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ORIGINAL ARTICLE

Characterization of artisanal gold mining activities in the tropics and their impact on sediment loading and stream flow in the Okame River catchment, Eastern Uganda

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Abstract Artisanal gold mining activities continue to degrade water resources in the tropical watersheds. In this study, we examined the spatial distribution of artisanal gold mining activities and their impact on sediment and mercury concentration in the Okame River catchment, Eastern Uganda. The spatial distributions of mining activities were assessed using both a TerraSAR-X radar satellite image of 2008 and Landsat image of 2013. Water samples and river bed deposits were collected on a monthly basis for a period of 1 year to assess the impact of mining activities on the streamflow variations and sediment concentration. Our results showed that the distribution of gold mining activities increased from 4.5 km^2 in 2008 to 19.9 km^2 in 2013. Human-induced sediment loading due to gold stone washing in the sampled tributaries of Okame River was responsible for the high concentration of suspended sediments (CSS), mercury and low water levels than prior to gold stone washing. River Omanyi (0.0191 mg l^{-1}) was the most highly contaminated stream with mercury followed by Nankuke River (0.0163 mg l^{-1}) and Nabewo River (0.0158 mg 1^{-1}) in the Okame. There was also a significant concentration and trend of soluble mercury contamination from the sampled rivers ($R^2 = 0.8$). The average concentration of mercury was found to be 0.004 ± 0.0009 mg l. This paper notes that artisanal mining activities have led to the reduction in streamflow rates, change of streamflow course and colonization of stream banks by riparian vegetation.

Keywords Artisanal gold mining · Sediments · TerraSAR-X · Mercury · Streamflow

Introduction

Mining activities may degrade intact ecosystems worldwide such as water bodies, land, vegetation and wetlands among others (Van Straaten 2000; Bowell 2003; Castendyk and Webster-Brown 2007; Mpamba et al. 2008). Depending on the intensity and severity of degradation, this destroys and deforms the earth's surface (Castro and Moore 2000; Gao et al. 2007) which reduces the landscape's aesthetic value through the abandonment of mined pits, tailings, water impoundments (Ghose 2003; Antwi et al. 2008) and colonization of river banks by riparian plants due to concentration of sediment deposits (Malm et al. 1990; Hilson 2001; Machiwa 2003; Xu 2007).

The effects of artisanal gold mining have a far much higher impact on water resources than the other components of the environment such as climate (Chakrapani 2005; Liquete et al. 2009; Verstraeten et al. 2009; Qiang et al. 2011). Broadly, the effects on the local water resources can be subdivided into two major groups: those affecting the availability of water in the area (quantitative aspect) and those, which have an impact on the quality of the available water (pollution aspect) (Coetzee 2004; Fang and Yang 2010). Both the quantitative and qualitative effects of mining activities on the water resources can result into increased occurrence of floods, decreased reservoir storage capacity, degradation of aquatic ecosystems (Bronsdon and Naden 2000; Reid and

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Trustrum 2002; Achite and Ouillon 2007; Gao 2008) and migration of river channels (Hume and McGlone 1986; Singer et al. 2001; Stubblefield et al. 2005; Wang et al. 2006). However, an increase in sediment loading in rivers plays an important role in the transportation of nutrients and pollutants (Milliman and Syvitski 1992; Steegen et al. 2000). In addition, the information on the weight and grain size of sediments is of increasing interest to those concerned with sediment transport and related problems (Xu 2007).

Generally, in Africa, an estimated value of 9 million people are engaged in artisanal gold mining activities with another 54 million depending on the sector as an indirect source of livelihood (Foster 1996; Hilson 2001; Valenzuela and Fytas 2002; Jønsson and Bryceson 2009; Jønsson and Fold 2011). However, a considerable section of local communities are engaged in unlicensed artisanal mining activities as a diversification from subsistence agriculture and participation in small-scale businesses (Mutagwaba 1998; Ogola et al. 2002; Hinton et al. 2003; Jønsson and Fold 2011). The extent and effect of artisanal gold mining activities on the earth's surface and especially in the developing countries can be assessed using a multidisciplinary approach (Luise and Cornelia 2011). An analytical approach of spatial and field data collection provide a significant understanding of the characteristics and magnitude of artisanal gold mining activities in relation to sediment loading, pollution and streamflow variation (Rajesh 2004). This approach can be supplemented by assessing the hydrodynamic properties of a river (Le et al. 2006; Zuo et al. 2012) to understand the mining effect on the river morphology.

