Morphometric parameters of Vranso watershed (Burkina Faso, West Africa) and their influence on the site's potential recharge

Lassany SORE [1], Youssouf KOUSSOUBE [1], Maxime WUBDA [1*], Issan KI [1], Drissa IDO [1]

Abstract

The response of a hydro-system to rainfall, is influenced numerous parameters, including morphometric features. Thus, knowing the characteristics of a watershed enables better management of risks and water resources. However, studies of West African drainage systems, particularly in Burkina Faso, rarely use morphometric parameters. In this context, the study of Vranso watershed contributes to better understanding of the functioning of the country's watersheds. To reach this objective, various morphometric indexes, including linear, shape, and relief parameters, were quantified using data from the Digital Elevation Model of Alaska Satellite Facility. Parameters extraction, measurements, and displays were performed using a Geographic Information System software, and calculations were performed using a spreadsheet program. Based on the obtained results, Vranso watershed is classified as seventh order. Its circularity index (0.13), elongation index (0.51), shape factor (0.42), and Gravelius coefficient (2.73) indicate that it is elongated. The calculated texture ratio (1.3), bifurcation index (3.5), flow frequency (0.24), infiltration factor (0.2), drainage density (0.84), and integral hypsometric relief index (0.2) suggest that the basin offers a significant capacity for the infiltration and recharge of its aquifers, a process that is facilitated by the connection between streams and tectonic structures.

Key words: Burkina Faso, DEM, Morphometric parameters, Recharge, Vranso, Watershed

Paramètres morphométriques du bassin versant du Vranso (Burkina Faso, Afrique de l'Ouest) et influence sur la recharge potentielle du site.

Résumé

La réponse d'un hydro-système aux précipitations, est influencée par plusieurs paramètres parmi lesquels, ceux morphométriques. Aussi, la connaissance des caractéristiques d'un bassin versant permet une meilleure gestion des risques et des ressources en eau dans cet espace. Cependant, les études de systèmes de drainage en Afrique de l'Ouest, en particulier au Burkina Faso, s'appuient rarement les paramètres

[1] Laboratoire Géosciences et Environnement (LaGE), Université Joseph KI-ZERBO, 01 BP 7021, Ouagadougou 01, Burkina Faso

***Corresponding author**: Maxime WUBDA, email : mwubda@gmail.com, ORCID : 0009-0007-0591-7423

DOI : https://doi.org/10.64707/revstsna.v45i01.1897

morphométriques. Dans ce contexte, l'étude du bassin versant du Vranso contribue à une meilleure compréhension du fonctionnement des bassins versants du pays. Pour atteindre cet objectif, divers indices morphométriques, notamment des paramètres linéaires, de forme et de relief, ont été quantifiés à partir des données du Modèle Numérique de Terrain de l'Alaska Satellite Facility. L'extraction, les mesures ainsi que l'affichage des paramètres, ont été effectués à l'aide d'un logiciel de Système d'Information Géographique et les calculs réalisés à l'aide d'un tableur. Sur la base des résultats obtenus, le bassin versant de Vranso est classé comme étant d'ordre 7. Son indice de circularité (0,13), son indice d'allongement (0,51), son facteur de forme (0,42) et son coefficient de Gravelius (2,73), indiquent qu'il est allongé. Le ratio de texture (1,3), l'indice de bifurcation (3,5), la fréquence d'écoulement (0,24), le facteur d'infiltration (0,2), la densité de drainage (0,84) et l'indice intégral de relief hypsométrique (0,2) calculés, suggèrent que le bassin offre une capacité importante d'infiltration et de recharge de ses aquifères, un processus facilité par la connexion entre les cours d'eau et les structures tectoniques.

Mots clés : Burkina Faso, MNT, Paramètres morphométriques, Recharge, Vranso, Bassin versant

Introduction

The knowledge of the water potential of a living environment is essential for the development of a sound policy for the sustainable and equitable management of this resource (Dofliger and Perrin, 2021; Geenway, 2021). Understanding water potential requires estimating the components of the water balance, namely precipitation, runoff, infiltration, and evapotranspiration, which are studied based on a morphological reference unit, which is the watershed (Galle *et al*, 2005; Sitondji *et al*, 2008). Watershed is commonly used for the study of hydrological balance because, theoretically, it is considered as a closed system in which runoff from precipitation is drained to a single outlet (Roche, 1963).

Resulting from tectonic movements (Castelford *et al*, 2012; Burbank and Anderson, 2013; Decaillau *et al*, 2023) and supergene weathering (Derbyshire, 1973), the morphological evolution of a watershed is determined by the action of environmental factors which, combined with geological ones, shape the various features of the basin, in depth (types of soil profile) and on the surface (surface conditions, topography) (Castelford *et al*, 2012; Grimaud *et al*, 2014; Chardon *et al*, 2016). The resulting physical characteristics of the basin, will in turn, control the water drainage pattern, that can be observed at a given time in the basin (Thomas *et al*, 2010; Mashauri *et al*, 2023).

Therefore, analyzing the morphometric parameters of a watershed is considered as an essential method for determining the influence of geomorphology on runoff, recharge, and hydrogeological potential of the subsoil (Kumar *et al*, 2020; Jothimani *et al*, 2022). In general, the morphometric approach applied to the study of a watershed, allows for a quantitative description of its geometry and is also useful for characterizing its drainage network, understanding its functioning (Faye, 2014; Mashauri *et al*, 2023), and ranking watersheds according to their hydrological behavior (Idrissi *et al*, 2022).

In Burkina Faso, although some research has been conducted on relatively small basins (Sanou, 1993; Palé *et al*, 2020), the use of morphometric parameters in the study of hydrological systems in the country remains very limited. Nowadays, however, it is possible to access watershed parameters without the long and often costly process of direct observations and measurements in the field. Indeed, the use of Geographic Information System (GIS) tools currently offers a good alternative for studying the morphometric characteristics of basins (Mahala *et al*, 2020, Idrissi *et al*, 2022; Benzougagh *et al*, 2016), due to the availability of satellite images (which are sometimes free) and the ease of processing, made possible by today's high-performance software.

Vranso watershed, which is presented in this article, is part of the larger Mouhoun watershed located in the west of the country. It has never been the subject of morphometric research. This study therefore, aims to contribute to a better knowledge of Vranso watershed in particular and Mouhoun watershed in general. It is a preliminary study focused on ascertaining the basic characteristics of the basin, which understanding is fundamental for a future instrumentation of the site for in situ hydrological or hydrogeological studies, or for modeling. It consists of a morphometric analysis, conducted using GIS tools, with the objective of assessing the hydrogeological potential of the watershed. It specifically includes: determining the morphometric parameters of the basin, showing the influence of the fracture network on the drainage one, and finally, assessing the impact of all these parameters on infiltration and potential recharge. This analytical approach applied to Vranso watershed should then, lay the foundations for a rapid, effective, and low-cost diagnosis of its water potential. This study is relevant in the context of the need to manage water resources in the country's large basins, both for domestic, agro-pastoral, and industrial needs, and for protection against natural disasters such as floods and droughts.

1. Study site

1.1. Location

Vranso watershed is located in west-central part of Burkina Faso (West Africa) (Cf; figure 1A). It is one of the sub-basins of the larger Mouhoun basin. It covers an area of approximately 5,686.10 km² and is located between coordinates (WGS 84 - UTM 30 P – m) 517202 and 620025 west longitude and 1341420 and 1448147 north latitude. Its outlet, which is not far from the bridge over the Mouhoun river on National Road 14 (RN14), near the village of Tiogo, is located at coordinates 518955 west longitude and 1349633 north latitude. The basin includes the localities of Réo, and Ténado in his south part, and Latodin, Lagaré, and Godyr in the north (Cf, figure 1B).

