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Detection of Neotectonic Signatures by Morphometric Analysis of Inkisi Group on Both Banks of the Congo River

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Abstract Several studies have stated the possibility of seismic hazards in the Congo Basin area. This study aims to conduct a morphometric analysis of the Inkisi Group which constitutes a part of the subsoil of the south-eastern Republic of Congo (RC) and the south-western part of the Democratic Republic of Congo (DRC), to detect neotectonic signatures. GIS and ASTER GDEM images have enabled the automatic extraction of morphometric indices, in particular the Hypsometric Integral (HI), the Relative Declivity Extension (RDE) index, along with the hydrographic network and its frequency density. Analysis of the hypsometric distribution of watersheds in the Congo Basin highlights two relief trends. The first relief trend is high (HI>0.5) and is represented by young and abrupt-type basins suggesting rejuvenated relief by neotectonics. The impact of neotectonics in this rejuvenation is evidenced by the RDE index, which reveals that the first order knickpoints in the drainage gradient are mainly located in these watersheds at HI>0.5. The second relief trend is low (HI<0.5) and encompasses the basins tending towards the "equilibrium" stage in which neotectonics is less active. The young basins constitute a NE-SW oriented strip that borders on both sides of the Congo River, thus revealing elevated seismic risk on these two banks. In the Republic of Congo, these young basins perfectly overlap the high lineament density network of the Inkisi group. Moreover, the densest areas of knickpoints in the drainage gradient are located along the course of the Congo River. Thus, the course of the Congo River corresponds with a tectonically active feature; the installation of seismographs along its borders is strongly recommended to better assess the seismic risk associated within it.

Keywords: *Neotectonics, Morphotectonics, Knickpoint, Inkisi, Congo*

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1. Introduction

Morphometric analysis constitutes a powerful tool for characterizing the evolution of relief in regions where outcrops are rare and where fault systems are too large to be studied locally [1]. It is based on several morphometric indices that provide indications of tectonic activity in a watershed [2]. The relief of a watershed is synthetically expressed by a hypsometric analysis [3]. Many works [3,4,5,6,7,8] have showed that the value of the HI reveals whether erosive or tectonic forces are shaping the relief of a watershed. Thus, it is possible to identify relief features rejuvenated by recent tectonic uplifts (neotectonics). In addition, relief breaks (knickpoints) in the drainage gradient help to identify the tectonic control of a drainage system [9]. Several indices have been proposed to identify them. The most used is the Stream Length (SL) Gradient index suggested by [10]. Added to this is the Relative Declivity Slope (RDE) index proposed by [11], which makes it possible to detect knickpoints on longitudinal profiles of rivers. The Knickpoint Finder tool developed and programmed in python language by [9] help to allow the automatic extraction of this index.

The hypsometric analysis and the calculation of the RDE index were applied to the watersheds of the Inkisi group of the left (Democratic Republic of Congo) and right (Republic of Congo) banks of the Congo River, whose works [12,13,14] report that the Inkisi group is strongly fractured in two preferential directions NE-SW and NW-SE. Thus, this study aims to localize the areas of these two countries exposed to seismic hazard where more advanced research on active tectonics must be carried out and the spatial planning redesigned.

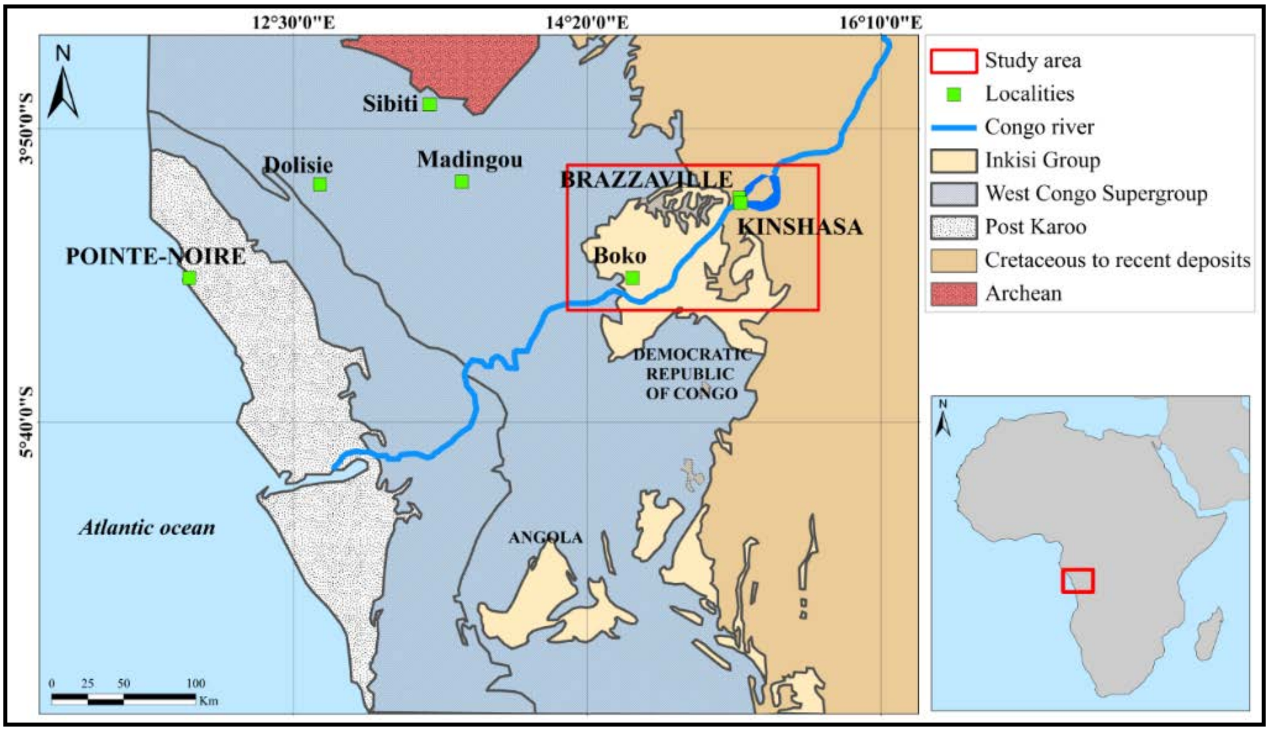

Figure 1. Distribution of the Inkisi group around Central Africa and location of the study zone (red rectangle) [22]

2. Geological Setting

This study concerns the Inkisi group that is located in Central Africa, precisely in Congo basin where it is part of the subsoil of countries as the Republic of Congo, the Democratic Republic of Congo, and Angola (Figure 1). It is essentially composed of arkosic sandstones [15] of fluvial origin of braided rivers type [16], resting in angular unconformity on the West Congo Supergroup [17]. According to [16], this rock formation presents, three (3) repetitive terms namely:

- a basal term constituted of coarse sandstones in massive beds containing thick elliptical pebbles of quartzitic, magmatic and metamorphic origin but generally more numerous in the lower part ;
- a middle term constituted of coarse sandstones with cross-bedding;
- a top term constituted of alternating of fine to very fine sandstones presenting horizontal laminations.

Recent studies of [18] showed that the Inkisi sandstones are affected by brittle tectonics, and the nature of the structural style has been described by the studies of [13,14]. More specifically, the Inkisi Group was affected by two phases of strike-slip tectonics. Both phases are associated with strike-slip faults and joints organized in two main fracture systems: the first one has a dominantly NE-SW trend, while the second has a NW-SE trend.

Concerning the age of the Inkisi group, it remains relative. The studies performed by [19] on the analysis of zircons in Brazzaville, in the Republic of Congo, showed that the proportion of late Neoproterozoic zircons represents more than 55% of all zircons analysed from the Group. On the other hand, the secondary populations of zircons are distributed in order of abundance between the Paleoproterozoic and the Archaean. Likewise, the analysis of the youngest detrital zircons, in the Democratic Republic of Congo, from that group performed by [20,21] show that their ages are estimated between 558 and 851 Ma. Those studies suggest that the Inkisi group dates from the Lower Paleozoic.

