

Fig. 1 Overview of the city of san pedro

The town of San Pedro is located in the once-dense, humid forest of the Guinean domain. (4) The soils of this locality are the result of the alteration of schist, migmatitic or granitic rocks rich in feldspar. (4) They are characterized by a high water retention capacity due to a clayey texture. Two landforms are found in San Pedro. High altitudes and low altitudes. The coastal plains open up wider with a cordon that closes the lagoon of Digboue. (2) The coast is a coastal fringe marked by rocky points giving a stepped shape. (4) Due to the proximity of the Atlantic Ocean and the presence of a dense forest, the city of San-Pedro is one of the regions of Côte d'Ivoire that is sufficiently watered. Indeed, the average annual rainfall is between 370 and 2300 mm with a temperature between 26 and 30°C. (23) According to the work of (18), (3) and (13). The SASCA domain, of which the city of San Pedro is a part, includes formations from the different geological ages: Archean, Eburnean and Post-Eburnean. The main waterway of the city of San Pedro is the San Pedro River, 112 km long, which originates in the north of the San Pedro region and flows into the Atlantic Ocean at the level of the city of San Pedro. There is also the presence of the Digboue lagoon, the surroundings of which are highly urbanized. Lake San Pedro is the first major victim of human human action on wetlands.

3. Materials and Methods

3.1. Materials and Data

For the study of the dynamics of flood zones, the ENVI 5.1 software was used for the pre-processing of satellite images. ArcGIS 10.5 software made it possible to visualize, manage, create, and analyze geographic data. This computerized environment allowed for digitization, spatial analysis and the production of thematic maps. SPSS software was used for statistical analysis of field data. A high-resolution digital camera was required to capture the flooded and infilled areas and other components of the human and biophysical environments. A GPS was used to build a database of the geographical coordinates of the flooded areas of the city. Finally, a survey sheet has been designed for the field survey. To achieve the objectives of this study, satelliteimages: Landsat (optical) images of the San Pedro region with 30 m resolution scenes 197-57 were used. They date respectively from 07-11-1984, 11-03-2000 and 15-11-2020. In addition to this database, there are geological and soil maps of Côte d'Ivoire at a scale of 1/50000 (26), the 12.5-meters precision digital elevation model (DTM), annual rainfall data (1980, 2000 and 2020) of San Pedro, Soubré and Sassandra. (23) and demographic data for the years 1978, 1998 and 2014 (11).

3.2. Methods

3.2.1. AHP Method

Risk is the conjunction of an issue and its vulnerability (20). The concept must be understood as the possibility of losing "what is important" (the stake) as a result of one's fragility (vulnerability). (31) To assess flood risks, several factors must be taken into account, grouped into two types of factors: vulnerability and hazards. Taking into account previous studies such as (20), (26), (27), and (29), instead of grouping the factors of flooding, the vulnerability study will take into account land cover (OS) and population density (DP). For vulnerability, as a state or process, varies in time and space, in its nature as well as in its intensity. It differs in particular according to population density, standard of living, land use, and characteristics of the territory. (17) To better understand the hazard, it is important to focus on the natural properties of the environment that may influence the flow or stagnation of water. Because the physical, topological, topographical, and geological characteristics and morphology of the watercourse, as well as the laws of hydraulics, have an impact on the concentration of flows. (12) It is, therefore, the slope (P), the type of soil (S), the drainage density (D), the zones of influence of the watercourses (ZI) and the annual rainfall intensities (I) that were taken into account to study the hazard. The Analytic Hierarchy Process (AHP) method consisted of breaking down a complex and unstructured situation by elaborating its hierarchy. (24) The process can be summarized in five steps: Identification and prioritization of criteria; classification and standardization of criteria; weighting of criteria; calculation of the IC coherence index; aggregation of criteria through a GIS. (25)

Identification and Prioritization of Criteria

The parameters listed above have been grouped into a homogeneous whole and arranged in different levels. Each element of the level is compared with all the other elements that make up the level. In the case of the flood hazard, the hierarchy set up in the flood has two levels:

- Level 0: The general objective is to establish the flood vulnerability map of the city of San Pedro
- Level 1: Decision or analysis criterion

Figure 2 shows the prioritization in the case of flood hazard.

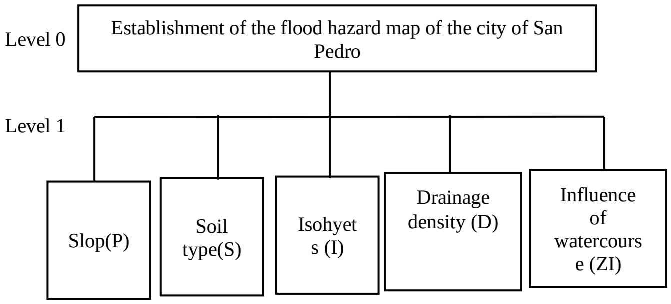


Fig. 2 Hierarchy of flood hazard parameters

Classification and Standardization of Criteria

The parameters were classified according to the literature synthesis of previous work. (20),(28), (29) and (30) The classification and standardization of the criteria and the classes of the various factors or criteria are codified according to their importance in favouring flooding or not. (24) This is valid for the factors and their different classes.

In the case of slopes, for example, the high slopes will designate the areas with a low slope, and the low slopes will designate the steep slopes. Then, after the slope (P) comes the soil type (S), followed by the annual rainfall intensities (I), then the drainage density (D) and finally, the zones of influence of the watercourses (ZI).

Table 1. Saaty scale for the comparison of criteria (25)

Value	Comparison	Ladder
1	Equally important	Both elements are equally important
3	Moderately important	One element is a little more important than the other
5	Highly important	One element is more important than the other
7	Very important	One element is much more important than the other
9	Extremely important	The dominance of one element is very remarkable
2,4,6,8	Intermediate values	Intermediate values between two judgments are used to refine the judgment

Weighting

The weighting consisted of comparing the relative importance of all the selected factors taken two by two to configure a reciprocal square matrix. This comparison is based on a numerical scale of 9 levels of pairwise comparison (25). When two parameters have the same importance in the phenomenon studied, the Saaty scale gives them the value of “1”. However, if one parameter is more important than the other, then it takes a higher value between 1 and 10 and the other, the inverse of this value. (24) Table 1 presents the Saaty scale (25) for the comparison of the criteria.

So we have P >>>S > > I > D> ZI. Table 2 shows the example of the matrix for comparing the different parameters of the flood hazard.

Table 2. Matrix resulting from the comparison of the different parameters of the flood hazard

	P	**S**	**I**	**D**	**ZI**
P	1	3	5	6	7
S	1/3	1	3	4	5
I	1/5	1/3	1	2	3
D	1/6	1/4	1/2	1	2
ZI	1/7	1/5	1/3	1/2	1
∑Wk	**1 ,842**	**4,783**	**9,833**	**13,5**	**18**

It should be noted that the ranges of values for the natural factors classes were obtained from the software used and those for anthropogenic factors by the author. An example of the factors of the flood hazard is illustrated in Table 3.