It is important to note that many hydrological studies have investigated the effect of artisanal gold mining activities on the environment and health, particularly in the form of heavy metal pollution (LaPerriere et al. 1985; Malm 1998; Grandjean et al. 1999; Van Straaten 2000; Ogola et al. 2002; Mol and Ouboter 2004; Eisler 2004) and sediment loading attributed to rainfall run-off (Martín-Vide et al. 2010). However, examining the effects of human-induced sediment loading due to artisanal gold stone washing in streams in the tropical catchments is an under-researched field (Chen et al. 2007). Therefore, the purpose of this study was to bridge this knowledge gap by assessing the spatial distribution and impact of artisanal gold mining activities on sediment loading (human induced), mercury concentration and streamflow variations in Okame River catchment, Eastern Uganda. This study demands that water managers take a holistic management approach of water resources in tropical catchments.

Methods

Study area

This study was conducted in the Okame River catchment found in Eastern Uganda (Busia District, Uganda) due to the widespread licensed and unlicensed gold mining activities to the other micro-catchments namely, River Solo and Aturukuku catchments. A catchment-based approach was adopted by the study to analyse the extent and spatial distribution of gold mining activities and their impacts on sediment concentration, mercury pollution and streamflow variations. The Okame River originates from the hills located in western Kenya and joins the Malaba River, which later pours its waters into Lake Kyoga in central Uganda. The upstream part of the catchment is in Kenya (60 percent), while the downstream section is in Uganda. The size of the catchment is 149.3 km^2. The tributaries of Okame River include Omanyi, Nankuke and Nabewo streams, which discharge their waters into the Okame River (Fig. 1).

The catchment is dominated by an undulating plain type of topography with an altitude of approximately 1128 m above sea level. Underneath the catchment exists the Pre-Cambrian rock types, which include granites, gneisses, quartzite and metamorphic rocks (Barasa et al. 2011). The soils fall under the ferralitic soil catena group, which is mainly composed of sandy loams. The soil layers have little differentiation in their horizons, possessing a fine granular structure, often moulded into layers, with weakly coherent clods which are very friable and porous (Otieno and Buyinza 2010). The catchment experiences an average annual rainfall of 1514 mm year^{-1}. The rainfall pattern is bimodal, with the first rainy season (short rains) starting from March to May and a longer rainy season extending from August to November. The mean annual maximum temperature is 28.7 °C, while the mean annual minimum temperature is 16.2 °C. The vegetation observed in the catchment has undergone considerable changes mainly due to the expansion of cultivated land, widespread gold mining activities and unplanned settlements. The main sources of livelihood are subsistence agriculture, gold mining and small-scale businesses among others.

Gold mining in the catchment

Gold was discovered in the catchment in 1932 and prospected in 1994, but it was until recently that actual mining has started with open-cast mining (Roberts 1986; Schlüter 2006). The goldfield occurs in volcanic rocks of greenstone type in the extreme south-east of Uganda, where the mineralization continues across the international boundary of

