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Full Length Research Paper

Effect of development on the morphology of Motoine/Ngong River Channel, Kenya

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The geomorphic response of a stream to urbanization is a common interruption to the channel geometry equilibrium with dire consequences of sedimentation of reservoirs, mass wasting processes and water quality deterioration. The channel morphology was investigated with respect to deforestation, an increase in built-up surfaces and bank instability within the Motoine/Ngong River sub-catchment of the Nairobi River Basin in Kenya. The study examined the relation between growth of built-up surfaces and channel morphology at four representative sampling points along the course of the River for the period 1976 and 2013 for which there was sufficient record. The findings indicate a steady spatial increase of the built-up surfaces by 50.9% during the period. The impervious surface reduced infiltration capacity, simultaneously increasing surface runoff and stream flow and seasonal flow variability. The increased discharge caused bank erosion in some places and sedimentation in the others, a sinuous channel morphology characterized by river cliffs, river bank cavities, collapsing overhanging banks, tension cracks, slip-off slopes, sand bars and a braided river channel. The changing storage capacity of the Nairobi dam is currently unknown due to lack of instrumentation and hydrological records.

Key words: Watershed/catchment, urbanization, built-up surfaces, erosion, sedimentation, channel morphology, Motoine/Ngong River.

INTRODUCTION

Urbanization is a pervasive and fast growing form of land use (Paul and Meyer, 2008) especially in developing countries as in Kenya. It is projected that more than 60% of the world's population will live in urban areas by 2030 (UN, 1997). The increasing population and rapid economic developments are key drivers of land use change (Mundia and Aniya, 2006). Land use change is responsible for loss of vegetation cover, removal of soil cover and replacement with impervious surfaces, leveled slopes, increase housing density and other built infrastructures that generate impervious surface and artificial drainage channels.

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Table 1. The effect of land use sequence on relative sediment yield and channel stability.

Land use	Sediment yield	Channel stability
Cropping	Moderate to heavy	Some aggradation and increased bank erosion
Retirement of land from cropping	Low to moderate	Increasing stability
Urban construction - early phase	Very heavy	Rapid aggradation and some bank erosion
Stabilization and late phase of construction	Moderate	Degradation and severe bank erosion
Stable urban and limited construction	Low to moderate	Relatively stable

Source: Modified from Krhoda, 1986.

The hydrological consequences of urbanization include higher surface runoff, reduction of lag time between precipitation and runoff and increased peak flows and reduced low flows (Rose and Peters, 2001; Krhoda, 2002). Urban development results to an initial phase of sediment mobilization, characterized by increased sediment production and sedimentation within channels (Table 1; Chin, 2006). Watershed erosion supplies only about 25% of the sediment to a river channel system in contrast to bank erosion and bluff retreat that contribute 41% (Foyle and Norton, 2007). The rest of the sediment is contributed by bank erosion especially during floods (Zang et al., 2006). Drastic increase in channel sinuosity and braiding have been attributed to increased sediment discharge (Ahmed and Fawzi, 2009; Thakur et al., 2011).

The challenges of sediment control in Nairobi have been investigated (Krhoda, 1986), however the contribution of bank erosion to sedimentation in rivers have not been investigated before. It is also known that sedimentation aggravates severity of flooding. The presents study therefore investigates the impact of urbanization on channel erosion in Nairobi, Kenya. The study was carried out in Motoine/Ngong river sub-catchment.

CATCHMENT CHARACTERISTICS OF THE STUDY AREA

The study area is the Motoine/Ngong river sub-catchment covering an area of about 127 km^2 is part of the upper Athi River basin in Kenya. The river is 42.3 km long (Kahara, 2002), has its source from Motoine swamp near Dagoretti forest (Monene, 2014) and flows into the Nairobi Dam before becoming Ngong River (Figure 1). The Ngong River passes through Nairobi's Industrial Area before its confluence with Nairobi River. The basin falls under a wet climatic zone with a mean annual rainfall ranging from 1000 to 1200 mm (UNEP, 2003). The long rains come in mid-March to mid-May, and the short rains during the months of November and December. The wettest month is April for the long rains, with average monthly rainfall of approximately 223 mm. November records highest rainfall for the short rains at an average of 166 mm. The driest months are August and September (FAO, CLIMWAT Database).