The Consistency Index

The calculation of the consistency index is done in two steps. First, the calculation of the eigenvector Vp. (Equation 1)

$$\mathrm{Vp} = \sqrt{}\mathrm{w1} \times \mathrm{w2} \times \mathrm{w3} \times \ldots.\ldots \times \mathrm{xwk} \qquad (1)$$

With w1, w2... wk: the different values assigned to the parameters when comparing them and k the number of parameters compared

Then, the weighting coefficient is determined by the following formula (Equation 2):

$$\mathrm{Cp} = \mathrm{Vp} \sum \mathrm{Vp} = \mathrm{Vp}\ \mathrm{Vp1} + \mathrm{Vp2} + \cdots + \mathrm{Vpk} \qquad (2)$$

With Vp, the eigenvector of the parameter whose Cp we want to calculate and Vp1, Vp2....Vpk, the different eigenvectors of each parameter. Table 4 below illustrates the different binary combinations carried out as well as the values of the eigenvectors (Vp) and the weighting coefficients (Cp) corresponding to the flood hazard. Vew (Table 4). The calculation of logical coherence follows this. It is a ratio which makes it possible to verify or validate the consistency of the original matrix. This ratio can be interpreted as the probability that the matrix is completed randomly. (27) If the value of the ratio is less than 10% then the assessments are consistent; otherwise, they may require certain revisions. The ratio is equal to the ratio of the coherence index (CI) to the random index (Ia): the Coherence Ratio is given in Equation 3.

$$Rc = \frac{\mathrm{Ic}}{\mathrm{I}a} \qquad (3)$$

Table 3. Summary of the classes, and ratings assigned to the different factors of the flood hazard

Study area: San Pedro		
parameter	**Intensity of the phenomenon**	**Odds**
Slope (%)	0-8	7
	9-16	5
	17-24	3
	>24	1
ground	Ferralitic Soil On shale	5
	Ferralitic Soil On granite	7
Isohyetes (I)	Very strong	7
	strong	5
	Average	3
Drainage density (Km^2)	0-1,5	7
	1,5-3	5
	>3	3
Zone of influence of watercourses	Weak	1
	Medium	3
	strong	5
	Very strong	7

Table 4. Weighting coefficient (Cp) of the different flood hazard parameters

	P	**S**	**I**	**D**	**ZI**	**Vp**	**Cp**
P	1	3	5	6	7	1,905	0,347
S	1/3	1	3	4	5	1,349	0,246
I	1/5	1/3	1	2	3	0,912	0,166
D	1/6	1/4	1/2	1	2	0,727	0,132
ZI	1/7	1/5	1/3	1/2	1	0,585	0,106
∑Wk	**1,842**	**4,783**	**9,833**	**13,5**	**18**	**5,480**	**1**

The values of the random index (Ia) are given as a function of the number of parameters compared, and these values in Table 5 have already been determined by Saaty (25). The table below shows us the different Values of Ia depending on the number of parameters. In the case of flood hazard, 5 factors are taken into account, so Ia will be equal to 1,12. Regarding the coherence index Ic, the calculation is done in six steps. This calculation will be illustrated by taking the case of the flood hazard map.

Stage 1: Normalize the original matrix by dividing each element of a column by the sum of that column;

Stage 2: Average each line to determine the priority vector [C];

Stage 3: Multiply each column of the matrix by its corresponding priority vector to determine the overall priority [D];

Stage 4: Divide each overall priority by its corresponding priority vector to determine the rational priority [E];

Stage 5: Determine the average of rational priorities (λ max);

$$(\lambda \text{ max}) = \frac{[E]}{\mathrm{k}} \qquad (4)$$

Stage 6: Calculate the consistency index (IC):

$$Ic = \frac{\lambda \text{ max} - \mathrm{k}}{\mathrm{k} - 1} \qquad (5)$$

Calculation of the Consistency Ratio (CR) of the flood hazard of the port city of San Pedro:

Calculating the average of rational priorities (λ max)
$\lambda \text{ max} = \frac{25,8}{5}$ car λ max=25 ;8 et k=5
λ max= 5,14

Consistency Index Calculation (IC):
$\mathrm{IC} = \frac{5,14-5}{5-1}$
IC= 0,035

Consistency Ratio Calculation RC:
$RC = \frac{0,035}{1,12}$
RC= 0,031 either 3,1 %; therefore RC < 10%.

Table 5. Random Index Value (25)

Number of variables	2	3	4	**5**	6	7	8	9	10	11
Ia	0	0,58	0,9	**1,12**	1,24	1,32	1,41	1,45	1,49	1,51

Tables 6 and 7, respectively, show the normalized matrix and the weight of the different parameters retained for the flood hazard.

Table 6. Normalized original matrix

	P	**S**	**I**	**D**	**ZI**	**Total Line**
P	0,543	0,627	0,508	0,444	0,389	**2,512**
S	0,181	0,209	0,305	0,296	0,278	**1,269**
I	0,109	0,070	0,102	0,148	0,167	**0,595**
D	0,090	0,052	0,051	0,074	0,111	**0,379**
ZI	0,078	0,042	0,034	0,037	0,056	**0,246**
Total Column	**1,000**	**1,000**	**1,000**	**1,000**	**1,000**	**5,000**

Table 7. Weight of parameters

Parameters	Weighting factor (weight)
Slope (P)	0.35
Soil (S)	0, 25
Isohyets (I)	0,17
Drainage density (D)	0,13
Zone of influence of watercourses (ZI)	0,10

The last step of the AHP method is the aggregation of the factors. It consists of the summation of the standardized and weighted values of each factor or criterion involved in the development of the given indicator. (27). This approach can be summarized by the following formula:

$$S = \sum \mathrm{Wi\ Xi} \qquad (6)$$

S: result;
Wi: Factor i Weight;
Xi: Standardized value of factor i.