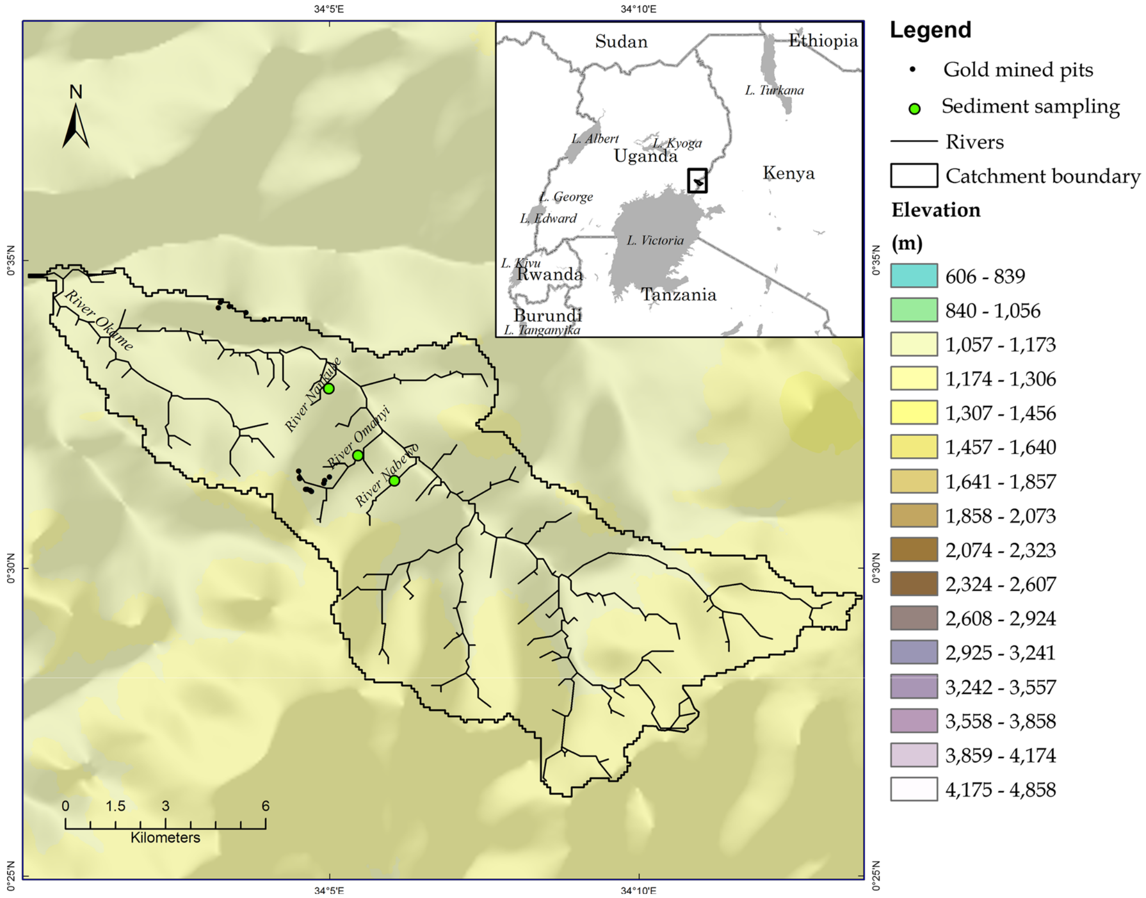

Fig. 1 Okame River catchment and the sampled sites

Kenya to become the Kavirondo goldfield (Roberts 1986; Kuehn et al. 1990; Schlüter 2006). However, gold mining activities are more rampant in the sub-counties of Busitema and Buteba in the Busia District of Uganda, covering an approximate area of about 134.6 km^2. The catchment has one of the largest gold mine deposits in the East and Central Africa. The extracted gold by the artisanal and small-scale miners is processed following procedures described by Telmer and Veiga (2009).

Sediment, streamflow and mercury data collection

Streamflow, suspended sediments and river bed deposits were collected from the selected stream cross sections on a monthly basis for a period of 1 year (2012). The selected streams were prone to gold ore washing and among these included: Omanyi, Nabewo and Nankuke Rivers. The streams were selected because they exhibited similar hydrodynamic properties. The sampling time frame was adopted because sediment data collected and analysed with a low frequency yield better predictions (Horowitz 2003). The streamflow, suspended and river bed deposit sediment data were collected at tributary level other than in the main Okame River, because of a high diversity of land surface conditions, human activities and high hydrological time lag of surface rainfall run-off (Lu et al. 2003). In addition, most sediment loading comes from small areas found within catchments (Xiaoqing and Yang 2003). The sediment and bed deposit data sets were collected from sections of high flow prior to gold stone washing, and after the washing process had taken place from the sampled streams.