3. Materials and Methods

3.1. Materials

We used the following data to carry out this study:

- Two scenes (014, 015) of Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Global Digital Elevation Map (GDEM);
- A cartographic database made up of topographic and geological maps of the Ministry of Mines and Energy (1995) from the Republic of Congo at 1:1 000 000 and the administrative map of Democratic Republic of Congo (2015) of Common Geographic Referential (RGC) of that country.

The different steps required to carry out this study required the use of the following software: Microsoft Office 2013, Microsoft Excel 2013 and ArcGIS 10.7.

3.2. Processing Methods

First, the two scenes 014, 015 of ASTER GDEM were combined into a mosaic. The resulting mosaic was cut out at the borders of the Inkisi group using the geological map of Congo and the corresponding map from the work of [22]. Based on this cut ASTER GDEM image, the morphometric indices, including the hypsometric integral (HI), the RDE index, as well as the hydrographic network and frequency density maps of this network, were calculated.

The hydrographic network was automatically extracted on ArcGIS 10.7 thanks to the various tools dedicated to

Hydrology using the D8 algorithm. This hydrographic network was then subdivided network was then produced using a mesh of 500 m x 500 m.

The hypsometric map was created automatically on ArcGIS and was classified into ten (10) elevation classes 50 m apart. On the basis of this map, a hypsometric analysis based on two parameters namely the hypsometric curve (HC) and the hypsometric integral (HI) was carried out to assess the characteristics of the watershed's relief of study area in order to detect its state of maturity. The graphical representation of the hypsometric curve (HC) bears on the abscissa axis, the percentage of the area of the basin that is above the altitude shown on the ordinate axis [23]. The hypsometric integral (HI) was obtained from the following formula [23,24]: HI = (average altitude - minimum altitude) / (maximum altitude - minimum altitude).

The Relative Declivity Slope (RDE) index developed by [11] is based on the Stream Length (SL) gradient index proposed by [10] and relates to the longitudinal profiles of rivers or drainage sections in order to detect their knickpoints. Any change along the longitudinal profile of a watercourse reflects possible tectonic influences that should be identified [2,10] (Figure 2). The RDE index is subdivided into two indexes namely RDEs and RDEt that have been automatically obtained from a DEM raster thanks to the use of the Knickpoint Finder tool integrated into ArcGIS 10.0 and developed in python language by [9]. This tool uses an algorithm which, extracts three-dimensional parameters of drainage from a raster with altimetric data. Then RDEs and RDEt indexes are calculated and knickpoints are automatically identified. According to [11]:

- the RDEs index refers to a drainage section along a river and is obtained by the following formula: RDEs=(ΔH/ΔL).L. "ΔH" is the difference in elevation between the two ends of that section; "ΔL", the length of the said section and "L" is the distance from the lower end of this section to the river's source (Figure 2);

- however the calculation of RDEt index takes into account the totality of a river from its source to the mouth, in particular, its total length, its total slope and the natural logarithm (ln) of the total length of that river: RDEt=(ΔH/ΔL).ln(L) [25,26].

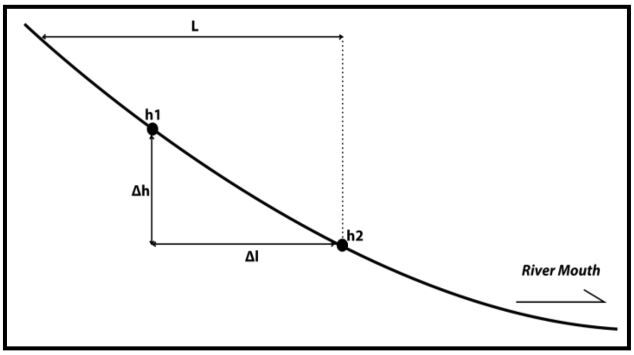

Figure 2. Measurement of RDEs index on a longitudinal profile of a drainage section

The full description of Knickpoint finder tool's functioning is described in [9].

The final objective is to obtain the value of the RDEs/RDEt ratio, which makes it possible to identify the sections of hydrographic networks that have abnormal slopes. Thus, when it is:

- greater than or equal to 2, the section is considered abnormal;
- between 2 and 10, the anomaly is said to be of second order;
- greater than 10, the anomaly is said to be of first order.

Finally, a comparison was made between the hypsometric distribution map of the different watersheds of the study area and that from the RDEs/RDEt report, in order to confirm the detected neotectonic signatures.

The methodological approach adopted is summarized in Figure 3.

