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Active morphological factors determining the locations of sand mines in dry-river channels

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ABSTRACT

In Kenya, most of the construction sand is derived from dry riverbeds. Due to rampant nature in which sand mining is carried out in these rivers, adverse environmental and social effects have been reported. In order to ensure sustainable sand mining activities, this study assessed active morphological factors determining sand abundance in the seasonal river Tyaa in Kitui, Kenya. The study adopted quantitative research design. Purposive sampling was used to select river Tyaa due to uncontrolled sand mining that was taking place there. Systematic sampling at 20 meter intervals was used while collecting data at the stretches of the river channel, thus constituting 2,000 meters in total. Data on independent variables, namely the river channel's width, depth, slope angles, bank position, weathering status, vegetation status, and erosion status was collected using physical measurements and logic guided observation. Binary logistic regression analysis was used to analyze the data, giving marginal effects and respective p-values. The study established four statistically significant factors responsible for sand abundance in the dry river channel's namely depth (p=0.001), width (p=0.001), slope angles (p=0.001) and bank position (p=0.001). The study concluded that these factors should be observed while siting sand mines along dry river channels to mitigate adverse environmental effects. The study recommended that National Environmental Management Authority of Kenya should apply the findings of this study in the establishment of the locations of sand mines and monitoring of the mining process in line with the existing guidelines and regulations.

Keywords: dry-river channels, morphological factors, sand abundance, sand mining, sustainable development

INTRODUCTION

Siting of the locations of sand mines in river channels, and specifically dry river channels, should primarily be determined by sand abundance. The abundance of sand in a river channel is a function of several natural watershed factors such as erosion status, slope angle, density of vegetation cover, and the climate of the area (Pankaj, 2021; Yang et al., 2015). In addition, the channel width, depth and meanders also influence the amounts of sand deposited in a river channel (Leton et al., 2020). Charlton further stated that the stream velocity is higher at the constricted portions of the channel, a factor which promotes hydraulic erosion as opposed to the wider and shallower sections of the river, where the deposition processes take place due to reduced velocity of the stream current.

According to Davis (1899), the stage of the river significantly influences the abundance of sand in the river channel, whereby increasing amounts of sand is noted from the youthful to the old stage, where the main activity is deposition. From the findings by Davis (1899), there is little sand deposits at the youthful stage of the river because the rivers main activity is erosion, coupled with a steep channel gradient, which promotes removal of the eroded materials. The middle stage of the river is marked by a near equilibrium state between the inflow of water and sediments, a factor that causes a constant riverbed elevation resulting from moderate amounts of sand deposited. The old stage of the river is characterized by aggradation of the river channel. This is because of the river's loss of the kinetic energy as a result of low slope gradient, which promotes deposition.

Several factors including slope, discharge and vegetation have been shown to have an effect on abundance of sand in a river channels. A study on the alluvial river channel evolution by Yanites (2018) established that changes along the river channel such as local uplift, change in resistance of the rocks over which the stream flows as well as discharge variation may influence abundance of sand on a river channel. This is because such factors promote river rejuvenation, which acts against deposition of materials on a river channel. A study on ephemeral rivers in Spain by Henriques et al. (2021) focused on the significance of vegetation on a river system. The study established that the presence of riverine vegetation along the riverbanks helped to reduce the bank erosion, hence protecting the sand reserves deposited on the shifting convex banks of the river channel. The roots of such vegetation bind the sand materials thus making them firm and resistant to quick removal by the river current.

Riverbank erosion modulates changes in channel morphology and patterns, and it takes place in two processes namely fluvial action and mass wasting. The impact of the channel flow is usually greater on the outer banks leading to fluvial undercutting of the bank toe eventually causing a slide (Chilikova-Lubomirova, 2020). This process generates sediments to the river channel, which are then transported downstream. According to Ferguson et al. (2022) and Huggett (2007), the relatively low gradient of the inner banks promotes deposition of some load from the sediment laden flow proceeding from the outer banks. These fluvial processes on the alternate banks not only determines sand abundance in different points in the channel but also perpetuates the migration of the river meanders.