There are three major geological provinces within the study area. The upper part of the catchment flows over the Upper Athi volcanics which is porous and permeable thus allows percolation and as a result recharges the Motoine/Ngong River. The Lower Athi volcanics further downstream of the study area weathers in to clayey materials and therefore less conducive as an aquifer. The clay soils impede drainage and wherever slope decreases they form swamps. The third geological province, the Kirichwa Valley Tuffs, are exposed along the channel upstream of Nairobi dam. The rest of the catchment until Kangundo River Bridge is composed of deeply weathered Nairobi phonolites. Ngong river rises from an altitude of about 1,980 m a.s.l and drains into the Nairobi River at 1,525 m a.s.l (Krhoda, 2002). The catchment has a gentle slope of 1.01% except along specific channel sections where slopes range from about 7 to 19% (Figures 1 and 2).

The Motoine River rises from Riu Swamp and is heavily used in the settled Dagoretti area. As the river flows eastwards (mainly underground) for most of its course, farmers in the valley impound its water for irrigation agriculture and domestic uses. The Motoine River starts receiving agrochemical pollution right from its head water in the Dagoretti area (sediments, dairy and abattoirs), and picks other forms of pollution as it flows through the Ngong Forest and the Kibera area. The soils exposed along the channel banks are generally dark grayish brown to very dark grayish brown clay, vertisols, with a high shrink-swell potential.

METHODOLOGY

Primary data collection was done during a field survey to measure river discharge, channel geometry, and identify erosion features in 2012. Discharges were measured using a current meter OTT C2 at 4 representative river cross sections at Motoine swamp outlet, Ngong Road Bridge, Dam inlet and Kangundo Bridge.

$$Q_r = \sum_{t=1}^{n} A c_i V_i. \quad (1)$$

where

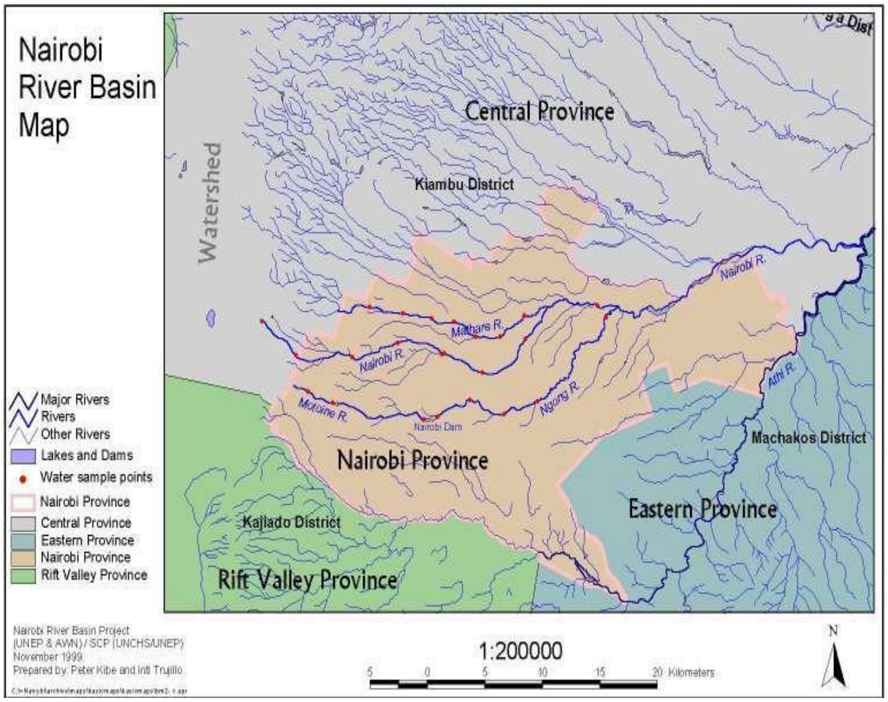

Figure 1. Basic map of Nairobi River Basin and surrounding provinces. Source: Krhoda, 2002. Nairobi River project Phase 1, UNEP/ROA, Nairobi.

Figure 2. Informal farming within the basin. Source: Krhoda, 2002. Nairobi River project Phase 1, UNEP/ROA, Nairobi.

Where: Q_r is the river discharge; Ac_i is the river cross section (m^2);V is the cross sectional velocity; i denotes any measurement in the series of velocity or cross sectional area.