1.2. Climate, soil and vegetation

The climate of Vranso watershed is classified as north sudanian type. The average rainfall over the last thirty years (1991–2020) in Réo (Saria synoptic station), is 860.50 mm, with an average annual temperature of 28.39°C (Bassolé *et al*, 2023). This climate zone is characterized by savanna with trees, shrubs and fairly dense grass cover during the rainy season. Along the rivers, gallery forests are sometimes found. Near villages or major towns, farming practices have degraded or reshaped the vegetation, which alternates between very short shrub layers dotted with large trees in fallow fields and shea tree parks in the fields currently in use. In its southwestern part, the basin includes the Tiogo classified forest, which is a fairly well-preserved area of vegetation. The vegetation in the basin grows on two predominant soil types (BUNASOLS, 2002). These are sesquioxyde soils or tropical ferruginous soils found in the western part of the basin, and poorly developed soils on crusts or clayey materials occupying the eastern part. Less common, hydromorphic soils are located in the lowlands that line the watercourses (Cf; figure 1C).

1.3. Geology and geomorphology

Vranso watershed lays on a Paleo-Proterozoic geological substratum (Castaing *et al*, 2003; Lompo, 2010), consisting mainly of plutonic rocks (primarily granitoids) and volcano-sedimentary formations (Cf; figure 1D). The volcano-sedimentary formations are mainly present in the central part of the basin in an area oriented northeast-southwest. They are constituted of sedimentary and tuffaceous schists, amphibolized basalts, and andesits, which were metamorphosed and deformed during the Eburnean orogeny (Castaing *et al*, 2003; Lompo, 2010). Elsewhere and throughout the basin, intrusive plutonic formations are found, represented by biotite granites, diorites, granodiorites, and tonalites (Castaing *et al*, 2003). In addition to these major formations, there are numerous quartz or dolerite veins that cut across the host rocks, following variable orientations (N45° to N60°).

The morphology of Vranso basin is typical of regions characterized by a predominantly granite substrate. The landscape consists of vast plains with very gentle slopes, from which a few minor elevations emerge. These elevations consist of armored mounds up to 60 m high (in the south of Pella village) and hills formed from the weathered remains of volcanic sedimentary rocks in the center (Kordié area) and north of the basin (Latodin area). Overall, altitudes vary between 249 m at the basin outlet and 543 m on the hills in its center.

1.4. Hydrography

The basin area is drained by a network of watercourses consisting of small gullies formed by regressive erosion, which collect water towards a main watercourse, named Vranso (Cf; Figure 1B). Approximately 100 km long, the axis of this watercourse overlaps with that of a major fault, visible on the geological map of the site (Cf; Figure 1D). Vranso river therefore appears to be a legacy of the site's tectonics. Although quite wide (20 to 30 m) in the area near the outlet, Vranso remains a temporary river, which dries up fairly quickly at the end of the rainy season. It flows into the Mouhoun river at the village of Tiogo. In its upper reaches, near Soum village (south of Nanoro), its course is obstructed by a small dam, whose water level during the rainy season affects the surrounding villages of Bokin and Simidin.

2. Data and methods

2.1. Data used

The present study is primarily based on the processing of data from the Digital Elevation Model (DEM) of our study site. These data were obtained from the ALOS satellite of the ALASKA Satellite Facility (ASF) Project and are available free of charge at: https://vertex.daac.asf.alaska.edu/. The spatial resolution of these data is estimated to be 12.5 m. Coverage of the site required the download of four scenes.

In addition to the DEM data, two physical and digital maps were used for geological and soil information purposes. These are the 1:200 000 soil map of Koudougou, 2002 edition, produced by BUNASOLS (BUNASOLS, 2002) and the geological map at the same scale for this region, edited by BUMIGEG, accompanied by its explanatory notes (Castaing *et al*, 2003).

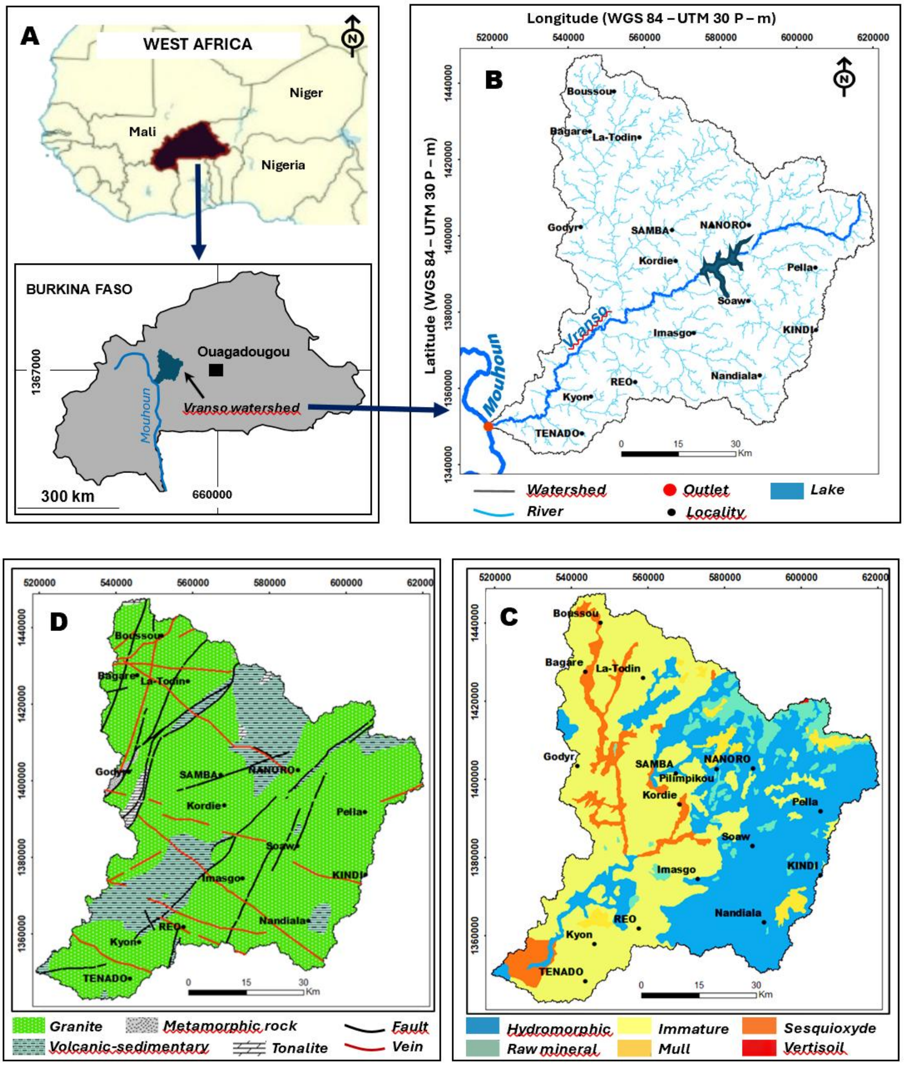

Figure 1: Overview of the study site. A) Location; B) Hydrography (extracted from DEM); C) soil map (extracted from soil map, Koudougou sheet, BUNASOLS, 2002); D) Lithology (extracted from geological map, Koudougou zone, Castaing et al, 2003).