An instantaneous sampler was used to collect water samples at one level and in the middle of each sampled stream for sediment assessment due to the low stream flow (John 2011). The water samples were taken to the laboratory for sediment and bed load measurements. In the laboratory, sieves of 63 μm were used to remove coarse suspended sediments from the water samples. Approximately, 25–100 ml of water from each sample was filtered onto a pre-ashed and pre-weighed GF/F 25-mm filter of pore size 0.45 μm, which was then dried at 60 °C at constant weight before weighing. A flow probe (model FP211) was used to measure stream discharge from the sampled streams.

The river bed deposit materials were sampled using a Van Veen grab sampler (Azamathulla et al. 2009) and delivered to the laboratory for grain size–particle size analysis. The samples were oven dried at 105 °C for 24 h, weighed (300 g) and sieved on a sieve shaker for 30 min for grain size analysis. Gold ore sieving was dependent on the largest particle size in the sample. The particle sizes were classified following the USDA Soil Survey Staff (1975) particle size classification scheme. The data were analysed using a linear mathematical relationship between the logarithmically transformed sediment concentration and discharge through regression analysis (Quilbé et al. 2006; Gao 2008). The relationship was later tested using a Student's *t* test. In addition, a one-way analysis of variance was carried out to test the significance of the bed deposit particle sizes in relation to the sampled streams. The daily suspended sediment loads per day from the sampled streams were computed using an established equation by the United States Army Corps of Engineers (1995). The equation is as follows

$$Q_s = K \cdot c \cdot q$$

where Q_s = sediment discharge (kg day^{-1}), c = sediment concentration (mg l^{-1}), q = water discharge (m^3 s^{-1}) and $K = 86.4$.

For the assessment of soluble mercury contamination, the sampled streams wholly undergo gold ore washing activities; however, the water samples were collected from areas of reach, i.e. before and after gold ore washing hotspots. Hotspots are areas of high concentration of gold ore washing activities. Three hotspots were selected along each stream and monitored for a month. These were defined depending on the number of people undertaking gold ore washing activities, direction of discharge and stage of the river. The water samples were analysed following Apostol et al. (1999) laboratory procedures.

Characterization of gold mining activities

The DLR's TerraSAR-X radar and Landsat satellite imagery were used to characterize gold mined pits in the catchment. The images were pre-processed and processed differently since the satellite data acquisition modes were different. The pre-processed level-1 TerraSAR-X (ScanSAR) image acquired on 21 May 2008 was obtained from the German Aerospace Centre (DLR) (Fig. 2). An overview of the TerraSAR-X satellite, its data modes and future developments are described by many scholars (Bamler et al. 2006; Zhiyong et al. 2009; Liu et al. 2011; Ortiz et al. 2012). The image was provided as a Single Look Slant Range Complex product (Fig. 2). The TerraSAR-X image was adaptively filtered using an Enhanced Lee (Ortiz et al. 2012) procedure and processed using an object-oriented classification algorithm in ENVI 4.7 software. The software showed low deviations in the area and shape of the pits (Neubert and Herold 2008). An orthorectified and cloud-free Landsat imagery of 30-m grid cell reflective size acquired on 19 April 2013 (Path 170 and row 60; zone 36 N) was used to map the open-cast pits. The imagery was filtered using the majority (3 × 3) filtering method and linearly stretched prior to classification (McDonnell 1981; Cleve et al. 2008). A hybrid approach of unsupervised and per-pixel-based segmentation was utilized in the characterization and quantification of artisanal gold mining pits. The approach was ideal because of the heterogeneous nature of the gold pits, tailings and their spectral reflectance (Lucas et al. 2007). The classified images were verified with the help of field data for a more accurate classification and Google Earth Pro imagery of 2008. However, information on the history, characteristics and distribution of artisanal gold pits was obtained from the local area key informants. The physical attributes of these pits were also obtained by measuring their geometry (depth, size, and water level) using a measuring tape. The change rate of the gold mined pits was computed following Peng et al. (2008) procedures.