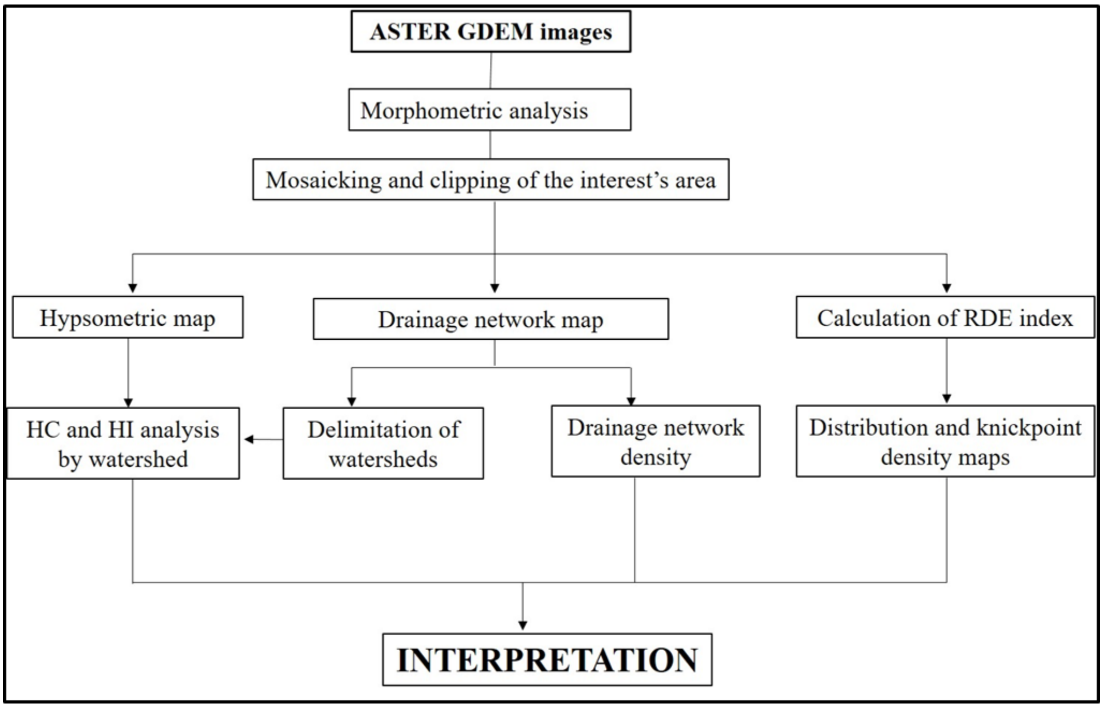

Figure 3. Methodology

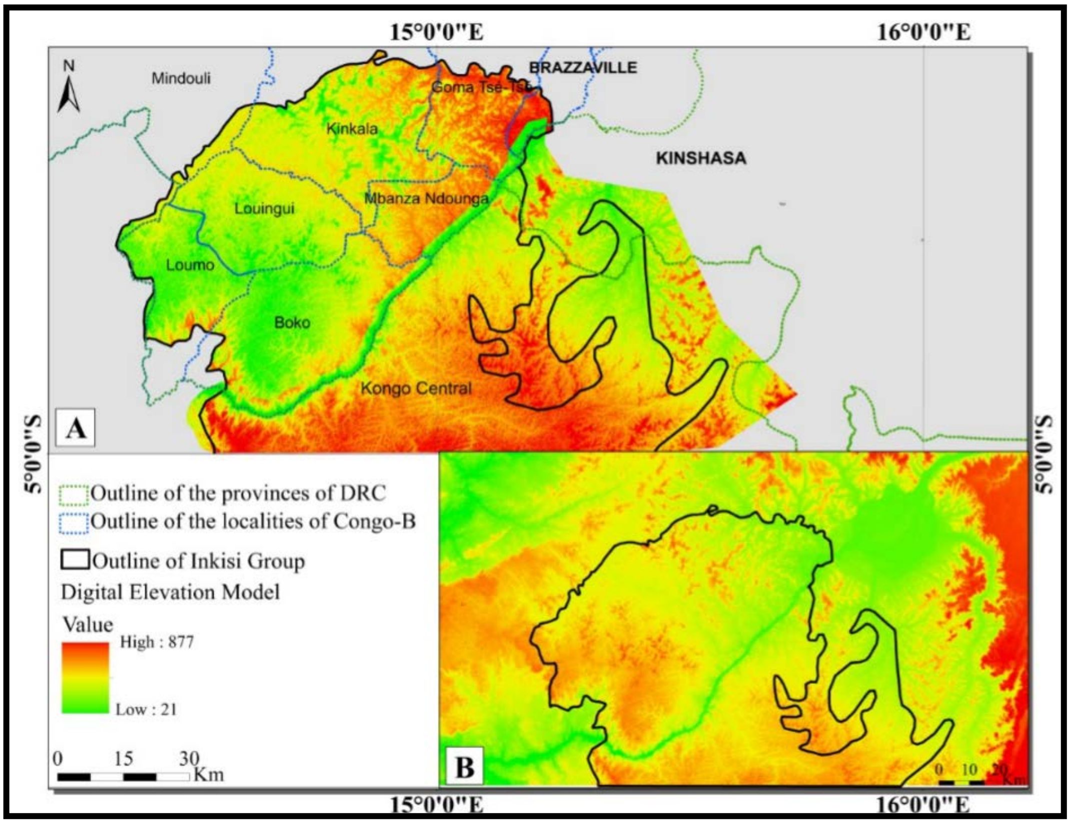

Figure 4. DEM in the study area. (A) Delimitation of the Inkisi group in the RC and the DRC. (B) Two scenes 014 and 015 ASTER GDEM mosaicked

4. Results

4.1. Mosaicking and Clipping of Study Area

Two ASTER GDEM scenes (014, 015) were mosaicked. To allow detection of neotectonic signatures in the drainage basins draining the Inkisi Group on both sides of the Congo River (Republic of Congo and the Democratic Republic of Congo), we proceeded in a clipping of Inkisi group's extent on the basis of that raster ASTER GDEM mosaicked (Figure 4A). The study area mainly concerned the Pool department in Republic of Congo, the area south of the capital Brazzaville in Republic of Congo (RC), as well as the southwest part of the capital Kinshasa and the province of Kongo Central in the Democratic Republic of Congo (DRC).

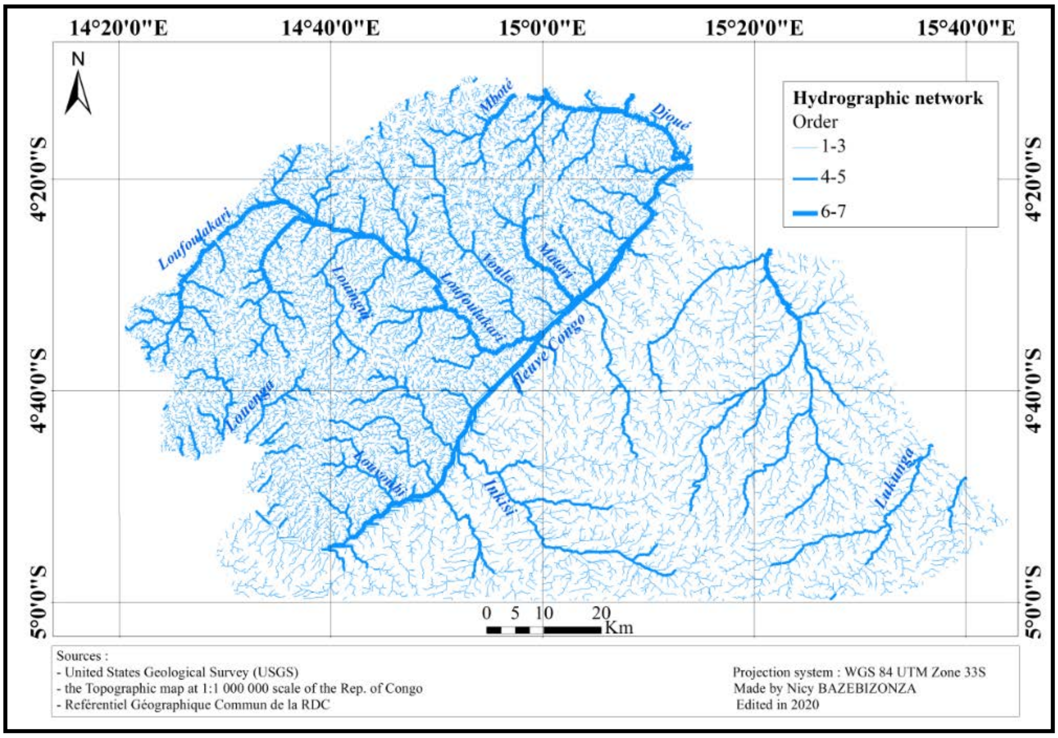

Figure 5. Hydrographic network draining the study area

4.2. Extraction of Hydrographic Network

The automatically extracted hydrographic network of the study area (Figure 5) shows the organization of rivers classified in seven (7) orders of importance according to the classification of [27]. By superimposing the hydrographic network extracted from the topographic base maps of Republic of Congo at 1: 1 000 000 scale, certain rivers including the Congo River and its main tributaries have been identified.

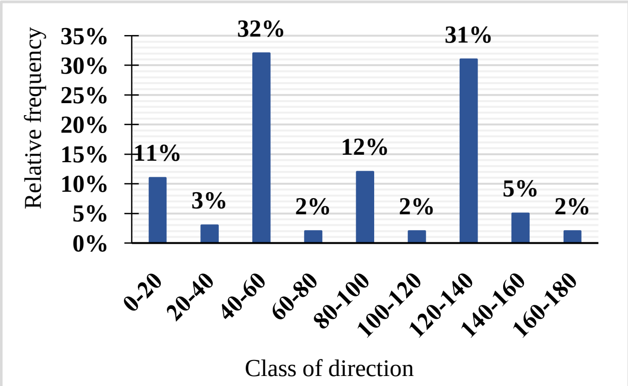

Figure 6. Frequency histogram relating to the classes of directions of the total hydrographic network

Figure 6 presents the distribution of direction classes for each order of the hydrographic network. Based on this graph, the global hydrographic network in the study area is mainly oriented:

- NE-SW with dominant direction classes (N000°-N020°, N040°-N060°). This direction is mainly represented by the Congo River;

- NW-SE with dominant direction classes (N120°-140°). This direction is mainly represented by the tributaries of the Congo River such as the Djoue, Loufoulakari, Voula, Matari in the Republic of Congo and the Inkisi in theDemocratic Republic of Congo. We also note an E-W oriented intermediate direction with dominant classes N080° -N100°.

4.2.1. Delimitation of Watersheds

There are several watersheds draining the study area, as depicted in Figure 7. The watershed identified as “35”, located in the Pool department, is the largest, with an area of 256.73 km^2 in Republic of Congo. The watersheds identified as “11” and “77” are the largest on the left bank, with areas of 169.06 km^2 and 138.52 km^2 respectively.

4.2.2. Frequency Density Map of the Hydrographic Network

The frequency density (km/km^2) of a hydrographic network is defined as the number of flow channels per unit area. The frequency density map of the hydrographic network in the study area (Figure 8) was obtained and classified into four classes. It shows that the hydrographic network is very dense on the right bank of the study area with densities varying between 0.9 and 8.9 km/km^2, while on the left bank the density is lower and varies between 0.2 and 1.9 km/km^2.