As established from several studies on sand mining in Kenya, bulk of construction sand is usually obtained from the dry riverbeds traversing dryland areas (Gitonga, 2017; Muiruri & Amimo, 2017; Wambua, 2015). Uncontrolled sand mining activity in these riverbeds has generated a lot of environmental effects such as soil erosion, loss of riparian vegetation, loss of water bound in sand aquifers, river channel incision, among others (Muiruri et al., 2020; Nabegu, 2013, 2014).

The objective of this study is to establish the key morphological factors influencing sand abundance in ephemeral river channels to inform proper siting of sand mines. In line with that, this study assessed how morphological factors such as erosion status, slope angles, width, depth, vegetation cover status, weathering status/geology, and riverbank position influence the sand abundance in the seasonal river Tyaa.

Due to the significant role of sand resource in the construction industry, there is need to exploit it in a sustainable way since that would guarantee sustainable development. Therefore, in light of the fast burgeoning demand for construction sand in the country (Mwaura, 2013), this study generates relevant technical information to help in guiding proper siting of the locations of sand mines along the seasonal river channels based on sand abundance criteria. This shall help mitigate the adverse environmental effects resulting from rampant sand mining activities. This type of information remains scarce in studies carried out in Kenya's dryland areas, and its availability will greatly enrich the existing technical literature and promote sustainable dry riverbed sand resource exploitation, hence making a positive contribution towards actualizing sustainable development.

METHODOLOGY

Research Design

This study used a quantitative research design. According to Asenahabi (2019), quantitative research design involves the numerical presentation and manipulation of observations for the purpose of describing and explaining the phenomena that those observations reflect. This research design enabled the researcher to obtain data through physical measurements on the various morphological variables influencing sand abundance in river Tyaa.

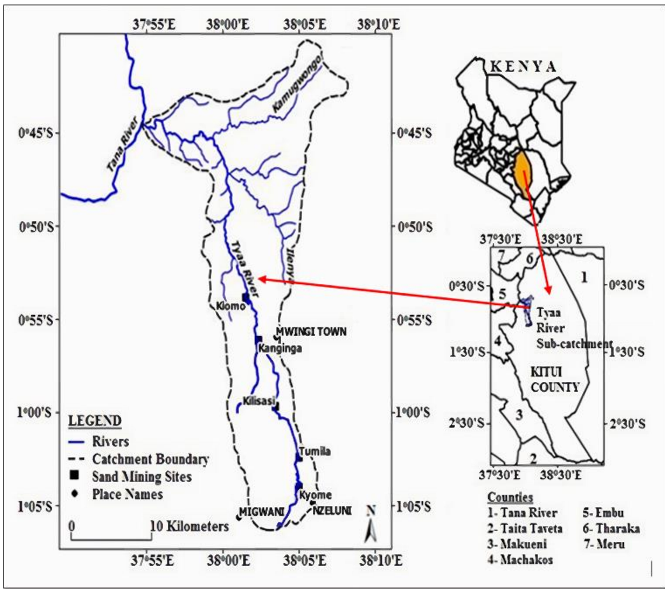

Figure 1. River Tyaa sub-catchment in Kitui Country (GOK, 2010)

Study Area

This study was conducted in Kitui County in the Eastern Region of Kenya. Kitui County covers an area of 30,437 km^2 (Republic of Kenya, 2018). The County has an altitude ranging from 400 m to 1,800 m; and is located between longitudes 370 00' E and 380 30' E, and latitudes 000 50' S and 010 00' S (**Figure 1**). On the other hand, river Tyaa and on which this study was carried out lies between longitude 370 55' E and 380 05' E and latitude 10 05' S and 00 45' S (**Figure 1**).

Climate and vegetation

Kitui County is a semi-arid area which falls within the Tana Catchment drainage basin (Republic of Kenya, 2014). According to Omoyo (2020), it have an average annual rainfall, evaporation and temperatures of 600 mm, 1,150 mm and 28^{o}C, respectively. In addition, the area has a bimodal rainfall pattern, with the long rains from March to May and the short rains from November to December (Mwatu et al., 2020). This results in the seasonal rivers in this area to experience flows during the said months and in extension for a time period not exceeding a week after the rains.

