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Effects of heterogeneous land use/cover types on river channel morphology in the Solo River catchment, Eastern Uganda

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Abstract

In the tropics, unmonitored land use/cover types cause significant effects on the narrowing and widening of river channels which affects the integrity of water resources. River channel planform extent was characterised using Landsat images while water and bedload samples were collected and analysed for a period of one year. The results revealed that in 1986 the channel planform covered 3.7sq.km in length than in 2013 where it increased to 4.2sq.km. Wetland (537.1mg l⁻¹) and bushland (186.3mg l⁻¹) cover types had the highest concentration of suspended sediments. Fine-sand (0.25mm), silty-sand (1mm) and silty-clay (0.125mm) bedload particle types dominated the riverbed along the channel from the sampled land use/cover types. The high concentration of sediments, bedload materials, bank-instability, and stream-flow were significant contributors to the narrowing and widening of the channel (P<0.05). Agricultural landuse was the major contributor of channel aggradation (0.8m) and degradation (0.25m) compared to tree-plantations, bushlands, forest and wetland cover types.

Keywords: River channel planform, sediments, streamflow, cross-sections

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1.1 Introduction

In East Africa, about 13 million hectares of natural forest cover have been lost over the same 20 year period; and the remaining forests are fragmented and under threat (FAO 2010). This is because land use changes have transformed land cover to farmlands, grazing lands, human settlements, mining and urban centers at the expense of natural vegetation. These changes are associated with deforestation, biodiversity loss and land degradation (Taillefumier and Pie'gay 2003; Maitima et al. 2009). The intensification of land use and cover types causes geomorphic responses such as increased sediment supplies, transport and deposition regimes (Darby and Thorne 2000; Allan 2004; Liebault et al. 2005; Qazi and Ashok 2011). These responses are governed by the mixing of river water (Clark and Wilcock 2000; Yang et al. 2001) and the hillsides; though the pattern of sediment load reacts to what is happening on the slopes and along the channel (Keller et al. 1997; Shi et al. 1999; Qiang et al. 2008). However, the resilience of river banks depends to a great extent on the presence of plant roots and soil type (Rosgen 1994; Stefano et al. 2011).

In Uganda, the Lake Kyoga basin experiences extensive land use and cover changes due to natural and anthropogenic processes (Mugagga et al. 2012). The modifications have led to severe soil erosion, disruption of water sources and drying up of rivers that alter river channel morphology (Odada et al. 2004; Kizza et al. 2009). The basin also experiences frequent recurrence of extreme weather events (floods and droughts) and increasingly erratic rainfall that are a big challenge to the management of water resources (Nsubuga et al. 2014). The impacts of erratic rainfall are manifested through increased rainfall runoff rates, changes in river boundary materials, and river flow regime (Madej and Ozaki 1996; Paquier and Saeed 2002; VanLooy and Charles 2005). Therefore, assessing the effect of land use and cover types on the river channel morphology is important in evaluating future flood risks, river morphological assessment and the scale of rainfall runoff in the catchment (Gilvear 2004; Cluett 2005; Formann et al. 2007; Unde and Dhakal 2009).

Geographical information science and remote sensing play an increasingly significant role in geomorphological studies (Downward et al. 1994; Hughes et al. 2006). The use of remote sensing and geographical information system's based data in the monitoring of river channel morphology permits the interpretation of catchment-wide channel trends and their associated instabilities (Thorne et al. 1996; Newson and Newson 2000.). While many studies have assessed the river channel movement (Milne and Sear 1997; Sarma et al. 2007), few studies have relatively monitored the occurrences of river channel narrowing and widening in a catchment dominated with mixed land use and cover types; and also extracted information on channel planform change that includes tributary connectivity, channel morphology and their extent (Chin and Gregory 2005).

Previous studies conducted in the Lake Kyoga Basin have only examined the effect of land use on water waste discharge (Simonpeter and Peter 2015); landslide, soil redistribution and sediment yield (Claessens et al. 2007), climate variability (Egeru et al. 2014), and monitoring of extreme weather events (Haye et al. 1999; Barasa et al. 2013). However, there is no study that has assessed the effect of heterogeneous land use and cover types on river channel morphology in any of catchments that experience high rainfall runoff rates, flash floods, daily waste water discharge and artisanal gold ore washing in the Lake Kyoga Basin. This study bridges this knowledge gap (i) by characterizing the extent of river channel planform change, (ii) assessing the effect of land use and cover types on sediment concentration and river bank stability; and (iii) their effect on the river channel aggradation and degradation in the River Solo catchment found in the Lake Kyoga Basin located in Eastern Uganda.