4.3. Hypsometric Characterization

The hypsometric map (Figure 9) shows the distribution of elevation in 50 m intervals across the entire study area. In Republic of Congo, it shows areas (Boko, Loumo, Louingui Sub-Prefectures) at high elevation, areas (in particular Kinkala) at relatively moderate elevation and areas (Mbandza-Ndounga Sub-Prefecture) at low elevation. This trend is also found in Democratic Republic of Congo, with zones of moderate to high elevation in the Kongo Central province and altogether low elevation southwest of the city-province Kinshasa.

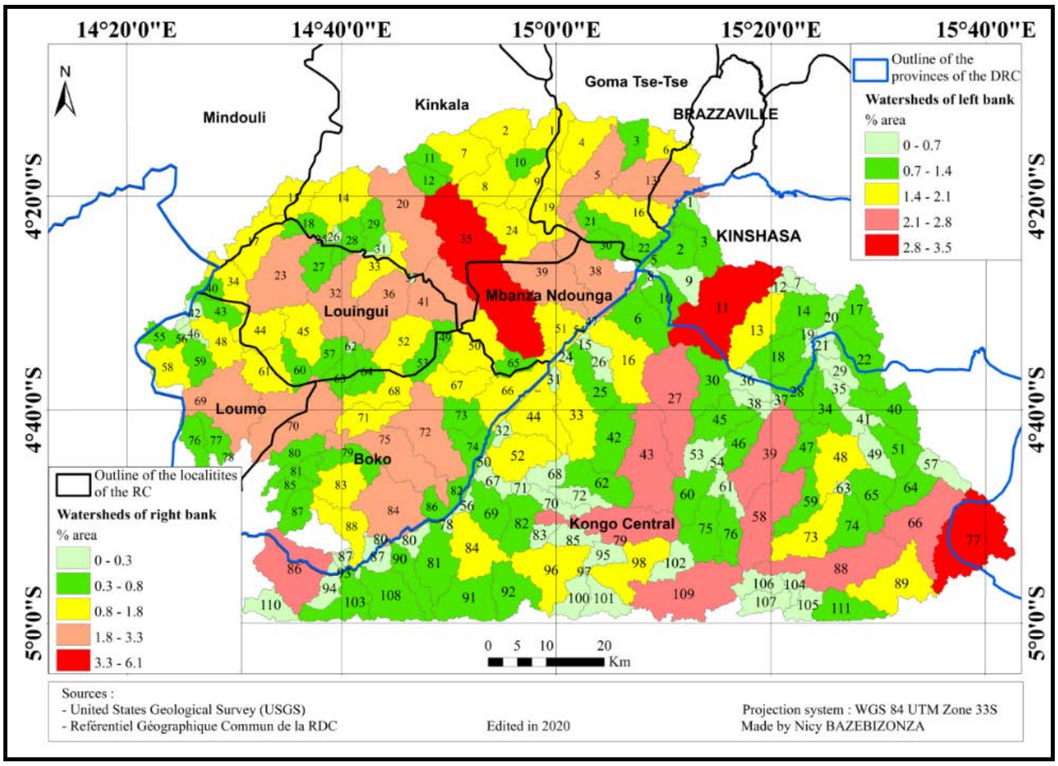

Figure 7. Distribution map of the different watersheds in study area

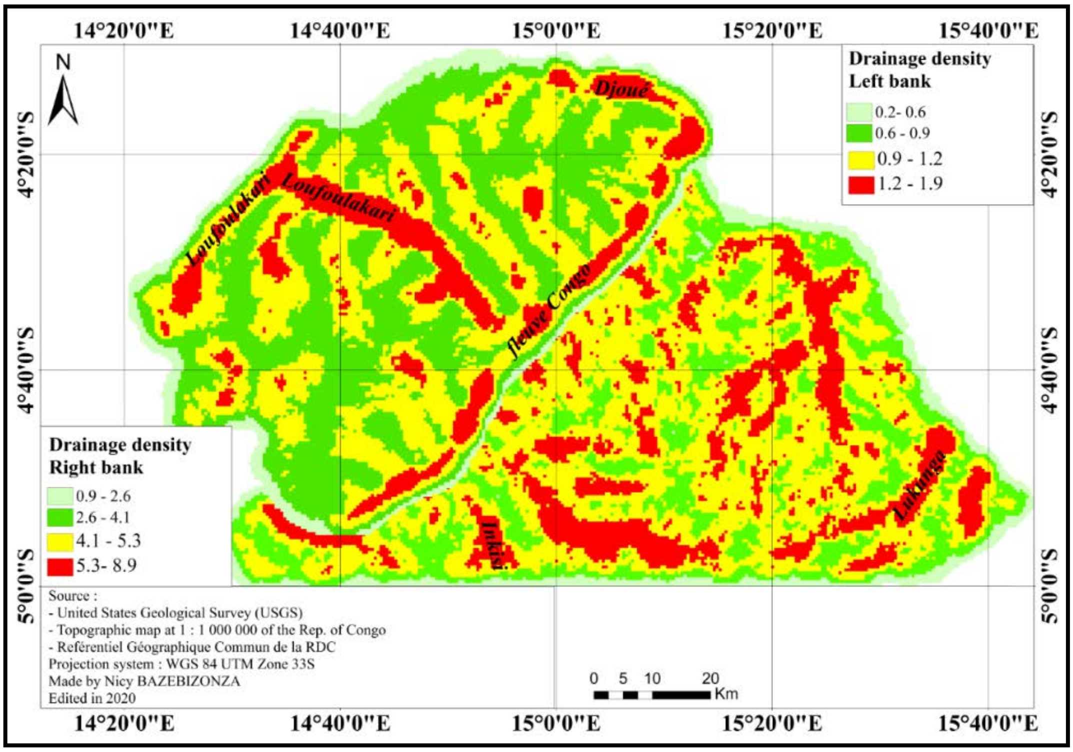

Figure 8. Frequency density map (km/km^2) of the hydrographic network draining the study area

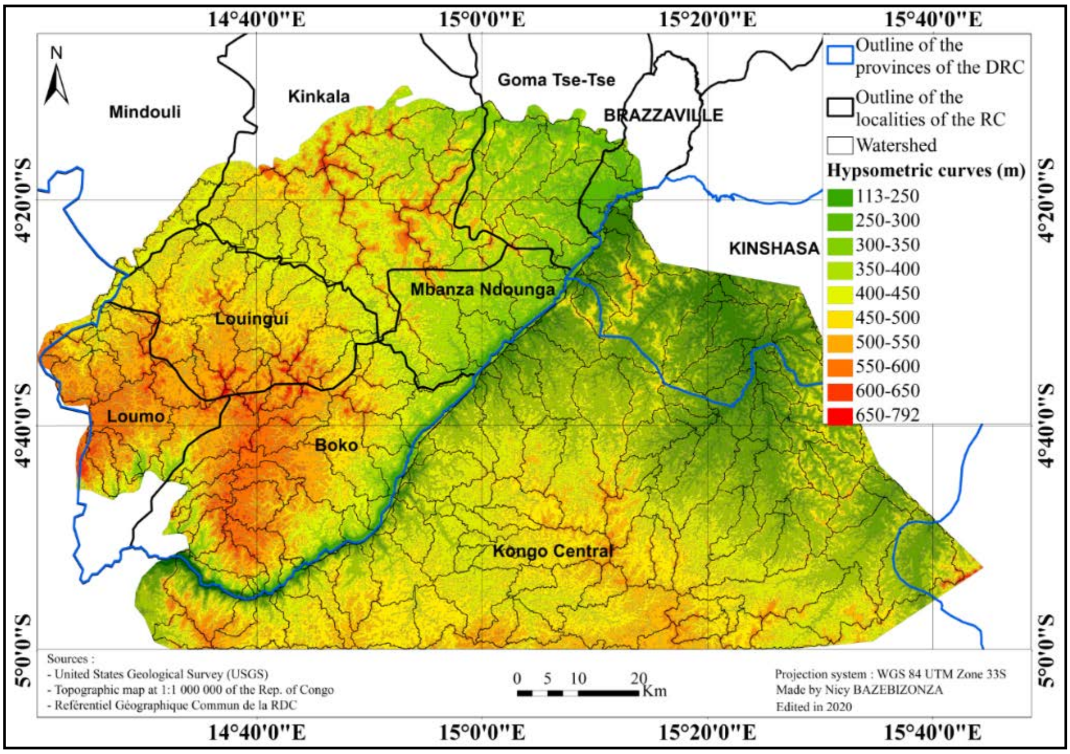

Figure 9. Hypsometric map of the different watersheds of the Inkisi group

The hypsometric curves of the overall study zone describing the repartition of elevations were produced in order to characterize its relief (Figure 10).