The evaporation rates of this area range from 1,800 mm to 2,400 mm per annum (Ngugi et al., 2020). This implies that the total annual evaporation rates exceed the total annual rainfall. As a result, the area suffers shortage of surface water, with the inhabitants left dependent on water embedded in sand aquifers on the dry riverbed and protected from evaporation (Brummelkamp, 2020; Ngugi et al., 2020).

Due to its hot and dry climate, the area is characterized by thorny drought resistant vegetation such as Acacia, which is scantly distributed. Additionally, the area develops tall grasses during the rainy season which fades out shortly after the rains.

Geology and drainage

The dominant rocks in this area are metamorphic rocks namely biotite gneisses, leucocratic gneisses and granulite's, all of which are of sedimentary origin (Pulfrey, 1954). These rocks have over time undergone intensive chemical and physical weathering, leading to formation of a thick crust of weathered regolith. The soil covering the area is basically red-brown sandy type, but of low fertility index due to scarcity of moisture (Mburu, 2013). This type of soil supports the growth of thorny bushes and scanty grass, which makes the area to experience severe soil erosion especially when it rains.

From its general topography, the study area's slopes run from west to east, with most rivers traversing the area having their origins in the higher grounds in the west. Most of these rivers traversing the area are ephemeral flows in their middle stages and joins river Tana downstream. Further, owing to the sandy nature of the soils covering the landscape, the area is characterized by a high rate of infiltration in events of light rains, and profound amount of surface flows during high rainfall events due to the presence of scanty vegetation cover (Muthomi et al., 2015).

Socio-economic activities

Due to the semi-arid nature, the area is considered marginal, with limited agricultural activities. However, the dominant economic activity in this area is rain-fed agriculture in its broad coverage. According to GOK (2010), the dominant economic activity in Kitui County is livestock farming, whereby drought resistant species of beef cattle and goats are reared. In addition, cereal crop growing of sorghum and millet are also carried out, though in small scale basis owing to the low crop production potential of the area due to low and unreliable rainfall received in the area. Fruit farming of mangoes is also practiced by most farmers.

Kitui County has a high poverty index of 61.56% compared to the national index of 45.2%, and rain-fed agriculture is not a well rewarding enterprise either in the area even though it is being practiced (GOK, 2010). Therefore, sand mining from the seasonal riverbeds provides an alternative income to the local communities. According to Republic of Kenya (2014), sand mining fetches appreciable income to those involved in it. However, this study noted that it is associated with local conflicts between the sand miners and the members of the community, since it interferes with their sources of water. The latter is obtained from the sand reserves on the dry riverbeds, and these are the sources the local community largely depends on during the dry season. Thus, this study assesses key morphological factors influencing proper siting of the locations of sand mines along the dry river channel, which would in turn guarantee minimal environmental effects hence alleviating some environmental based conflicts in study area.

The Scope of the Study

The study targeted the reaches measuring 400 meters on either side of the sampled five active sand mining sites identified along river Tyaa (**Figure 1**). These sites were selected due to their ease of accessibility. In addition, the study considered the said reaches as an adequate representative sample of river Tyaa, based on their cumulative lengths and spatial distribution.

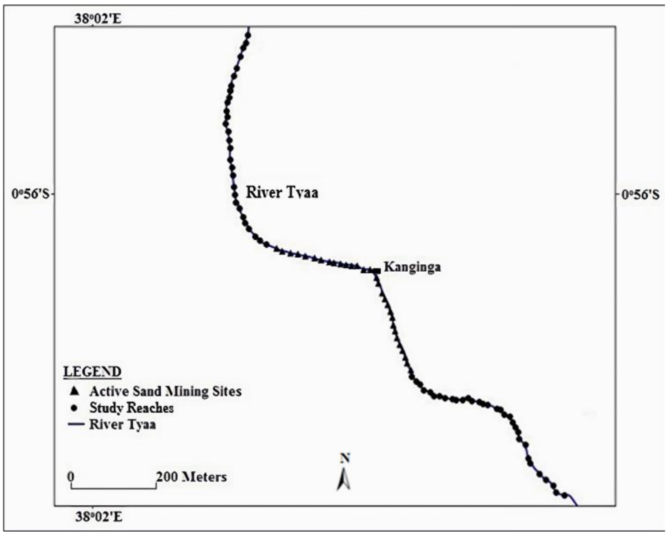

Figure 2. Sample of systematic sampling in reaches bordering active sand mines (Source: Authors' own elaboration)