2.1 Description of study area

The study was conducted in the Solo River catchment (lat. 0.515518°, lon. 34.031277°) a tributary of the Malaba River located in the Lake Kyoga basin in Eastern Uganda. The river originates from the two main valleys found in Busia town council in Eastern Uganda. The size of the catchment is 71.8sq.km (Figure 1). The catchment was selected for this study because of the significant impacts of land use and cover changes and climate on the water resources; and its hydrological contribution to the Albert Nile through Lake Kyoga in Uganda. The catchment experiences an annual average temperature of 27.9°C. The highest temperatures are experienced in the months of January to March with 29.3°C respectively. The annual minimum temperature experienced is 15.9°C; which is experienced in the months of March to May and October to December. The highest amount of precipitation is received in the months starting from March to May (280 mm/month, 240 mm/month) and August to November (183 mm/month, 170 mm/month). The major soil types that underlie the catchment are sandy-loam and clay. The sandy-loams are found in the upland areas while the clays are in the valleys (i.e. wetlands). These soil types have a little difference in their defining soil-layer horizons. The soil types fall under a soil catena group of Petric plinthosols and Gleysols (NEMA 1997). The most predominant land use and cover types are subsistence agriculture (crop growing), tropical high forest (fully stocked), bushlands, tree plantations and wetlands. The major socio-economic activities carried out in the catchment include subsistence farming, small scale businesses, charcoal burning, sale of timber and poles, brick making, formal and informal employment among others

3.1 Methods

3.1.1 River channel planform change

The study utilised two sets of ortho-rectified and cloud free Landsat TM/ETM+ (30m, band 5 and 7) images of 1986 and 2013 (Table 1) which were downloaded (<http://glovis.usgs.gov/>), geometrically aligned and enhanced using majority filtering method (Mouchot et al. 1991) prior to the assessment of the river channel planform change. The channel planform information extraction included tributary connectivity, channel morphology and extent.

Table 1: Acquired Landsat image specifications

Satellite	Dates	Bands	Zone
Landsat (30m) P170R60	12 th /January/1986	5	WGS 1984 UTM zone 36N
Landsat (30m) P170R60	21 st /January/2013	7	WGS 1984 UTM zone 36N

The selected bands offered a moderate distinctive reflectance signature that allowed the channels to be mapped (Leal 2002). The planform change was quantified by cross-tabulating attributes of the channel classes (erosion/deposition/no change channel) within the specified spatial units or polygons defining the channel reaches (Maidment et al. 1994) for each particular cross-section. The channel coverage per year was determined following Maidment et al. (1994) procedures. However, this study did not map the river channel planform change in the tropical high forest (Busitema – Forest Reserve) because of accessibility and visibility due to satellite limitations.

2.3.2 Sediments, river bank stability and cross sectional assessment

Stream flow data, water, and river bed deposit samples were collected on a monthly basis for a period of one year (2012) from the selected land use and cover types (agriculture, bushlands, tree plantation and wetland) along River Solo. Streamflow was measured using a handheld flow-probe (model FP211). Suspended sediments were separated using sieves of 63 μ m to remove coarse sediments from the water samples. Water (25 – 100 ml) from each sample was filtered onto a pre-ashed and pre-weighed GF/F 25 mm filter of pore size 0.45 μ m and then dried at a constant weight at 60°C before weighing. The suspended sediment data was analysed following a one-way analysis of variance procedure to test the significance of land use on the channel morphology and river hydrodynamic parameters (discharge, suspended sediments, stream width, and depth). Whereas the river bed deposits were sampled using a Van Veen grab sampler (Azamathulla et al. 2009) for grain-size analysis. The samples were oven dried at 105°C for 24 hours, all weighed at 300g and sieved on a sieve shaker for 30 minutes to determine the grain-sizes. The river bed deposit particle sizes were classified following Xiaoqing and Yang (2003) index of soil stability for materials comprising of river banks and channel beds (α_{bank} and α_{bed}). The principal factor analysis was carried out to determine the most predominant river bed deposit grain sizes from the sampled land use and cover types.

A series of soil samples were collected along the river bank in the different soil profiles (horizons) from the sampled land use and cover types to determine the stability of the bank to channel aggradation or degradation in the catchment. The undisturbed soil samples were subjected to a direct shear stress box test in the laboratory in accordance with the British Standard (BS-1377: part 7: 1990) procedures. This method permitted a direct shear test to be made by relating the shear stress at failure to the applied normal stress. Shear strength parameters (cohesion and friction angle) were of primary concern in the examination of channel widening, narrowing and bank stability (Thorne et al. 1996). The soil profile bulk density was determined using a core method (Black and Hartge 1986), because bulk density is an important parameter to describe the soil function. The stability of the river bank was also examined in terms of root availability and abundance to bind the soil particles together. The abundance of roots in the soil profiles was assessed following FAO (2006) procedures.

A cross-sectional analytical approach was adopted to determine the channel narrowing or widening. The study laid out multiple cross-sections (10) along the major land use and cover types to identify appropriate sites for morphological monitoring. Two cross sections were fixed after the river bends (areas of reach) and topographically surveyed for two years (2011-2012). The surveyed cross sections were fixed in the agricultural and tree plantation land use and cover types. The river cross-sections were surveyed with the use of a Garmin Global Positioning System (GPS), an automatic level, stadia rod and distance meters. This approach made it possible to approximate the conditions of stream bed deposit particle movement at various levels of streamflow (Hardy et al. 2005). The surveyed land use and cover types were purposively selected because they presented a series of stable and unstable natural bends and banks compared to the other land use and cover types. In addition, we adopted a catchment-wide examination of the dynamics influencing the river channel morphology. These were examined through a conduct of 10 key informant interviews that included the local residents and local government natural resources officials who were knowledgeable about the dynamics in the catchment. This was important because understanding the morphological channel adjustments must be considered in a broader catchment scale context (Raven et al. 2010).