Further information on historical perspective relating to land use change and floods occurrence were obtained by administering a structured questionnaire. Statistical measures of central tendencies, correlation analysis and calculation of percentages were used to determine temporal and spatial changes in land use and channel characteristics. Suspended sediments samples were collected during the rainy seasons at each cross section with discharge measurements. Sediment discharge was determined using the expression:

$$Q_s = Q_w.C_s.K \quad (2)$$

Where: Q_s is sediment discharge; Q_w is water discharge; K is a constant.

There was little discharge during the dry seasons. Secondary data was obtained from topographical maps covering the basin with a scale of 1:50,000 while geological and soil information was obtained from maps. Socio-economic and population data were obtained from census report (1999). Additional data on changes in land use were obtained from satellite imageries for the years 1976, 1984, 1995, 2002 and 2013 from the Department of Resources

Table 2. Land use changes from 1976-2013.

Land cover (%)	1976	1984	1995	2002	2013
Wetland	0.24	0.24	0.24	0	0
Bare ground	57.48	18.44	3.25	32.54	23.86
Grassland	2.14	7.59	10.84	0.54	1.3
Forest	15.18	6.50	8.68	7.59	8.68
Other vegetation	2.17	35.79	34.70	14.86	15.18
Built up area and road	22.78	31.45	42.30	44.47	50.98

Source: Monene, (2014).

Surveys and Remote Sensing (DRSRS).

RESULTS AND DISCUSSION

Land use changes between 1976 to 2013

Nairobi City has grown at a rate of 3.7% per annum since 2003 compared to 60% in the early 1960s (UNEP/ UNHABITAT/GOK/NCC, no date). The spatial change of land use/land cover between 1976 to 2013 in Motoine/ Ngong river sub-catchment is shown in Table 2. The areas covered by wetland, bare ground, grassland and forest have seen remarkable decrease in the 37 years of record. Apart from built-up surfaces the other land use patterns in the sub-catchment were bare ground, grassland, forest and other vegetation. Other vegetation pattern of land use registered an increase as well from 2.17% in 1976 to 15.18% in 2013, an increase of 600% reflecting dynamics of urban growth and land use change. Between 1984 and 2000 a large population migrated in to Nairobi City and grassland and bush were cleared to settle in the lower part of the study area. Similarly large parts of Ngong Road forest were cleared for road construction, development of schools, churches, public cemeteries and other social facilities. The built-up surfaces within the sub-catchment increased from 22.7% in 1976 to 50.9% in 2013, an increase of 124%. Mundia and Aniya (2006) attributed such changes in land use to population growth and rapid economic development of Nairobi. Increase in built-up surfaces and reduction of grassland and forest cover increase surface runoff and erosion. The hydrological implication is that as land cover is removed and replaced by pavements, the storm runoff is expected to increase, sediment transport will increase and channel geometry will change.

Water balance of Nairobi Dam

The Nairobi Dam was constructed in the late 1940's as a source of fresh drinking water for the city of Nairobi. The poundage stabilized the flood flows of the river thus impacting on channel geometry. However, over the past decades the dam has reached hypereutrophic levels and is generally of little hydrologic and socio-economic impacts. The dam is nevertheless an essential part of the river course. The water balance of the dam has been estimated from the annual rainfall, using the expression:

$$R = R_o + E_p + dS \quad (3)$$

Where: R: rainfall (mm), R_o: Runoff, E_p: Evapotranspiration, dS: Change in water storage.

The annual rainfall estimated from the isohyets over dam is about 875 mm while the surface area of the dam is 356,179 m^2. The total contribution of rainfall to the dam is 311,656m^3 per year. The evaporation rate is about 1750 mm per annum. Evapotranspiration from the water hyacinth (*Eichhornia crassipes,* which is native to the Amazon basin, Brazil) may be higher than potential evaporation and has been estimated at 3 to 4 times the rate of potential evaporation (Van den Weert and Kimmerling, 1974). The total water loss as a result of evapotranspiration is about 711,289 m^3 per annum. The loss of storage possibly has influenced the channel adjustment over the years.

