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Application of Morphometric Analysis and Thiessen Method for a Geo-Hydrological Study Using GIS Techniques: Case of the Mpanda Watershed, Northwestern Burundi

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Abstract

The morphometric parameter analysis of a drainage watershed and spatial rainfall distribution over a basin play an important role to understand the hydrological behaviour of a watershed. A quantitative analysis of morphometric parameters of Mpanda watershed and its sub-watersheds has been carried out using Geographical Information System (GIS) techniques. Morphometric parameters for that watershed and its sub-watersheds were evaluated from three perspectives: watershed geometry, watershed shape, and drainage network in order to establish a relationship with hydrological characteristics of the basin. Based on geometry and shape parameters, the Mpanda watershed and its sub-watersheds have moderate elongated to very elongated shapes, which results in limited peak flood development at the watershed outlet. The watershed is a fifth order basin and the first order streams dominate the basin (±50 %). The development of stream segments in the study area is affected by rainfall and groundwater discharge. The mean bifurcation ratio indicates geological heterogeneity, higher permeability and lesser structural control. The drainage density and stream frequency indicate that the watershed has permeable subsurface material, good vegetation cover, causing more infiltration of water and recharging groundwater aquifers. The average rainfall calculated using Thiessen method for a period of 20 years over the entire Mpanda watershed is 1341 mm. The basin can be separated in two sub-basins and it can be observed that the upper basin receives almost twice the rainfall recorded in the alluvial plain basin. The results of this study provide information on morphometric characteristics and spatial rainfall distribution that can serve as a basis to improve planning, and management of watershed resources.

Keywords: Morphometric Parameter, Thiessen Method, Mpanda Watershed, Burundi

Introduction

Morphometric analysis is an important aspect of characterization of watersheds [1]. Quantitative description of the watershed geometry (morphometric analysis) requires measurement of linear features, gradient of channel network and contributing ground slopes of the drainage basin [2]. Various important hydrologic phenomena can be correlated with the physiographic characteristics [3]. Drainage basin/watershed analysis based on morphometric parameters is very important for watershed planning since it gives an idea about the basin characteristics regarding slope, topography, soil condition, runoff characteristics, surface water potential, etc. [4, 5]. In this study, The Geographical Information Systems (GIS) using Digital Elevation Model (DEM) were convenient tools. Those tools will be used to delineate Mpanda watershed and its sub-watersheds, and to extract hydrographic network. GIS software will allow also using Thiessen method for spatial rainfall distribution in the whole watershed. This spatial rainfall distribution will allow us to estimate the average rainfall of the basin and sub-basins. This rainfall is the basis for surface runoff water supply and aquifer recharge which will provide the base flow during dry season periods.

Considering the role of the Mpanda River in the alluvial plain, especially for the irrigation of rice cultivation and food crops, the objectives of this study are to analyse geometry, shape and drainage network parameters of the Mpanda watershed; to determine the average precipitation of the whole basin, and the spatial rainfall distribution in its two sub-basins (upper basin and plain basin).

Materials and Methods

Study Area

The Mpanda watershed extends over two geomorphologically different zones, including the alluvial plain and the Mirwa foothills (Fig 1). Its upstream limit is close to the dividing line between the Congo Basin and the Nile Basin at an altitude of ~2,670 m, while its outlet into the Rusizi River is at an altitude of 777 m (Fig 1). The total area of this watershed calculated from DEM interpolations is 451.59 km². From the upstream limit to the entrance point of the Mpanda into the plain (point 2; on Fig 1), the surface of the upper watershed is 240.65 km². The surface of the alluvial plain basin is 210.84 km².

