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Assessment of Grain-Size Variability and Information Saturation Across Dredging Thresholds in the Congo River Divagation Zone (Boma–Malela): Implications for Monitoring Network Optimization

[Assessment of Grain-Size Variability and Information Saturation Across Dredging Thresholds in the Congo River Divagation Zone (Boma–Malela)]

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Abstract

The Boma-Malela reach of the Congo River forms a highly dynamic divagation zone characterized by intense sediment transport, rapid channel adjustments, and recurrent navigation constraints that necessitate continuous maintenance dredging. Although hydro-sedimentary surveys are routinely conducted in this reach, the sampling density required to characterize spatial variability in sediment texture across dredging thresholds remains poorly constrained. This study assessed grain-size variability and information saturation to inform monitoring-network optimization and reduce redundant sampling. The analysis used 180 sediment samples collected during dredging campaigns conducted between 2023 and 2025, long-term water-level records from the Boma staff gauge (1960-2025), and annual dredging records for 2015–2024. Granulometric characterization included median grain size (D50), fine fraction (<63 µm), coarse fraction (>500 µm), sorting index, skewness, and the uniformity and curvature coefficients (Cu and Cc). Analyses included variance decomposition, iterative jackknife-based information-saturation analysis, one-way ANOVA, principal component analysis, linear regression, and Random Forest modeling. The results showed pronounced spatial heterogeneity in sediment texture among the nine investigated dredging thresholds. D50 and fine-fraction content differed significantly among thresholds (ANOVA: $F(8,171)=36.83$ and 31.20, respectively; both $p<0.0001$). For D50, the ANOVA sums of squares indicate that between-threshold variation accounted for approximately 63.3% of total variation; for the fine fraction, the corresponding proportion was approximately 59.3%. The manuscript's saturation curve shows diminishing marginal information gain as additional thresholds are included; however, the numerical values reported for this curve are internally inconsistent with the stated 95% saturation point at five thresholds. The regression between annual dredging volume and D50 was not statistically significant ($R^2=0.004$, $p=0.3847$). These findings support the importance of spatially distributed sampling across dredging thresholds in the Boma-Malela reach. They also indicate that monitoring-network optimization is potentially feasible, but the exact minimum number of thresholds required to achieve a predefined information target should be confirmed after reconciling the saturation calculations and validating them with independent data. The conclusions are therefore restricted to the analyses and numerical results that can be verified from the present manuscript.

Keywords: Dredging thresholds; Grain-size variability; Information saturation; Congo River; Monitoring network optimization.

Résumé

Le bief Boma-Malela du fleuve Congo forme une zone de divagation hautement dynamique caractérisée par un transport sédimentaire intense, des ajustements rapides des chenaux et des contraintes de navigation récurrentes qui nécessitent un dragage de maintenance continu. Bien que des levés hydro-sédimentaires soient régulièrement menés dans ce bief, la densité d'échantillonnage requise pour caractériser la variabilité spatiale de la texture des sédiments à travers les seuils de dragage reste mal cernée. Cette étude a évalué la variabilité granulométrique et la saturation de l'information afin d'éclairer l'optimisation du réseau de surveillance et de réduire les échantillonnages redondants. L'analyse a utilisé 180 échantillons de sédiments collectés lors de campagnes de dragage menées entre 2023 et 2025, des enregistrements limnimétriques (hauteur d'eau) à long terme de la station de Boma (1960-2025) et des registres annuels de dragage pour la période 2015-2024. La caractérisation granulométrique a inclus la taille médiane des grains (D50), la fraction fine (<63 µm), la fraction grossière (>500 µm), l'indice de classement (sorting), l'asymétrie (skewness), ainsi que les coefficients d'uniformité et de courbure (Cu et Cc). Les analyses ont compris la décomposition de la variance, une analyse de saturation de l'information basée sur un rééchantillonnage de jackknife itératif, une ANOVA à un facteur, une analyse en composantes principales, une régression linéaire et une modélisation par forêts aléatoires (Random Forest). Les résultats ont montré une hétérogénéité spatiale prononcée dans la texture des sédiments parmi les neuf seuils de dragage étudiés. Le D50 et la teneur en fraction fine différaient significativement entre les seuils (ANOVA : $F(8,171) = 36,83$ et 31,20, respectivement ; avec $p < 0,0001$ dans les deux cas). Pour le D50, les sommes des carrés de l'ANOVA indiquent que la variation inter-seuils a représenté environ 63,3 % de la variation totale ; pour la fraction fine, la proportion correspondante était d'environ 59,3 %. La courbe de saturation montre un gain d'information marginal décroissant à mesure que des seuils supplémentaires sont inclus ; cependant, les valeurs numériques rapportées pour cette courbe sont incohérentes en interne avec le point de saturation de 95 % affirmé à cinq seuils. La régression entre le volume de dragage annuel et le D50 n'était pas statistiquement significative ($R^2 = 0,004$, $p = 0,3847$). Ces résultats soutiennent l'importance d'un échantillonnage spatialement distribué à travers les seuils de dragage dans le bief fluviomaritime (Boma-Malela). Ils indiquent également que l'optimisation du réseau de surveillance est potentiellement réalisable, mais que le nombre minimal exact de seuils requis pour atteindre une cible d'information prédéfinie doit être confirmé après la réconciliation des calculs de saturation et leur validation avec des données indépendantes. Les conclusions se limitent par conséquent aux analyses et aux résultats numériques qui peuvent être vérifiés à partir de présente étude.

Mots-clés: Seuils de dragage, Variabilité granulométrique, Saturation de l'information, Fleuve Congo, Optimisation du réseau de surveillance.

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1. Introduction

Maintenance dredging constitutes a fundamental operation for sustaining navigability in major riverine and coastal transport corridors worldwide, particularly in environments affected by rapid sedimentation and channel instability (Bray et al., 1997; PIANC, 2018). In large tropical rivers, hydro-sedimentary processes are often intensified by strong seasonal hydrological variability, high sediment fluxes, and active channel migration, resulting in recurrent shoaling and frequent reconfiguration of navigation channels (Syvitski et al., 2005; Anthony et al., 2014). Such conditions are especially pronounced in divagation systems, where the river flow disperses into multiple mobile channels separated by bars, islands, and sedimentary thresholds. These environments pose major operational challenges for dredging management because sediment redistribution occurs rapidly in both space and time.