2.4 Results

2.4.1 River channel planform change

The river channel planform occupancy results showed that the catchment experienced drastic channel adjustments and land use/cover changes. In 1986 the channel planform covered 3.7sq.km in length; than in 2013 where it increased to 4.2sq.km. The mapped occupancy was very distinctive than in the 1980s which reflected a decrease in size and shift of the channel in the studied period. The study also shows that the river channel reaches had an occupancy equivalent to 1km per section of the river. The occupancy of the river channel planform increased by 0.5sq.km in the studied period (Figure 2). The study noted that there is a decreasing (narrowing) trend in the occupancy of the channel planform in the catchment (Figure 3).

2.4.2 Sediments, river bank stability and cross sectional assessment

2.4.2.1 Suspended sediments

The descriptive statistics for the measured concentration of suspended sediments are given below in Table 1. The highest distribution of concentrated suspended sediments was recorded from the wetland cover type which had a mean value of 537.1 mg^l⁻¹ followed by bushlands (186.3 mg^l⁻¹), tree plantation (156.9 mg^l⁻¹), tropical high forest (70.6 mg^l⁻¹) and lastly from agricultural (89.1 mg^l⁻¹) land use. The concentration of suspended sediments with discharge is illustrated in Figure 4.

Table 1 Descriptive statistics of annual suspended sediments

Statistics	Agriculture	Tree plantation	Bushlands	Forest	Wetland
Units	Mgl ⁻¹				
Minimum	11.0	39.0	32.5	9.0	40.0
Maximum	160.0	708.0	786.0	184.0	3140.0
1st Quartile	38.1	53.8	46.0	39.9	111.3
Median	90.5	77.0	74.5	64.0	279.5
3rd Quartile	128.8	122.0	166.0	77.8	584.0
Sum	1069.5	1883.0	2235.5	847.5	6445.5
Mean	89.1	156.9	186.3	70.6	537.1
Variance (n)	2403.0	36577.1	54251.7	2455.6	673759
Standard deviation (n)	49.0	191.3	232.9	49.6	820.8
Variation coefficient	0.6	1.2	1.3	0.7	1.5
Skewness (Pearson)	-0.2	2.0	1.7	1.0	2.6
Kurtosis (Pearson)	-1.3	3.0	1.4	0.2	5.5

The study shows a strong relationship between discharge and the concentration of suspended sediments as observed in the tree plantation, bushland, forest and wetland cover types (Figure 4). The concentration of the suspended sediments was closely related to the stream depth, width and discharge. These caused a significant contribution to the narrowing and widening of the river channel morphology ($P < 0.05$). However, the stream width ($R^2 = 0.5$) had a much higher contribution than stream depth and discharge on the river channel aggregation and degradation.

2.4.2.2 Bedload

The principal component analysis results revealed that fine sand (0.25 mm), silty sand (1 mm) and silty clay (0.125 mm) were the most predominant particle sizes that dominated the channel bed. The river banks generally had a low bulk density from the sampled land use and cover types. The tropical forest-fully stocked (1.9 Mg/m³) had a relatively higher amount of bulk density than the wetland cover type (1.6 Mg/m³) which had the lowest amount. This study revealed that tree plantation (cohesion=12, angle of internal friction=27) and bushland

(cohesion=14, angle of internal friction=22) land cover types had the most stable river banks compared to the channels under agriculture, wetland and tropical high forest (Table 2).

Table 2 River bank physical soil parameters from the sampled land use and cover types

Land use	Bulk density	Normal stress	Shear strength	Cohesion	Angle of internal friction	Landscape slope classification (%)
	Mg/m ³	δ_n	t_s	C(kPa)	Φ (Degree)	
Tropical High Forest	1.9	34.1	33.1	8	37	2 (Very gently sloping)
		47.7	43.6			
		74.9	63.8			
Wetland	1.6	34.1	31.7	2	41	7 (Sloping)
		47.7	44.3			
		74.9	67.4			
Tree plantation	1.8	34.1	29.1	12	27	6 (Sloping)
		47.7	36.4			
		74.9	49.9			
Bushlands	1.8	34.1	27.7	14	22	3 (Gently sloping)
		47.7	32.7			
		74.9	44.3			
Agriculture	1.8	34.1	16.2	4	19	4 (Gently sloping)
		47.7	19.2			
		74.9	30.1			

2.4.2.3 Cross sectional geometry and root abundance assessment

The soil profiles showed that bulk density and root abundance were relatively higher in the first soil horizon A than in the sub-soil layer (horizon B). The biggest number of root sizes was 6 mm (coarse) and 4 mm (medium), though these were few (Figure 5). The cross-sectional geometrical assessment revealed that the agricultural land use (crop growing) experienced higher rates of both channel aggradation (0.8 m) and degradation (0.25m) than the channel under tree plantation (Figure 6 and 7). The right stream bank under the agricultural land use (crop growing) was the most affected bank by aggradation; while the left bank for tree plantation. Subsequently, the goodness of fit statistic showed that the river channel bed slope under the agricultural land use ($R^2=0.09$) did not influence both channel aggradation and degradation unlike the channel under tree plantation ($R^2=0.7$).