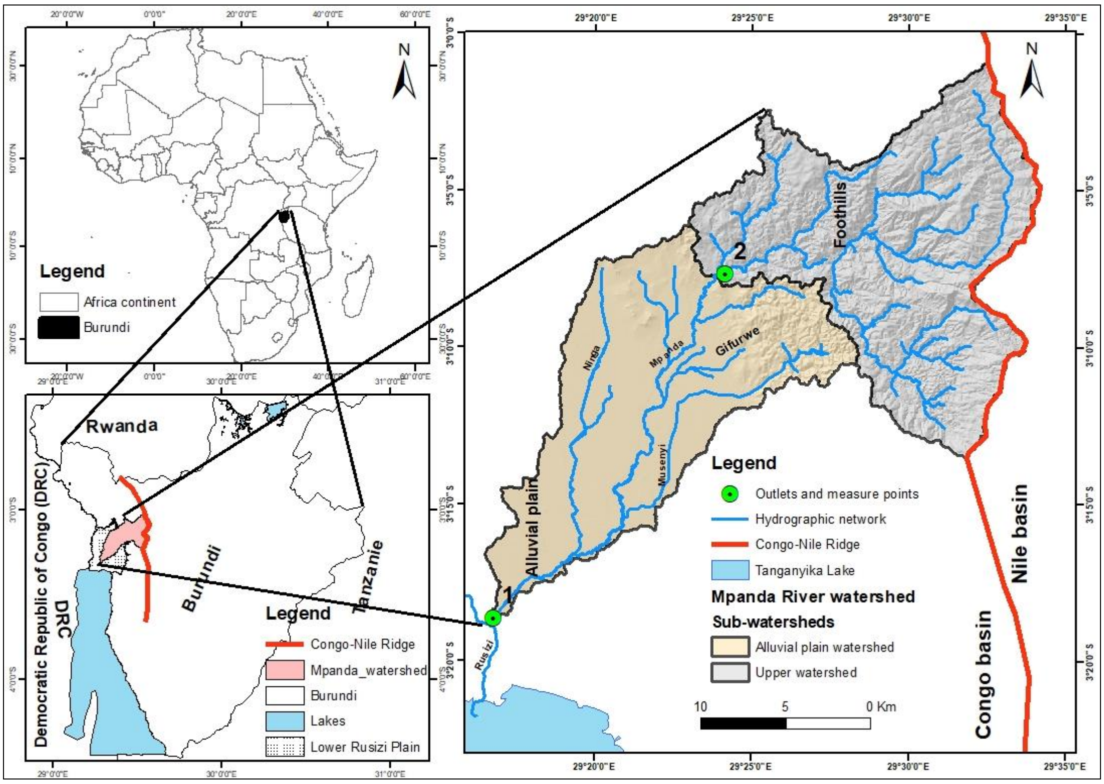

Fig 1: Location of the study area with two geomorphic zones

The geology of the Mpanda river watershed consists of a Precambrian and a Cenozoïc units. The Cenozoïc in the area consists of Holocene, Middle Pleistocene and undifferentiated Cenozoïc formations (Table 1) and these formations occupy the major part of the basin located in the alluvial plain (Fig 2).

Table 1: General description of Cenozoïc formations

Age	General description
Holocene (Ho)	Essentially of alluvial cone deposits developed at the foot of escarpments and deposits due to spreading runoff occupying a large part of the lower Rusizi plain, the recent alluvium of the Rusizi and its delta, as well as the beaches of Lake Tanganyika with coastal barriers mainly on the northern side.
Middle Pleistocene (Pm)	Alluvial cones with flow-shetflood sedimentary mechanisms and fluvio-lacustrine formations: coarse sands to fine silt-clay deposits.
Undifferentiated Cenozoic (Ci)	alluvial terraces, conglomerates and sandstone-quartzite rocks

Precambrian outcrops consist of Middle Proterozoic magmatic and metamorphic formations [6, 7] consisting of the granitic intrusion (γ), Bubanza Complex (Bb), Rushubi-Muyebe formation (Rb-My), Buhonga complex and Mikiko formation.

Table 2: General description of Middle Proterozoic magmatic and metamorphic formations [6]

Formation	General description
Granite intrusion (γ)	Granite with oriented texture of magmatic origin. It consists of feldspar, quartz, biotite and muscovite, sometimes garnet.
Bubanza complex (Bb)	metasedimentary lithology. The bedrock is essentially made up of sandstone and psammite benches alternating with more pelitic levels; all these rocks have a typical greenish grey colour.
Rushubi-Muyebe formation (Rb-My)	Mainly pelitic sediments and is generally well classified. However, this pelitic assemblage appears under different facies resulting from the sedimentary phase and the varying degrees of metamorphism from one region to another.
Buhonga complex (Bg)	Intruded areno-pelitic or contaminated granitoid sediments. Quartzites seem to be the best preserved lithology; they are very often cataclased parallel to the foliation of the gneissic granites.
Mikiko formation (Mk)	Located on the tops of the crest, it comprises at the base a conglomeratic level whose main elements are quartzite pebbles, followed by a coarse detritic level.

The fault contact between the plain and the Precambrian is generally masked by recent sediments [6]. The structure of the Precambrian basement is largely given by generally NS and NW-SE oriented megastructures whose emplacement is considered in two major deformation phases. The first phase is characterised by structures belonging to an overlapping tectonic regime directed from NW to SE and accompanied by granitic magmatism (granitic intrusion and Bubanza complex). The second phase consists of major folds that are manifestations of the metasedimentary cover of the thrusting regime (Rushubi-Muyebe Formation and Buhonga Complex). These major structures are subsequently affected by deformation characterised by a more or less NS to NNW-SSE schistosity [6].