All these data are processed using two tools:

- ArcGIS 10.0, which is Geographic Information System (GIS) software, used to process downloaded digital data and produce maps;
- Excel, which is a spreadsheet program in the Microsoft Office suite, used to perform simple calculations and create graphs.

2.2. Processing methods

The data processing protocol consists of three major operations: firstly, the extraction of morphometric and hydrometric parameters; secondly, the measurement of morphometric indices; and thirdly, the testing of the alignment of the hydrographic network.

2.2.1. Extraction of basin parameters

The morphological and hydrographic parameters of Vranso basin were extracted using the ArcToolbox spatial analysis module, following a series of standard techniques (Rai *et al*, 2017), namely:

- The orrection of input DEM by filling discontinuities (*Fill Sinks (FS)*);
- The calculation of water flow direction based on the altitudes of neighboring cells (*Flow Direction (FD)*);
  - The calculation of the cumulative water flow in a cell from all potential upstream drainage paths (*Flow Accumulation (FC)*), with a fixed threshold of 1000 pixels;
- The division of the hydrographic network into segments. The pixels traversed by the same segment bearing the same value (*Stream Segmentation (SS)*);
- The identification and prioritization of the hydrographic network (*Stream Definition (SD)*). The drainage network of the Vranso basin was determined using Horton scheme (Horton, 1945) and classified according to Strahler method (Strahler, 1964);
- The extraction of the main watercourse draining the basin (*Longest Flow Path (LFP)*);
- The determination of sub-basins in the area of interest, based on segments of the hydrographic network (*Catchment Grid Delineation (CGD)*);

- The Conversion of defined sub-basins into vector format (*Catchment Polygon Processing (CPP)*);
- The Conversion of segmented hydrographic network into vector format (*Drainage line Processing (DLP)*).

2.2.2. Morphometric indexes calculations

Morphometric indexes were determined using mathematical formulas developed by several authors. In total, there are around fifteen parameters, which are grouped into three categories of indexes and presented in the table 1.

- *Shape indexes.* They refer to the geometric characteristics of the watershed and provide information on its hydrological behavior in response to rainfall events. Indices such as the elongation ratio (Schumm *et al*, 1956), the form factor, and the Gravelius coefficient, determine the velocity, type of flow, and concentration time in a basin (Gravelius, 1914; Horton, 1932; Miller, 1953);
- *Linear indexes*. They are determined based on the geometric parameters of the basin, but also on specific features of the hydrographic network, namely the order, the average length, the total length, and the streams number (Horton, 1945). These linear indexes (the bifurcation ratio, length ratio, drainage density, etc.) play an essential role in understanding the functioning of the drainage system, the infiltration capacity, and the potential recharge of a basin (Sukristivanti *et al*, 2018; Lawmchullova *et al*, 2024);
- *Relief index*. It refers specifically to the integral hypsometric index (HI). It is a morphometric parameter that determines the stage of evolution of a watershed. It can also reflect groundwater infiltration conditions through the structure of the relief. It is calculated using Strahler's equation (Strahler, 1952), whose parameters are taken from a hypsometric curve obtained by dividing the Digital Elevation Model (DEM) into classes of equal altitude and calculating the area of each class.

2.2.3. Hydrographic network alignment test

The analysis of influence of structural features on the drainage network, is based on a comparison alignment test between the directions of drainage sections and the orientations of tectonic structures. In the event of watercourses being subject to structural control, it is to be expected that, they will be align with the known tectonic structures directions. When the influence of tectonics is evident on the drainage system, this implies that faults and fractures act as preferential drains for infiltration and underground flow (Macka, 2003). The reference for this analysis is the basin fracture map. The production of this map, was facilitated by the ArcGIS software, which involved the manual extraction of lineaments, following the application of directional filters. The validation process entailed a comparison with the Koudougou geological map (Castaing *et al*, 2003) for large structures and field verification for small lineaments.

2.3. Field observations

Following the data processing phase, field missions were conducted to check and validate some of the results obtained. Field observations consisted of random checks focused in particular on lithology and structure features, but also on landscape reconnaissance (soil, vegetation, land use) and major structures such as, armored mounds, granite or green rock outcrops, fractures and shear zones, watershed outlets, etc.

2.4. Presentation of results

Depending on the type of result, it will be presented in one of the following ways:

- Graphical form with curves showing variations or trends;
- Table form for numerical values that can be categorized;
- Maps (using Mercator projection: WGS 84 – UTM 31 P – m) for spatialized values.;
- Single numerical values for isolated indicators, followed by comments in the text.

3. Results and discussions

3.1. Shape parameters and implications

The calculated shape parameters are presented in table 2. The determination of these values was primarily based on the surface area, perimeter, and length of the basin, with the corresponding values displayed at the top of the table.

Table I: References of morphometric parameters calculation methods

	Parameter / Index	Calculation method	References
Shape indexes	Gravelius compactness ratio (K_G)	$K_G = P/2\sqrt{\pi * A}$ where A= Basin area (km^2), P = Basin perimeter (km)	***(Gravilus, 1914)***
	Form factor (Ff)	Rf = A/ (Lb)^2 where A= Basin area (km$^{2)}$, Lb = Basin length (km)	***(Horton, 1932)***
	Circulatory ratio (Rc)	Rc=4 π A/P^2 with A= Basin area (km^2), π = 3.14, P = Basin perimeter (km)	***(Miller, 1953)***
	Elongation ratio (Re)	[(4×Ap)/Lb)]1/2where A= Basin area (km^2) Lb = Basin length (km)	***(Schumm, 1956)***
Linear indexes	Stream order (U)	Prioritizing of streams	***(Strahler, 1964)***
	Stream number (Nu)	Nu = N1+N2+…Nn	***(Horton, 1945)***
	Stream Length (Lu)	Lu= L1 +L2 …… Ln	***(Horton, 1945)***
	Mean stream length (Lsm)	Lu/Nu, where Lu = Total length of streams of a given order 'U', Nu = Total number of stream segments of a given order 'U'	***(Strahler, 1964)***
	Bifurcation ratio (Rb)	Rb = Nu/Nu +1, where Nu = Total number of stream segments of a given order 'U'; Nu+1 = Number of segments of the next higher order	***(Schumm, 1956)***
	Drainage density (Dd)	Dd = L/A where L= Total length of streams (km); A= Basin area (km^2)	***(Horton, 1945)***
	Drainage texture (T)	T = N1/P, where N1= Total number of order 1 streams; P = Basin perimeter (km)	***(Horton, 1945)***
	Infiltration number (If)	If = Fs * Dd; where Fs = Frequency of streams; Dd = Drainage density	***(Zăvoianu, 1985)***
	Torrentiality ratio (Ct)	Ct = (Hmax - Hmin) /A1/2 where Hmin & Hmax = minimum and maximum elevation (m), A = Basin area (km^2)	***(Gravilus, 1914)***
	Stream frequency (FS)	FS = N/A where N = number of streams; A = basin area (km^2)	***(Horton, 1945)***
Relief index	Integral hypsometry (HI)	HI = (H – Hmin)(Hmax – Hmin) where H= average elevation (m); Hmin & Hmax = minimum and maximum elevation (m)	***(Strahler, 1952)***

Based on these results, the following observations can be made:

- *Gravelius coefficient*. This expresses the degree of compactness of the basin and reflects the speed at which runoff water concentrates at the outlet (Gravelius, 1914). When this coefficient approaches or equals 1, the basin assumes a perfect circular form and is considerate highly compact. As the watershed becomes more elongated, this value is predicted to exceed 1. The value of 2.73 measured for the Vranso basin, thus indicates that it is elongated;

Table II: Watershed features and shape indexes.