2.5 Discussion

The study reveals that the catchment has experienced drastic channel adjustments and changes in a mosaic distribution of land use and cover types over 27 years of the assessment period. The changes have been observed in all the land use and cover types (forest, agriculture, bushlands, tree plantations and wetland) found in the catchment. Land use and cover changes have also been noticed in the Lake Kyoga Basin by other scholars such as Chhetri et al. 2003; Mugagga et al. 2012 and Petursson et al. 2013. The observed changes have resulted into channel planform change causing channel distinctive boundaries. Boix-Fayos et al. 2007 also noted that the anthropogenic causes of land use and cover changes are responsible for the lateral displacement of rivers channels over a long period. This finding was also noted by Surian and Rinaldi (2003) who observed that there is a strong relationship between human activities and channel adjustments for any catchment.

The highest sediment concentrations across the studied land use and cover types were reported during the rainy season because of high precipitation intensities and intensification of agricultural practices such as over grazing, deforestation, over cultivation, bush and grassland burning. These activities have accelerated rainfall runoff rates resultant into sediment loading and deposition in the Solo River catchment. Erratic rainfall events have been observed in the Lake Kyoga catchment by Barasa et al. (2013) who noted that the frequency of extreme events (droughts and floods) have reduced from a 4-10 year period to a 1-3 year period. More extreme wet events in the Kyoga Basin (rainfall variability index >2.6) were experienced between 2004 and 2009 than between 1984 and 2003 (Egeru et al. 2014). Jiang et al. 2014 also noted that the trends and changes in erosion in the Kyoga basin are linked to precipitation/climate change as well as changes in land cover. This finding is also in agreement with Walling and Fang (2003) who reported that land disturbances in small catchments cause a significant impact on sediment mobilisation and sediment fluxes. This was evident in the wetland, bushland and tree plantation compared to forest cover type.

Higher stream flow rates were also significant determinants of sediments in the channel. This finding also relates to the results of Shi and Zhang (2005) and Coco et al. (2006) who reported that wetlands, which are normally in the floodplains represent a major sediment sink in many drainage basins. The rates of sediment concentration were high in the downstream stream section of Solo catchment because of the vast and interconnected wetland system connecting to River Mpologoma wetland system that extends to Lake Kyoga.

Fine sand (0.25 mm), silty sand (1 mm) and silty clay (0.125 mm) bedload particle types were the most predominant river bed deposits. The fine nature of these materials was attributed to the continuous cultivation of perennial crops and soil type. This study demonstrates the characteristic of the catchment soil composition. This gravel-to-sand transition and associated modifications in channel form were induced by a break in valley slope and an increase in bank

resistance from the cohesive bank material. This study is in conformity with the findings of Bamutaze et al. 2010 in the Lake Kyoga Basin that water infiltration influences runoff and soil loss especially the steady state infiltration rates generally increase with the slope gradient and were crop type independent ($P < 0.05$). Similarly, Darby and Thorne (2000) and Yang et al. (2001) also noted that sand on the riverbed is influenced by river discharge as well as catchment hydrodynamics. The bedload materials were also determined by bank erosion rates that occurred due to the low bulky density, angle of internal friction and root abundance in the soil sub-layer of the river bank. The type and density of riparian vegetation (grasses, shrubs or trees) are known to stabilize the river bank stability and stable channel form. However, the tree plantation and bushlands had the most stable river banks. The overbank slope angle was also a significant determinant.

This study also notes that the river channel under agricultural land use experienced the highest rates of both channel aggradation and degradation as compared to tree plantation, wetland and bushland cover types. The rates were attributed to poor agricultural practices such as cultivating upto the river channel boundary which weakened the river bank leading to incidents of channel aggradation and degradation. The river channel aggradation under the tree plantation was attributed to livestock trampling of the stream bank in search of drinking water. The aggradation increased the rates of in-channel sedimentation that reduced the water depth and diversion of the river course. This finding was also reported by VanLooy and Martin (2005) that channel changes and growth in the riparian vegetation and livestock rearing may cause the narrowing and widening of river channels. Therefore, there is a necessity for controlled livestock grazing to prevent river channel degradation (Smith et al. 1993).

2.6 Conclusion

The higher the discharge rates the higher the concentrations of suspended sediments from the sampled land use and cover types. Tree plantation and bushland had the most stable river banks compared to wetland and agricultural land use and cover types. The channel morphological parameters (stream depth, width, and discharge) also had a significant impact on the concentration of suspended sediments. The agricultural land use (crop growing) experienced the highest rates of both channel aggradation and degradation than the channel under tree plantation. This study strongly affirms that the stability and instabilities of the river channel geometry had significant impact on the variation of sediment concentration and catchment streamflow.