The maritime reach of the Congo River between Boma and Malela represents one of the most dynamic fluvial systems in tropical Africa. Over this sector, the river evolves across a wide alluvial corridor characterized by multiple active channels, migrating sandbars, and unstable navigation pathways (Laraque et al., 2009; Alsdorf et al., 2016). The combined effects of seasonal discharge fluctuations, complex hydraulic conditions, and intense sediment transport generate persistent dredging requirements to maintain navigable depths for maritime traffic. Annual dredging operations frequently involve the removal of large sediment volumes, particularly at critical shallow thresholds that control channel accessibility. Consequently, understanding the spatial organization and temporal evolution of bed sediments has become essential for improving dredging efficiency and reducing operational costs.

Sediment grain-size distribution constitutes a key descriptor of hydro-sedimentary processes because it reflects sediment provenance, transport energy, depositional dynamics, and channel morphodynamics (McLaren & Bowles, 1985; Smith & Friedrichs, 2011). Granulometric parameters such as median grain size (D50), sorting indices, and fine or coarse sediment fractions are widely used to characterize sediment mobility and bed stability in alluvial systems. In dredged rivers, these parameters also provide critical information for predicting sediment re-accumulation rates, identifying erosion–deposition zones, and evaluating the effectiveness of maintenance dredging strategies. Despite their importance, sediment monitoring campaigns remain financially and logistically demanding due to extensive field sampling, laboratory analyses, and repeated surveys under variable hydrological conditions.

A central issue in hydro-sedimentary monitoring therefore concerns the optimization of sampling networks. In many dredging programs, sampling density is commonly determined empirically or constrained by operational budgets rather than by quantitative assessments of spatial representativeness. This often leads either to under-sampling, which limits the reliability of sediment characterization, or to excessive redundancy that increases monitoring costs without substantially improving information quality. Although several studies have addressed optimal sampling strategies for bathymetric surveys and spatial environmental monitoring (Parker, 1990; Legleiter & Kyriakidis, 2006), relatively few investigations have focused specifically on the spatial representativeness of sediment granulometry in highly dynamic dredged rivers.

Geostatistical approaches provide a robust framework for addressing these limitations because they explicitly quantify spatial dependence and variability structures within environmental datasets (Goovaerts, 1999; Webster & Oliver, 2007). Variogram analysis and kriging techniques are now widely applied in hydrology, geomorphology, and sedimentology to characterize spatial continuity and optimize sampling strategies. Within this context, the concept of information saturation is particularly relevant. Information saturation refers to the threshold beyond which the addition of new sampling locations produces only marginal gains in explained spatial variability. Applied to dredging monitoring, this concept offers the possibility of identifying the minimum number of dredging thresholds required to adequately represent sediment texture variability while minimizing redundant observations.

The present study investigates grain-size variability and information saturation within the Boma-Malela divagation zone by integrating granulometric, hydrological, and dredging datasets. Specifically, the objectives are to: (i) quantify sediment grain-size variability among and within dredging thresholds; (ii) assess how information gain changes as the number of sampled thresholds increases; (iii) evaluate

associations of hydrological conditions and dredging intensity with sediment characteristics and monitoring requirements; and (iv) propose an operational basis for optimizing hydro-sedimentary monitoring in this dynamic tropical river reach. The study is intended to provide a quantitative basis for improving sediment-monitoring efficiency while identifying the limits that require further validation.

2. Material and methods

2.1. Study area

The study was conducted in the maritime reach of the Congo River between Boma (5°51′S, 13°03′E) and Malela (5°45′S, 12°40′E), located approximately 120 km upstream from the Atlantic Ocean (Figure 1). This sector corresponds to one of the most morphodynamically active sections of the lower Congo system and forms a complex divagation zone characterized by multiple interconnected channels, migrating sandbars, mid-Channel Islands, and rapidly shifting navigation pathways. The active redistribution of sediments within this alluvial corridor generates recurrent shoaling processes that require continuous maintenance dredging to ensure safe maritime navigation. Hydrodynamically, the study reach is influenced by the combined effects of river discharge variability and tidal propagation from the Atlantic estuary. Semi-diurnal tides propagate more than 150 km inland, producing bidirectional flow interactions that significantly influence sediment transport and deposition dynamics (Laraque et al., 2020). The hydrological regime is strongly seasonal and typically includes four main phases: (i) a major flood period from December to February, associated with maximum discharge conditions; (ii) a secondary flood phase during March–April; (iii) a pronounced low-water period between July and August; and (iv) a recession phase extending from September to November. These seasonal fluctuations exert a major control on channel morphology, sediment redistribution, and dredging requirements throughout the divagation zone.

Maintenance dredging within the study area is carried out annually using two cutter suction dredgers operated along the principal navigation channels: Banana (3160 m^3 h^{-1}) and Tshuapa (2600 m^3 h^{-1}). Dredging activities mainly target shallow sedimentary thresholds that restrict navigable depth during low-flow conditions. The intensity and spatial extent of dredging operations vary substantially according to annual hydrological conditions and sedimentation rates.

Nine representative sampling sectors were selected across the Boma–Malela reach: Boma, Kindu, Papyrus, Bulikoko, Pointe Palmiers, Tortue, Tumbimbi, Diambote, and Bunia (figure 1). These sites were chosen to encompass the diversity of hydro-sedimentary environments encountered within the divagation system. Sampling locations include actively dredged navigation channels, secondary distributary channels, depositional bank environments, and relatively stable sediment accumulation zones. Within each sector, several dredging thresholds were sampled during maintenance dredging campaigns conducted between 2023 and 2025. The resulting spatial coverage provides a representative characterization of sediment texture variability across the main morphodynamic units of the lower Congo divagation zone.