Results

Characterization and classification of gold mined pits

In general, artisanal gold mining activities are widespread all over the catchment. The most common type of mined and abandoned gold pits was rectangular in shape, followed by the circular ones. The average depth of rectangular pits was 16.3 m, while 5.1 m for the circular ones. However, on average each pit was accessed and mined by approximately 22 people annually (Table 1).

Spatial distribution of artisanal gold mining activities

The image classification results for the studied period showed that there was a relatively high increase in the extent and widespread distribution of the artisanal gold mining activities in the area. In the year 2008, the extent of gold mined pits covered 4.5 km^2 but later increased to 19.9 km^2 in 2013. Therefore, this study demonstrates that the annual rate of change of gold mining activities in the studied period was 15.5 percent. Most of the mining activities were carried out more in the upland areas than the low-lying plains such as wetlands and river bottoms (Fig. 3). The extracted gold ore was ground and later

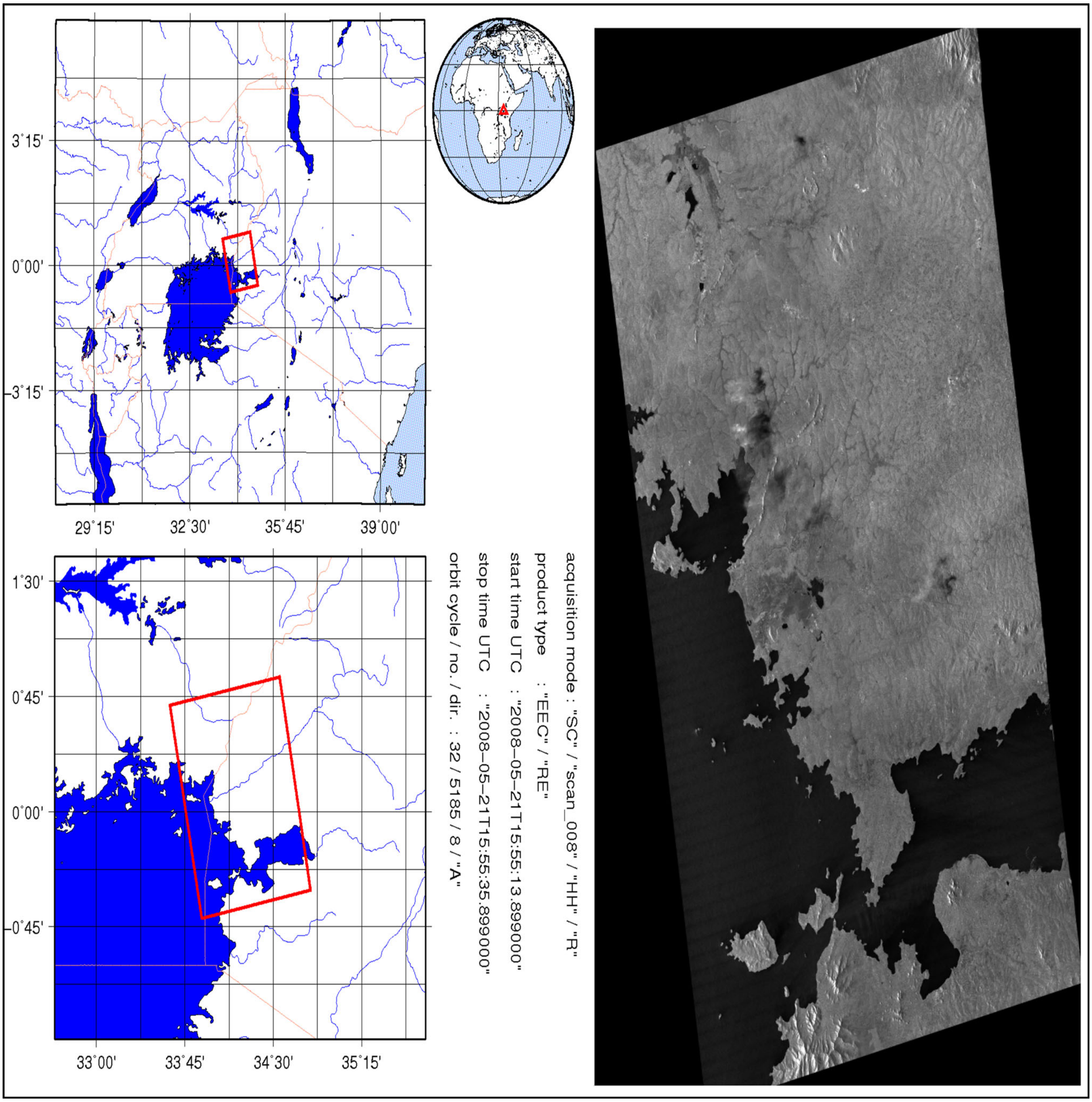

Fig. 2 TerraSAR-X (X-HH) acquisition scene by the satellite

washed into the nearby streams and impounded water points.

Concentration of suspended sediments and mercury