River channel changes due to urbanization

Stream morphology reflects the balance between erosion and deposition processes induced by geology, gradient and energy of flow at differing flow stages. The Motoine river channel is narrow, crosses a seasonal swamp and flows over a flat section in its most upstream section. It is crossed by two bridges namely at Ngong Road and the Kangundo Road. At Bridge 1 a well cut-out channel valley and initial meanders along its course begin to form. Channel incision accompanied by increased runoff causes a deep and steep meandering channel with outcrop rocks on its bed at the Nairobi dam inlet. The valley consequently widens at the Bridge 2 and the wide and deep channel with meanders and braids form as the gradient decreases from 19% to between 10%. The mean of the study reach is 14.5%.

From the weir of the Nairobi Dam downstream the river channel is for the most part channelized as it flows through the Industrial area. Runoff from the impervious surfaces such as iron sheet roofs of the Kibera settlement as shown Figure 3 and the new Ayany Highrise Towers (Figure 4) contribute significant amounts of roof runoff into the river especially during rainstorms. During dry seasons, the amount leaving the dam through the spillway becomes a mere trickle, but when there are heavy rains, it floods. In November 2001, the flow from spillway was measured at 0.2 m^3/s. These processes result to development of very steep banks or cliffs. Watson and Basher (2006) found that undercutting occurs as a result of redirection and acceleration of flow around obstructions such as debris and vegetation within the channel.

Figure 3. Housing in Kibera informal settlement.

Figure 4. The Ayany Highrise housing scheme in Kibera Area.

Erosion of the River Banks

River bank erosion is a natural geomorphic process which occurs in all channels as they adjust their size and shape to convey the discharge and sediment supplied from the catchment. Accelerated river bank erosion is often associated with land use change. According to Watson and Basher, (2006) river bank erosion processes are classified into two, those dominated by gravitational failure (mass movement and individual grain failures) and those where hydraulic–induced failure mechanism (fluvial erosion) dominates. The mass movement and fluvial erosion are often linked and both were observed along the Motoine/Ngong river channel particularly at and around Kangundo Road Bridge. These processes or mechanisms of slope instability, operate on the bank either simultaneously or sequentially (Thorne and Furbish, 1995). The hydraulic processes at or below the water surface entrain sediment and directly contribute to erosion, involving bank undercutting, and basal cleanout and gravitational mass failure processes (including shallow and rotational slides, slab failures, earth flows and dry granular flows).

Gravitational mass failure processes

Prolonged rainfall events cause strength reduction and increase in unit weight of the materials causing the channel banks to collapse. Gray and Sotir (1996) noted failures occurring when the erosion of the bank and the bed adjacent to the bank have increased the slope angle to a point where it reaches a condition of limiting stability. Localized erosion of joint filling material, or zones of weathered rock, can effectively decrease interlocking between adjacent soil blocks thus significantly reducing the soil shear strength. The resulting decrease in shear strength may allow a previously stable soil mass to move causing slope failure. In addition, localized erosion may also result in increased permeability and ground-water flow thus affecting the stability of rock slope.

The shear strength of a soil mass is the internal resistance per unit area that the soil mass can offer to resist failure and sliding along any plane inside it. Shear strength is a term used in soil mechanics to describe the magnitude of the shear stress that a soil can sustain. On the other hand, shear resistance of soil is a result of friction and interlocking of particles, and possibly cementation or bonding at particle contacts. Rate of loading, degree of compaction, density and moisture content of the soil materials also affect its slope stability. Amongst these factors, moisture content appear to be the most significant in that water forms bridges between sand grains resulting in negative pore pressure. Permeability of the soil affects seepage pattern and water levels in the slope. This, in turn, can affect shear resistance of the material depending on the size and shapes of the particles, degree of compaction and the gradation of soil and its density (Aubeny and Lytton, 2004). Due to interlocking, particulate material may expand or contract in volume as it is subject to shear strains. If soil expands its volume, the density of particles will decrease and the strength will decrease; in this case, the peak strength would be followed by a reduction of shear stress. The functional relationship between normal stress and shear stress on a failure plane can be expressed in the following form:

$$_{f} = f( ) \quad (4)$$

The failure envelope defined by Equation 4 is a curved line. For most soil mechanics problems, it is sufficient to approximate the shear stress on the failure plane as a linear function of the normal stress. The relationship between the peak shear strength and the normal stress, σ, can be represented by the Mohr-Coulomb equation in the form:

$$_{f} = \quad + \quad (5)$$

Where: **c**: cohesive strength, resistance per unit area, : angle of internal friction, : normal stress on the failure plane, $_{f}$: shear strength.