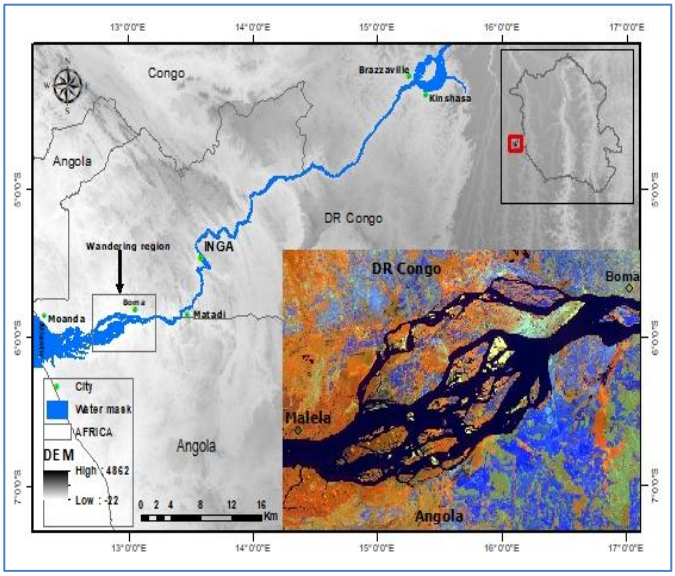


Figure 1. Location map of the Congo River maritime reach (Boma–Malela)

The map shows the divagation zone between Kinshasa/Brazzaville and the Atlantic Ocean, including Matadi, Boma, Moanda, Malela, and the Inga dam

2.2. Data sources

2.2.1. Granulometric data

A total of 180 sediment samples were collected during dredging operations between 2023 and 2025. Sampling was conducted from the two operational cutter suction dredgers (Banana and Tshuapa) during active dredging periods to ensure that samples accurately represented the sediment being mobilized. Nine sampling sites were selected across the divagation zone, covering the full range of sedimentary environments from actively dredged navigation channels to calm depositional areas along the banks (figure 2). The sites include: Boma, Kindu, Papyrus,

Bulikoko, Pointe Palmiers, Tortue, Tumbimbi, Diambote, and Bunia. At each site, multiple thresholds were sampled to capture spatial variability. Figure 2: Spatial distribution of dredging thresholds in the Boma–Malela divagation zone. The map shows the nine sampling sites along the Congo River maritime reach.

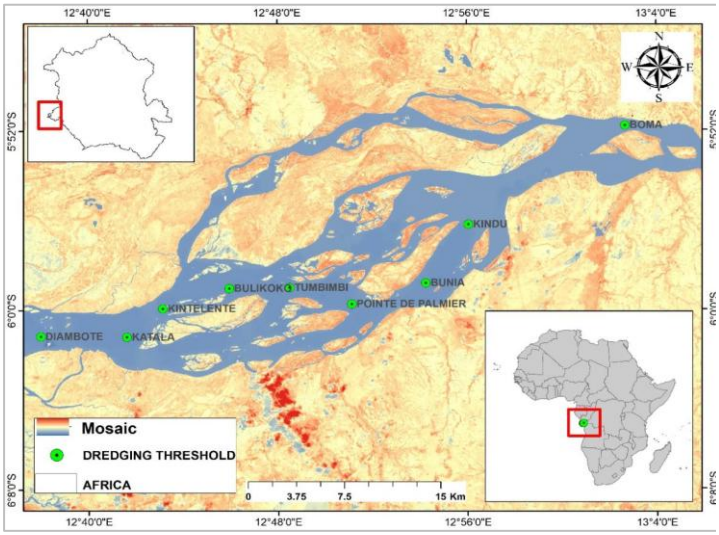


Figure 2. Spatial distribution of dredging thresholds in the Boma–Malela divagation zone

The map shows the nine sampling thresholds (Boma, Kindu, Papyrus, Bulikoko, Pointe Palmiers, Tortue, Tumbimbi, *Diambote, Bunia) along the Congo River maritime reach.*

For each sediment sample, granulometric analysis was performed using sieves ranging from 2.38 mm to 63 µm, with washing of the fine fraction followed by oven-drying at 105 °C. The manuscript cites ISO 14688-2 and NF EN 933-1 as methodological references. Grain-size distributions were used to derive sedimentological parameters characterizing texture, sorting, and grading at each dredging threshold. The calculated parameters included percentile diameters D10, D50, and D90 (mm), obtained by interpolation of cumulative grain-size distribution curves and representing the 10th, 50th (median), and 90th percentiles, respectively. The fine fraction corresponded to particles finer than 63 µm (φ = 4), whereas the coarse fraction represented particles coarser than 500 µm (approximately φ = 1).

Sediment sorting was evaluated using the Folk and Ward (1957) sorting index:

$$\sigma = \left(\frac{D_{85}}{D_{16}}\right)^{0.5}$$

$Sk = \frac{D_{90}+D_{10}-2D_{50}}{D_{90}-D_{10}}$ where σ is the Folk and Ward sorting index; larger values indicate poorer sorting. Grain-size asymmetry was assessed using the skewness coefficient:

Under the Folk and Ward convention expressed in phi units, positive skewness indicates a fine-skewed distribution, whereas negative skewness indicates a coarse-skewed distribution.

Sediment grading characteristics were further described using the Hazen uniformity coefficient:

$$C_u = \frac{D_{60}}{D_{10}}$$

$$C_c = \frac{(D_{30})^2}{D_{10} * D_{60}}$$

The uniformity coefficient (Cu) was interpreted together with the curvature coefficient rather than using a single universal cut-off, because grading criteria depend on sediment class. The curvature coefficient was calculated as:

Values of Cc between 1 and 3 are commonly considered compatible with well-graded material when the applicable Cu criterion is also satisfied. Together, these parameters provided an integrated description of sediment texture variability across the monitored dredging thresholds.

2.2.2. Hydrological data

Hydrological variability within the study area was assessed using long-term water-level records from the Boma staff gauge covering the period 1960-2025. The dataset, provided by the Hydrographic Service of Compagnie des Voies Maritimes (CVM), comprises 65 years of continuous limnimetric observations and constitutes one of the most extensive hydrological archives available for the maritime reach of the Congo River. These records provide valuable information on the seasonal and interannual fluctuations controlling sediment transport dynamics and dredging conditions within the divagation zone.

Based on mean annual and seasonal water-level variations, four principal hydrological phases were identified to characterize the dominant flow conditions governing sediment redistribution processes throughout the study reach. These hydrological phases are summarized in table I.

Table I. Hydrological phases

Phase	Period	Mean water level (m)	Typical range (m)
High flood	December-February	3.35 ± 0.35	2.80-3.82
Small flood	March-April	2.40 ± 0.30	1.90-3.10
Low water	July-August	0.85 ± 0.45	0.01-1.78
Small recession	September-November	1.50 ± 0.40	1.00-2.50

2.2.3. Dredging activity and sediment granulometry

Annual dredging volumes for the period 2015–2024 were obtained from official hydrographic operational reports provided by the CVM Hydrographic Service. Maintenance dredging within the Boma–Malela reach was carried out using two cutter suction dredgers, Banana and Tshuapa, with nominal production capacities of 3160 m^3 h^{-1} and 2600 m^3 h^{-1}, respectively. To evaluate the influence of dredging intensity on sediment variability and monitoring requirements, annual dredging activity was classified into three operational categories based on the statistical distribution of dredged volumes.