Sampling Techniques

The sampling for this study was done at two levels, namely the river channel and the study reaches along the selected river channel. The purposive sampling technique was used to select river Tyaa. This was informed by the existing literature and the common knowledge that most supply of construction sand in Kenya comes from ephemeral rivers, and that unregulated sand mining was taking place in river Tyaa. These aspects would help the study generate important information that would lead to proper siting of the locations of sand mines in river channels. This will help in preventing related sand mining adverse effects on the environment, particularly in the dry-land areas.

Secondly, systematic sampling was then employed at 20 meters intervals while collecting data on variables of interest, as illustrated on Kanginga site (**Figure 2**). Systematic sampling was preferred because it ensured adequate coverage, hence presenting detailed data which would promote accurate analysis and synthesis of the factors influencing sand abundance in the ephemeral river channel.

Data Collection

To establish the active morphological factors influencing sand abundance in river Tyaa, data was collected on various independent variables such as bank **position** (concave and convex) of the river channel which was obtained through direct observation; **slope angles** of the river channel, which was obtained through physical measurements using an Abney Level; river channel's **width** and **depth** which were obtained through physical measurements using a hand held GPS; and finally, **vegetation** cover status, **weathering** status/geology and **erosion** status, all of which were acquired through logic aided applications (**Appendix A**). Whereas the dependent variable in this study was sand abundance in river Tyaa.

Data Analysis

Quantitative method was used in data analysis, presentation, and interpretation of study results. The method helped in making inferences into the relationships existing between dependent and independent variables in this study.

Table 1. Binary logistic regression model output

Variables	Marginal effects	Standard error	Z	P>|z|
Bank position	-0.7498	0.0658	-11.386	0.001***
Slope angles	-0.2344	0.0504	-4.647	0.001***
Width	0.1465	3.9948	0.036	0.001***
Depth	-1.4454	0.2913	-4.961	0.001***
Vegetation status	-0.0213	0.1120	-0.190	0.849
Erosion status	-0.0833	0.0993	-0.838	0.402
Weathering status	0.0769	0.0995	0.773	0.440

Note. Significance codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

In establishing active morphological factors influencing sand abundance along river Tyaa (**dependent variable**), data on independent variables namely the bank position, slope angles of the channel, vegetation cover status, weathering status/geology, erosion status and the river channels width and depth were imported into R-statistical software environment and the binary logistic regression analysis carried out (Tranmer & Elliot, 2008). This generated the marginal effects (MEs) and the respective p-values, which helped to point out the significant morphological variables influencing abundance of sand in the river channel.

The binary logistic regression analysis (equation 4) predicts presence or absence of a characteristic or outcome based on values of a set of predictor variables. Logistic regression models (LRMs) belongs to a broader class of generalized linear models (GRMs). However, LRM's are distinguished from the ordinary GRM's by the range of their predicted values, the distribution of the predicted error terms and the assumptions of the variance of the predicted responses. Simply, logistic regression can be understood as a pursuit for $\boldsymbol{\beta}$ parameters that best fit.

Whereby,

$$Y = \left\{e^{\beta_0+\beta_1 X_1 \ldots + \beta_n \times n + E}\right\} > o, \tag{1}$$

where $\boldsymbol{e}$ is the exponential function, $\boldsymbol{\beta_0}$ is the $\boldsymbol{Y}$ intercept, $\boldsymbol{\beta_1}$ is the gradient of variable $\boldsymbol{X_1}$, while $\boldsymbol{X_1, X_2, \ldots, X_n}$ represents all the other independent variables considered in the model. $\boldsymbol{E}$ is an error factor spread by the standard logistic distribution (latent variable). The error term $\boldsymbol{E}$ is not observed hence termed "latent". Instead these errors are calculated by an iterative search process, usually carried out using R statistical software.