The flood hazard map is thus obtained from the following formula
Flood hazard = (0,35 x P) +(0,25 x S) +(0,1 7x I) +(0,13 x D) +(0,10 x ZI)

The method that was chosen for the combination of layers in the GIS is that of the operational approach of the single synthesis criterion of Roy. (28). Although here we are dealing with flood hazard, the principle remains the same. For each parameter, the weight (Cp) is multiplied by the different corresponding notes. This calculation is carried out with the "Raster Calculator" tool of the "Map Algebra" sub-module of the Arcgis software. Index intervals are obtained to which vulnerability classes are assigned. (9) Determination of index intervals. is based on the intrinsic vulnerability method. (27)

This method makes it possible to convert vulnerability indices into percentages in order to better understand the expression of the classification of degrees of vulnerability. The indices are divided into five classes of vulnerability ranging from "very low" to "very high", illustrated in Table 8. The degree of vulnerability increases with the index. (29) Although this formula was initially applied for vulnerability, the same principle was used for the cards that concern this study.

$$\mathrm{Iv}(\%) = \frac{\mathrm{Iv-Ivmin}}{\mathrm{Vmax-Ivmin}} \qquad (7)$$

Table 8. Vulnerability index

Vulnerability Index	Degree of vulnerability
0 – 30 %	Very weak
31 – 45%	Weak
46 – 60%	Medium
61 – 75%	Strong
75 – 100%	Very strong

3.2.2. Field Survey Sampling

Any map developed must be preceded and ended by a field survey to corroborate the results. Documents and existing works on the city of San Pedro cannot provide all the information expected for the construction of the database, so resorting to field surveys was essential. The sample was determined based on the specific objectives. It mainly took into account places near wetlands, that is to say, Lake San Pedro, the San Pedro River, the Digboue lagoon, the lowlands and swamps of the city, as well as the wetlands which are undergoing backfilling. Households not near wetlands were also interviewed. Sampling This is done following a probabilistic spatial sampling procedure. (10) Probabilistic spatial sampling or systematic random sampling in space, which is oriented towards the spatial dimension. (10) This sampling method was used in the work of (20) and (8) in the city of San Pedro. It produced excellent results and was less expensive. It consists of spatially covering the entire sampling base by transposing onto the study area a grid of cells (meshs) of the same size (one hectare) and then selecting a point (household) in each cell. The random selection of a point is done from a table of random numbers. A first number on the X axis and a second on the Y axis. These values correspond successively to the values on the abscissa and the ordinate. Another selection method is to choose an interval so as to space a point in space. (21) The spacing value depends on the sample size. If the number of samples is equal to 50 (n=50) and the number of cells is 25 (m=25) then the number of points per cell is equal to the number of samples out of the number of cells, or. 50/ 25. In this case we randomly choose two points per cell. For this survey, one household per square grid of 100 m on a side (i.e. a geographical entity of one hectare) was interviewed. A single head of household would make it possible to encompass all aspects linked to the perception of risks within this geographical space. However, this sampling base of 3698 heads of household still remains significant. According to updated city data, 85% of households live near wetlands or on embanked wetlands, i.e. 36,985 households. (11) (20) The sample size was defined as 10% of the 3698 heads of household. This proportion of 10% is an empirical method used by the social sciences to define the sample size of a population. (7) in (20). The application of this method made it possible to define the size of the sample at 370 heads of households to be interviewed within 370 different meshes. The sampling frame is the list numbered from 1 to 3698 meshes. This involved interviewing a head of household by mesh. Then, the drawing step (P) is determined according to the formula:

$$\mathrm{P} = \frac{\mathrm{N}}{\mathrm{n}} \qquad (8)$$

N=the number of meshes (3698)
n =sample size (370 heads of households).

The step of the draw is then 10. The first plot number between 1 and the randomly drawn step is 10, the second plot number is then 20 (10+ the step), the third 30 and so on until the 370th household. To these target households were added 100 households which are not near wetlands but which are indirectly impacted by flooding. This, therefore, gives a total of 470 households interviewed.

Field Data Processing

For data processing, the Khi2 statistical test was used through the SPSS Statistica software. The Khi2 contingency test was carried out on different points, which were grouped into two qualitative variables: the «dynamism of wetlands» and «flooding». She made it possible to see their correlation between her. Know if one factor or phenomenon has a considerable impact on the other.

4. Results and Discussion

4.1. Results

4.1.1. Flood Hazard

Slope and Soil Map

The San Pedro city slopes map shows that the city has low slopes in the majority of the city. This is a factor that favours water stagnation since the city is located at a low altitude. Slopes are a very important factor in rainwater runoff; A space with high slopes will tend to facilitate flow, unlike low slopes. The majority of the steep slopes of the city are found at the level of the extensions of the city; this area of the port city of San Pedro is not prone to runoff flooding. The limits of the old city, on the other hand, have mostly “low” slopes. There are some steep slopes in the districts of « Château », « CMA », « Soleil » and slightly in « Sotref ». In « Cité » and « Balmer » the slopes are medium and are low for the other districts of « Bardot », « Zimbabwe », « Seweke », « Lac » et « Soleil » The slopes are low. (Figure 3). In the city of San Pedro, two litho-stratigraphic domains dominate. These lithological domains have a high capacity to retain water, and they are ferralitic soils on schist and ferralitic soils on granites in Figure 4. This lithology does not favor the infiltration of rainwater; therefore, it favors stagnation. These first two natural factors of the flood show that the city of San Pedro lithologically and topographically favors flooding.

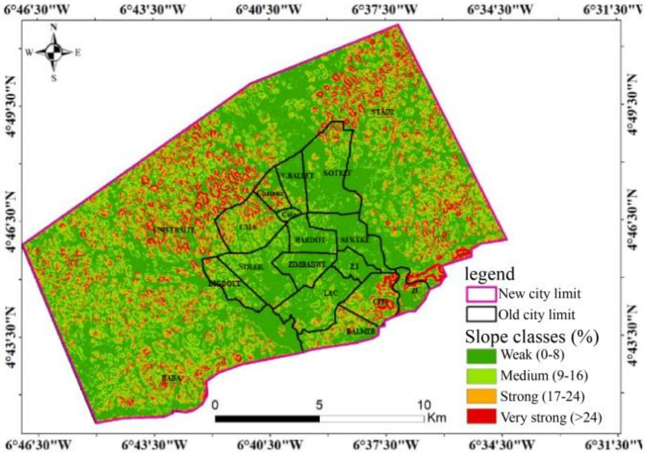


Fig. 3 Map of the slopes of san pedro

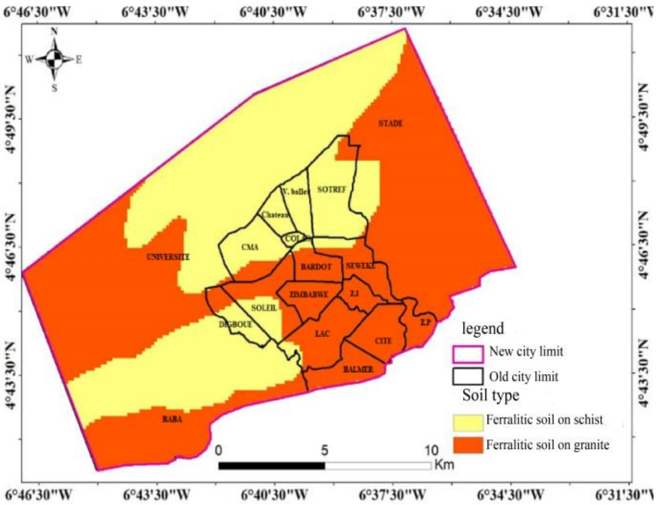


Fig. 4 Lithostratigraphic map of san pedro

Drainage Density Map and Stream Influence Zone

The drainage density of the city of San Pedro is generally between 0 and 3 km^2, which means that rainwater is poorly drained, hence its stagnation. This is explained by the fact that the city has low slopes and, reciprocally, rainwater is difficult to drain. The drainage density depends on the topography and lithology of the watershed, as well as rainfall and anthropization.