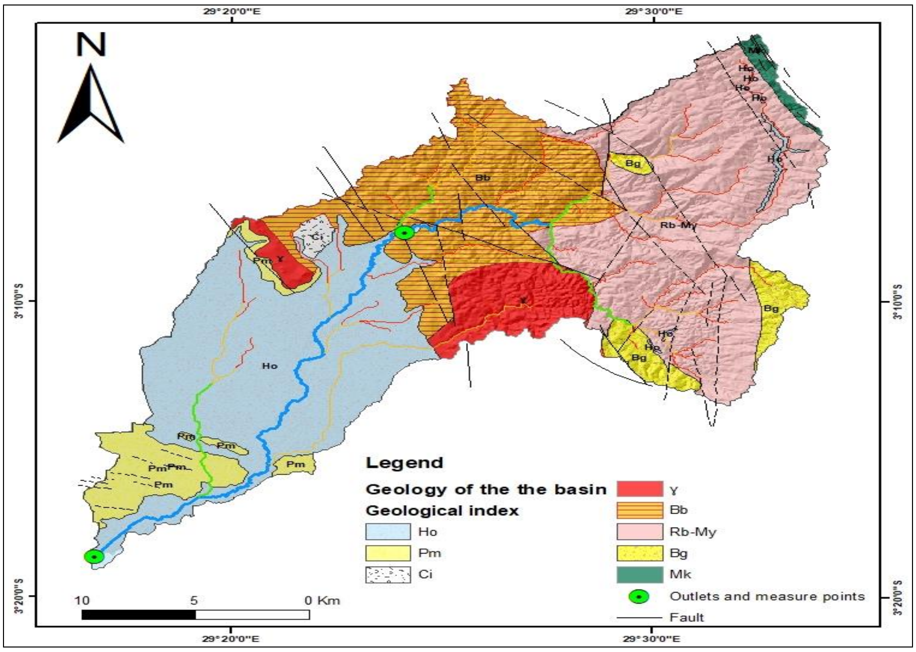

Fig 2: Geological map of the study area [8]

The climate of Burundi is therefore tropical tempered by the altitude which varies from 771 to 2670 m [9]. The country alternates between a rainy season (October to May) and a dry season (June to September). In general, rainfall increases with altitude. The minima observed in the Rusizi plain are around 500 mm and the maxima are around 2200 mm in the high-altitude areas [10]. However, all regions have a bimodal rainfall pattern with peaks in April [11]. The temperature distribution closely follows the relief with an annual average of 23°C in the Rusizi plain and 16°C on the Congo-Nile ridge [10].

Parameter Estimation Methods

A GIS software was used for the delineation and calculation of the morphometric parameters of the Mpada watershed. A DEM of the study area was extract from the local DEM of Burundi. Morphometric characteristics are quantitative indicators of a basin elements that influence the magnitude and variability of hydrogeological processes in different ways [2]. They are a quantitative basis for predicting basin response based on some easily calculated parameters [2]. Two categories of parameters will be calculated: parameters related to the geometry of the basin, such as extent, dimensions and shape indexes; parameters related to the drainage network, such as stream length, stream order, drainage density, bifurcation ratio and stream frequency. Those morphometric parameters are described in Table 3.

Table 3: Different morphometric parameters

Parameters	Methods	References/components	Units
Surface (A)	Direct measurement	catchment area for precipitation that flows into a river	km²
Perimeter (P)	Direct measurement	Perimeter of the basin [5-12]	km
Axial length (L)	$L = \frac{P + \sqrt{P^2 - 16A}}{4}$	The longest length of the stream from catchment outlet to remotest point on the basin boundary [5-12]	km
Mean width (W)	$W=A/L$	-	km
Compactness factor (K_c)	$K_C=0,28PA^{-1/2}$	[13]	
Circularity ratio I	$C = (4\pi A)/P^2$	[5]	
Elongation ratio I	$E = \sqrt{1.27A}/L$	[5]	
Form factor (F_f)	$F_f=W/L$	[5-14]	
Stream order (S_μ)	Direct measurement	[5]	
Bifurcation ratio (R_b)	$R_b=N_\mu/N_{\mu+1}$	N_μ=No. of stream segments of a given order and $N_{\mu+1}$=No. of stream segments of next higher order [5]	
Stream length (L_μ)	Direct measurement	Length of the stream [5]	m
Drainage density (D_d)	$Dd=L_t/A$	L_t is total stream-segment lengths cumulated for all orders [5]	Km/km²
Stream frequency (F)	$F=N_o/A$	N_o is the total number of stream segments of all orders [5]	km^{-2}