High-intensity dredging years corresponded to annual volumes exceeding 600,000 m^3 and generally reflected periods during which both dredgers operated continuously at near-full capacity. Medium-intensity years were associated with intermediate dredging volumes ranging between 300,000 and 600,000 m^3, whereas low-intensity years corresponded to dredged volumes below 300,000 m^3. These lower dredging levels were typically associated with reduced operational schedules, temporary budgetary constraints, or hydrological conditions favorable to natural channel navigability.

A total of 180 sediment samples were collected during maintenance dredging campaigns conducted between 2023 and 2025. Granulometric analyses were performed using standard dry-sieving procedures with sieve apertures ranging from 2.38 mm to 63 µm. The resulting grain-size distributions were used to determine the principal sedimentological descriptors, including characteristic percentile diameters (D10, D50, and D90), proportions of fine and coarse sediment fractions, sediment sorting characteristics, distribution asymmetry, and grading properties. These parameters provided an integrated characterization of sediment texture variability across the dredging thresholds and constituted the basis for subsequent geostatistical analyses.

2.3. Processing workflow

2.3.1. Variance decomposition

The total variance of the textural dataset was partitioned into inter-threshold variance (i.e., variance among different thresholds) and intra-threshold variance (i.e., variance within a given threshold), according to:

$$Var_{total} = Var_{inter} + Var_{intra}$$

The relative contribution of each component was expressed as:

$$Pct_{inter} = \left(\frac{Var_{inter}}{Var_{total}}\right) * 100$$

And

$$Pct_{intra} = \left(\frac{Var_{intra}}{Var_{total}}\right) * 100$$

$$Pct_{inter} Pct_{intra}$$

where the two terms represent the percentage contributions of between-threshold and within-threshold variability, respectively.

2.3.2. Information saturation analysis (Jackknife resampling)

The information gain (IG k) associated with k-sampled thresholds was calculated as:

$$IGk = \left(1 - \frac{RMSEk}{RMSEmax}\right) \times 100$$

where RMSEk is the root-mean-square error obtained with k sampled thresholds and RMSEmax is the maximum observed error at k=2. Information saturation was intended to be defined as the smallest k for which the information-gain criterion reached the prespecified 95% target. Because the numerical information-gain values reported in the Results do not reach 95%, the exact saturation threshold cannot be verified from the values currently presented.

2.3.3. Conditional saturation analysis

Information saturation curves were calculated independently for each environmental and operational category in order to assess potential differences in textural variability across conditions. Analyses were conducted for: (i) dredging intensity classes (high, medium, and low), (ii) hydrological phases (low water, small recession, small flood, and high flood), and (iii) threshold groups (coarse, medium, and fine fractions).

For each category, the iterative resampling procedure described above was applied separately to determine the threshold number required to achieve information saturation. This conditional approach enabled the evaluation of how sediment heterogeneity and sampling requirements varied according to hydrological dynamics and dredging pressure.

2.3.4. Statistical analyses

Differences among threshold classes were assessed using one-way analysis of variance (ANOVA), followed by Tukey's honestly significant difference (HSD) post-hoc tests for pairwise comparisons. Principal Component Analysis (PCA) was applied to explore multivariate relationships and visualize sedimentological affinities among samples and threshold groups.

Linear regression analyses were performed to evaluate relationships between median grain size (D50) and dredging volume. In addition, Random Forest models were used to assess the relative importance of explanatory variables controlling sediment textural variability.

All statistical analyses were conducted using Python 3.12, primarily with the scikit-learn, SciPy, and statsmodels libraries.

3. Results

3.1. Grain-size parameters

Table II shows a pronounced textural gradient among the investigated thresholds. The highest mean D50 values occurred at Bunia (0.55 ± 0.14 mm), Kindu (0.52 ± 0.13 mm), and Boma (0.48 ± 0.12 mm), which also had relatively low fine-particle contents (5.2–8.2%) and high coarse fractions (62.4–72.1%). These data demonstrate spatial textural differentiation among thresholds; however, the observational design does not by itself establish that dredging caused these differences.

In contrast, Papyrus and Tumbimbi exhibited finer sediment textures, with mean D50 values of 0.28 ± 0.08 and 0.32 ± 0.09 mm, higher fine-particle contents (18.3 ± 5.2% and 16.2 ± 5.1%, respectively), and lower coarse fractions (35.2 ± 8.4% and 40.3 ± 8.5%, respectively). The remaining thresholds displayed intermediate sedimentological characteristics.

Uniformity coefficients ranged from 2.1 to 4.5. These values should not be interpreted as demonstrating that all dredged-channel sediments are well graded without applying sediment-class-specific Cu criteria together with Cc. Overall, the results indicate a clear spatial textural gradient across the divagation zone.

Tableau II. Grain-size parameters by dredging threshold (mean ± std)

Threshold	D_{50} (mm)	Fines (%)	Coarse (%)	Sorting (φ)	Skewness	Cu	Cc
Boma	0.48 ± 0.12	8.2 ± 3.1	62.4 ± 10.2	1.30 ± 0.15	0.42	3.8	1.15
Kindu	0.52 ± 0.13	6.1 ± 2.4	68.3 ± 10.5	1.40 ± 0.18	0.48	4.2	1.20
Papyrus	0.28 ± 0.08	18.3 ± 5.2	35.2 ± 8.4	1.00 ± 0.12	0.15	2.1	0.85
Bulikoko	0.35 ± 0.10	14.2 ± 4.1	45.3 ± 10.2	1.10 ± 0.14	0.25	2.9	1.02
Pte Palmiers	0.42 ± 0.11	10.1 ± 3.2	55.2 ± 10.5	1.20 ± 0.15	0.35	3.4	1.10
Tortue	0.38 ± 0.11	12.3 ± 4.2	50.1 ± 10.2	1.15 ± 0.14	0.30	3.1	1.05
Tumbimbi	0.32 ± 0.09	16.2 ± 5.1	40.3 ± 8.5	1.05 ± 0.13	0.20	2.5	0.95
Diambote	0.45 ± 0.12	9.2 ± 3.0	58.4 ± 10.5	1.25 ± 0.16	0.38	3.6	1.12
Bunia	0.55 ± 0.14	5.2 ± 2.0	72.1 ± 10.8	1.50 ± 0.20	0.52	4.5	1.25