The city of San Pedro is located in the watershed of the San Pedro River. In this register, there is poor drainage in the districts of «Zimbabwe», «Digboue», «Seweke», «Bardot», «Lac», «Industrial Zone», «Soleil» and «Sotref» with a drainage of 0 to 0,3Km^2. The other areas of the city have medium and strong drainage. In terms of the city’s extensions, there is an average (0,8Km^2) and strong (greater than or equal to 1,5Km^2) drainage; only a few points in the area have poor drainage shown in Figure 5.

The map of the zone of influence of the watercourses shows that within a radius of about 1 km from the banks, the city’s watercourses have an influence on areas. These are, therefore, areas vulnerable to flooding that are unfortunately urbanized; we can see that the northern districts of the city have a strong influence on the nearby watercourse, which is the San Pedro River. The district of « Lac » is an area very influenced by Lake San Pedro, the biggest victim of human human action in the city.

This lake has been undergoing very intensive filling over the last forty years. The districts of « Zimbabwe », « Soleil », « Bardot », and « CMA » are districts built either in swampy areas or in swamps filled in, hence the strong influence of seasonal watercourses in these areas during rainy periods. The district of « Digboue » is at the level of the shores of the Digboue lagoon, so it is an area very influenced by the lagoon. It can be seen that the areas with little influence on the rivers are the extensions of the city in Figure 6.

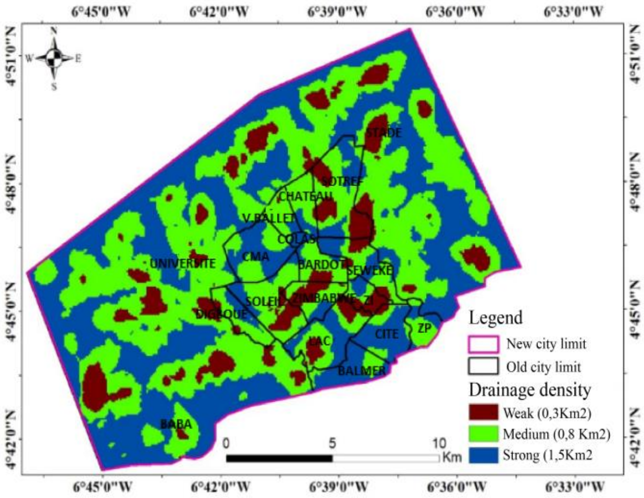


Fig. 5 San pedro drainage density

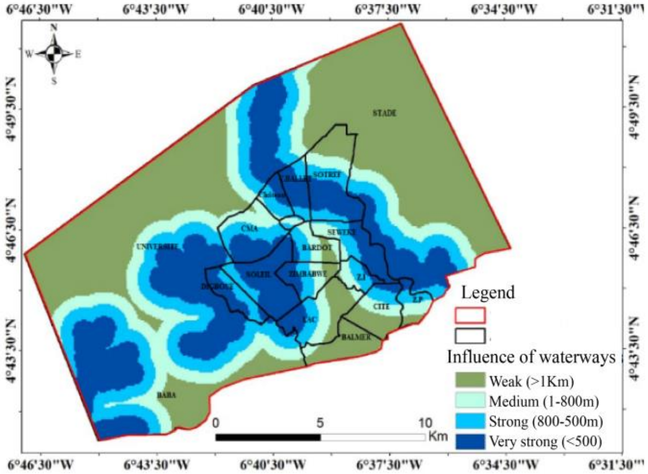


Fig. 6 Map of the zones of influence of the rivers of san pedro

Annual Rainfall Intensity From 1980 to 2020

In the city of San Pedro, the annual rainfall intensities during the forty years (1980 to 2020) exceed 1900mm of rainfall. In the 1980s, rainfall intensities were high over most of the old city, with annual rainfall of more than 1900mm, from the port area to the «Sotref» district. It should also be noted that at that time there was a lot of vegetation in the city as it was only a small part that was urbanized. In 2000 and 2020, there was a reversal of areas of high rainfall. The rainfall intensities in the city are divided into three zones from east to west.

Heavy rainfall is observed in the west of the city at the level of the city extensions. That is to say, from the «University» neighborhoods to the village of «Baba» (more than 1900mm of annual rainfall). It should also be noted that the city's plant cover is important in terms of the city's extensions. In the districts of CMA, «Soleil» and «Digboue», the annual rainfall is between 970mm and 1900mm.

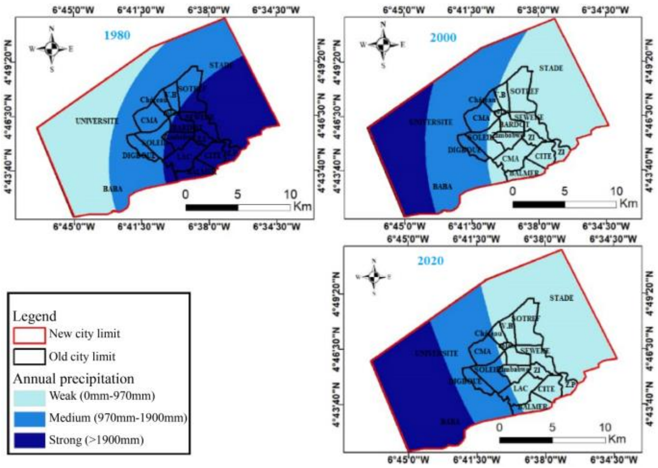


Fig. 7 Map of isohyets of the city of San Pedro from 1980 to 2020

Map of Flood Hazard from 1980 to 2020

About half of the study area's area has a 61% to 75% chance of flooding taking into account the city's natural factors. The areas with a high flood hazard rate have increased from 45,78% in 1980 to 48.52% in 2000 and 47% in 2020. The districts of the city that have a 75% to 100% risk of flooding due to hazards extend over the limits of the old city. Areas with a very high rate of flooding due to hazards have increased from 9,45% in 1980 to 11,51% in 2000 and 21,82% in 2020. It can be seen that during the forty years the high rate of flood hazard occupies more than half of the study area. This could be explained by the fact that the natural parameters of the study area listed above are favorable to water stagnation, and also climate change has impacted the volume of annual rainfall. The results of the above-mentioned maps of natural factors related to flooding announced that the port city of San Pedro had natural assets that favored flooding because the slopes are low, the lithology is difficult to permeate, the rainwater drainage density is low, and watercourses influence the majority of anthropogenic areas during rainy periods in Figure 8.