Then, Hypsometric Integrals of the right and left banks were calculated.

- Right bank: HIr = (418.2 - 132) / (755 - 132) = 0.46. This curve (Figure 10A) describes a concavo-convex shape with an HI of the order of 46% of initial mass not eroded. The value of the HI provides information on the current mass of the relief that has not yet been consumed by erosion. The relief corresponding to the right bank of the study area is considered to be at the (mature) equilibrium stage according to the theoretical model of the state of maturity of the watersheds (Figure 11), as proposed by [27];

- Left bank: HIl = (486.81- 113) / (792 - 113) = 0.55. This curve (Figure 10B) also describes a concavo-convex curve characterizing a relief of the mature type or at equilibrium.

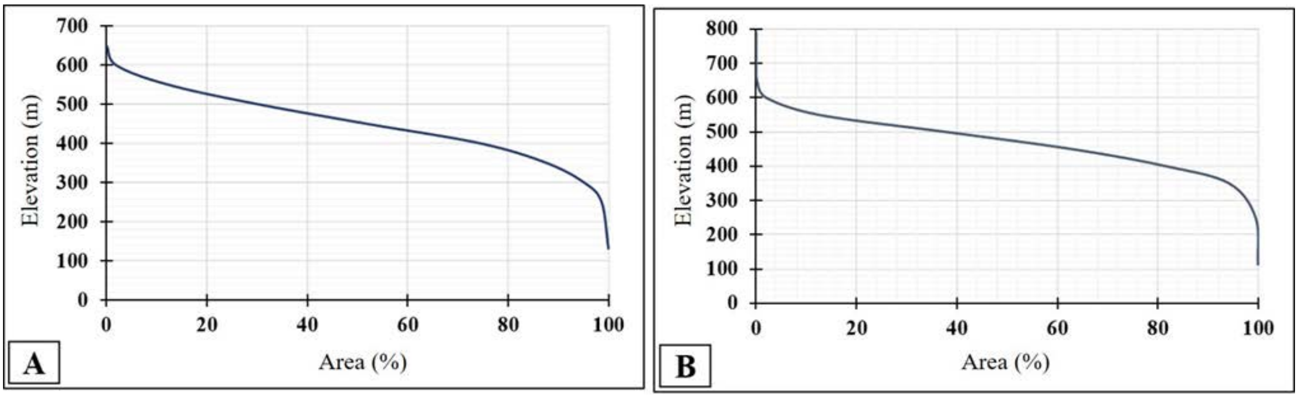

Figure 10. Hypsometric curves in the study zone. (A) Right bank (RC). (B) Left Bank (DRC)

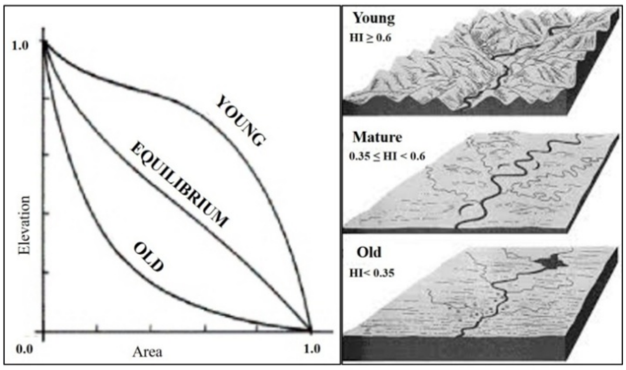

Figure 11. State of maturity of the relief of the watersheds according to [27]

Hypsometric analysis was then performed at the watershed scale (Figure 12) in order to identify more specifically the response of each watershed to tectonic activity. That (Figure 12) shows that the values of HI appear slightly dispersed and between 0.439 and 0.595, the mean of which (0.5) appears as a standard value to present the two relief trends that emerge. The first trend is represented by the watersheds in red whose HI values are greater than 0.5. This NE-SW oriented trend borders the Congo River and is found on both sides of the latter. In Republic of Congo, the trend covers the meridional parts of the sub-prefectures of Boko, Mbandza Ndounga, Goma Tse-Tse and the southern part of the capital Brazzaville. On the left bank, this trend is encountered in the province of Kongo Central as well as at the border between the latter and the capital Kinshasa following a NW-SE orientation. The second trend is represented by the green watersheds whose HI values are less than 0.5.

Focusing on the right bank, the hypsometric distribution map was superimposed on the frequency density map of the lineaments (with a transparency of 40%) (Figure 13) from the work of [28] in order to spatially analyze these two parameters. This analysis shows that the catchments with high HI are perfectly superimposed on the corridor of high lineament density bordering the Congo River.