Sediments reached the streams through two main processes: both human- and natural-induced sediment loading. This study shows that human-induced sediment loading due to the washing of gold ore in the rivers had a higher impact on the concentration of suspended sediments (CSS) than the natural process (surface and bank erosion) from the sampled streams. Prior to human-induced sediment loading, the highest concentration of suspended sediments recorded was 160 mg l^{-1}. After gold washing, the concentration increased up to 864 mg l^{-} during the sampling period. Under the natural process or prior to gold ore washing, the highest CSS was recorded in Omanyi River (808 mg l^{-1}), followed by Nabewo (244 mg l^{-1}) and Nankuke (160 mg l^{-1}) Rivers. After gold ore washing, the highest CSS was still recorded in Omanyi (878 mg l^{-1})

Table 1 Characteristics of the sampled artisanal gold mined pits

Characteristics	Variable	Parameters
Morphology	Altitude	1137 m
	Number of pits sampled	33
Pit geometry	Number of rectangular	24
	Number of circular	9
	Average area of rectangular pits	40 m
	Average area of circular pits	193.4 m
	Mean pit depth (circular)	5.1 m
	Mean pit depth (rectangular)	16.3 m
Landscape slope type		Gently sloping
Land use	Dominant land use and cover	Subsistence farming, gold mining, wetland
Labour	Annual average number of miners per pit	22
Soil	Soil composition type	Sandy loam soils
	Parent materials	Volcanic and metamorphic rocks
Accessibility	Gold pit accessibility	Leasehold/hiring
	Land tenure	Customary system
	Mineral type	Gold
	Frequency of mining	Permanent
	Area accessibility	Moderately accessible

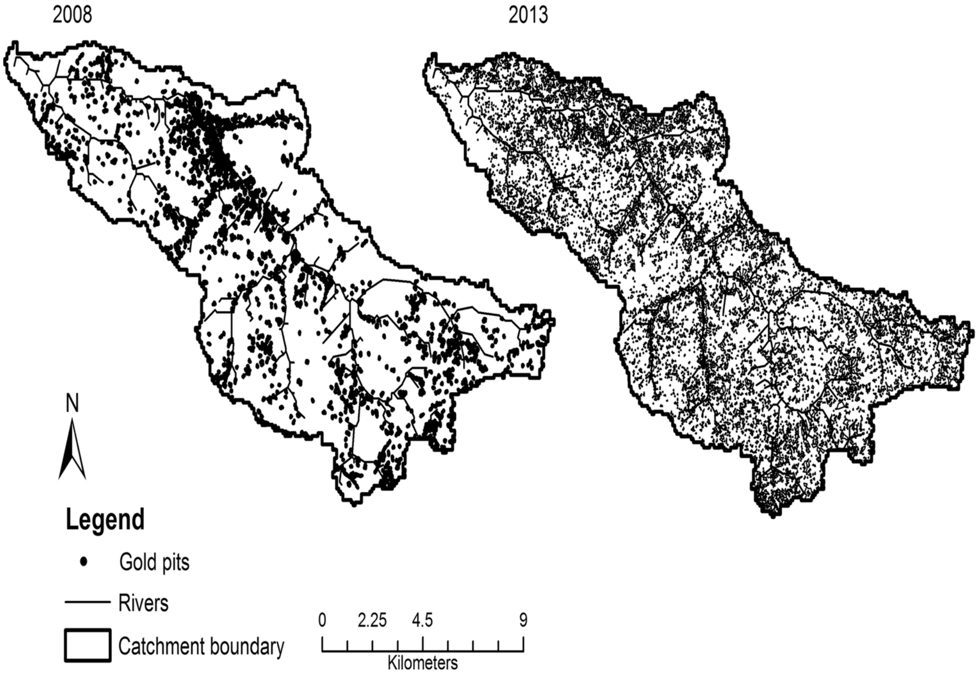

Fig. 3 Extent of gold mining activities in the Okame River catchment between 2008 and 2013