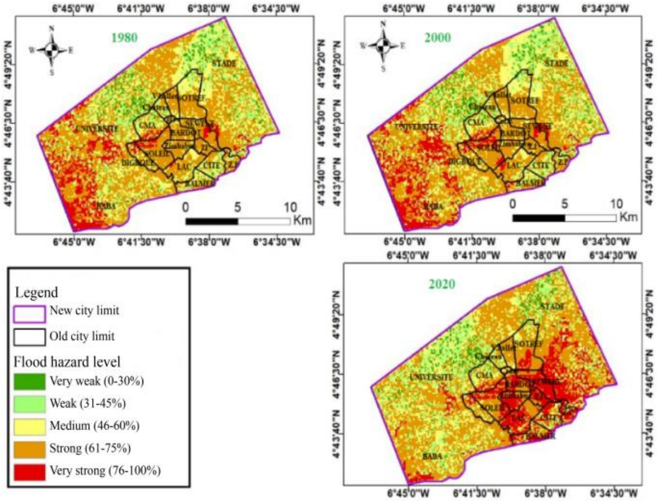


Fig. 8 Flood hazard in the city of San Pedro from 1980 to 2020

4.1.2. Vulnerability to Flooding

Population Density and Land Cover of the City of San Pedro from 1980 to 2020

In 1980, the populations were more concentrated in the neighbourhoods of « Bardot » and « Seweke », with more than 76% of the population. In the 1980s, the city of San Pedro was at the beginning of its economic boom with the construction of the Autonomous Port of San Pedro. Wealthy people lived in neighbourhoods such as « Cité », while middle-income people were more present in the « Lac » and « Seweke» neighbourhoods with the social housing of the SICOGI. People with modest incomes were found in the « Bardot » and « Colas » districts. At that time, the urbanization of the city of San Pedro was limited to these neighbourhoods and the « Port area ». In 2000, the expansion of the city led to the creation of a new district. The populations then moved into new spaces, such as the « Zimbabwe » district, which began to populate with an average density of 15 to 30 inhabitants per hectare. About 50% of the population was settled in the medium-density neighbourhoods. New areas will be invested by the populations, such as the « CMA », « Soleil », « Victor Ballet », « Château », and « Sotref » districts with 0% to 30% of the population. At the same time, the Cité district is decongested and goes from a high to medium population density (16 inhabitants per hectare). At the same time, the « Cité » district is decongested and goes from a high population density (61 to 75% of the population) to a medium population density (16 inhabitants per hectare). The « Seweke » and « Bardot » districts still have a very high population density of more than 50 inhabitants per hectare; more than 75% of the population lives there.

It should be noted that at that time, there was the largest slum in West Africa in the « Bardot » district. Other areas that were already urbanized, such as the « Lac » district, grew and began to occupy the shallows and marshy areas with embankments. In 2020, new districts will be created. Districts such as « Baba » and the « University» (extension) were gradually populated, as shown by the low population density (0 to 15 inhabitants per hectare). The «Digboue» district, also with a low population density (0 to 15 inhabitants per hectare), is a district that was created for the resettlement of the natives formerly settled at the mouth of the river in the Balmer district. The population density of the Bardot district will go from very high density, i.e. more than 50 inhabitants per hectare, to medium density (15 to 30 inhabitants per hectare) following the demolition of the shantytown that was located there in Figure 9. These populations will move into the other districts of the city, mainly the districts of « Victor Ballet », « Château » and « Sotref », whose population density will increase from Low density to high density (30 to 50 inhabitants per hectare) for the first two and medium density (15 to 30 inhabitants per hectare) for the third. The «Colas » district still has a very high population density (more than 50 inhabitants per hectare).

It should be noted that the increase in population density includes the acceleration of urbanization in the city. The land use map for the three years shows that the urbanization of the city has evolved around rivers and swamps. These places are areas where the flood hazard is high. As a result, moving there makes residents vulnerable to flooding in Figure 10.

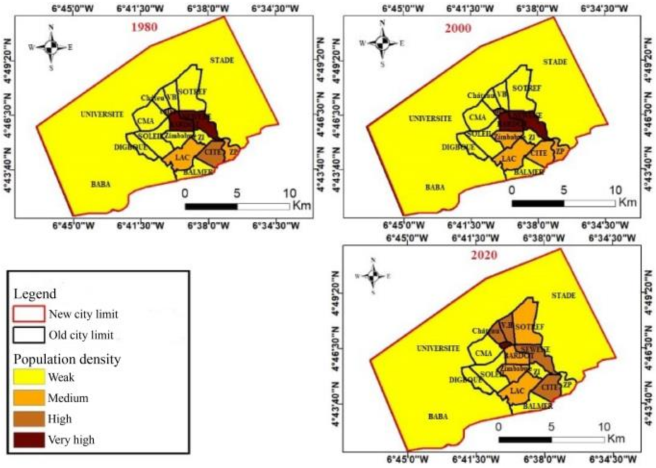


Fig. 9 Population density from 1980 to 2020

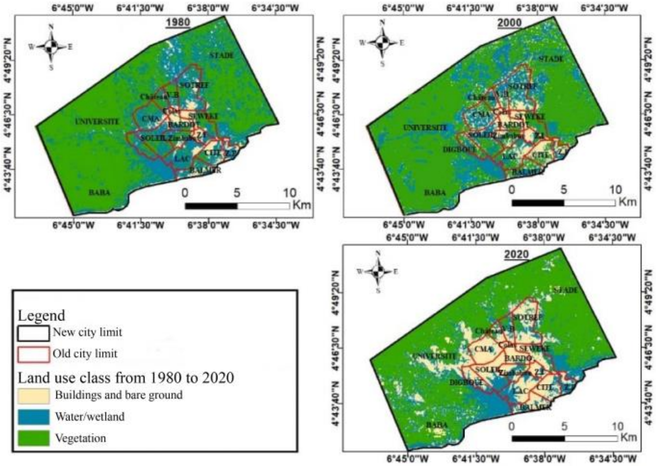


Fig. 10 Land use from 1980 to 2020

Flood vulnerability Map from 1980 to 2020

In 1980, 36,39% of the study area was located in an area with less than 30% flood vulnerability (very low). Areas with flood vulnerability between 61% and 75% (high) occupy 9.39%. These are the neighbourhoods of «Lac», «Port zone», «Industrial zone», and «Colas», districts and part of the «Seweke» district. As for the «Bardot district, the northwest part of «Seweké» and «Cité», they have a flood vulnerability of more than 75% and represent 2,19% of the city's surface area. At that time, the city of San Pedro was more concentrated in these areas. In 2000, the areas with very low and low vulnerabilities, which were respectively 36,39% and 22,48% in 1980, increased to 22,71% and 26,53% in 2000. The areas with medium vulnerabilities, which represented 29,55% of the city's surface area in 1980, rose to 21,77% in

2000. There is also an increase in areas of high vulnerability, which have increased from 9,39% of the territory to 27,14%. Twenty years later the percentage of areas with high vulnerability is increasing. New locations such as «Zimbabwe», «CMA», and «Lac», which had a flood vulnerability of between 31% and 50% in 1980, have a flood vulnerability of up to 75% in 2000 in some places. The city has expanded to other neighborhoods, as a result of which the natural environment has been urbanized. The very high vulnerability to flooding, which occupies 1.86% of the study area, remains concentrated in the «Colas» and «Bardot» districts. In 2020, vulnerability to flooding in the port city of San Pedro increased once again. The areas of the city that had flood vulnerabilities of between 61% and 75% will increase to more than 75%, or from 1,86% of the surface area of the study area in 2000 to 3,38% in 2020. Almost the entire extent of the neighborhoods on the old city limit has a flood vulnerability of between 60% and 75%, or. 40% of the city The territories of the city with a flood vulnerability of between 46% and 60% will decrease from 21,77% in 2000 to 19.51% in 2020 of the entire study area. In forty (40) years, the territories with high flood vulnerability, which were 9.39% in 1980, have increased to 40% of the entire area of the port city in 2020 in Figure 11.