Parameters		Units	Values
Basin surface erea (sq.km)		km^2	5686.10
Basin perimeter (P)		km	730.41
Equivalent length (Lb)		km	116.17
Gravelius coefficient (kg)		-	2.73
Form factor (Ff)		-	0.42
Elongation ratio (Re)		-	0.51
Circulatory ratio (Rc)		-	0.13

- *Form factor*. This index is employed to evaluate the geometry of the basin and its effect on runoff. The calculated value this ratio is 0.42. This value, which is less than 0.5 (the value above which a basin is considered circular), also suggests that the basin is elongated, despite its visual appearance, which appears to indicate the opposite;

- *Elongation ratio*. It allows precise characterization of the basin morphology. The values of the elongation ratio are known to vary between 0.6 and 1.0, and can be grouped into four categories: circular (> 0.9), oval (0.9 - 0.8), less elongated (0.70 - 0.8), and elongated (< 0.7) (Sukristivanti *et al*, 2018). For Vranso watershed, the calculated value of 0.51 thus indicates an elongation of the watershed. This elongation ratio is consistent with the form factor and the compactness ratio;

- *The circulatory ratio*. This index value varies between 0 (elongated basin) and 1 (circular basin). With a value of 0.13, the determined circulatory ratio indicates a certain elongation of the basin, thus confirming the results of the previous indexes.

All of the shape index values determined, indicate an elongation of Vranso watershed. This elongation is in a northeast-southwest direction, following the axis of the main watercourse. Hydrologically, this morphology is known to promote rapid runoff with flood concentrations at the outlet (Gravelius, 1914).

However, by analyzing in detail the morphology of the basin, it appears that the orientation of its axis is primarily determined by its southern part, despite this area representing only five percent of the basin's total surface area. As shown in Figure 2, isolating this southern part of the basin (sub-basin 1), allows to observe that, the northern part (sub-basin 2) is elongated following a northwest-southeast axis (N155). This orientation is perpendicular to that of the main river flow, and is indicative of the sub-basin's complex functioning. Furthermore, Sub-basin 1 shows a different axis of elongation (N5°) compared to the entire basin.

Based on these initial analyses, we recommend prioritizing the characterization of flows at the outlets of sub-basins 1 and 2, in any future study of the basin's hydrological behavior.

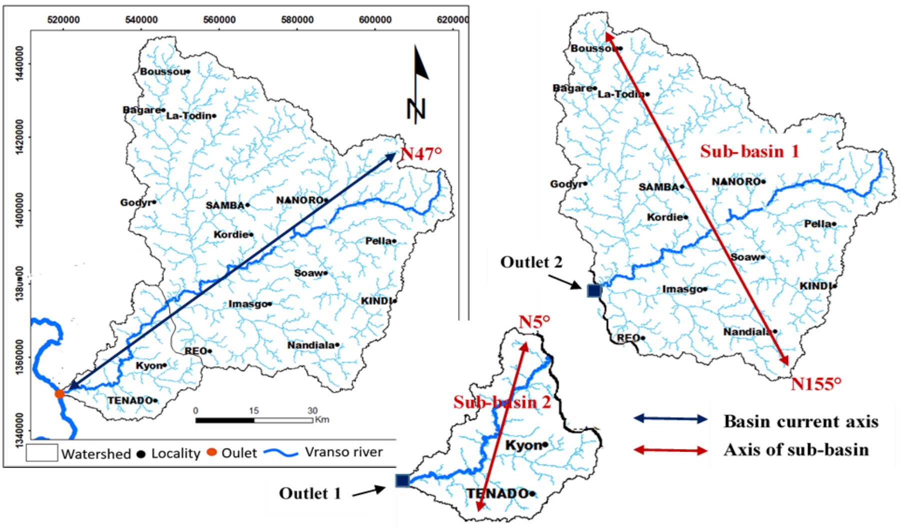

Figure 2: Watershed elongation directions.

3.2. Analysis of linear indexes

In this section, we analyze the watershed's hydrographic network characteristics through a dozen parameters presented in Tables III and IV.

Table III: Hydrographic linear indexes.

U	**Nu**	**Lu** (km)	**Lsm** (km)	**RL**	**Rb**
1	944	2448.54	2.59	-	2.98
2	317	1202.84	3.79	0.49	4.88
3	65	549.21	8.45	0.46	3.61
4	18	283.23	15.74	0.52	6
5	3	127.71	42.57	0.45	1.5
6	2	81.41	40.71	0.64	2
7	1	61.31	61.31	0.75	-

Table IV: Hydrographic spatial indexes

Parameter	**Unit**	**Value**
Drainage density (Dd)	Km/km²	0.84
Hydrographic density (F)	Km^{-2}	0.24
Torrentiality coefficient (Ct)	-	0.14
Infiltration Number (If)	-	0.2
Drainage texture (T)	-	1.3
Stream frequency (Fs)		0.24

- *Stream order (U)*. According to Strahler prioritization method (Strahler, 1964), the Vranso is a seven-order basin, with the southwest part of the river Vranso, corresponding to a seven-order stream. The total number of streams in this basin, is 1,568. 944 of these are of order 1 (Cf; Table III), representing nearly 70% of the hydrographic network. These characteristics of the Vranso drainage network suggest that the basin is mature and geologically permeable;
- *Stream length (Lu)*. It's an indicator of the contributing area to the basin for a given order (Horton, 1945). In the basin, the total length of watercourses is 4,754.25 km, with 2,448.54 km for order 1 streams and 1,202.84 km for the order 2. The Vranso, which is order 7, measures only 61.3 km (Cf; Table III). The significant

irregularity in length between the different orders of streams would indicate geological and morphological control in the basin. Order 1 and 2 streams, most often located upstream of steep slopes, are subject to morphological control, unlike order 3 streams, which are more controlled by structural. The layout and length of these streams, thus suggest a structural connection that promotes groundwater recharge through the fractures they overlap;

- *Stream length average (Lsm)*. The length average calculated for the different orders of the basin are shown in Table III. These values can globally be considered high and are characteristic of plains or plateaus (Strahler, 1964). Therefore, our first deduction is that the basin consists mainly of plains or plateaus. From a hydrological point of view, unlike the general shape of the basin, the average length of streams shows that it is rather favorable to slow flows. However, a closer look reveals that, in addition to being numerous, order 1 and 2 streams have shorter average lengths. This could suggest that they are controlled by lithology (low permeability terrain) and morphology (steep slopes). On the other hand, the very few order 3 streams, which are very long, would suggest control by structural (Macka, 2003);
- *Stream length Ratio (RL)*. It provides information on the characteristics of the underlying rock surface and the degree of drainage (Strahler, 1964). In the Vranso basin, it varies from 0.45 to 0.75, which indicates that the network has a balanced and coherent structure, ensuring good drainage of the basin;
- *Bifurcation ratio (Rb)*. This ratio provides information on the degree of branching of the drainage network and the evolution of watersheds. A high value for this ratio indicates structural control over the hydrographic network (Sukristivanti *et al*, 2018). This value generally varies between 3.00 and 5.00 for watersheds where geological structures do not control the drainage network. Conversely, bifurcation values between 5.00 and 8.04 indicate irregularities between orders, highlighting the existence of geological disturbances (Strahler, 1964). As shown in Table 3, the bifurcation ratio calculated for Vranso basin varies between 2.00 and 6.00, offering two possibilities for analysis. On the one hand, values between 3 and 5 are observed for order 2, 3, and 4 streams, suggesting that geological structures do not significantly influence the drainage network pattern for these orders. The values for order