river followed by Nankuke (864 mg l^{-1}) and Nabewo (465 mg l^{-1}) rivers (Fig. 4). The concentration of sediments slowed discharge, reduced water levels and resulted into the colonization of stream channel by dense riparian vegetation. These variations in the CSS also varied according to dry and wet seasons. For instance, prior to human-induced sediment loading, the CSS was closely related to the rainfall events experienced in the catchment especially in the months of March–April and October–November. Conversely, the CSS was relatively high in the remaining dry months across the sampled gold ore washed streams (Fig. 5). The high concentrations of sediments were also in relation to the high mercury contamination attributed to transport mechanisms of sediments within the streams ($R^2 = 0.8$). The average concentration of 0.004 ± 0.0009 mg L-l in the sampled streams was

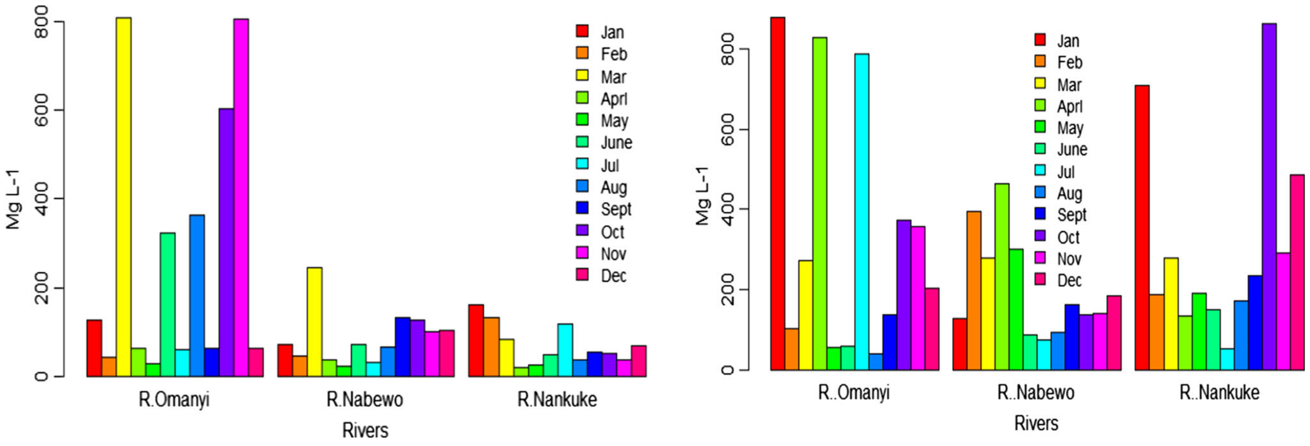

Fig. 4 Suspended sediment concentration before and after gold ore washing in the sampled rivers