GLM construction for predicting, for instance, the probability ($\boldsymbol{P}$) of sand abundance in a dry river channel based on the dataset of the distinct parameters namely the bank position, slope angles of the channel, vegetation cover status, weathering status/geology, erosion status and the river channels width and depth would take the form $\boldsymbol{P(x)}$:

$$P(x) = \frac{y}{1+y}. \tag{2}$$

Assuming that

$$y = \beta_0 + \beta_1^p + \beta_2^a + \beta_3^v + \beta_4^g + \beta_5^e + \beta_6^w + \beta_7^d + E, \tag{3}$$

where $\boldsymbol{p}$ is bank position, $\boldsymbol{a}$ is slope angles of the channel, $\boldsymbol{v}$ is vegetation cover status, $\boldsymbol{g}$ is weathering status/geology, $\boldsymbol{e}$ is erosion status, $\boldsymbol{w}$ is channels width, and $\boldsymbol{d}$ is channels depth.

Then,

$$P(x) = \frac{e^{(\beta_0+\beta_1^p+\beta_2^a+\beta_3^v+\beta_4^g+\beta_5^e+\beta_6\times w+\beta_7\times d+E)}}{1+e^{(\beta_0+\beta_1^p+\beta_2^a+\beta_3^v+\beta_4^g+\beta_5^e+\beta_6\times w+\beta_7\times d+E)}}. \tag{4}$$

Given that bank position ($\boldsymbol{p}$) is the sole determinant of sand abundance, then the probability of sand abundance shall be:

$$P(x) = \frac{e^{(\beta_0+\beta_1^p+E)}}{1+e^{(\beta_0+\beta_1^p+E)}}. \tag{5}$$

If $\boldsymbol{P(x)} \geqslant 0.5$, then its chances of occurring is **0**, meaning there is low sand abundance and if $\boldsymbol{P(x)} \leqslant 0.5$, then its chances of occurring is **1** and the sand abundance is high. The LRM output value has only two choices, high or low sand abundance, coded as **1** and **0**, respectively.

To obtain the coefficients of $\boldsymbol{\beta_0, \beta_1, \beta_2, \ldots, \beta_n}$, a statistical summary of the tabulated dataset in R statistical software was generated. The cases are independent, and the variables are not linear combinations of each other. Finally, to obtain MEs (partial variations) of the respective predictor variables, the package 'margins' is employed hence giving a more simplified model output (**Table 1**).

Model development and optimization

The data was imported into R-statistical software's environment whereby it was divided into model training data (70%) and model testing data (30%) as recommended by (Kim et al., 2018). Training data was used to develop a binary LRM as well as optimizing its accuracy, while the testing data was used to test the accuracy of the model.

The model testing results indicated that the model was able to predict the placements of the data with an accuracy of 85%. In addition, the model gave out MEs and p-values which indicated the level of statistical significance of each variable in regard to sand abundance in river Tyaa's channel.

RESULTS AND DISCUSSION

The results showed that four variables namely the riverbank position, channel width, depth and slope angles were statistically significant in influencing sand abundance in river Tyaa channel. This was deduced from MEs and their respective p-values. **Table 1** shows the results based on LRM output for individual independent variables.

Effect of Riverbank Position on Sand Abundance

The results showed that riverbank position had actively contributed to abundance of sand in a river channel as seen from MEs and p-values of riverbank position, respectively (**Table 1**). This implies that the convex banks had a sand abundance of 74.9% more compared to the concave banks which is significant as indicated by the respective p-value 0.001. This finding agrees with that of Ferguson et al. (2022), who established that the convex banks were characterized by deposition while the concave banks were characterized by active erosion. In the same vein, the findings agree with those of Chilikova-Lubomirova (2020), who expressed that the concave banks experience greater hydraulic impact of the river water current, a factor that weakens the riverbank thus promoting removal of materials unlike in the convex banks.