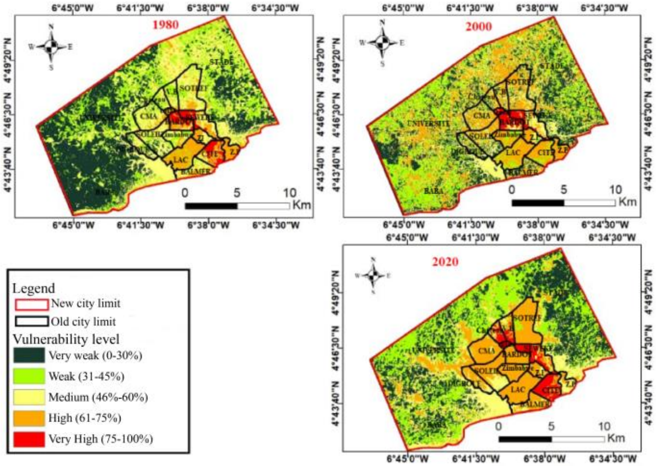


Fig. 11 Vulnerability to flooding of the City of San Pedro from 1980 to 2020

4.1.3. Dynamism of flood risks in the city of San Pedro

In 1980, the risk of more than 75% of flooding was concentrated at the limits of the old city. Precisely in the districts of « Seweke », « Bardot », « Zimbabwe », « Cité » and «Lac». The high and very high risks of flooding occupy, respectively, 14,53% and 2% of the surface of the study area. 35,29% of the area of the study area has a flood risk of less than 45%, and 7,71% has a flood risk of less than 30%. As for the risk of flooding between 45% and 60%, it occupies 40,43% of the study area. As for the area of areas with a flood risk between 61% and 75%, it has increased from 14,53% to 26,53%. Naturally, the areas of areas with a very low and low risk of flooding have decreased, from 7,71% and 35,29%, respectively, to 5,4% and 27,6%. This is due to the city's population boom and the creation of new neighbourhoods near the wetland that was previously unurbanized, increasing the risk of flooding during rainy seasons. In 2020, the areas with a flood risk of more than 75% increased again. They have risen from 1,45% to 2,41%. Areas at risk of flooding between 60% and 75% also increase to 41,15%. All urbanized areas of the port city of San Pedro have very high to medium flood risks. The vast majority of the boundaries of the ancient port city of San Pedro have à high risk of flooding. From 1980 to 2020, areas at high risk of flooding have expanded from 14,53% of the area of the study area to 41,15%, and those at very high risk of flooding from 2% to 2,41%. In forty years, about half of the city of San Pedro has a flood risk of between 60% and 75%. The wetlands are urbanized, which in turn accentuates the flooding in the city in Figure 12. As urbanization evolves, the wetlands in the city of San Pedro decrease and the areas at high risk of flooding also increase. In 1980, wetlands accounted for 33,3% of the city's surface area, buildings and bare ground 6,89%, and areas at high risk of flooding accounted for only 14,53% of the study area.

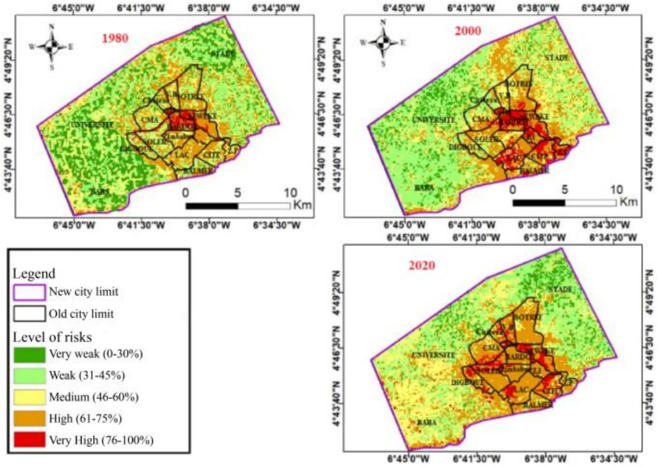


Fig. 12 Flood risk map of the city of San Pedro from 1980 to 2020

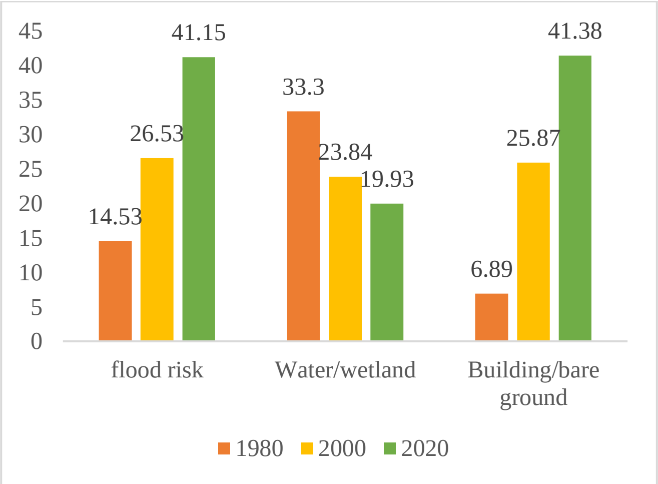


Fig. 13 Evolution of wetlands, buildings and flood risk from 1980 to 2020

Fig. 14 Construction close to the shores in the sun district in the vicinity of the digboue lagoon

In 2000, with the demographic growth (150453 inhabitants) of the city, wetlands increased to 23,84%, while urbanized areas increased to occupy 25,87% of the study area, and consequently, areas with a high risk of flooding also increased to 26,53%. In 2020, it is still the same dynamic as in 2000. In forty years, wetlands have increased from 33,3% to 19,93%, buildings have increased from 6,89% to 41,38%, and areas at high risk of flooding have increased from 14,53% to 41,15% shown in Figure 13.