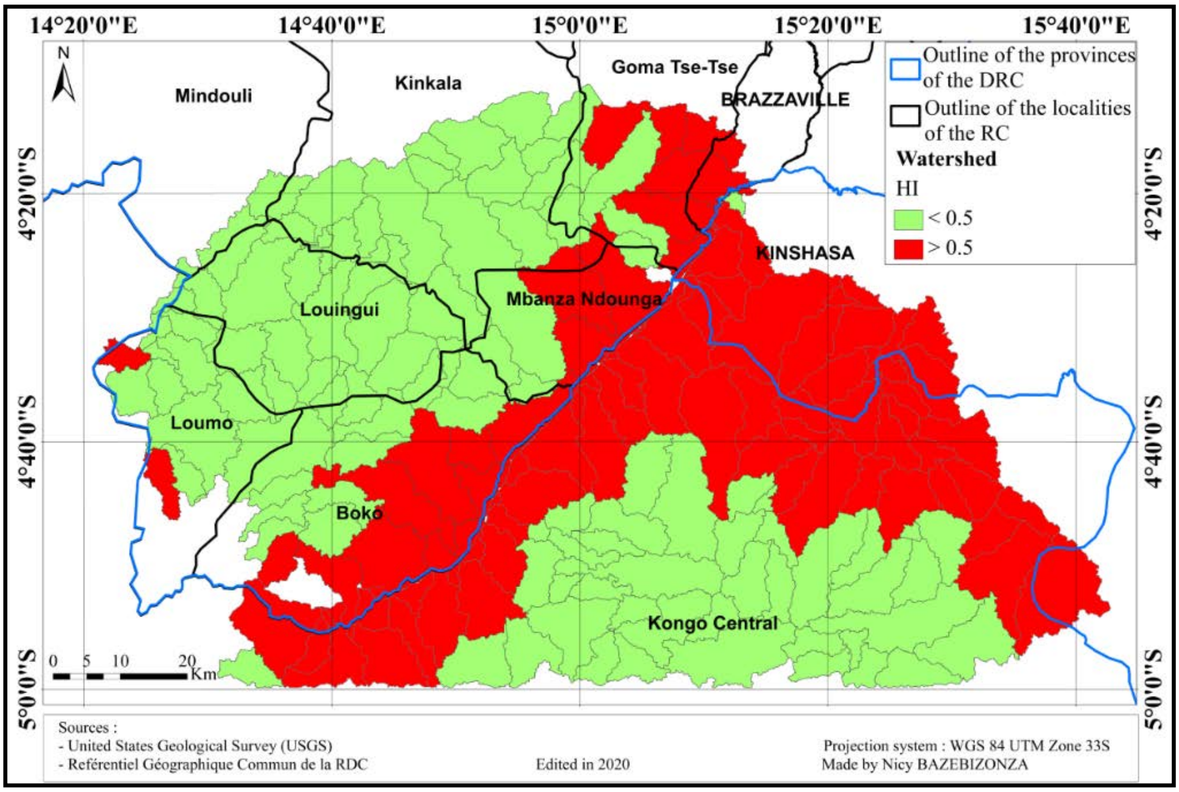

Figure 12. Hypsometric distribution map of the different watersheds

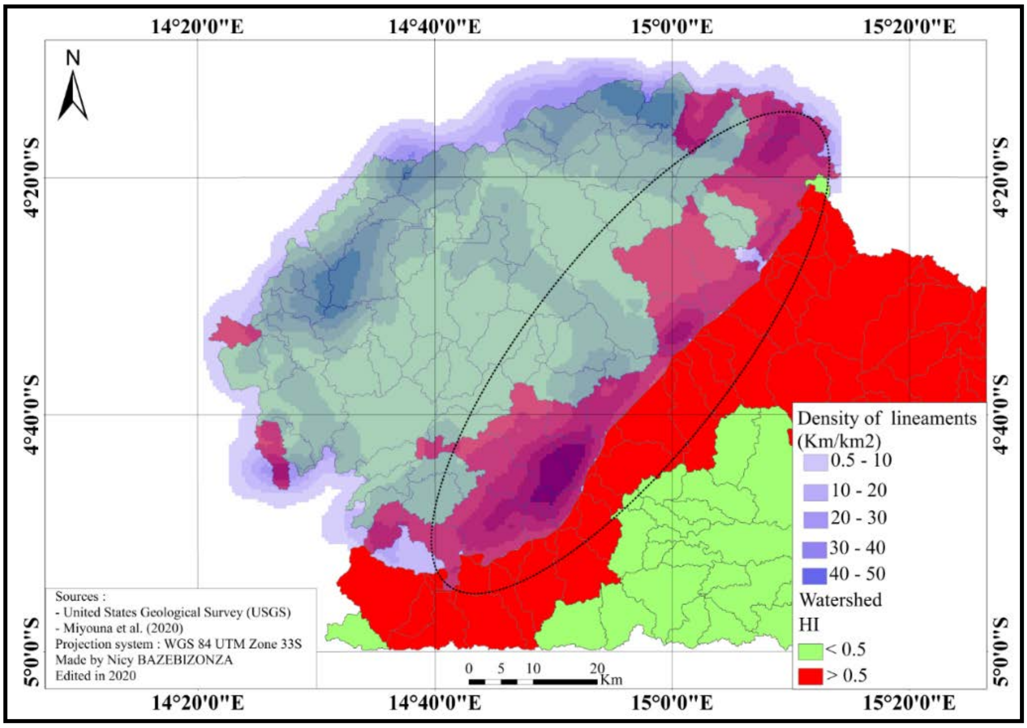

Figure 13. Superimposing the frequency density of the lineaments on the hypsometric distribution map

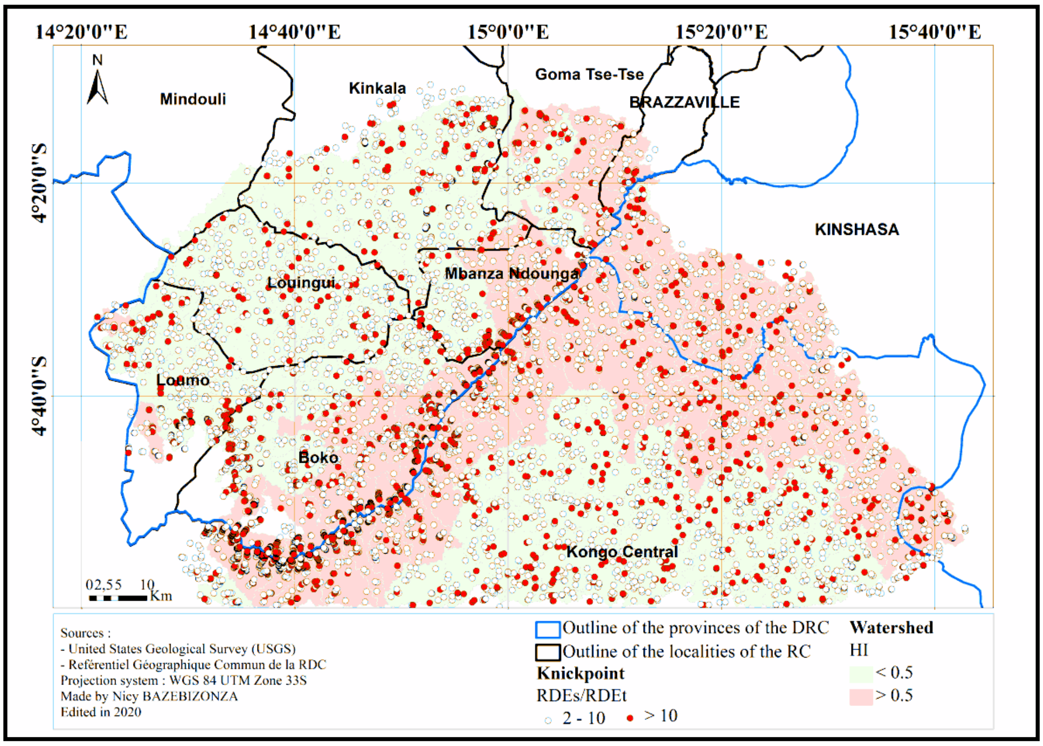

Figure 14. Knickpoint map superimposed on the hypsometric distribution map of the watersheds (85% transparency) of the study area

4.4. RDE Index

The result of the calculation of the RDEs/RDEt ratio is mapped and presented in Figure 14. In total, 4 320 knickpoints are identified in the study area, including 2 617 on the right bank and 2 003 on the left bank of the Congo River. The mapping shows that the value of this ratio is greater than or equal to 2. This indicates that most sections of the hydrographic network have abnormal slopes in certain places. The so-called first order anomalies are mainly found along the Congo River and even coincide with the watersheds at HI> 0.5 (Figure 14).

A density map in knickpoints/km^2 (Figure 15) of these knickpoints was then produced, which shows that the areas of greatest density coincide with the Congo River. They are also localized in a scattered way in Kongo Central and in the Pool department, at the level of major rivers such as the Djoue and Loufoulakari. In Kongo Central, the Inkisi river has a great density of knickpoints. Moreover, the sections of the Congo River encountered in the southern part of the Boko sub-prefecture have the highest concentration of knickpoints.