The average normal inter-granular contact force per unit area is called the effective stress. In saturated soil, the total normal stress at a point is the sum of the effective stress (') and pore water pressure (u), or

$$= \ ' + u \quad (6)$$

The volume change behavior and inter-particle friction depend on the density of the particles, the inter-granular contact forces, and to a somewhat lesser extent, other factors such as the rate of shearing and the direction of the shear stress. The soil is free to dilate or contract during shear if the soil is drained. In reality, soil is partially drained, somewhere between the perfectly undrained and drained idealized conditions. The shear strength of soil depends on the effective stress, the drainage conditions, the density of the particles, the rate of strain, and the direction of the strain.

When soil expands its volume, density of particles and the shear strength will decrease. The shear strength of soil depends on the effective stress, the drainage conditions, the density of the particles, the rate of strain, and the direction of the strain. Slope failure occurs in high bluffs and contribute to bank erosion through the process of undercutting and removal of the toe material along the channel bank (Kiss et al., 2013). The most critical condition is strength reduction due to rapid drawdown after a high flow stage exceed the resisting forces. The resisting forces are related to shear strength of the bank materials, and expressed by Fredlund et al. (1978) as:

$$_{o} = c'+(\ -u_{a}) \tan' + (u_{a}-u_{w}) \tan^{b} \quad (7)$$

Where: $_{o}$ = shear strength (kPa), **c'** = effective cohesion (kPa), = normal stress (kPa), u_a = pore air pressure (kPa), ' = friction angle in terms of effective stress (degrees), u_w= pore water pressure (kPa), ^{b} = angle representing the rate of strength relative to friction.

The angle ' ranges between 11° and 30° with a mean of 18°. Stream flow variability causes frequent refreshing of channel bar surfaces, sometimes bar destruction and re-formation removes or minimizes vegetation on bar surfaces (Fuller, 2007). Instead the presence of vegetation cover on channel bars are indicators of channel stability and limited erosive capacity. The present research therefore investigates river channel morphology resulting from an urbanization process over the last 37 years and suggests necessary steps for land use management and river channel restoration.

The variation of strength characteristics of black clays across the study area would be reflected by the distribution of shear strength parameter, (φ`). Soil depths of less than 0.50 m are characterized by relatively higher maximum (30°), minimum (16°) and mean (21°) values; than those of 0.50 m depth and greater which have maximum, minimum and mean values of 23°, 11° and 17°, respectively.

Increasing moisture content of clay-like soil turn them to sticky mud and reduces the soil's shear resistance to sliding. The soil Liquid Limit (LL) is defined as the moisture content above which the soil behaves as a liquid, and the Plastic Limit (PL) is the moisture content above which the soil behaves plastically. The numerical difference between the Liquid Limit and Plastic Limit is termed the Plasticity Index (PI). The plasticity index (PI) is the size of the range of water contents where the soil exhibits plastic properties. The PI is the difference between the liquid limit and the plastic limit;

$$PI = LL – PL \quad (8)$$

Where: PL is the Plastic Limit, and LL is the Liquid Limit.

$$PL = (\text{mass of water}/\text{mass of oven-dry soil}) \times 100 \quad (9)$$

Using the British Standard relationship (BS 1377: 1967), that is,

$$PI = 2.13 * LS \quad (10)$$

Where: LS is Liquid clays, values ranging between 21 and 29% for clays.

According to Johnson and De Graff (1988), the shear strength of soils is usually inversely proportional to their plasticity. As a result, the observed slight decrease of strength characteristics of black clays with depth could be attributed to a corresponding slight increase of their plasticity (PI) with depth. Published laboratory test results indicate that the plasticity range of vertisolic soils typically found in the middle and lower catchment range between 25 and 45% and the Liquid Limit (LL) is between 50 and 70 (USDA, Soil Conservation Service, 1971. Guide for

Interpreting Engineering Uses of Soils, Washington, D.C., 86 p).

Hydraulic processes

In the first type, erosion changes the geometry of the potentially unstable bank by removal of material at the toe of the bank and reduces the confining stress that may be stabilizing the slope. Photogrametry survey immediately after the slab failure revealed that collapse of overhanging blocks of undercut river banks depended on bank height and angle of slope. The critical height of slope depends on shear strength, density and bearing capacity of the slope foundation. Slope stability generally decreases with increase in height of slope. As the slope height increases, the shear stress within toe of slope increases due to added weight. Shear stress is also related to the mass of the material and the slope angle. With increasing slope angle, the tangential stress increases which result in increase in shear stress thus reducing slope stability.