Public Perception of the Dynamism of Flood Zones

According to observations on the ground and the stories of the populations, wetlands have regressed over the last forty-five years. For 87% of the population, wetlands have regressed. This regression has occurred over time until most areas have reached tens of metres or even disappeared in some areas. Of the households surveyed, the majority of households, 82%, indicate that over the last 45 years, wetlands have regressed for the majority by more than 10 meters. It should be noted that with the economic boost that the city of San Pedro experienced with the establishment of the port from 1968 to 1971, there was an explosion in the population of the city, from which the demand for housing increased over the years. This has led to the soaring price of housing and land. The most vulnerable populations have, therefore, moved to the cheapest places to settle and these places are the edges of wetlands. An example of almost non-existent embankment wetlands is shown in Figure 14.

The cause of the flooding in the city of San Pedro is due to several factors. Most of them are due to uncontrolled urbanization and the high cost of land in areas that are not at risk. Given the high cost of land, rents in areas that are not at risk are exorbitant for most of the city's population, so they fall back on cheaper and accessible land or housing located in precarious areas and at risk of flooding. It should be noted that this anarchic urbanization has depicted the evacuation of rainwater because the places supposed to receive runoff water are backfilled for construction or even obstructed by construction. Not to mention the lack of infrastructure for sewage and rainwater pipes clogged with waste or homes. Figure 15 is an example of a dwelling built on a gutter in the Seweke district.

Fig. 15 Clogged and degraded gutters in Seweke

The Khi2 test performed on the two variables "wetland dynamics" and "flooding" determined during the field survey yielded a Khi2 value equal to 30.977[a] with 30 degrees of freedom. The P-value associated with such Khi2 is equal to 0.000, a very low value well below 5%. From such a result, it is concluded that there is a significant association between wetland dynamism and flooding in San Pedro.

4.2. Discussion

GIS is a very important tool in environmental management. Several previous studies have used GIS to solve environmental problems such as (1), (5), (8), (19), (20), (21) and (26). The work of (19) used GIS and remote sensing in their study on the mapping of flood risk areas in the semi-mountainous region of western Côte d'Ivoire to establish five levels of flood risk (very low, low, moderate, high and very high). To better identify floods in San Pedro, the factors were divided into two main groups of factors: hazards (slope, soil, drainage density, isohyets and area of influence of watercourses) and vulnerability (land use and population density) because there are risks when they have victims and damage. This methodology has made it possible to identify the places in the city with natural predispositions to promote floods and also the impact of human action that has accentuated these floods. The work of (12) on the flood risk areas of Cocody and Abobo indicates that low slopes, poor drainage, high rainfall intensity, high water accumulation, high population density and significant anthropogenic activity accentuate the high risk of flooding. These results are consistent with those of this study because the different maps of the natural factors of flooding have shown that the city of San Pedro has low slopes, low drainage, dense rainfall, difficult soil permeability and a strong influence of watercourses. The flood hazard map obtained from its various maps showed that 47% and 21,82% of the city's area has a high and very high flood hazard level. In addition to natural factors, the vulnerability map, which took into account population density and land use, showed that 40% of the city has a vulnerability to flooding between 60% and 75%. Although it is a real decision-making tool, For more precision and realism, the various maps developed are followed by a field survey of the population. It was done through direct observation, interviews with the main local actors, GPS surveys and a questionnaire survey of the target populations. Time and means, in particular, are lacking. The interviews of the populations were carried out following a probabilistic spatial sampling procedure, which made it possible to visit a total of 470 households that reflected the social and environmental realities of the space they represented in the city of San Pedro. This sampling method proved to be productive in the work of (10), (20), and (8) in his work on the vulnerability to flooding of the city of San Pedro. (20) He used the probabilistic method of sampling. This technique allowed him to interview 370 families within the limits of the old city and this sampling was sufficiently representative to achieve his objectives. This number of households was pushed to 470 in this study because the demography has evolved as well as urbanization. This test is a powerful tool that has made it possible to verify the hypothesis that human action through the urbanization of wetlands promotes flood risks in the city of San Pedro. The results of this test confirmed the results obtained by the cards. This methodology is identical to that of similar work carried out by (20) and (8) in the city of San Pedro and other previous authors such as (21). Although the work of the first authors mentioned above focuses on flood vulnerability, the results obtained in this study have shown the advantages of this sampling method in the study of flood risks. The work of (1) on the mapping of the flood zones of the San Pedro River basin indicated water levels of about 21 meters with flood return periods of 2 to 100 years. The field survey also measured water levels during runoff flooding in different territories indicated by the flood risk maps of the port city of San Pedro. Thus, in the Victor Ballet district, during the rainy season of August 2020, the water levels went up to 60cm in the Zimbabwe district. The height of rainwater reached one meter in places and up to 1.5m in the CMA district. All his observations made it possible to corroborate the results of the maps in the field and to target the flooded areas after the rainy episodes in the city. According to (5) in his work on the Occupation of Risk Areas in San Pedro, where he cites (9), nearly 66% of the urban land has a high impermeability index, and the limits of the old city have a high risk of flooding. These results are consistent with the results of the work carried out during this study by going beyond the city limits considered by the above-mentioned author. (5) Although the study area is not sufficiently provided with data, this study has just enriched the previous work to combat flooding in the city of San Pedro by taking into account the natural, anthropogenic and the fact that the city has evolved which impacts the evolution of the areas at risk of flooding.

5. Conclusion

It shows that human action on nature often has devastating effects on the world in general and in the city of San Pedro in particular. To understand this phenomenon in the city, a well-developed methodology allowed us to achieve our objectives regarding flooding in the city. However, GIS and remote sensing are adequate tools for environmental management. A field survey is necessary to corroborate the results obtained by these tools. Thus, the natural conditions of the city (geomorphology, type of soil, rainfall intensity, etc.) do not favour the rapid infiltration of rainwater. But human action has colonized the city's wetlands (shoals, the banks of the lake and river of San Pedro etc.), only favor flooding in a city already with natural predispositions to flooding.

References

[1] Kouassi Nazaire Kouakou, "*Mapping of Flood Zones in the San Pedro River Watershed (Southwest of Ivory Coast)*," Master Degree Thesis, Jean Lorougnon Guede University of Daloa, 2019. [Publisher Link]

[2] J.M. Avenard et al., *The Natural Environment of Côte D'ivoire: Memoirs n°50*, ORSTOM, pp. 1-401, 1971. [Publisher Link]

[3] J. Camil, "*Petrography, Chronology of Archaean Granulitic Complexes and Associated Formations in the Man region (Ivory Coast). Implication for the Geological History of the West African Craton State*," Doctorate Thesis, Université d'Abidjan, pp. 1-306, 1984. [Publisher Link]

[4] O. Z. De Lasme, "*Contribution to a Better Knowledge of the Fissured Aquifers of the Precambrian Basement; Case of the San Pedro Region (South-West of Ivory Coast)*," Ph. D. Dissertation, University Félix Houphouët-Boigny, 176p, 2013. [Google Scholar]