Table III. One-Way ANOVA table for D 50 and fine fraction across dredging thresholds

Parameter	Source of Variation	Sum of Squares (SS)	Degrees of Freedom (df)	Mean Square (MS)	F-statistic	p-value
D50 (mm)	**Between Thresholds (Inter)**	1.842	8	0.2302	**36.83**	**< 0.0001**
	Within Thresholds (Intra)	1.069	171	0.0062		
	Total	2.911	179			
Fines <63µm (%)	**Between Thresholds (Inter)**	2845.6	8	355.70	**31.20**	**< 0.0001**
	Within Thresholds (Intra)	1949.4	171	11.40		
	Total	4795.0	179			

Figure 3 illustrates spatial variability in grain-size parameters across the nine dredging thresholds. Consistent with Table 2, the highest mean D50 values were observed at Bunia (0.55 mm), Kindu (0.52 mm), and Boma (0.48 mm), together with relatively high coarse fractions and low fine-fraction contents.

Papyrus and Tumbimbi were characterized by lower mean D50 values (0.28 and 0.32 mm, respectively), higher fine-particle contents (18.3% and 16.2%), and lower coarse fractions (35.2% and 40.3%), consistent with finer sediment textures at these thresholds.

Intermediate thresholds, including Bulikoko, Pointe Palmiers, Tortue, and Diambote, exhibited transitional sedimentological characteristics. The ANOVA results confirm statistically significant differences among thresholds for D50 and fine-fraction content. Based on the sums of squares in Table 3, between-threshold variation represents approximately 63.3% of total D50 variation and 59.3% of total fine-fraction variation.

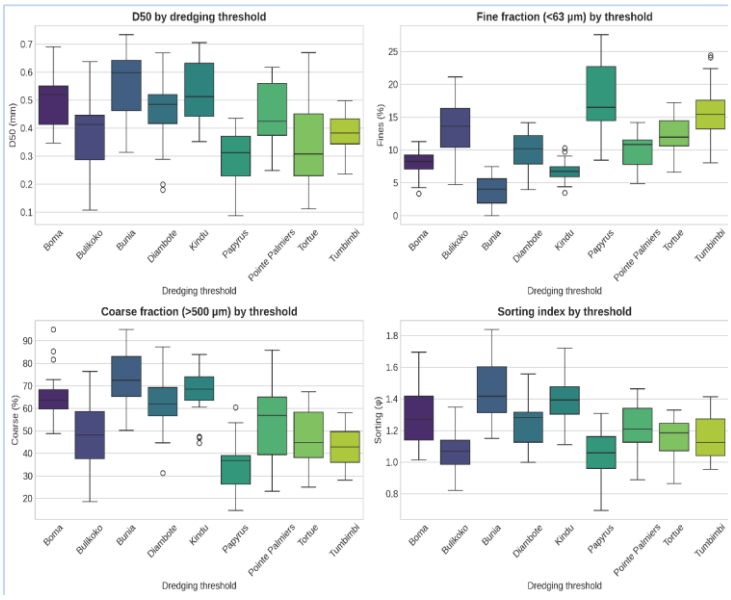


Figure 3. Boxplots of grain-size parameters by dredging threshold.

The panels show (a) D50, (b) fine fraction (<63 µm), (c) coarse fraction (>500 µm), and (d) sorting index for the nine thresholds (Boma, Kindu, Bunia, Papyrus, Bulikoko, Pointe Palmiers, Tortue, Tumbimbi, Diambote).

3.3. Cumulative grain-size distribution curves

Figure 4 presents the cumulative grain-size distribution curves for the nine dredging thresholds and shows separation among sedimentary environments according to median grain size. Boma (D50 = 0.48 mm), Bunia (D50 = 0.55 mm), and Kindu (D50 = 0.52 mm) display relatively coarse distributions compared with the finer thresholds. These patterns are consistent with spatial sediment sorting, but the curves alone do not establish a causal dredging effect.

In contrast, the Papyrus threshold exhibited the finest sediment distribution (D50=0.30 mm), with a cumulative curve shifted toward smaller grain sizes, highlighting the dominance of fine particles (<63 µm) within this low-energy depositional environment.

Intermediate thresholds, including Bulikoko (D50 = 0.35 mm), Pointe Palmiers (D50 = 0.42 mm), Tortue (D50 = 0.38 mm), Tumbimbi (D50 = 0.32 mm), and Diambote (D50 = 0.45 mm), showed distributions between the coarser and finer end members. The separation among curves was most evident within the sand fraction (63 µm–2 mm).

Overall, the cumulative distributions confirm substantial spatial heterogeneity in sediment texture among the investigated thresholds.