5 to 7 streams, on the other hand, exceed the threshold of 5 (for order 5 watercourses) or are less than 3 (for order 6 and 7 watercourses). This suggests geological control over their course, a kind of tectonic heritage on the drainage network. The superposition of the hydrographic network on geological features promotes indirect recharge of aquifers from streams;

- *Drainage density (Dd)*. The drainage density value for Vranso basin, calculated based on Horton method, is estimated to be 0.84 km/km^2. This is indicative of a relatively low density, suggesting a coarse texture of the hydrographic network. The presence of such a texture has often been observed to be associated with permeable underground material, dense vegetation, low average slope, and low presence of local major relief (Gao *et al*, 2022). It also implies slower flows and longer response times, thereby promoting significant infiltration and limited surface runoff (Sukristivanti *et al*, 2018). The spatial organization of the drainage density of Vranso watershed's hydrographic network based on pixel (3 x3 km) calculation, is illustrated in Figure 3. Values are represented by shades of blue for high values and red for low ones. The values arrangement displayed, enables the following observations to be made. Firstly, there is a demonstrable correlation between major northeast-southwest geological structures (black lines in the figure) and high density areas. Secondly, some low density areas correspond to sub-basin limits (green lines). Thirdly, there are density organizations that are difficult to explain at first examination. One of this case is clearly evident in the extreme southeast, where high density zones do not appear to exhibit any discernible pattern, except perhaps topography;

- *Torrentiality coefficient (Ct)*. It expresses the intensity of the flow regime and its value increases with the occurrence of torrential flows. Torrentiality coefficient for the watershed is 0.14. This low value reflects the less torrential nature of the flows through the hydrographic network. As low torrential runoff is characteristic of areas with gentle slopes, low torrentiality value obtained for this watershed, indicate that, the general topography of the basin consists mainly of flat terrain. Such a landscape feature is known to favor infiltration (Gravelius, 1914);

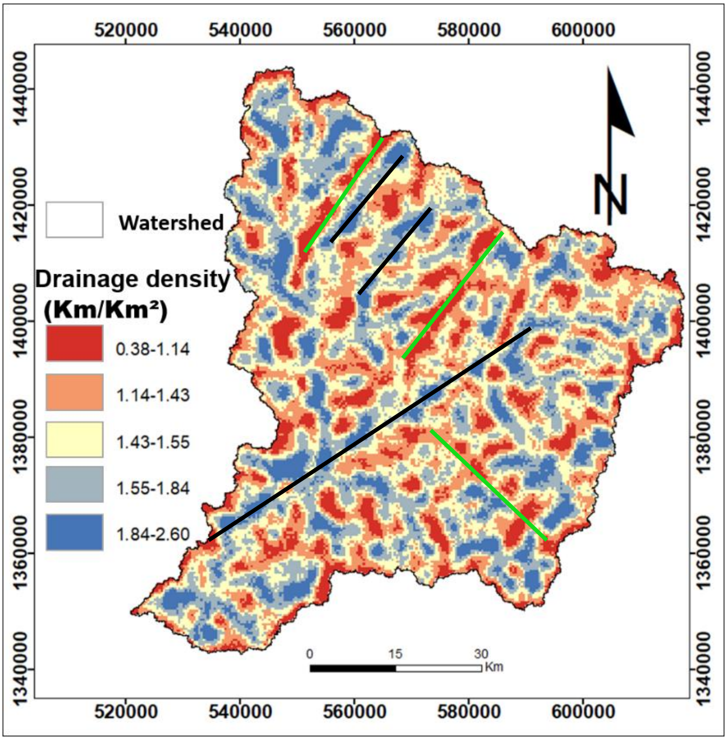

Figure 3: Drainage density map. Black lines in the figure represent high-density alignments that follow geological structures, and green lines delineate low-density areas that follow topographical ridgelines.

- *Texture ratio (T)*. The value obtained for this parameter is 1.3. According to Smith's classification (Smith, 1950), this value (< 4) indicates that the basin has a coarse texture, a characteristic that was already highlighted by the drainage density value. From a geological perspective, the coarse texture is indicative of the presence of underlying massive rocks, which are covered by relatively thick layers of weathered material (Mohaimen *et al*, 2024). The presence of such an underground structure within the watershed, would facilitate diffuse recharge;

- *Infiltration number (If)*. It provides information on the infiltration regime. Low values for this index indicate rapid infiltration and thus, less significant runoff. Infiltration number for Vranso watershed is 0.2, which means that the watershed has a significant infiltration capacity;

- *Stream frequency (Fs)*. This index represents the total number of streams of all orders per unit area. A low value for this index indicates that the watercourses are controlled by fractures, while a high frequency indicates a steeper slope in relation to surface runoff (Melton, 1958). The low stream frequency value of 0.24 reflects the fragmentation of the hydrographic network controlled by the fracture network. It also implies high permeability of the basin, resulting in a high groundwater infiltration capacity.

The detailed study of the hydrographic network of Vranso watershed reveals that the basin has reached a state of maturity, thereby exhibiting geological characteristics that are conducive to infiltration processes. The number of streams, their length, and their frequency, demonstrate a correlation with the level of fracturing of the underlying substrate. This configuration of the network is an additional factor that promotes infiltration. This basin's characteristic is corroborated by the other calculated indexes.

3.3. Analysis of hypsometric parameters

- *Altitude classes*. The analysis of altitude classes, associated with slope one, is used in this section to deduce the influence of relief on runoff in the basin. As illustrated in Figure 4A, the altitudinal distribution map reveals that, the predominant classes are those situated between 269-304 m and 304-339 m, accounting for 57.4% and 31.1% of the basin, respectively. Furthermore, they occupy the center and the outlet zone of the basin, which can be considered to be its most active zone from a hydrological perspective. These parts of the basin, characterized by gentle to moderate slopes, constitute an accumulation area for water flowing with higher speed from surrounding zones with steeper slopes. As illustrated in Figure 4B, the eastern and northeastern parts of the basin appear to have the steepest slopes. Consequently, these areas are expected to generate the most rapid runoff. The consequence of this configuration is that the watercourses in the center of the basin are under pressure, with the possibility of water spreading outside the riverbeds. These temporary inundations, which sometimes extend beyond the major riverbeds, increase infiltration, which under these conditions, occurs under pressure.

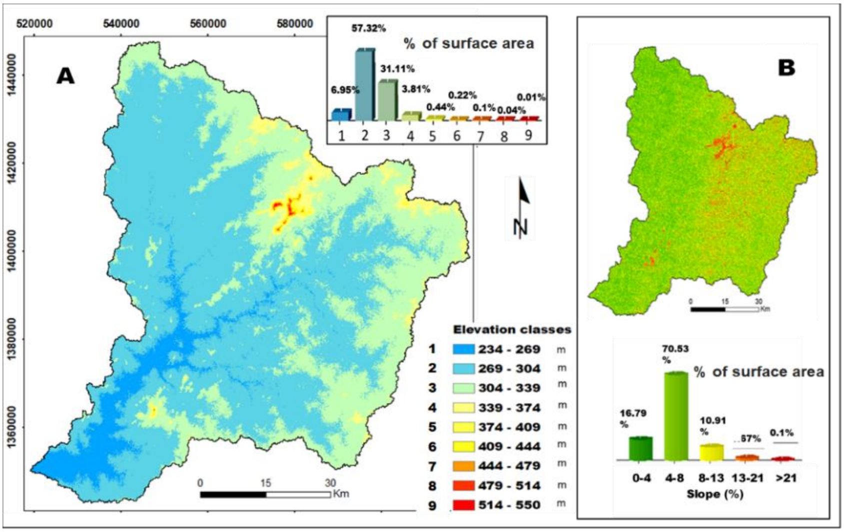

Figure 4: Spatial distribution of elevations (A) and slopes (B).