Spatial and temporal variability of the average annual rainfall is very important [16]. The average volume of water that falls on a basin is equal to the quotient of the rainfall (m³) and the surface area in m² [16]. If P is the precipitation height required on the total basin of area A, P_1 on the polygon of area A_1, P_2 on A_2 and P_n on A_n, we obtain:

$$P = \frac{A_1}{A}P_1 + \frac{A_2}{A}P_2 + \ldots + \frac{A_n}{A}P_n \quad (1)$$

Data collected from the Geographical Institute of Burundi (IGEBU) show that there are five stations involved in the calculation of rainfall in the Mpanda catchment area, three of which are located in the foothills and two in the plain. Fig 3 shows the spatial distribution of the hydroclimatological stations and the Thiessen polygons calculated by a GIS software. In this figure, it can be seen that most of the rainfall in the basin is recorded at the Musigati station in the foothills and the Imbo station in the plain. The Teza station records rainfall in the north-eastern part of the basin while the Bujumbura station records rainfall in the southern part of the basin. The Rwegura station located in the north is only involved in recording a very small part of the rainfall in the basin.

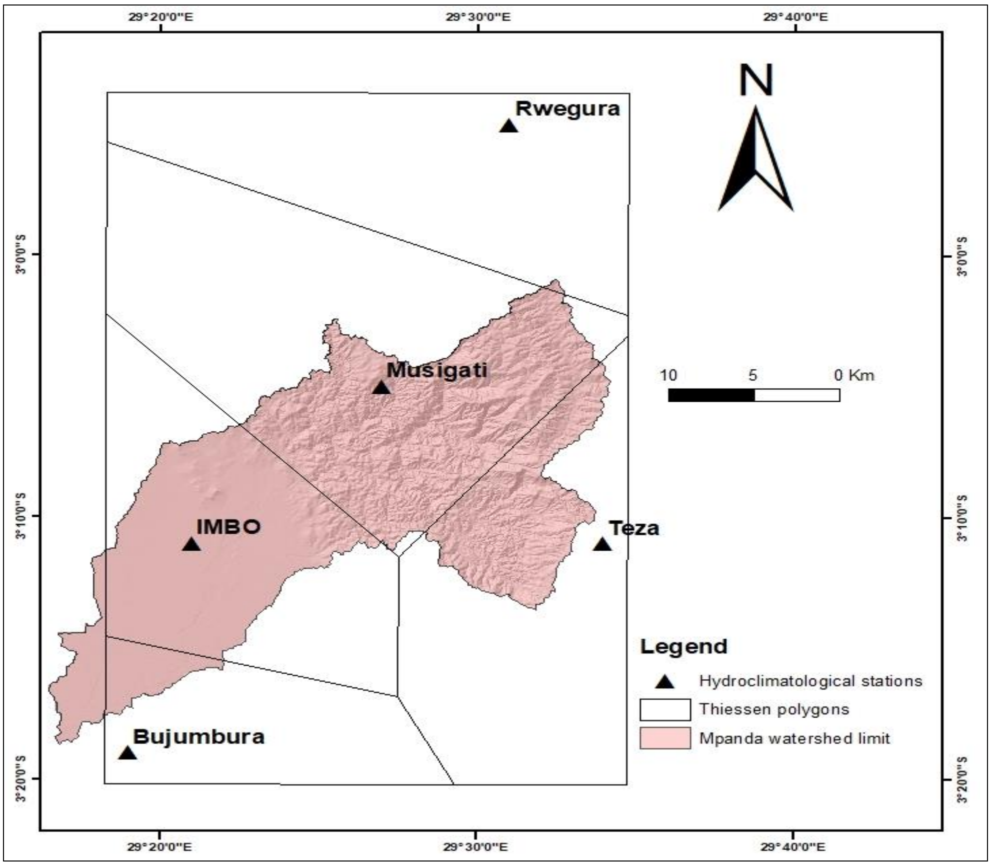

Fig 3: Spatial distribution of hydroclimatological stations and Thiessen polygons