Key factors that cause undercutting of river banks are discharge, characteristics of bank material and local soil moisture condition (Thorne and Furbish, 1995). Erosion processes of river banks occur as a result of direct removal of bank materials by the shearing action of flow. Once they were undercut the overhanging upper parts of the river bank becomes unstable. These overhanging upper parts eventually collapse into the river. This is aided by mass wasting that occurred as a result of undercutting of the river banks under the influence of gravity (Figures 5 and 6). Widening of the river channel (Kiss et al., 2013; Nasermoaddeli and Pasche, 1998) found that undercutting of the river banks, avalanche of the submerged zone of the river bank and failure of the overhang were dominant processes on non-cohesive river banks. The vertisols and vertic gleysols and the channel banks are planted Napier grass, maize, beans and a variety of vegetables. For this reason, the river banks have been undercut, the soils have desiccation or tension cracks and frequently collapses in to the channel. Undercutting was prevalent along river bends. Velocities decrease closer to the outer bank and near the bed of the channel.

Slab failure

Slab failure involves sliding and forward toppling of a deep seated mass into a channel along stress (dessication) cracks (Merz, 2010) which occur during the preceding dry period (Figure 7). Other sections where the cracks had progressed lost resistance and had collapsed into the channel (Figures 8). The slab failure occurs on a steep, low height, clay bank during low flow conditions (Watson and Basher, 2006). The process are rather

Figure 5. Land slide of high river cliffs. Source: Monene, 2014: Pictures taken on 17/12/13 and 5/9/13.

Figure 6. Collapsing of banks. Source: Monene, 2014: Pictures taken on 17/12/13 and 5/9/13.

Figure 7. Unstable outer bank showing cracks. Monene, 2014: Photographs were taken 10 m downstream of Kangundo Road Bridge on 17/12/2013.

Figure 8. Collapsed outer bank. Monene, 2014: Photographs were taken 10 m downstream of Kangundo Road Bridge on 17/12/2013.

Figure 10. Basal Cleanout of the outer bank. Monene, 2014: Photographs were taken near Kangundo Road Bridge on 28/12/2012.

Figure 9. Basal Cleanout of the inner bank. Monene, 2014: Photographs were taken near Kangundo Road Bridge on 28/12/2012.

complex thus combining scour at the bank toe, high pore-water pressure along the bank material and the development of tension cracks at the top of the bank. An accumulation of failed loose blocks that seemed to offer temporary protection to the lower section of the river bank were soon washed away (Figures 9 and 10).

Decreasing bank resistance to erosion were caused by rapid drawdown of water levels after a rainfall event, consistent lowering of the water table during the dry season, existence of erodible river banks and desiccation of the river bank material. During dry weather the soil loses moisture and contracts. It is during contraction that cracks develop in the soil and subsequently collapse into the river. During the wet season the clay soils absorb moisture and expand. The cracks were on the outer bank of the river, were about 2 m deep and seemed quite unstable. The collapse of these unstable blocks results to erosion of banks, exposes a new surface to erosion, causes soil loss and supplies sediments to the river.

Some points of the river banks portrayed basal cleanout as they had been freshly swept clear of loose soil particles. Direct observation and photography revealed that flash floods had removed supportive and protective bank material, either vegetation or loose soil particles and uprooted vegetation that had colonised the river banks. It was noted that the removal of collapsed bank material left the lower river bank material exposed to a continuous cycle of undercutting, collapse and removal, and the subsequent transportational process thus widening the bank especially during the rainy seasons. Friedman and Lee (2002) found that channel widening was dominant process occurring within hours during infrequent floods.

Cavitation process

Cavitation is an erosion process involving air bubbles trapped in the water that get compressed into small spaces like cracks in the river's banks. These bubbles eventually implode creating a small shockwave that weakens the bank materials. The shockwaves are very weak but over time the materials will be weakened to the point at which they fall apart. The bank consist of fine-grained cohesive loamy sands materials. River bank cavities or pop out failure were observed near the base of the river bank at about 100m upstream of Bridge 2 (Figures 11 and 12) along a steep inner bank. The cavities occurred at the middle and lower parts of the banks which imply that secondary circulation. The bridge causes channel constriction creating backwater effect that likely generates secondary circulation thus causing

Figure 11. Undercutting of outer bank. Source: Monene 2014: Photos taken on 17/12/2013 during wet season) and 5/9/2013 during dry season.