- *Hypsometric curve*. It is shown in Figure 5. Its typical profile corresponds to the mature phase of a basin's evolution (Lawmchullova *et al,* 2024), (Strahler, 1952). The curve indicates that 5% of the basin's surface area is situated at an altitude greater than 340 m, with the vast majority, nearly 90% of the basin, lying between altitudes of 340 and 265 m. This profile suggests the presence of : an extensive basin floor, a moderate to steep slope, and a resistant plateau (Strahler, 1952). Consequently, it suggested a variation in infiltration capacity at three levels, namely: high infiltration capacity on the extensive basin floor, resulting in diffuse recharge; low infiltration capacity in areas with moderate to steep slopes, resulting in limited potential recharge; and possible infiltration on resistant plateaus, often due to the presence of fractures and tectonic joints, resulting in localized recharge.

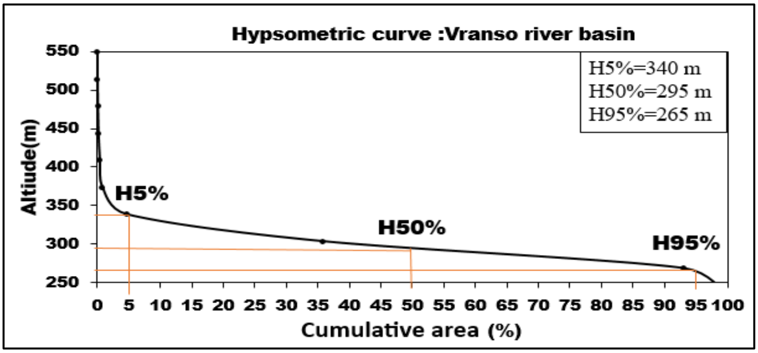

Figure 5: hypsometric curve of the basin.

- *The hypsometric integral (HI)*. It allows the determination of the non-eroded material volume in relation to the original volume of the basin. Depending on the value of the integral, there are three possible scenarios: HI < 0.3 for plains, HI between 0.3 and 0.6 for mature basins, and HI greater than 0.6 for young basins (Strahler, 1952). The value of 0.21 obtained for the basin indicates that it is dominated by a plain. This, in turn, suggests that the basin has passed through the young and mature stages and can therefore be considered to be old.

The results of this hypsometric analysis thus corroborate the conclusions of the hydrographic network study, particularly with regard to the age of the basin (mature basin) and its predisposition to promote infiltration.

3.4. Structural control of drainage networks

To analyze the influence of structure on the hydrographic network organization, we present in this section the fracture map of the basin, illustrated in Figure 6A. The lineaments depicted on the map correspond to a variety of responses, some of which remain indeterminate with respect to their correlation with tangible features on the ground. The confirmed structures include faults and shear lines, which are accidents and deformations inherited from regional structures and already represented on the geological map of the site (Cf; figure 1C), as well as major veins, which are also represented on the same map. Conversely, the lineaments presented as fractures have been designated as such by extrapolation. Indeed, while some were validated based on field observations (figure 6B and 6C), others could not be validated due to a lack of visible evidence. Furthermore, given the large number of lineaments shown on the map, the probability that some of them do not correspond to fractures is not negligible, and this has consequences for the hydrographic network alignment test.

Based on the fracture map, the alignment test of the hydrographic network carried out, led to the following observations:

- There is a significant alignment of the hydrographic network in the NE-SW and NW-SE directions, which corresponds to the major directions of regional discontinuities (faults and shear lines). The NE-SW alignment mainly concerns streams of orders 4 (N41°E±26°) and 7 (N55°E±11°) (Cf; figure 7), whose orientation corresponds to that of the majority of faults (N37±14°) and shear lines (N44°E±11°). The streams aligned in a NW-SE direction are those of order 3 (N70°E±17°) and 6 (N77°E±24°) and correspond to a secondary direction of the faults;

- Order 1 (N105°±22°) and 2 (N139°E±15°) watercourses appear to align with the major NW-SE direction, which corresponds to the main direction of the veins (Cf; figure 6A). This alignment is possible due to the known role of veins, which often constitute obstacles to flow, forcing it to follow their path over varying distances. However, this interpretation is difficult to validate due to the characteristics of the directional rosettes of these two orders of watercourses, which show a wide variety of directions. It is indeed equally possible to propose their alignment with the directions of the lineaments. Analysis in this latter case is more complex, especially since the nature of the lineaments in the field is uncertain.

-

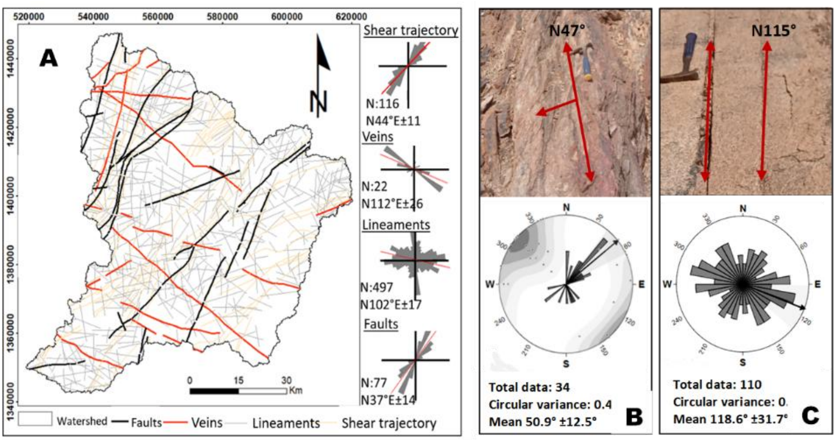

Figure 6: Structural overview of Vranso watershed. A) Fracture map; B) Field validation of location and directions of shear zones; C) Fractures directions identification on the site.

The results of this test, ultimately show that the layout of the hydrographic network as a whole is quite complex. It is undoubtedly a combination of topographical and structural influences. The weakest river orders, 1, 2, and 3 to a certain extent, are those for which it is difficult to demonstrate the impact of the structural factor. The main reason for this, is that the watercourses originate in areas with fairly steep slopes at the head of the basin.

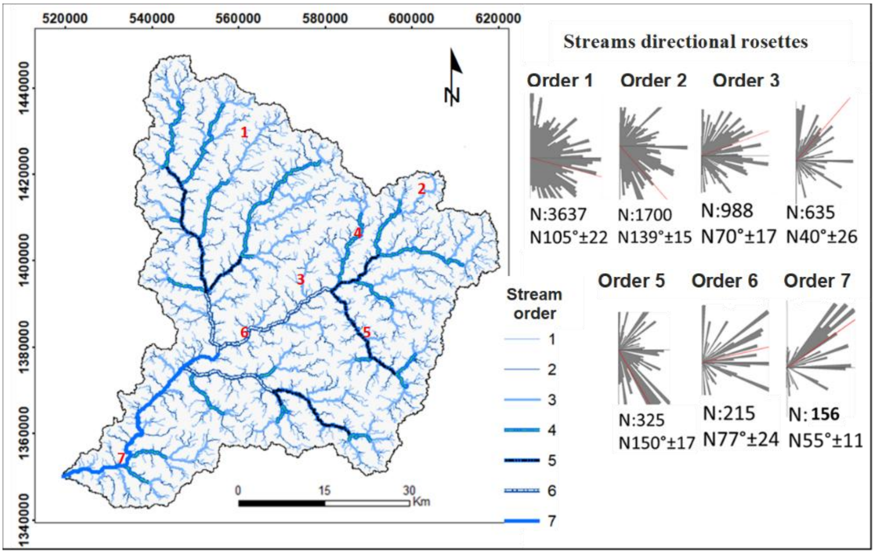

Figure 7: Hydrographic network map with the stream orders and their corresponding rosettes.