[5] Bazoumana Diarrassouba, Atsé Calvin Yapi, and Williams Abel Kouadio, "Occupation of Risk Zones in San Pedro (Ivory Coast): Between Laxity of the Authorities and Carelessness of the Population," *European Scientific Journal*, vol. 18, no. 26, pp. 46-69, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[6] Ministry Of Construction, Housing and Urban Planning, Republic of Côte d'Ivoire, [Online]. Available: https://construction.gouv.ci/

[7] Stéphane Beaud, and Florence Weber, *Guide to Field Investigation: Producing and Analyzing Ethnographic Data*, La Découverte, pp. 1-334, 2010. [Google Scholar] [Publisher Link]

[8] Florent Gohourou, Michel Desse, and Émile Aurélien Ahua, "Dynamics of informal economy actors around water resources in the city of San-Pédro (Ivory Coast)," *Proceedings of the International Conference: Land Use Planning for Sustainable Development*, Abomey-Calavi, Bénin, pp.79- 97, 2019. [Google Scholar] [Publisher Link]

[9] T. Gogbe et al.,"Mapping of Areas Vulnerable to Flood Risks,"*Journal of Geography*, vol. 1, pp. 19-33, 2015.

[10] Hervé Gumuchian, Claude Marois, and Véronique Fèvre, *Introduction to Research in Geography: Planning, Territorial Development, Environment*, Presses de l'Université de Montréal, pp. 1-425, 2000. [Google Scholar] [Publisher Link]

[11] The Global Results of the 5th General Population and Housing Census, National Institute of Statistics, 2021. [Online]. Available: https://www.ins.ci/

[12] Moïse Koffi Kouame et al., "Flood Risk Mapping in Cocody and Abobo-Abidjan (Ivory Coast)," *Francophone University Editions of Africa*, pp. 430-447, 2023. [Google Scholar] [Publisher Link]

[13] Alain-Nicaise Kouamelan, "*Geochronology and Geochemistry of the Archean and Proterozoic Formations of the Man Ridge in Ivory Coast. Implications for the Archean-Proterozoic Transition*," Doctoral Thesis, University of Rennes, pp. 1-319, 1996. [Google Scholar] [Publisher Link]

[14] Jean-Luc Kouassi, "*Monitoring the Dynamics of Land Use Using Satellite Imagery and Geographic Information Systems: Case of the Regional Water and Forest Directorate of Yamoussoukro (Ivory Coast)*," End of Studies Dissertation, National Polytechnic Institute, Félix Houphouët-Boigny, Yamoussoukro, pp. 1-74, 2014. [Publisher Link]

[15] Ricardo Zapata Marti et al., *Assessment of Losses, Damage and Needs Following the Floods of June 2018 in Abidjan*, World Bank, European Union and United Nations Development Program, Report Produced by the Government of Ivory Coast, Abidjan, pp. 1-220, 2019. [Publisher Link]

[16] Matthew McCartney, Living with Dams: Managing the Environmental Impacts, *Water policy*, vol. 11, no. 1, pp. 121-139. 2009. [CrossRef] [Google Scholar] [Publisher Link]

[17] Sylvia Becerra, "Vulnerability, Risks and the Environment: The Chaotic Itinerary of a Contemporary Sociological Paradigm," *Vertigo - The Electronic Journal in Environmental Sciences*, vol. 12, no. 1, 2012. [CrossRef] [Google Scholar] [Publisher Link]

[18] André Papon, and R. Lemarchand, *Geology and Mineralization of South-West Ivory Coast. Summary of the Work of The Sasca Operation 1962-1968*, SODEMI, pp. 1-285, 1973. [Publisher Link]

[19] Mahaman Bachir Saley et al., Mapping of the Flooding Risk Areas of Westenr Semi-Mountainous Region of Côte D'ivoire: Contribution of Digital Elevation Model and Satellite Imagery, *Contemporary Publishing International*, vol.5, pp.53-67, 2005. [Publisher Link]

[20] Kinakpefan Michel Traore, *Analysis of the Vulnerability of the Coastal Town of San Pédro (South-West of Ivory Coast)*, Doctoral Thesis, Institute of Tropical Geography, Abidjan-Cocody, pp. 1-355, 2016. [Google Scholar] [Publisher Link]

[21] Jean-Christophe Vilatte, *Methodology of the Questionnaire Survey,"* Culture and Communication Laboratory, University of Avignon, pp. 1-56, 2007. [Google Scholar] [Publisher Link]

[22] Mari´etou Ndao, *Dynamics and Environmental Management of Wetlands in Senegal From 1970 to 2010: Study of Land Use by Remote Sensing of Niayes with Djiddah Thiaroye Kao (in Dakar), Mboro (in Thiès and Saint-Louis)*, Geography, Toulouse le Mirail University - Toulouse II; University of Saint-Louis (Senegal), 2012. [Publisher Link]

[23] *San Pedro City Weather Data*, SODEXAM, 2022. [Online]. Available: https://www.sodexam.com/

[24] Thomas L Saaty, "A Scaling Method for Priorities in Hierarchical Structures," *Journal of Mathematical Psychology*, vol. 15, no. 3, pp. 234-281, 1977. [CrossRef] [Google Scholar] [Publisher Link]

[25] Thomas L Saaty, *The Analytic Hierarchy Process: Planning, Priority Setting*, Resource Allocation, McGraw-Hill, New York, 1980.

[26] Pierre Vennetier et al., *Atlas of Ivory Coast*, Altas Jeune Afrique, vol. 1, pp. 1-72, 1978. [Publisher Link]

[27] Anowa Evrade Larissa Eba et al., "Evaluation of The Vulnerability to Flooding of Municipalities Near Major West African Cities: The Case of The Municipality of Bingerville (East of Abidjan, Ivory Coast)," *European Scientific Journal*, vol. 17, no. 14, 2021. [CrossRef] [Publisher Link]

[28] J.J. Assi, *Delimitation of the Protection Perimeters Around the SODECI Water Intake on the Bia in Aboisso (South-East of Côte d'Ivoire): Cartographic and GIS Approach*, Master Thesis, Felix Houphouet Boigny University, pp. 1-76, 2018.

[29] J.P Jourda et al., Evaluation of the Degree of Protection of Groundwater: Vulnerability to Pollution of the Bonoua Aquifer (South-East of Ivory Coast) by the DRASTIC Method," *ESRI Francophone Conference Proceedings*, Versailles, vol. 10, 2007. [Google Scholar]

[30] Anowa Evrade Larissa Eba et al., "Evaluation of the Vulnerability to Pollution of Surface Water Intended for the Supply of Drinking Water to a Metropolis. Case of the Aghein Lagoon in Abidjan, (South of Côte D'ivoire)," *European Scientific Journal*, vol. 12, no. 36, pp. 306-326, 2016. [CrossRef] [Publisher Link]

[31] Pascale Metzger, and Robert D'Ercole, "Risks in Urban Areas: Elements for Reflection," *EchoGéo*, vol. 18, 2024. [CrossRef] [Google Scholar] [Publisher Link]