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Conflict of Interest

Authors declare no conflict of interest

2.8 References

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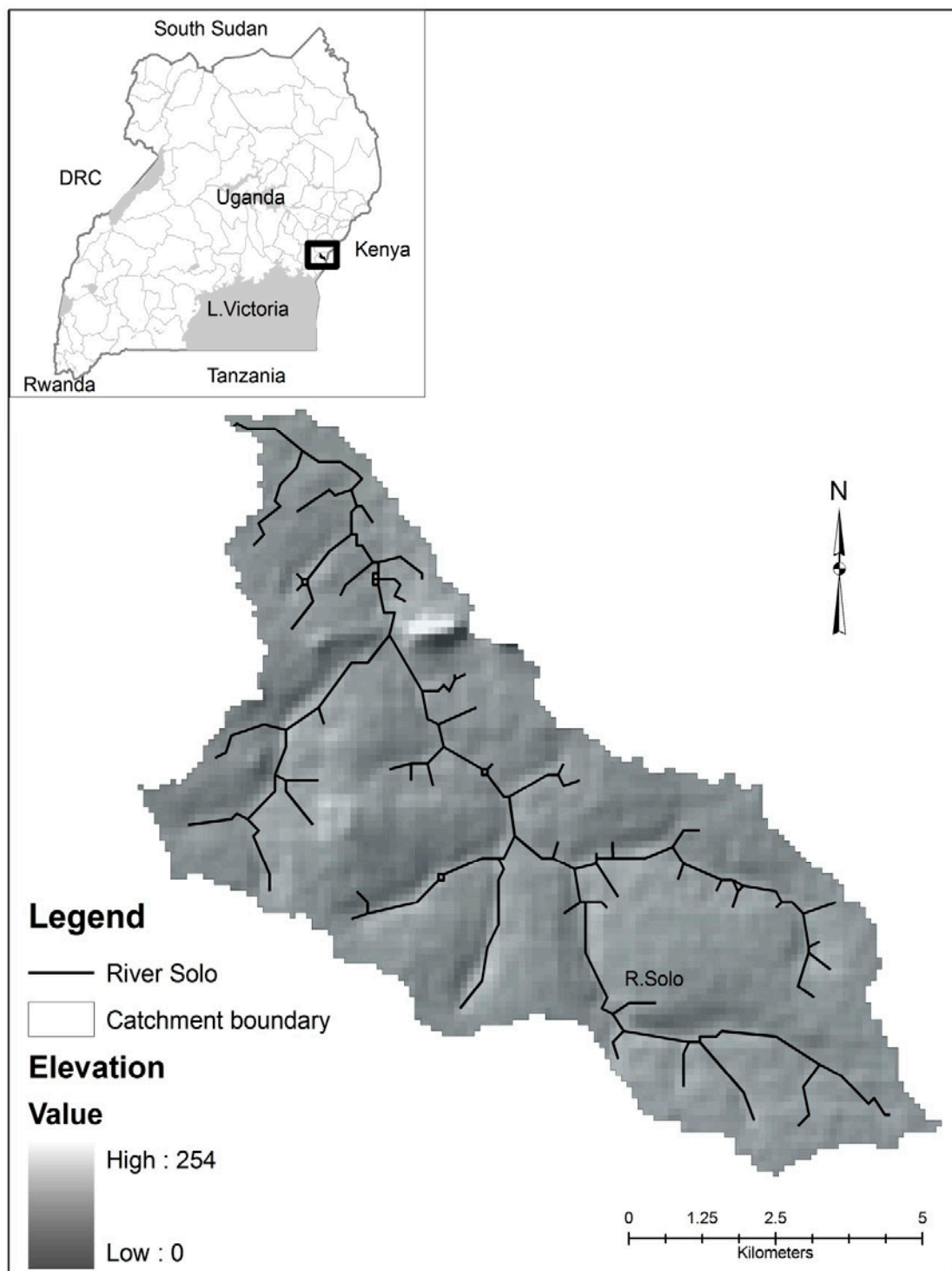