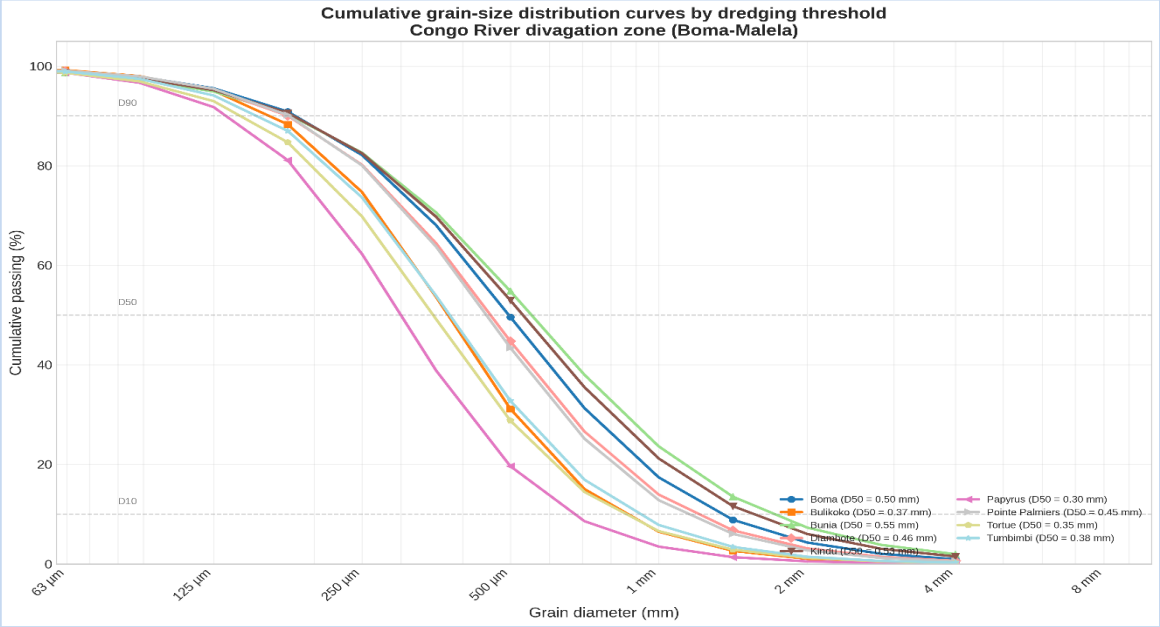


Figure 4. Cumulative grain-size distribution curves by dredging threshold

Curves shift right for dredged channels (Boma, Bunia, Kindu), indicating coarser sediments, and left for depositional zones (Papyrus, Tumbimbi), reflecting finer textures. Intermediate thresholds show transitional positions.

3.4. Principal Component Analysis (PCA) of grain-size parameters

Figure 5 presents PCA results for seven grain-size parameters. The first two components explain 73.1% of total variance (PC1: 60.6%; PC2: 12.5%). Sample projections show a textural gradient along PC1, with coarser thresholds tending toward the positive side and finer thresholds toward the negative side. The loading pattern indicates that PC1 is positively associated with D50 and coarse fraction and negatively associated with fine fraction, whereas PC2 is more strongly associated with sorting and skewness. These multivariate patterns support textural differentiation among thresholds but do not, on their own, demonstrate causation by dredging.

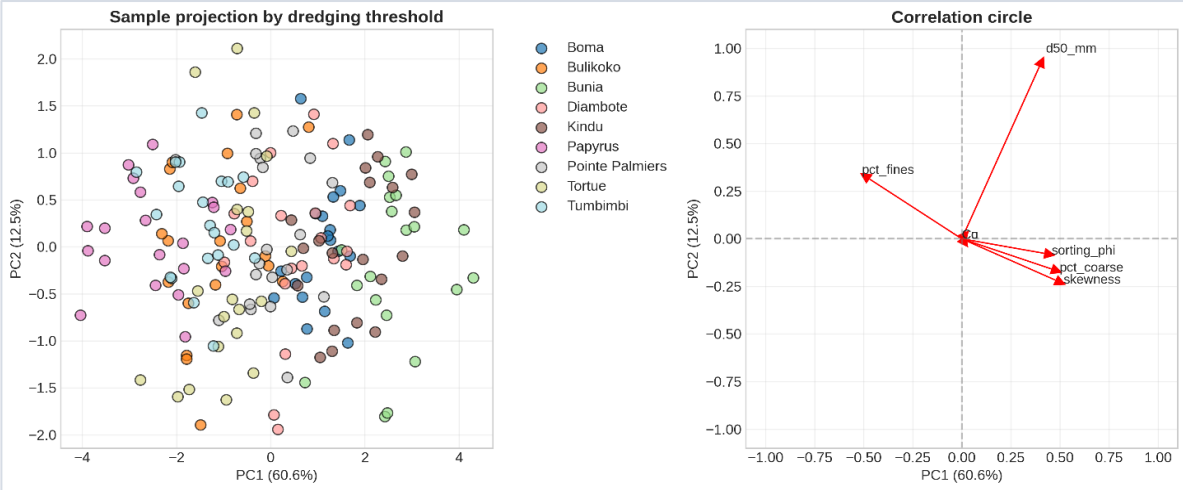


Figure 5. PCA of grain-size parameters by dredging threshold

Left panel shows sample projections: dredged channels (Boma, Kindu, Bunia) plot on positive PC1 side, depositional zones (Papyrus, Tumbimbi) on negative side. Right panel shows correlation circle.

Table IV. Eigenvalues, proportion of variance, and variable loadings for the first two principal components (PC1 and PC2)

Variable	PC1 (60.6%)	PC2 (12.5%)	Cumulative (73.1%)
D50 (mm)	**+0.482**	+0.421	Main coarse vector
Fine fraction < 63 µm %)	**-0.458**	+0.162	Deposition indicator
Coarse fraction (µm %)	**+0.491**	-0.105	Dredging winnowing indicator
Sorting index (σ, ϕ)	+0.385	**-0.512**	Hydrodynamic energy
Skewness (Sk)	+0.402	**-0.548**	Distribution asymmetry
Uniformity Coefficient (Cu)	+0.082	+0.015	Grading characteristic
Curvature Coefficient (Cc)	+0.065	+0.008	Curve shape
Eigenvalue	**4.24**	**0.88**	

3.5. Influence of dredging volume on grain-size characteristics

The left panel of Figure 6 shows the relationship between annual dredging volume and D50 in dredged channels (Boma, Kindu, Bunia). A weak positive correlation is observed (R^2 = 0.004, p = 0.3847), indicating no statistically significant relationship at the 95% confidence level. This suggests that other factors, such as hydrological regime or spatial variability, may modulate the direct effect of dredging intensity on sediment coarsening.

The right panel presents D50 boxplots classified by dredging intensity (Low, Medium, High). A descriptive increase in median D50 is shown from low- to high-intensity categories. However, because the linear regression between annual dredging volume and D50 was not statistically significant (R^2 = 0.004, p = 0.3847), the apparent boxplot trend should not be interpreted as evidence that dredging intensity causes sediment coarsening without an appropriate inferential comparison among intensity classes.