Results and Discussion

Morphometric Parameters

The shape of the catchment area influences the characteristics of the runoff resulting from a given rainfall [17]. Area of a watershed (A) and perimeter (P) are the important parameters in quantitative geo-morphology [14]. Watershed area directly affects the size of the storm hydrograph, the magnitudes of peak and mean runoff [18]. The maximum flow discharge per unit area is inversely related to size [18, 19]. K_c is defined as the ratio of the perimeter of the basin to that of a circle of the same area [20]. It is approximately equal to 1 for an almost circular catchment and greater than 1 when the catchment is elongated [20]. L and W of the basin influence the floods, they are reduced if L is greater than W. F_f represents the number of times that W is contained in L and is a measure of its elongation [2]. The total catchment area of the Mpanda River estimated from the DEM is 451.59 km² of which the upper catchment area is 240.65 km² (53 %) and the alluvial plain catchment area is 210.84 km² (47 %). The results on the geometry and shape parameters of the Mpanda watershed are shown in Table 4.

Table 4: Geometry and watershed shape parameters

Watershed	A (km²)	P (km)	L (km)	W (km)	K_c	C	E	F_f
Mpanda (whole basin)	451.59	145.7	66	6.8	1.9	0.26	0.36	0.10
Upper watershed	240.65	96.43	42.56	5.69	1.72	0.32	0.41	0.13
Alluvial plain watershed	210.84	90.94	40.24	5.23	1.75	0.31	0.40	0.13

The Mpada river watershed has an elongated shape with a NE-SW direction. The upper basin has an E-W direction while the alluvial plain basin has a NE-SW direction. Both sub-basins are elongated (K_c values in Table 4). C indicates that Mpanda watershed and its sub-basins are elongated to very elongated (C<0.6). F_f indicates that watersheds analysed are elongated to very elongate. The mean value of F_f is 0.12, with maximum and minimum values of 0.13 and 0.10, far from the reference value of 0.78 for the circle [2]. E confirms also that the Mpanda watershed is very elongated (E<0.8). Whether it is for the whole Mpanda catchment area, or at the sub-watershed scale, L is largely greater than W (Table 4), this situation indicates an elongated watershed. The results of all the shape and geometry parameters analysed above confirm that the study area is an elongated watershed. This situation is favourable to low peak flood flows for the same rainfall, due to the longer time it takes for the water to reach the outlet.

Like the watershed delineation, the drainage network was also automatically hierarchized from the local DEM using GIS software. This classification takes into consideration the Strahler method which adopts the hydrographic unit as the section [21]. The proposed method assigns a value of '1' to all headwater reaches in the basin; the meeting of two '1' reaches produces a '2' reach after their confluence; the meeting of two '2' reaches produces a '3' reach, and so on (Fig 4). In the case of the Mpanda catchment, the highest value is 5 which refers to its main river bed (Fig 4). When extracting the drainage network in the Mpanda watershed, the minimum length of 500 meters for a segment was considered.

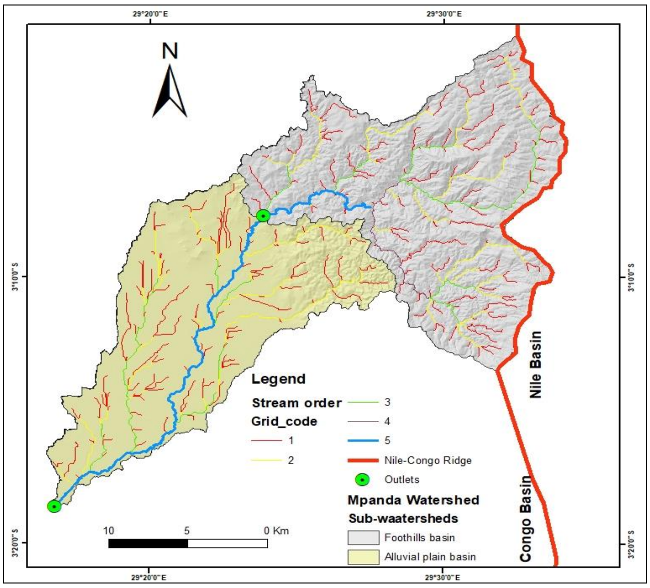

Fig 4: Drainage network and stream order in the Mpanda river basin

In this part of the study, the drainage analysis was carried out about parameters as stream order, stream length, bifurcation ratio, drainage density and stream frequency using mathematical formulae as given in Table 3 and the results are summarized in Tables 5, 6.