Before these watercourses accumulate enough water, their flows are guided by topography which determines their course. Once off the steep slopes (i.e. the basin and sub-basin boundaries and the slopes of the few hills in the basin), the water flows over terrain that is mostly gently sloping. This implies that the water flowing in the gullies has insufficient energy to surmount all the impediments it comes across. Water flows alongside the obstacles, (veins for example), then take advantage of some weak spots (fault lines or fractures) to cross and trace their path following the slope. This explains why the higher-order watercourses (4, 5, and 7) located in the middle of the basin, have a much more noticeable alignment with the structure.

These alignments of the drainage network with the major directions of regional and local structures suggest a certain structural control over the drainage network, revealing a tectonic heritage in the organization of the watercourse layout. This type of control is typical of bedrock environments where discontinuities direct flow (Savadogo, 1984). These river-discontinuity connections promote localized recharge in Vranso basin.

Conclusion

Morphometric analysis of Vranso hydro-system, has brought to light several significant indicators for understanding its hydrological and hydrogeological functioning. The shape indexes calculated for the basin, indicate that it is elongated and thus, favorable to runoff. However, this conclusion must be tempered in light of detailed analyses demonstrating that, elongation can be oriented in multiple directions, depending on the sub-basins under consideration. Therefore, the impact of basin shape on runoff appears to be quite complex.

The main indicators obtained through the study of the basin's hydrographic network, indicated that the drainage system is characterized by streams whose layout, length, number, and frequency appear to be linked to the underlying geological substrate. This correlation is substantiated through the alignment test of the hydrographic network with the predominant orientations of the geological structures and features present at the site, such as faults, fractures, veins, and shear zones. This interconnection between the hydrographic network and the structural organization of the geology, establishes conducive conditions for effective water infiltration within the basin, thus reducing runoff. This characteristic of the basin is further accentuated by its advanced age, which leads to the predominance of gentle slopes across most of its surface. These slopes favor slow runoff, though they can potentially result in temporary flooding, thereby generating infiltration under pressure.

This study thus shows that Vranso watershed has a significant potential for recharge, which deserves to be evaluated in greater detail and, above all, to be preserved in a context where the protection of natural resources is one of the country's priorities.

Conflict of interest

All authors declare no conflicts of interest.

Authors' contribution

SL: Article initiator, data collection and processing

KY: Main reviewer

WM: Writing and editing

KI: Second reviewer

ID: Data collection and processing

References

Bassolé Z., Yanogo I. P., Idani F. T., 2023. Caractérisation des sols ferrugineux tropicaux lessivés et des sols bruns eutrophes tropicaux pour l'utilisation agricole dans le bas-fond de Goundi-Djoro (Burkina Faso). *Int. J. Biol. Chem. Sci. 17(1), 2023,* PP 247 – 266. https://dx.doi.org/10.4314/ijbcs.v17i1.18

Benzougagh B., Boudad L., Dridri A., Sdkaoui D., 2016. Utilisation du SIG Dans l'analyse morphométrique et la prioritisation des sous-bassins versants de Oued Inaouene (Nord-Est du Maroc). *European Scientific Journal February 2016 edition vol.12, No.6 ISSN: 1857 – 7881 (Print) e - ISSN 1857- 7431,* PP 283-306. http://dx.doi.org/10.19044/esj.2016.v12n6p283

Bureau National des Sols du Burkina (BUNASOLS)., 2002. Carte des sols du Burkina Faso à 1/ 200 000e, Feuille de Koudougou, 2002, *BUNASOLS, Burkina Faso.*

Burbank D. W., Anderson R. S., 2013. Tectonic Geomorphology, Second Edition. *Environmental & Engineering Geoscience, 19(2),* PP 198 – 200. https://doi.org/10.2113/gseegeosci.19.2.198

Castaing C. *et al*., 2003. Notice explicative de la carte géologique à 1/200 000, feuille ND-30-IV, Koudougou. *Bureau des Mines et de la Géologie du Burkina (BUMIGEB), 2003*.

Castelltort S., Goren L., Willett S. D., Champagnac J. D., Herman F., Braun J., 2012. River drainage patterns in the New Zealand Alps primarily controlled by plate tectonic strain. *Nature Geoscience, 5(10),* PP 744 – 778. https://doi.org/10.1038/ngeo1582

Chardon D., Grimaud J., Rouby D., Beauvais A., Christophoul F., 2016. Stabilization of large drainage basins over geological time scales: Cenozoic West Africa, hot spot swell growth, and the Niger River. *Geochemistry, Geophysics, Geosystems, 17(3),* PP 1164 – 1181. https://doi.org/10.1002/2015gc006169.

Delcaillau B., Graveleau F., Rao G., Le Béon M., Delcaillau D., 2023. Geomorphic Responses to Fold Growth: Example from the Eastern Segment of Qiulitage and Yakeng Folds, Southern Tian Shan, China. *Elsevier BV*, 48 p. https://doi.org/10.2139/ssrn.4392185

Derbyshire E., 1973. Climatic Geomorphology. *Macmillan Education UK, Ed 1973,* 296 p. https://doi.org/10.1007/978-1-349-15508-8

Dörfliger N., Perrin J., 2011. Ressources en eau : une gestion nécessairement locale dans une approche globale. *Geosciences, 2011, 13,* PP 94 – 101. https://hal-brgm.archives-ouvertes.fr/hal-00662456

Faye C., 2014. Méthode d'analyse statistique de données morphométriques : corrélation de paramètres morphométriques et influence sur l'écoulement des sous-bassins du fleuve Sénégal. *Cinq Continents 4 (10) 2014, ISSN: 2247-2290*, PP 80 – 108.

Galle S., Séguis L., Arjounin M *et al.*, 2005. Evaluation des termes du bilan hydrologique sur le bassin versant de la Donga par mesure et modélisation. *Actes du colloque Ecosphère Continentale, ECCO, Toulouse, déc. 2005,* PP 412 – 416. https://www.researchgate.net/publication/282172008

Gao H., Liu F., Yan T., Qin L., Li Z., 2022. Drainage Density and Its Controlling Factors on the Eastern Margin of the Qinghai–Tibet Plateau. *Frontiers in Earth Science, Vol 9, 2022,* 15 p. https://doi.org/10.3389/feart.2021.755197

Greenway J., 2021. Water resources management versus the world. *AIMS Geosciences, 7 (4) (2021)*, PP 589-604. https://doi.org/10.3934/geosci.2021035

Gravelius H., 1914. Grundrifi der gesamten Gewcisserkunde. Band I:Flufikunde (Compendium of Hydrology ; *Vol.I, Rivers, in German).Goschen,Berlin,Germany*, PP 138-141.