The Role of Slope Angles on Sand Abundance

The results indicated that slope angles were active contributors of sand abundance on the river channel, as seen from MEs and p-values, respectively (**Table 1**). This means that a unit reduction in slope angle led to 23.44% increase in abundance of sand, which is significant as indicated by the respective p-value 0.001. The convex banks were established to have lower slope angles and high sand abundance compared to the concave banks. According to Chilikova-Lubomirova (2020), low river channel angles characterizing the convex banks encourage deposition of sand since it facilitates slow movement of water. On the other hand, Dutta et al. (2021) pointed out that concave banks are characterized by active erosion, a factor that discourages deposition and accumulation of sand since the slope angles on such banks are high.

River Channel Width and Sand Abundance

As deduced from MEs and p-values in **Table 1**, a unit increase in river channel width led to 14.65% increase in sand abundance, which is significant as pointed out by the respective p-value 0.001. This implies that sand abundance increases with increase in width of a river channel. The study established that an increase in channel width causes spreading out of the river water thus compromising its speed hence the load carrying ability. Reduced speed of the river water leads to deposition at wider sections of the river channel as opposed to the narrow sections of the channel which are often characterized by high speed of water flow which in turn promotes erosion as opposed to deposition. Armanini (2018) arrived at similar results in a study on the geomorphic classification and evaluation of river channel width in relation to sand bars.

River Channel Depth and Sand Abundance

The channel depth was established to influence sand abundance along the river channel. MEs and p-values in **Table 1** indicate that a unit decrease in the river channel depth leads to 144.54% increase in sand abundance, which is significant as indicated by the respective p-value 0.001. It is therefore evident that shallower sections of the river channel are characterized by high sand deposition and accumulation. This finding agrees with that by Dutta et al. (2021), who found that narrow and deep sections of the river channel are characterized by high speed of the river current since they act as constrictions, a factor that promotes erosion processes as opposed to deposition. Increase in depth of a river channel is usually coupled with increasing slope angle, a factor that discourages deposition. Active deposition of sand on a river channel leads to reduced depth and slope angles, an aspect that promotes deposition hence high sand abundance.

SUMMARY OF FINDINGS, CONCLUSION, AND RECOMMENDATIONS

The study established that there were four significant morphological variables that were responsible for sand abundance in the river channel namely the river channel width (p=0.001) depth (p=0.001), slope angle (p=0.001), and bank position (p=0.001) as shown by their respective p-values.

Based on the above findings, the study concluded that there is need to observe these four key channel morphological factors while siting the locations of sand mines in ephemeral rivers. Siting the locations of sand mines in zones of high sand abundance would minimize adverse environmental effects that result from rampant sand mining.

The study recommended that siting of the locations of sand mines should be done appropriately by regulatory authorities such as National Environmental Management Authority of Kenya (NEMA) using sand abundance criteria. In respect to that, sand mines should be located at the shallow convex banks with low slope angles and at the wide sections of the river channel to ensure minimal adverse environmental effects. Further, there should also be strict enforcement of sand mining guidelines and regulations by NEMA on riparian belts.

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Data sharing statement: Data supporting the findings and conclusions are available upon request from corresponding author.

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APPENDIX A

Guidelines on Logic Application in Data Collection on Some Physical Variables (Adapted from Ekström et al., 2018)

Table A1. Data on sand abundance status

S/N	Sand abundance status	
	High (1)	**Low (0)**

Note. Sand occupying the riverbed at levels above 1.5 metres from the top of the riverbank was termed as high while that occupying the riverbed at levels below 1.5 metres from the top of the riverbank was considered low.

Table A2. Data on vegetation cover

S/N	Vegetation cover status	
	High (1)	**Low (0)**

Note. Slopes with less than 30% vegetation cover were deemed to have low vegetation, while those with above 30% vegetation cover were termed high.

Table A3. Data on erosion status

S/N	Erosion status	
	High (1)	**Low (0)**

Note. Slopes characterized by both rills and gullies and are scantly vegetated were considered highly eroded, while those characterized by simple rills but without galleys and were vegetated termed as lowly eroded.

Table A6. Data on channel width, depth, and slope angles

S/N	Channel width, depth, and slope angles		
	Width (meters)	**Depth (meters)**	**Slope angles**

Note. This involved measuring and recording the actual values of the river channel's width, depth, and slope angles.