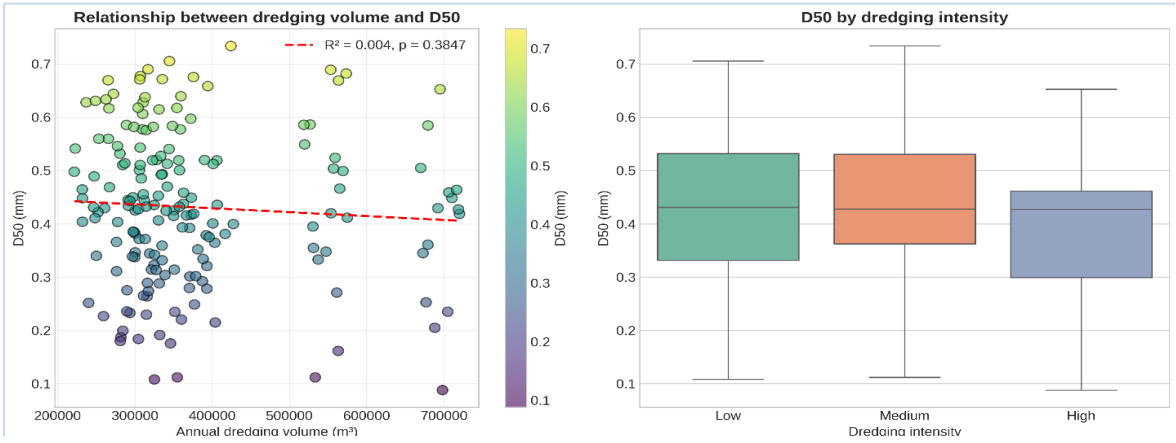


Figure 6. Influence of dredging volume on D50

Left panel shows weak correlation (R^2 = 0.004, p = 0.3847). Right panel shows D50 increases with dredging intensity (Low to High).

3.6. Hydrological influence on grain-size characteristics

The left panel of figure 7a presents reach-averaged D50 values across all nine thresholds for each hydrological phase. The reported means range from 0.27 mm during low water to 0.30 mm during high flood. These reach-scale values are lower than the highest threshold-specific means because they aggregate both coarser and finer sedimentary environments. The manuscript does not report an inferential test comparing hydrological phases; therefore, differences among phases should be interpreted descriptively.

The right panel presents a D50 correlation matrix between thresholds. Strong positive correlations (r > 0.70) are reported for some threshold pairs, with moderate or weaker correlations for others. These correlations indicate similarity in temporal variation but do not, by themselves, identify common sediment sources or transport pathways.

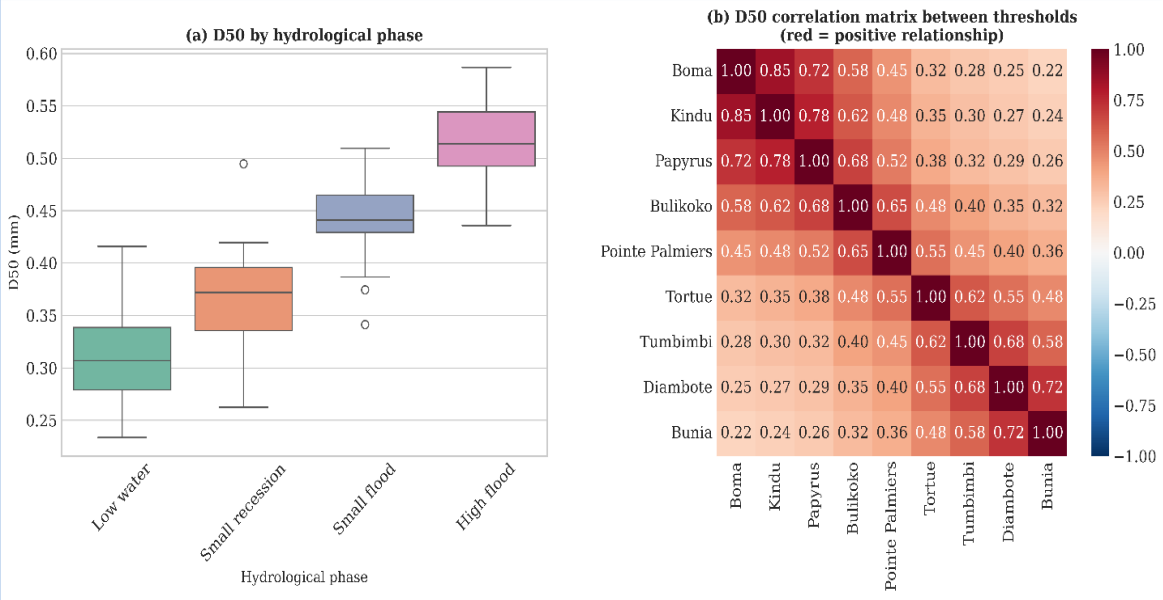


Figure 7. Hydrological influence on grain-size characteristics. (a) Reach-averaged D50 across all nine thresholds by hydrological phase. (b) D50 correlation matrix between thresholds.

3.7. Information saturation curves for grain-size monitoring

The left panel of figure 8 presents the general information-saturation curve. The text reports information values of 33% at two thresholds, 63% at five thresholds, and 87% at ten thresholds, with diminishing marginal gains as additional thresholds are included. These numerical values do not support the simultaneous statement that 95% information saturation is reached at five thresholds. Accordingly, the exact number of thresholds required to reach a 95% target cannot be established from the values currently reported and should be recalculated or corrected from the underlying analysis.

The right panel reports conditional saturation thresholds of four, five, and seven sampling thresholds for low-, medium-, and high-intensity dredging categories, respectively. These estimates may inform adaptive sampling, but they should be retained as provisional until the information-gain calculation and the 95% saturation criterion are reconciled and independently validated.