Grimaud J. L., Chardon D., Beauvais A., 2014. Very long-term incision dynamics of big rivers. *Earth and Planetary Science Letters, 405,* PP 74 – 84. https://doi.org/10.1016/j.epsl.2014.08.021

Horton R. E., 1932. Drainage-basin characteristics. *Eos, Transactions of the American Geophysical Union, 13(1),* PP 350 – 361. https://doi.org/10.1029/tr013i001p00350

Horton R. E., 1945. Erosional development of streams and their drainage basins; hydrophysical approach to quantitative morphology.

Geological Society of America Bulletin, 56(3), 275 p. https://doi.org/10.1130/0016-7606(1945)56[275:edosat]2.0.co;2.

Idrissi S., Taous A., 2022. Analyse morphométrique et hydrographique du bassin versant du Beht et de ses principaux affluents en utilisant le système d'information géographique. *Revue Marocaine de Géomorphologie. N°6. (2022), ISSN : 2508-9382,* PP. 83 – 103. http://revues.imist.ma/?journal=remageom

Jothimani M., Abebe A., Berhanu G., 2022. Application of Remote Sensing, GIS, and Drainage Morphometric Analysis in Groundwater potential Assessment for sustainable development in Iyenda River Catchment, Konso Zone, Rift Valley, Southern Ethiopia. *IOP Conference Series: Earth and Environmental Science, 982(1), 012032.* 15 p. https://doi.org/10.1088/1755-1315/982/1/012032

Kumar L., Joshi G., Agarwal K. K., 2020. Morphometry and Morphostructural Studies of the Parts of Gola River and Kalsa River Basins, Chanphi-Okhalkanda Region, Kumaun Lesser Himalaya, India. *Geotectonics, 54(3),* PP 410 – 427. https://doi.org/10.1134/s0016852120030048

Lawmchullova I., Lalrinkimi ., Udaya Bhaskara Rao., 2024. Morphometric analysis of the Middle Tuirial watershed, Mizoram, India and its significance for soil loss risk. *Science Vision, 24(1),* PP 12 – 23. https://doi.org/10.33493/scivis.24.01.02

Lompo M., 2010. Paleoproterozoic structural evolution of the Man-Leo Shield (West Africa). Key structures for vertical to transcurrent tectonics. *Journal of African Earth Sciences, 58(1),* PP 19 – 36. https://doi.org/10.1016/j.jafrearsci.2010.01.005

Macka Z., 2003. Structural control on drainage network orientation an example from the Loucka drainage basin, south-east margin of the Bohemian Massif (S Moravia, Czech Rep.). *Landform Analysis, Vol. 4, 2003*, PP 109 – 117.

http://yadda.icm.edu.pl/yadda/element/bwmeta1.element.baztech-a2cbf266-40f9-4698-8e48-fca58b96d050/c/Macka_Structural_control_on_drainage.pdf.

Mahala A., 2020. The significance of morphometric analysis to understand the hydrological and morphological characteristics in two different morpho-climatic settings. *Applied Water Science, 10(1),* 16 p. https://doi.org/10.1007/s13201-019-1118-2

Mashauri F., Mbuluyo M., Nkongolo N., 2023. Influence des paramètres hydro-morphométriques sur l'écoulement des eaux des sous-bassins versants de la Tshopo, République Démocratique du Congo. *Revue Internationale de Géomatique, 2023, Vol 32,* PP 79 – 98. https://doi.org/10.32604/RIG.2023.044124

Melton M. A., 1958. Geometric Properties of Mature Drainage Systems and Their Representation in an E4Phase Space. *The Journal of Geology, 66(1),* PP 35 – 54. https://doi.org/10.1086/626481

Miller V. C., 1953. A quantitative geomorphic study of drainage basin characteristics in the Clinch Mountain area, Virginia and Tennessee. *Project NR 389042, technical report 3, Columbia University, Department of Geology, ONR, Geography Branch, New York,* PP 389 - 402.

Mohaimen A., Nath B., & Hasan Md. R., 2024. Geospatial-based tectono-morphometric analyses of the drainage system in the Chengi and Myinee River basins in the Chittagong Hill Tracts, Bangladesh. *Geosystems and Geoenvironment, 3(1), 100224,* 15 p. https://doi.org/10.1016/j.geogeo.2023.100224

Palé S., Kekele A., Da D. E. C., 2020. Caractérisation géomorphométrique des formes de relief dans le bassin versant du Poni, au Burkina Faso. *Afrique Science, 17 (3) (2020), ISSN 1813-548X,* (PP 62-77). http://www.afriquescience.net

Rai P. K., Mohan K., Mishra S., Ahmad A., Mishra V. N., 2017. A GIS-based approach in drainage morphometric analysis of Kanhar River Basin, India. *Applied Water Science, 7(1),* PP 217 – 232. https://doi.org/10.1007/s13201-014-0238-y

Roche M., 1963. Hydrologie de surface. *ORSTOM, Gauthier-Villars Editeur, Paris, 1963,* 431 p. https://horizon.documentation.ird.fr/exl-doc/pleins_textes/pleins_textes_5/b_fdi_30-30/32926.pdf

Sanou D. C., 1993. Ruissellement et érosion sur petits bassins versants : le cas de Imiga/Tibin. *Aspects des milieux naturels du Burkina Faso, Centre de recherche sur les espaces tropicaux, 1993, Pays enclavés,* PP 85 – 114. https://www.persee.fr/doc/payen_0989-6007_1993_ant_7_1_920

Savadogo A. N., 1984. Géologie et hydrogéologie du socle cristallin de Haute Volta. Étude régionale du bassin versant de la Sissili. *Thèse de* *doctorat, Université Scientifique et Médicale de Grenoble, France, 1984,* 350 p. https://theses.hal.science/tel-00764194

Schumm S. A., 1956. Evolution of drainage systems and slopes in badlands at Perth Amboy, New Jersey. *Geological Society of America Bulletin, 67(5),* (PP 597 – 646). https://doi.org/10.1130/0016-7606(1956)67[597:eodsas]2.0.co;2

Sintondji L. O., Awoye H. R., Agbossou K. E., 2008. Modélisation du bilan hydrologique du bassin versant du Klou au Centre-Bénin : Contribution à la gestion durable des ressources en eau. *Bulletin de la Recherche Agronomique du Bénin, Numéro 59, 2008,* PP 35 – 48.

Smith K. G., 1950. Standards for grading texture of erosional topography. *American Journal of Science, Vol 248, 1950,* PP 655 – 668. https://doi.org/10.2475/ajs.248.9.655

Strahler A. N., 1952. Hypsometric (area-altitude) analysis of erosional topography. *GSA Bulletin, 63(11),* PP 1117 – 1142. https://doi.org/10.1130/0016-7606(1952)63[1117:haaoet]2.0.co;2

Strahler A. N., 1964. Quantitative geomorphology of drainage basins and channel networks. In : Chow V, (Ed) Handbook of Applied Hydrology. *McGraw Hill Book Company, New York,* PP 439 – 476.

Sukristiyanti S., Maria R., Lestiana H., 2018. Watershed-based morphometric analysis: A Review. *IOP Conference Series: Earth and Environmental Science, 118, 012028,* 5 p. https://doi.org/10.1088/1755-1315/118/1/012028

Thomas J., Joseph S., Thrivikramaji K. P., 2010. Morphometric aspects of a small tropical mountain river system, the southern Western Ghats, India. *International Journal of Digital Earth, 3(2*), PP 135 – 156. https://doi.org/10.1080/17538940903464370