Figure 1 River Solo catchment

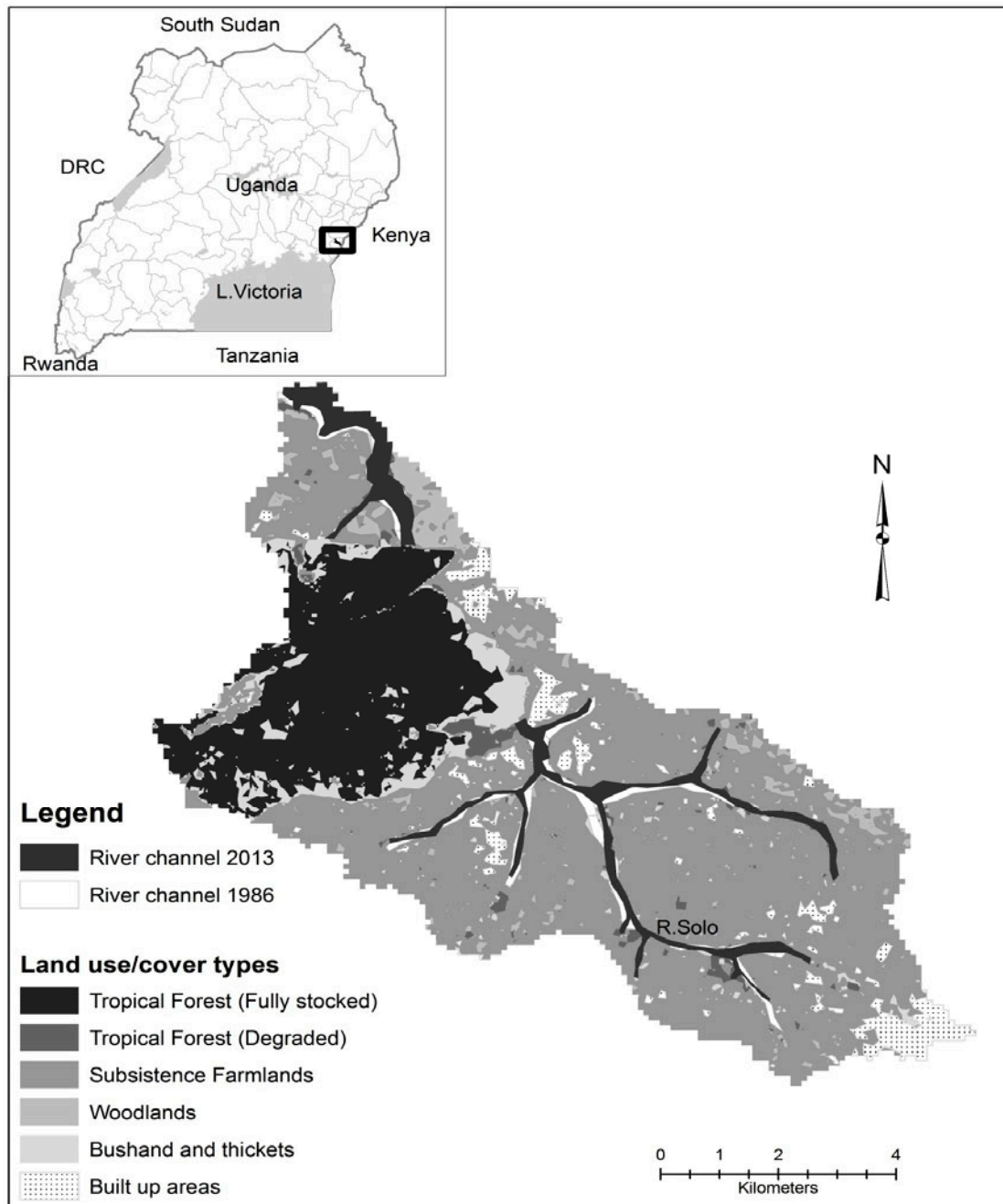


Figure 2 Channel planform of River Solo catchment

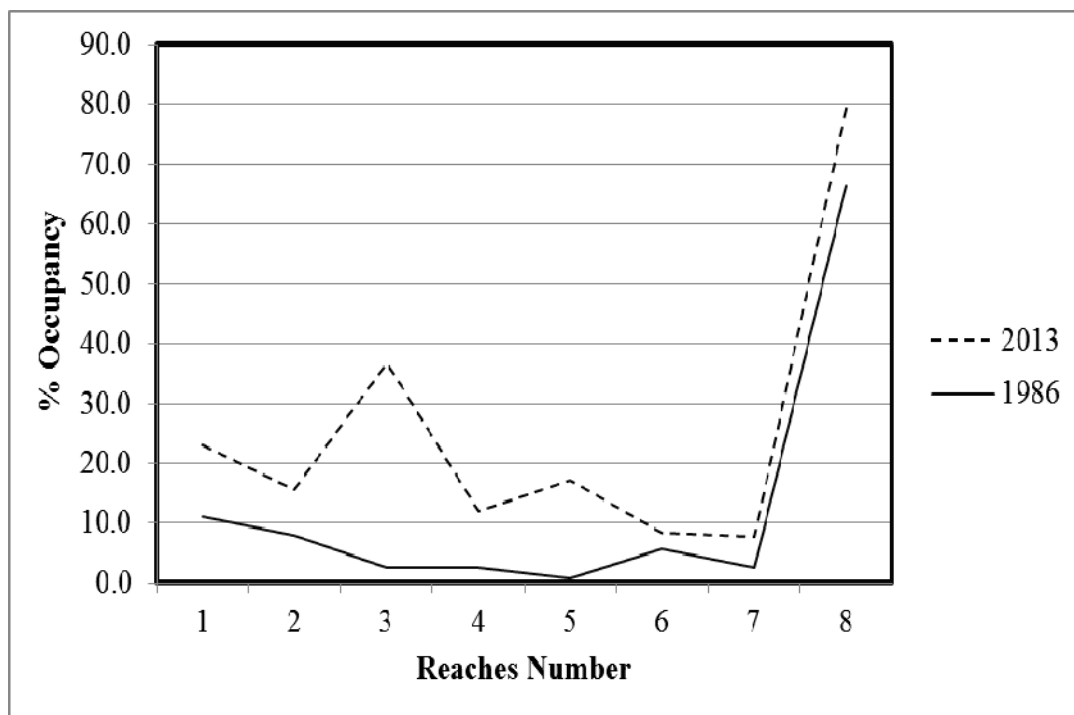


Figure 3 Occupancy of the river channel planform