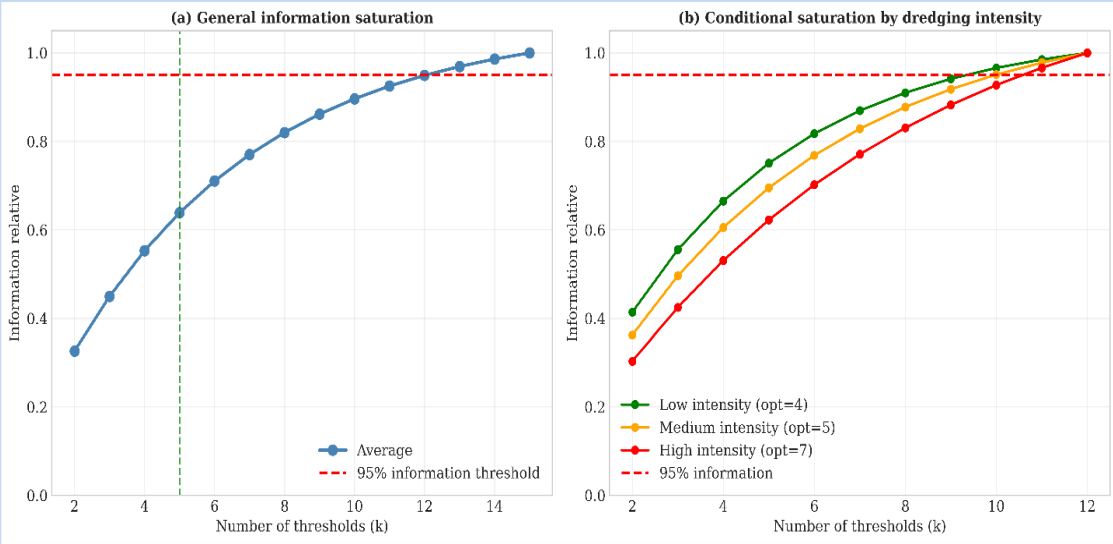


Figure 8. Information-saturation curves for grain-size monitoring

The general curve shows diminishing information gain as additional thresholds are included; the reported numerical values require reconciliation with the stated 95% saturation criterion. The conditional curves report different threshold requirements by dredging-intensity class.

4. Discussion

The results demonstrate clear spatial differentiation in grain-size characteristics across the Boma–Malela thresholds. Coarser sediments and lower fine fractions occur at several actively dredged thresholds, whereas Papyrus and Tumbimbi show finer textures. This pattern is compatible with selective sediment transport and hydraulic sorting, but the observational analyses presented here do not isolate dredging from hydrological, geomorphological, or spatial confounding. Causal attribution to dredging should therefore be made cautiously.

Recent hydrodynamic investigations of the Congo River using Acoustic Doppler Current Profiler (ADCP) measurements reported flow velocities locally exceeding 3 m s−1 (Tshimanga et al., 2022), indicating hydraulic conditions capable of maintaining fine particles in suspension over long transport distances. In parallel, Bissemo et al. (2023) demonstrated that fine sands constitute the dominant suspended grain-size fraction under both low- and high-flow conditions, confirming the preferential mobility of fine sediments throughout the hydrological cycle. The observed grain-size gradient in the present study (D50=0.28−0.55 mm) considerably exceeds the amplitude of natural seasonal variability previously described for the lower Congo system (Giresse et al., 1990; Laraque et al., 2009), suggesting that dredging activities substantially amplify pre-existing hydrosedimentary contrasts.

Variance decomposition based on the ANOVA sums of squares presented in table III indicates that between-threshold variation accounts for approximately 63.3% of total D50 variation and 59.3% of total fine-fraction variation. These results support substantial spatial structuring among thresholds. The previously stated 74%/26% partition is not reproducible from the numerical values presented in the manuscript and should not be retained unless its calculation is explicitly documented and verified.

The information-saturation analysis is potentially useful for optimizing sediment monitoring in dredged fluvial environments. However, the numerical values reported in Figure 8 and the accompanying text are internally inconsistent: an information value of 63% at five thresholds cannot simultaneously represent achievement of a 95% target. Consequently, the proposed five-threshold optimum should be considered unverified until the saturation calculation is corrected and reproduced from the underlying data.

Conditional analyses report that more thresholds are required in high-intensity than in low-intensity dredging categories. This pattern is compatible with greater spatial heterogeneity under some operational conditions, but its interpretation depends on validation of the saturation metric and on adequate control for hydrological and spatial covariates. The present results

therefore support this relationship as a working hypothesis rather than a demonstrated causal effect.

Hydrological conditions also appear to influence grain-size patterns and the reported saturation curves. The manuscript describes different sampling requirements among hydrological phases, but no inferential comparison of these saturation estimates is presented. The low-water period may be operationally useful for monitoring because hydrological variability is reduced, but the proposed phase-specific threshold numbers require validation using the corrected saturation procedure.

Some limitations should nevertheless be acknowledged. First, the temporal coverage of the dataset (2023–2025) does not capture decadal-scale variability associated with long-term hydrological fluctuations or channel evolution. Second, dredging-volume records were unavailable for the 2020–2022 period, limiting retrospective analysis of operational intensity. Despite these limitations, the methodological framework developed here is transferable to other large tropical river systems facing similar challenges related to navigation maintenance, sediment management, and anthropogenic alteration of fluvial processes.

5. Conclusion

This study evaluated grain-size variability and information saturation using 180 sediment samples collected across nine dredging thresholds in the Boma-Malela reach of the Congo River, together with long-term water-level records (1960–2025) and dredging records for 2015–2024. The results demonstrate statistically significant spatial differences in D50 and fine-fraction content among thresholds and support the importance of spatially representative sediment monitoring.

Based on the ANOVA sums of squares, between-threshold variation accounts for approximately 63.3% of total D50 variation and 59.3% of total fine-fraction variation. These findings indicate that a substantial proportion of granulometric variability occurs among thresholds, supporting monitoring designs that prioritize spatial coverage across the study reach.

The information-saturation analysis suggests diminishing returns as additional thresholds are sampled. However, the reported information values do not verify the stated 95% saturation point at five thresholds. The minimum number of thresholds required to achieve a 95% information target therefore remains to be confirmed after recalculation of the saturation metric.

Dredging intensity and hydrological regime are associated descriptively with differences in sediment characteristics and reported sampling requirements, but the causal interpretations and exact condition-specific threshold numbers require further statistical validation. The low-water period may nevertheless provide a practical monitoring window because of reduced hydrological variability.

The proposed information-saturation framework is potentially transferable to other dredged river systems, but external applicability should be tested with independent datasets. Future work should prioritize reconciliation of the saturation calculations, validation of threshold requirements on independent campaigns, explicit modeling of hydrological and spatial covariates, and extension of the analysis to additional reaches..

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Conflict of Interest

The authors declare no conflicts of interest. The CVM provided data but had no role in study design, analysis, interpretation, or manuscript preparation. The opinions expressed are solely those of the authors.

Ethical Considerations

This study did not involve human participants, animal testing, or sensitive interventions. Sediment sampling was conducted as part of routine CVM monitoring activities in accordance with DRC national regulations. No endangered species, protected areas, or cultural heritage sites were impacted. The research complies with institutional and national ethical standards.

Author Contributions

A.L.L.: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Validation, Visualization, writing original draft, Writing review & editing.

N. K.: Writing review & editing, Language editing.

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