Table 5: Drainage network parameters of the Mpanda watershed

(S_μ)	(N_μ)	(L_μ): km	(R_b)
1st	247	256.490	2.09
2nd	118	127..279	1.4
3rd	84	71.363	7.6
4th	11	16.642	0.33
5th	33	43.921	

Table 6: Drainage density and Stream frequency of Mpanda basin and sub-basins

Watershed	(D_d): km/km²	(F): km^{-2}
Mpanda	1.23	1.09
Upper watershed	1.04	0.99
Alluvial plain watershed	1.23	1.21

The primary step in drainage basin analysis is to designate stream orders [18-22]. As per the [22] ordering scheme, the study area is a 5th order drainage watershed as shown in Fig 4 and Table 5. The Mpanda watershed has a high number of first-order channels, with a number of 247 in a total of 493 which represents 50.1 % of the whole drainage network. Higher S_μ is associated with greater discharge [18]. In the study area it can be seen that most of the drainage network is largely concentrated in the upper basin compared to the alluvial plain basin.

N_μ is an amount of stream channels in a given order. In the study area, results show that the Mpanda stream is represented by 493 streams linked with 5 orders of streams as shown in Fig 4 and Table 5 sprawling over an area of 451.59 km². N_μ is directly proportional to size of the contributing basin and to channel dimensions as show in Table 5. A higher N_μ indicates lesser permeability and infiltration (upper basin).

L_μ is indicative of chronological developments of the stream segments including interlude tectonic disturbances [17]. In the study area, the total length of the stream segments is 511.696 km. Results represented in Table 5 show that the total length of stream segments is high in case of first order streams and decreases with increase in the stream order except the 5th order stream whose length is higher than the total length of the 4th order stream segments as shown in Table 5 and Fig 4.

R_b is closely related to the branching pattern of a drainage network [18, 19]. The R_b shown in Table 5 vary between 0.33 and 7.6. This high variation of R_b is related to the heterogeneity in basin geometry and lithology. The highest R_b (7.6) is found between 3rd and 4th order that indicates corresponding highest overland flow and discharge attributable to highly less permeable rock formation associated with high slope configuration [18]. The high R_b indicates also early hydrograph peak with a potential for flash flooding during the storm events in the area in which these stream orders dominate [18-23]. At the scale of the catchment, this vulnerability linked to the peak between the 3rd and 4th order will be compensated by other streams and the development of floods at the entrance of the Mpanda in the plain is less developed and progressively decreases in the plain. The relatively lower value of R_b in the plain (5th order) suggests the geological heterogeneity, higher permeability and lesser structural control.

D_d determines the time travel by water [19]. A high D_d reflects a highly dissected drainage basin with a relatively rapid hydrological response to rainfall events, while a low D_d means a poorly drained basin with a slow hydrologic response [18]. The D_d of the Mpanda drainage watershed is moderate (1.23 km/km²) and indicates that the watershed has permeable subsurface material, good vegetation cover (upper watershed), causing more infiltration of water and recharging groundwater aquifers (alluvial plain watershed).

F of the whole basin is 1.09/km² as shown in Table 6. The upper basin has a low F (0.99/km²) while the alluvial plain watershed presents a relatively high F (1.23/km²). F mainly depends on the lithology of the basin and reflects the texture of the drainage network [18]. Those values of F reflect that the basin has good vegetation, high infiltration capacity and later peak discharges owing low runoff rate. F shows positive correlation with D_d, the runoff is slower and flooding is less likely in basins with a low to moderate D_d and F [24].

Spatial Rainfall Distribution

Five stations (Fig 3) share the role of recording rainfall over the entire Mpanda river catchment area. As these stations are unequally distributed over the entire catchment area, rainfall averages will be calculated according to the area covered by each measuring station (Fig 5). Two stations Musigati and Imbo cover the largest part of the basin, respectively 40 and 34 % of the total area (Fig 5 and Table 7).

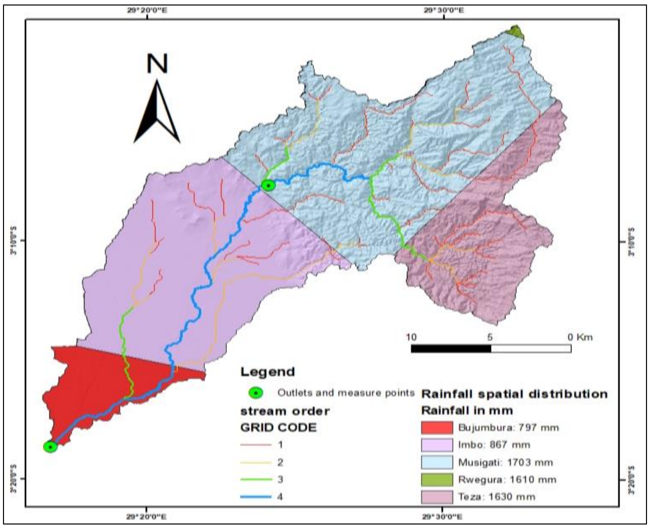

Fig 5: Spatial rainfall distribution over the entire Mpanda river watershed using the Thiessen method

The area of each polygon and the corresponding average rainfall calculated over a period of 20 years (1995-20015) are shown in Table 7.