Figure 12. Pop out failure results to cavities. Source: Monene 2014: Photos taken on 17/12/2013 during wet season) and 5/9/2013 during dry season.

Figure 13. Dry season channel braids.

Figure 14. Wet season channel braids.

additional pressure on the banks. As earlier discussed flow of Motoine/Ngong river varies between seasons and flash floods rise and fall rapidly after a rainfall event. The pore pressure along the river banks caused small to medium sized blocks of fine grained cohesive material to fall out leaving a cavity. The fine cohesive materials allow the buildup of positive pore water pressure and strong seepage within its structure causing the roof of the cavity to collapse resulting to river bank retreat.

Channel braiding and bars

Channel braiding is a reflection of increased sediment discharge of reduction in discharge and hence sedimentation within the channel. Motoine/Ngong River, downstream the Kangundo road Bridge, has channel bars that get eroded and disappear at high flow stages. The channel is braided downstream the Bridge 2 (Figures 13 and 14). Church and Jones (1982) found that at higher flow stages the largest volumes of sediment are transported and the channels are scoured. During the falling stage maximum deposition occurs as discharge and flow competence are reduced. The channel bed aggrades and the bar emerges. The channel constriction at the bridge no. 2 after which the water spreads out, channel width increases, and depth decreases. The bar surfaces have vegetation indicative that the bars are stabilizing. The bar separating the channels was larger during the dry season than during the rainy season. The bar disappeared at high flow stages and reformed as discharge fell.

The bars at Motoine/Ngong river had no vegetation. This implies that there is frequent refreshing of bar surfaces, bar destruction and re-formation. This means there is increased erosion and flood frequency and magnitude. Presence of vegetation indicates a degree of stability. Material composition of the bar varies between seasons. The dry season bar was composed of finer materials. During the rainy season the fine materials forming the bar had been eroded by flash waters, leaving behind boulders.

Figure 15. Channel meanders. Monene, 2014: Photos taken on 17/12/2013 and 5/9/2013 respectively.

Channel bed deformation process

Previous studies reveal that the processes of bed degradation and lateral erosion destabilize the upper part of the bank (Figure 15). The role of basal erosion is to reshape bank geometry by entraining sediment from the submerged portion of the bank surface when the flow shear stress is greater than the bank resistance force. Basal erosion steepens the bank surface by fluvial undercutting at the bank toe. Consequently, bank failure such as planar, toppling and cantilever, occurs depending on various failure mechanics of cohesive or non-cohesive soil. Outer bank experiences additional pressure caused by the centrifugal force of the current in a bend.

Rocky outcrops

As slope decreases the volcanic rock outcrops emerge showing that further channel incision has been curtailed (Figure 16). In this respect, the appropriate channel response to increased discharge is basically flooding, a feature characteristic of the lower part of the basin.

Figure 16. Outcrop rocks near dam inlet. Monene, 2014: Photos taken on 17/12/2013 and 5/9/2013 respectively.

Conclusions

There has been spatial change in land use in Motoine/ Ngong River sub-catchment during the period of study. The change was characterized by both increase and decrease of the area covered by respectively the forest, grassland and bare ground. During the study period the coverage by wetland, bare ground, grassland and forest were lower in 2013 than in 1976 and together these cover 75.04 of the catchment in 1976 but only 33.84% in 2013. Built up area and road surfaces was the only pattern that recorded a steady increase from 22.78% in 1976 to 50.98% in 2013. The other vegetation types increased and decreased according to the dynamics of land use in the catchment. There has been spatial increase in built-up surfaces from 1976 to reach 50.9% of the catchment in 2013. The increase in impervious surface cover reduces infiltration while increasing surface run-off and stream flow. Erosion and sedimentation resulting from flow variability are associated with rainfall events. Channel morphology characterized by meanders, braiding , river cliffs, river bank cavities, collapsing overhanging banks, tension cracks , slip-off slopes sand bars have been associated with changes in land use and stream flow variability.

Conflict of Interests

The authors have not declared any conflict of interests.

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