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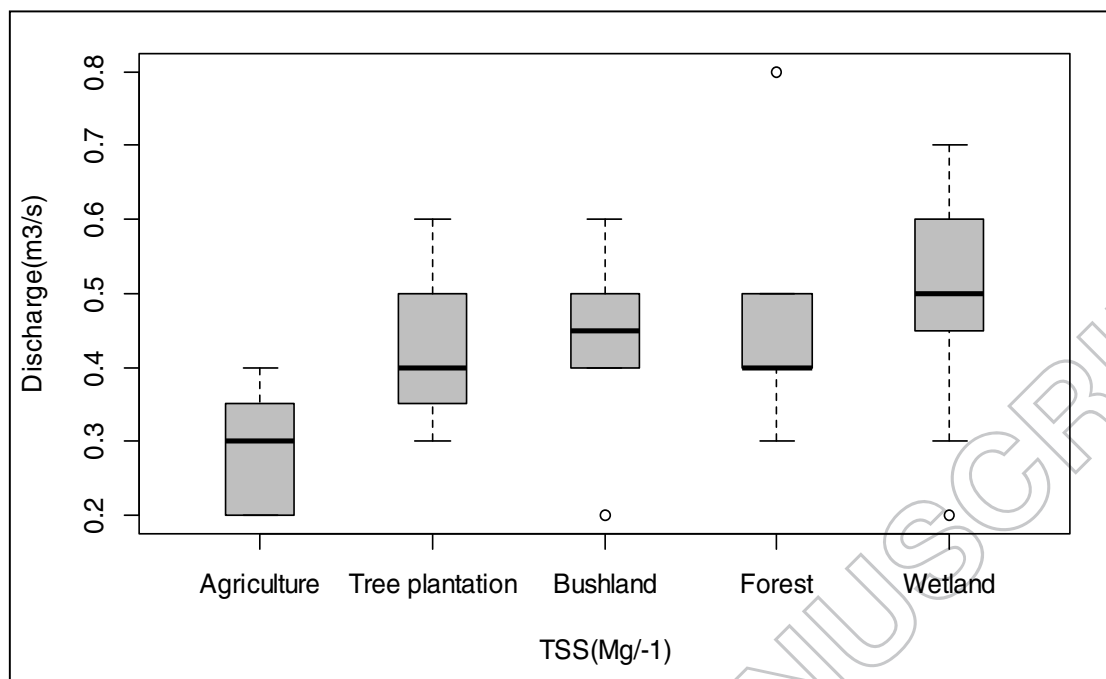


Figure 4 Suspended sediment concentrations in relation to stream discharge

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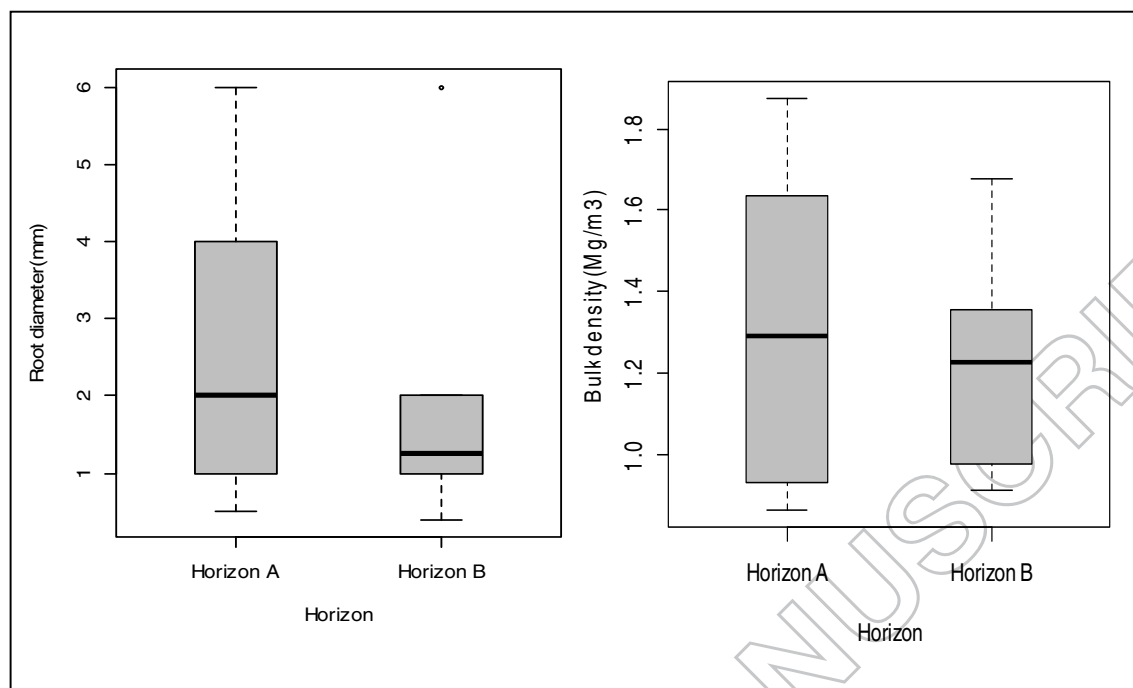