Table 7: Thiessen polygon areas and Average rainfall calculated for each station

Station	Area (m²)	Average rainfall (mm)	Average rainfall (m)
Musigati	185527055	1703	1.703
Imbo	150696160	867	0.867
Teza	802133511	1630	1.630
Bujumbura	34454689	797	0.797
Rwegura	598439	1610	1.610

$$P = 1m \times (1.703\frac{185527055}{451590000} + 0.867\frac{150696160}{451590000} + 1.630\frac{80213511}{451590000} + 0.797\frac{34454689}{451590000} + 1.610\frac{598439}{451590000})$$

P=1.341 *m (1341 mm)*

The average rainfall calculated using Thiessen method for a period of 20 years over the entire Mpanda watershed is 1341 mm. The variation of rainfall is also a function of altitude and the study area is located in two geomorphologically different zones (Fig 1). In order to better quantify the precipitation that falls in each area, it is necessary to perform separate calculations between the alluvial plain, which receives less rainfall, and the foothills, which receive a lot of rainfall. Fig 6 and 7 show the spatial distributions of precipitation and the stations involved in their calculation for the upper basin and the alluvial plain basin respectively.

For the upper basin, four stations Musigati, Teza, Rwegura and Imbo are involved in the rainfall recording (Fig 6). The Musigati station is recording more than 66 % of the rainfall in the upper Mpanda basin while the Imbo station is involved in less than 1 %.

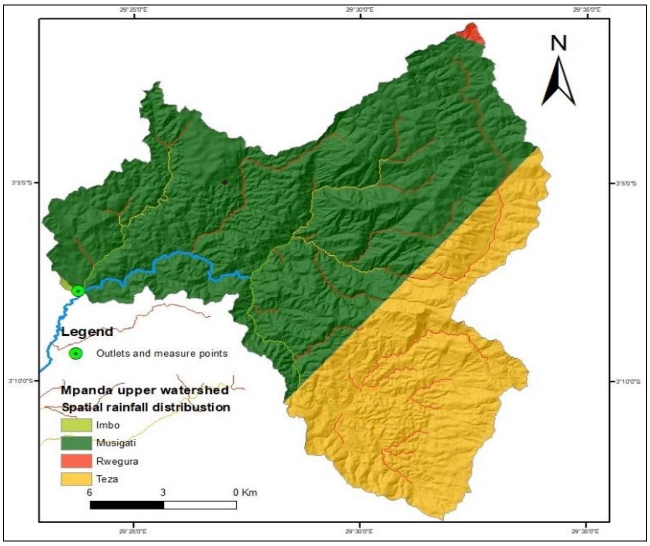

Fig 6: Spatial rainfall distribution in Mpanda upper watershed using Thiessen method

Table 8 shows the areas of the Thiessen polygons for each station (upper watershed) and the corresponding average rainfall.

Table 8: Thiessen polygon areas and average rainfall calculated for each station (Mpanda Upper watershed)

Station	Area (m²)	Average rainfall (mm)	Average rainfall (m)
Musigati	160068350	1703	1.703
Teza	79803174	1630	1.630
Rwegura	598439	1610	1.610
Imbo	176940	867	0.867

Knowing the area of the upper basin, which is 240646903 m², and using the Thiessen method, we have:

$$P = 1m \times (1.703 \times \frac{160068350}{240646903} + 1.630 \times \frac{79803174}{240646903} + 1.610 \times \frac{598439}{240646903} + 0.867 \times \frac{176940}{240646903})$$

$P_{upper\ basin}$*=1.696 m (1696 mm)*

For the alluvial plain basin, three stations (Bujumbura, Imbo and Musigati) are involved in rainfall recording (Fig 7). The

Imbo station records more than 71 % of the rainfall in the sub-basin.