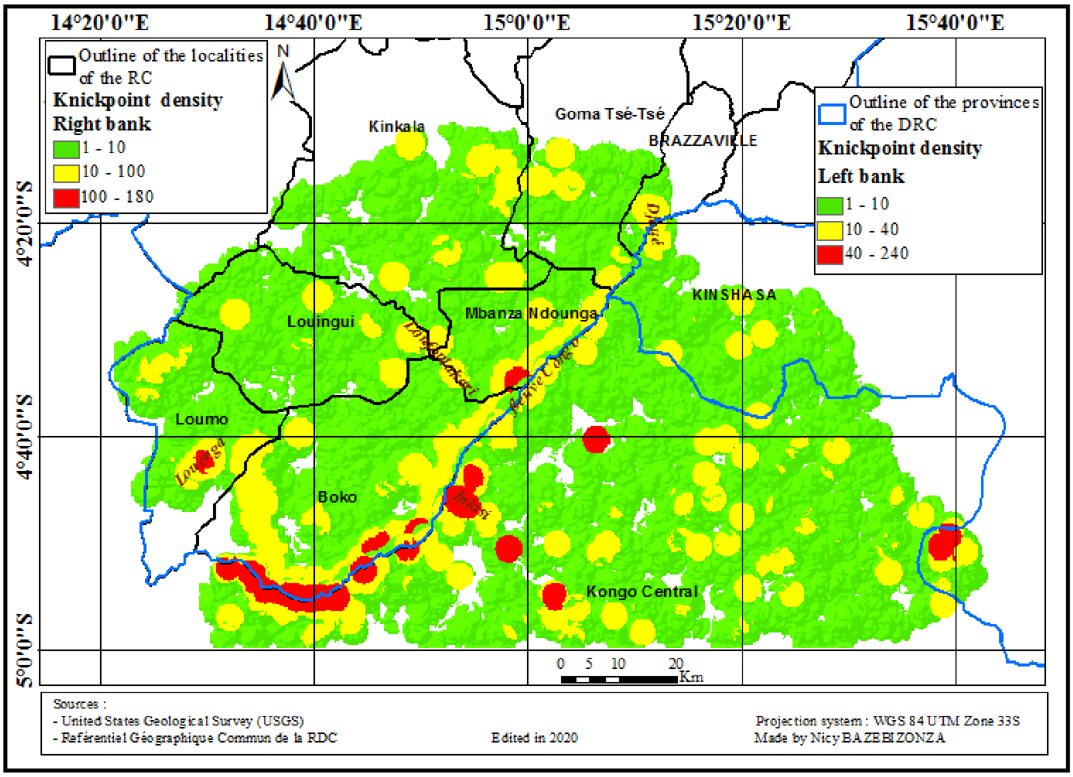

Figure 15. Knickpoint density map

5. Discussion

The curve of the hypsometric distribution (Figure 10) indicates the degree of maturity of the relief (young, equilibrium, and old) as well as the erosive capacity of a basin [3]. The value of the hypsometric integral (HI) is around 46% of the initial mass of the non-eroded relief on the right bank and 55% on the left bank. These values are used to characterize the shape of the resulting hypsometric curves. According to the classification of [27], the hypsometric curves of the two banks are concavo-convex because their HI values are between 0.35 and 0.6. This concavo-convex shape (Figure 10) is confirmed by observing the hypsometric curves' shape. Thus, the study area's relief is considered mature or at the equilibrium stage (Figure 9) in accordance with the theoretical model of the state of maturity of the watersheds (Figure 11) proposed by [27]. Mature basins represent an intermediate stage between young basins (steep basins) rejuvenated by tectonic uplifts and old basins (soft plain) not rejuvenated by tectonics. Analysis of the hypsometric curves allows us to affirm that the study area's relief is shaped by a balance between the forces of tectonics and erosion. Nevertheless, the analysis of the HI shows that the relief of the left bank is more rejuvenated by neotectonics than that of the right bank. Indeed, the overall HI of the watersheds (0.55) covering the Inkisi group on the left bank is higher (therefore younger) than that (0.46) on the right bank. This is confirmed by the analysis of the frequency density of the hydrographic network on both banks. We note that the hydrographic network (Figure 8) is very dense (0.9 - 8.9 km/km^2) on the right bank and much less dense (0.2 - 1.9 km/km^2) on the left bank. This is explained by the fact that the relatively mature relief of the right bank allowed the hydrographic network to densify well while that of the left bank rejuvenated by neotectonics did not allow the hydrographic network to densify. In this regard, [29] affirms: "the density of drainage increases rapidly during the youth stage to reach their maximum at the beginning of maturity".

More specifically, interesting details are provided to us at the scale of the various watersheds where the HI vary between 0.439 and 0.595. The hypsometric distribution map (Figure 12) shows two relief trends. The first trend is high and is represented by the watersheds with a HI higher than 0.5 and the second (low) by the watersheds with a HI lower than 0.5.

- The watersheds in red (HI>0.5), having convex hypsometric curves, constitute mainly a NE-SW oriented band which borders both sides of the Congo River (Figure 12). Another network of these watersheds is oriented NW-SE and is located at the border between the city-province Kinshasa and the province of Kongo Central to Republic of Congo in the southern part of Brazzaville, and in the sub-prefecture of Goma Tse-Tse. These are watersheds whose HI is very close to 0.6, characteristic of young and steep type basins. These watershed areas are therefore of a young tendency. Indeed, high values of HI give evidence of intense tectonic activity [1]. This assertion is confirmed by the work of [30] in India, in the Himalayan region, that of [4] in Greece and many others [3,31] who have shown the interest of using HI in the detection of neotectonic signatures. On the strength of this, we can affirm that these watersheds (in red) (Figure 12) are characterized by a rejuvenation of the relief linked to tectonic uplift.
- The watersheds in green (IH<0.5) (Figure 12), conversely, move away from the young stage and tend towards older relief and a lesser preponderance of tectonic tendency compared to the basins in red.

In the Pool department of the Republic of Congo, the HI pattern reflects increased immaturity of the watersheds, correlated with an expansion in tectonic power from west to east within the Inkisi group. This pattern is reversed in Democratic Republic of Congo, especially in Kongo Central, where there is an increase in the immaturity of the basin from east to west showing convergence around the Congo River. Everything suggests that the course of the Congo River would be tectonically active. Work of [28] report this out by stating that the flow of large rivers (Loufoulakari, Djoue) such as the Congo River is controlled by large fracturing corridors. The superimposition of the frequency density map of the lineaments from the work of [28] with that of the hypsometric distribution makes it possible to detect the active fracturing corridor. Figure 13 shows that the basins with a young tendency coincide with the network of high lineament density that is oriented NE-SW, which borders the Congo River. This implies that the lineaments of this network are potentially active and are responsible for the observed high HI values. Paleostress determination in Brazzaville by [14] indicates that the stress field resulting from a second tectonic phase, which generated the NE-SW oriented fractures, is still active. He goes further by stressing that this E-W compression phase would be linked to the ridge-push of the Atlantic Ocean. Our results confirm this.

The Knickpoint Finder tool detected 4 320 knickpoints in the drainage gradient of the study area. This high number of knickpoints is explained by the density of the hydrographic network extracted. The value of the RDEs/RDEt ratio was used to represent these knickpoints (Figure 14). This choice is justified because it allows identifying the greatest local anomalies which are particularly important in neotectonic studies instead of small local anomalies such as waterfalls and rapids [9]. First-order anomalies (knickpoints) (RDEs/RDEt>10) coincide with rejuvenated watersheds (HI>0.5). This confirms that the young reliefs identified by hypsometric analysis are indicative of neotectonic action. It should be noted that the term neotectonic is used to indicate active fault movement in the last 35 000 years or repeated fault activity several times in the last 500 000 years [2].

In addition, the densest areas of knickpoints (Figure 15) correspond to sections of the Congo River and show a linear trend that is oriented NE-SW. In the Pool department of Congo Brazzaville, they correspond to sections of large rivers such as the Djoue, Loufoulakari, and Louenga. A great density of knickpoints is reported in the southern part of the Boko sub-prefecture. In Kongo Central in Democratic Republic of Congo, they correspond to sections of large rivers like the Inkisi.

In view of all the above, we can affirm that the right and left banks of the Congo River are tectonically active. The cities of Brazzaville and Kinshasa, as well as the Pool department and the province of Kongo Central, would be therefore exposed to elevated seismic risk. The stakes of elevated seismic risk are potentially high, including questions of public safety and spatial planning, as well as the realization that civil engineering works must take seismic risk into account. In-depth studies including the installation of seismographs along the two banks of the Congo River are strongly recommended in order to better assess the seismic risk.

A large study is also recommended to carefully observe the 4 620 knickpoints extracted by the Knickpoint Finder tool, by use of photo-interpretation of satellite images available through Google Earth. Image analysis must be accompanied by field work in areas where it is possible.

6. Conclusion

The present work, which aims to use morphometric analysis to detect neotectonic signatures in the Inkisi group, shows evidence that this rock formation is affected by neotectonic activity. This study presents two relief trends in the study area. One is high (HI>0.5) and the other low (HI<0.5). The high trend (HI>0.5) presents a hypsometric curve with a convex shape, characteristic of watersheds whose relief is rejuvenated by recent tectonic movements. This is confirmed by the calculation of the RDE index, which shows that the first order knickpoints in the drainage gradient are mainly located in these catchments at HI>0.5. These are the watersheds that border the right and left banks of the Congo River. In the Republic of Congo (RC), these watersheds are located in the meridional part of the sub-prefectures of Boko, Mbandza-Ndounga, Goma Tse-Tse and the capital Brazzaville. In addition, they are superimposed on the zone of high lineament density of the same localities. Thus, these lineaments would probably be active, making the right bank of the Congo River an area with significant seismic risk. Spatial planning and the construction of civil engineering works must take this risk into account.