Figure 5 The abundance of roots and bulk density as per the soil horizons

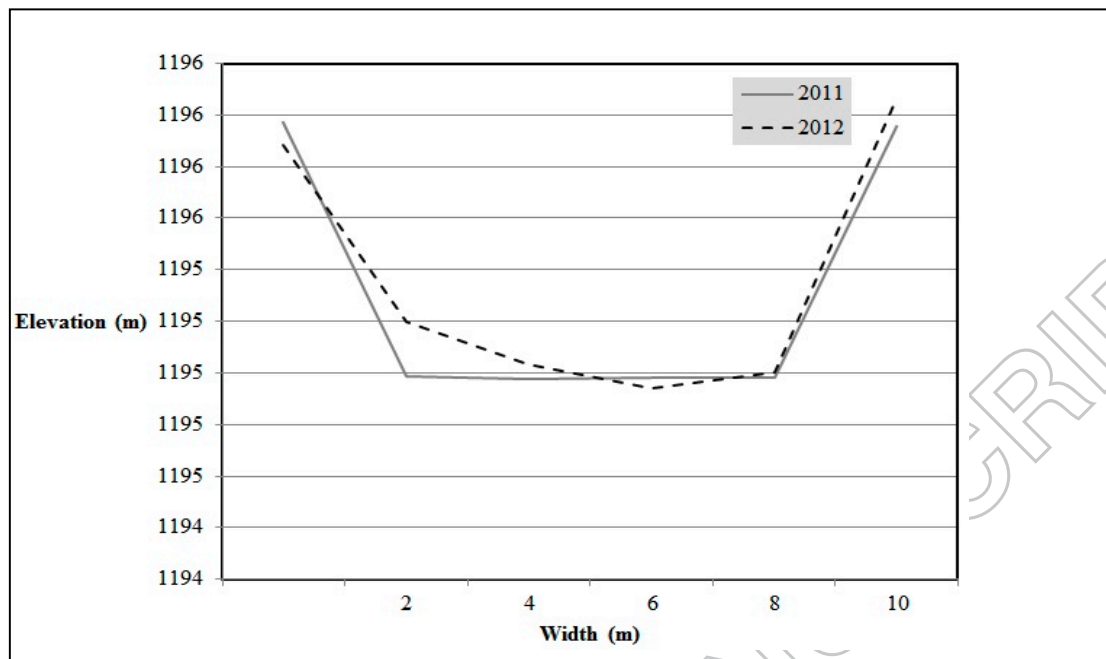


Figure 6 A cross-section from the tree plantation land cover

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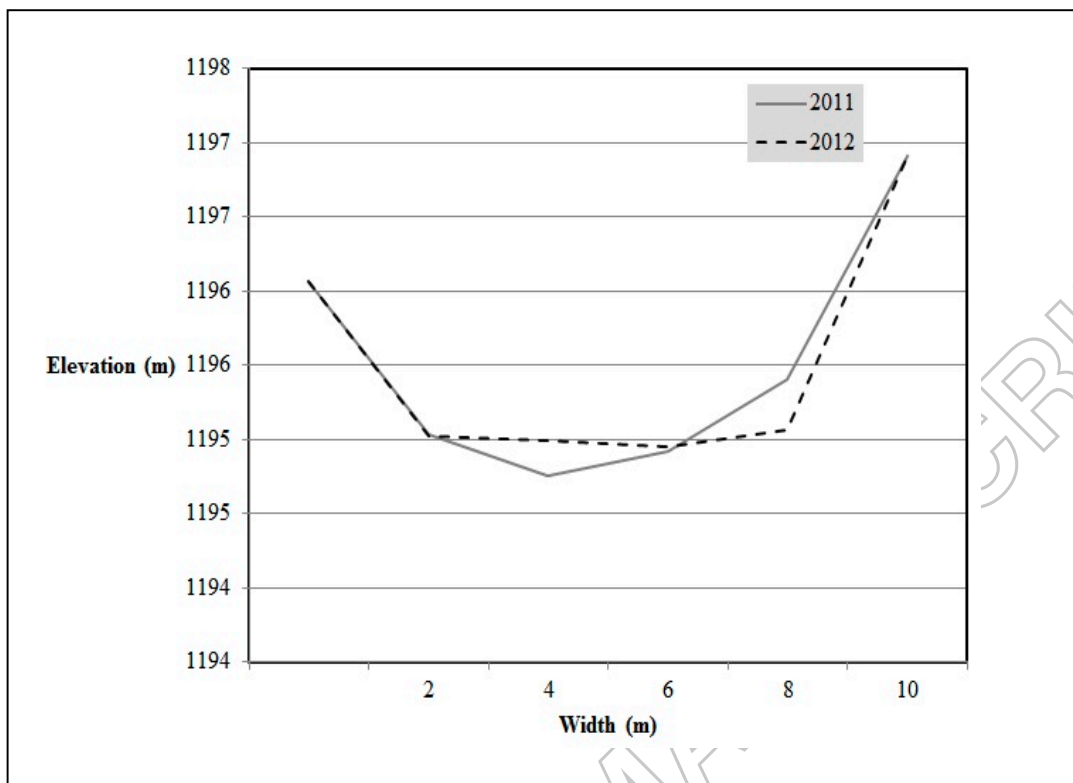


Figure 7 A cross section from the agricultural land use

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