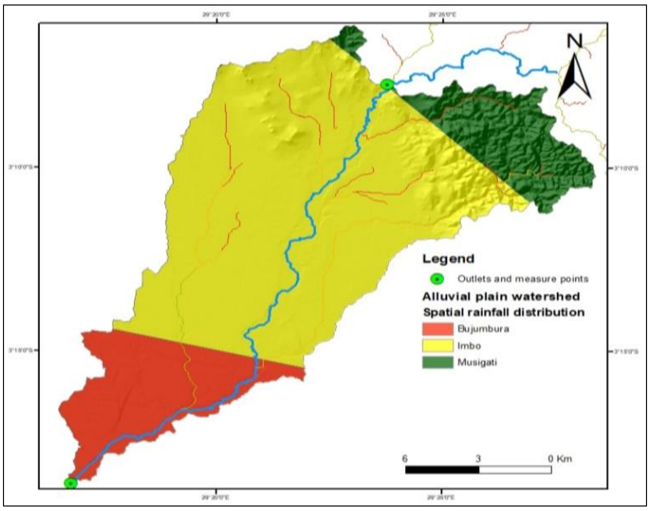

Fig 7: Spatial rainfall distribution in Mpanda alluvial plain watershed using Thiessen method

Table 9 shows the areas of the Thiessen polygons for each station (alluvial plain watershed) and the corresponding average rainfall.

Table 9: Thiessen polygon areas and Average rainfall calculated for each station (Mpanda alluvial plain watershed)

Station	Area (m^2)	Average rainfall (mm)	Average rainfall (m)
Imbo	150399029	867	0.867
Bujumbura	34582301	797	0.797
Musigati	25861621	1703	1.703

Knowing the area of the alluvial plain basin, which is 210842951 m², and using the Thiessen method, we have:

$$P = 1m \times (0.867 \frac{150399029}{210842951} + 0.797 \frac{34582301}{210842951} + 1.703 \frac{25861621}{210842951})$$

$P_{alluvial\ plain\ basin}$=0.958 m (958mm)

Regarding the rainfall distribution, it is clear that the Mpanda watershed is located in two climatologically different zones where the upper sub-basin receives almost twice the rainfall recorded in the alluvial plain basin. It is this rainfall in the foothills (upper basin) that feeds the river flows upstream of the Mpanda's outlet into the plain and is also responsible for the infiltrations that recharge the water table, which in turn feeds the base flows during dry periods.

Conclusions

This study has shown that GIS software is very useful for the analysis of geo-morphometric aspects of drainage watersheds and spatial rainfall distribution. GIS based approach facilitates analysis of different morphometric parameters like watershed shape and geometry, drainage network parameters to establish relationships among the drainage watershed morphometry and topographical, geological, structural and hydrological aspects. The shape and geometry characteristics analysed show that the Mpanda watershed and its sub-watersheds have elongated shapes (K_c>>1, L >> W, C << 0.6 and F_f << 0.78) which indicates longer concentration time during a rainfall and cannot develop peak floods at the watershed outlet. The Mpanda watershed is a 5th order basin. The 1st order streams dominate the basin (±50 %). The development of stream segments in the study area is affected by rainfall and groundwater discharge. The mean R_b indicates geological heterogeneity, higher permeability and lesser structural control. The D_d and F are the most useful criterion for good morphometric classification of a drainage watersheds that control the runoff pattern and other hydrological parameters of a drainage watershed. The D_d of the Mpanda drainage basin is moderate (1.23 km/km²) and indicates that the watershed has permeable subsurface material, good vegetation cover (upper basin), causing more infiltration of water and recharging groundwater aquifers (alluvial plain watershed). Values of F reflect that the Mpanda watershed has good vegetation, high infiltration capacity and later peak discharges owing low runoff rate. The F shows positive correlation with D_d, the runoff is slower and flooding is less likely in basins with a low to moderate D_d and L_μ.

The average rainfall calculated using Thiessen method for a period of 20 years over the entire Mpanda river watershed is 1341 mm. This average precipitation over the twenty years concerned appears to be low if we consider the precipitation recorded by the stations in the foothills. This is why we have subdivided the Mpanda basin into two sub-basins and we conclude that the upper basin receives almost twice the rainfall recorded in the alluvial plain basin. This rainfall in the foothills is the source of the drainage system and the infiltration that recharges the water table and supplies the base discharges during the dry season. Thiessen method has allowed a spatial distribution of rainfall over the entire Mpanda catchment area.

The results of this study can serve as a baseline for water resource managers and agricultural managers, especially in the plain, for water management of the Mpanda River in order to plan the irrigation of rice and food crops during the dry season. The upper basin should be managed to reduce runoff and promote infiltration that recharges the aquifer feeding the base flow of the main river especially during the dry season.

Acknowledgments

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