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References

[1] Sedrette, S. Extraction semi-automatique des linéaments et des indicateurs morphométriques dans un environnement SIG pour la caractérisation morphostructurale et néotectonique de la région de Nefza dans le Nord-Ouest de la Tunisie. *Thèse de doctorat*, Université de Tunis EL MANAR, Tunisie. 223p. 2017.

[2] Keller E. A., Pinter N. Active tectonics: Earthquakes, Uplift and Landscapes. *Prentice Hall*, New Jersey, 1996, 338p.

[3] Laabidi A., El Hmaidi A., El Abassi M. Apports du modele numerique de terrain mnt à la modelisation du relief et des caracteristiques physiques du bassin versant du Moyen Beht en amont du barrage El Kanser.... *European Scientific Journal*, 12 (29): 258-288. 2016.

[4] Argyriou A. A Methodology for the Rapid Identification of Neotectonic Features using Geographical Information Systems and Remote Sensing: A Case Study from Western Crete,

Greece. *Thesis*, University of Portsmouth, United Kingdom, 269p. 2012.

[5] Hurtrez J.E., Sol C., Lucazeau F. Effect of Drainage Area on the Hypsometry from an Analysis of Small-Scale Drainage Basins in the Siwalik Hills (Central Nepal). *Earth Surface Processes and Landforms*, 24: 799-808. 1999.

[6] Kale V.S., Sengupta S., Achyuthan H., Jaiswal M.K. Tectonic Controls upon Kaveri River Drainage, Cratonic Peninsular India: Inferences from Longitudinal Profiles, Morphotectonic Indices, Hanging Valleys and Fluvial Records. *Geomorphology*, 227: 153-165. 2014.

[7] Sedrette S., Rebai N., Mastere M. Evaluation of neotectonic signature using morphometric indicators: Case study in Nefza, North-West of Tunisia. *Journal of Geographic Information System*, 08: 338-350. 2016.

[8] Willgoose G., Hancock G. Revisiting the Hypsometric Curve as an Indicator of Form and Process in Transport-Limited Catchment. *Earth Surface Processes and Landforms*, 23: 611-623. 1998.

[9] Queiroz G.L., Salamuni E., Nascimento E.R. Knickpoint finder: a software tool that improves neotectonic analysis, *Computer Geosciences*, 76: 80-87.

[10] Hack J.T. Stream-profile analysis and stream-gradient index. *J. Res. U.S. Geol. Survey*, 1 (4): 421-429. 1973.

[11] Etchebehere M.L.C., Saad A.R., Perinotto J.A.J., Fulfaro V.J. Aplicação do Índice « Relação Declividade-Extensão - RDE » na Bacia do Rio do Peixe (SP) para Detecção de Deformações Neotectônicas. *Revista do Instituto de Geociências USP - Série Científica*, São Paulo, 4(2): 43-56. 2004.

[12] Delvaux D., Ganza G., Kongota E., Fukiabuntu G., Mbokola D., Boudzoumou F. …. Nkodia H.M.D. The “fault of the Pool” along the Congo River between Kinshasa and Brazzaville is no more a myth: Paleostress from small-scale brittle structures. *Geophysical Research* Abstracts, 19 (1): EGU2017-15143-1. 2017.

[13] Miyouna T., Nkodia H.M.D., Essouli O.F., Dabo M., Boudzoumou F., Delvaux D. Strike-slip deformation in the Inkisi Formation, Brazzaville, Republic of Congo. *Cogent Geosci.* 4: 1542762. 2018.

[14] Nkodia H.M.D. Style structural et tectonique de la Formation de l’Inkisi, à Brazzaville, Republique du Congo. *Mémoire de Master*, Université MARIEN NGOUABI, République du Congo. 93p. 2017.

[15] Sounga J. D., Affaton P., Noack Y., Mialoundama F. Albitization in the Inkisi sandstones, Republic of Congo: Characterization and interpretation. *Global journal geological Sciences*, 10(2), 175-186. 2012. 2012.

[16] Boudzoumou F. La chaîne Ouest-Congolienne et son avant-pays au Congo : relations avec le Mayombien ; sédimentation des séquences d’âge Protérozoïque supérieur. *Thèse de doctorat*, Université Aix-Marseille, France, 220p. 1986.

[17] Scolari G., Van Daalhoff H. Le Précambrien de la chaîne congolaise du Mayombe; état des connaissances géologiques, le problème des orogenèses. *Bull. Bur. Rech. Géologiques Minières*, (3): 163-181. 1965.

[18] Delvaux D., Ganza G., Mees F. & Lahogue P. Use of hybrid fractures in paleostress determinations: Palygorskite-bearing fractures in Kinshasa, DR Congo. Session TS2 (PICO) EGU2014-8917, (pp. 1-31). Kinshasa. 2014.

[19] Affaton P., Kalsbeek F., Boudzoumou F., Trompette R., Thrane K., Frei R. The Pan-African West Congo belt in the Republic of Congo (Congo Brazzavile): Stratigraphy of the Mayombe and West Congo. *Precambrian Research, 272*: 185-202. 2016.

[20] Frimmel H. E., Tack L., Basei M.S., Nutman A. P., A. P., Boven A. Provenance and chemostratigraphy of the Neoproterozoïc West congolian Group in the Democratic Republic of Congo. *Journal of African Earth Sciences*, 46: 221-239. 2006.

[21] Straathof G. B. Neoproterozoic low latitude glaciations: An African perspective. PhD, *thesis*, University of Edinburgh, U.K, Edinburgh, 263p. 2011.

[22] Tack L., Wingate M., Liégeois J.-P., Fernandez-Alonso M., Deblond A. Early Neoproterozoic magmatism (1000-910 MA) of the Zadinian and Mayumbian Groups (BasCongo): onset of Rodinian rifting at western edge of the Congo craton. *Precambrian Research*, 110: 277-306. 2001.

[23] Keller E.A., Pinter N. Active Tectonics: Earthquakes, Uplift, and Landscape, Prentice Hall Earth Science Series. 2nd edition. *Prentice Hall Inc.*, Upper Saddle River, New Jersey. 2002.

[24] Pike R.J., Wilson S.E. Elevation-relief ratio, hypsometric integral and geomorphic area - altitude analysis. *Geological Society of America Bulletin*, 82: 1079-1084. 1971.

[25] Etchebehere M.L.C., Saad A.R., Santoni G., Casado F.C., Fulfaro, V.J. Detecção de prováveis deformações neotectônicas no vale do rio do Peixe, Região Ocidental Paulista, mediante aplicação de índices RDE (Relação Declividade-Extensão) em segmentos de drenagem. Revista UNESP *Geociências*, 25(3): 271-287. 2006.

[26] Seeber L., Gornitz V. River profiles along the Himalayan arc as indicators of active tectonics, *Tectonophysics*, 92: 335-367. 1983.

[27] Strahler A. N. Hypsometric (area-altitude) analysis of erosional topography, *Geological Society of America Bulletin*, 63: 1117-1142. 1952.

[28] Miyouna T., Bazebizonza N. C., Essouli F. O., Kempena A., Nkodia H.M.D., Boudzoumou F. Cartographie par traitement d’image satellitaire des linéaments du groupe de l’Inkisi en République du Congo: implications hydrogéologique et minière. *Afrique Science*, 16(4): 68-84. 2020.

[29] Schumm S.A. The evolution of drainage systems and slopes in bad lands at Perth, Amboi, New Jersey. *Geol. Soc. Ame. Bull.* 67 (5), 597-646. 1956.

[30] Bhat M.A., Dar T. A., Kaboo, B. A. Morphotectonic and Morphometric analysis for Neotectonic activity of Kehmil basin, Kashmir Himalayas: Using Geospatial techniques. *International Journal of Advance Research in Science and Engineering.* 7(04): 918-929. 2018.

[31] Carozza J.-M., Delcaillau, B. Réponse des bassins versants à l’activité tectonique: l’exemple de la terminaison orientale de la chaîne pyrénéenne. Approche morphotectonique. Géomorphologie: relief, processus, environnement. *Groupe français de géomorphologie (GFG)*, pp.45-60. 2000.