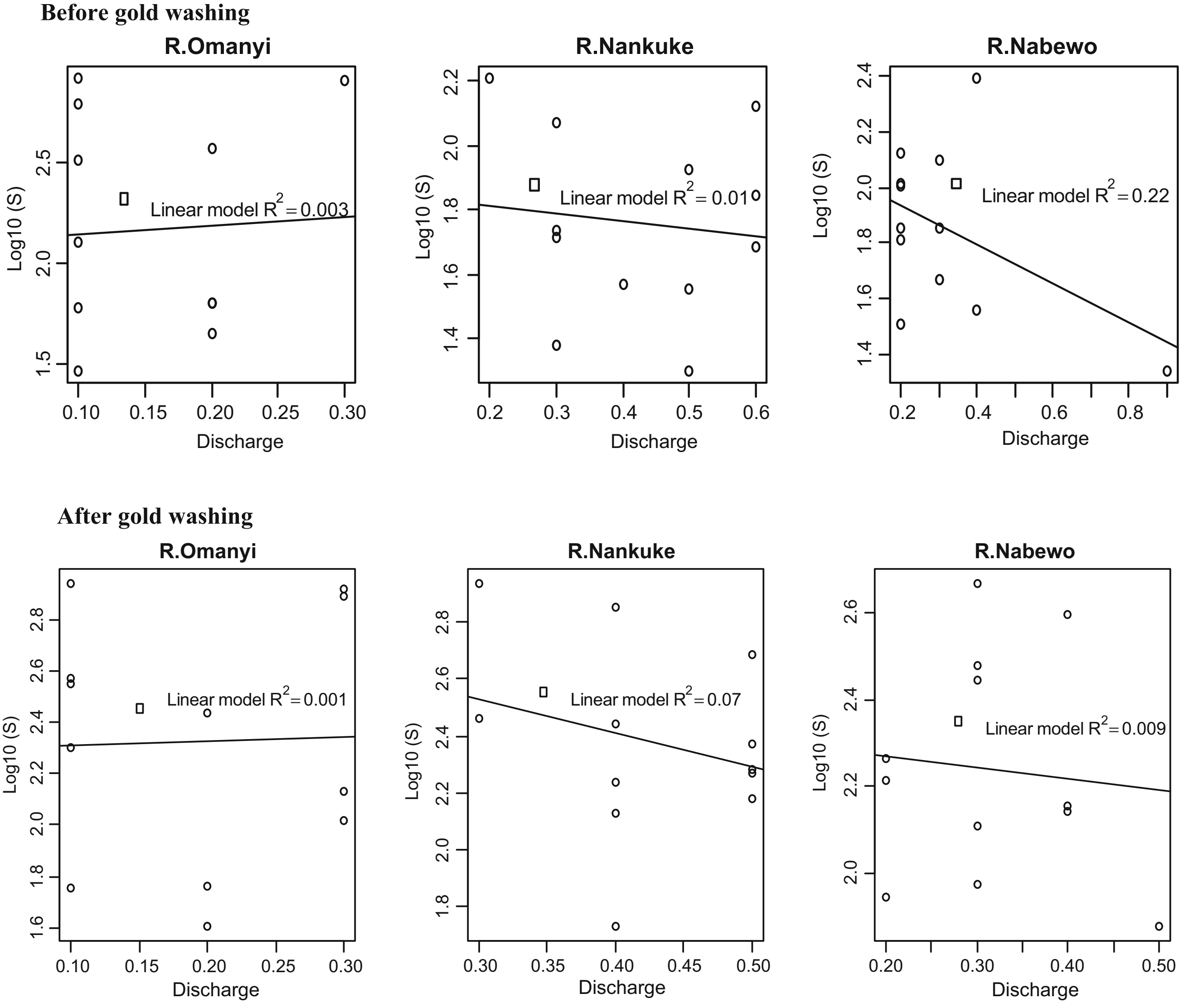

Fig. 5 Sediment concentrations (*S*) in relation to discharge, after logarithmic transformation of *S* ($n = 12$), *S* = Sediment concentration (mg l^{-1}); Discharge ($m^3\ s^{-1}$) in the three sampled streams

reflected in the degradation water quality and loss of biota observed in the riparian vegetation (Table 2).

Before gold ore washing, the highest stream contributors of suspended sediments to Okame River were Omanyi River (47.7 thousands kg annum^{-1}), Nankuke River (29.9 thousands kg annum^{-1}) and Nabewo River (26.5 thousands kg annum^{-1}). Whereas after washing, the main river contributor of human-induced sediments was Nankuke (130.6 thousands kg annum^{-1}) followed by Omanyi (70.6 thousands kg annum^{-1}) and Nabewo (66.8 thousands kg annum^{-1}) Rivers. The study results also revealed that provided other factors held constant, artisanal gold mining activities stand out as the main contributor of suspended sediments from the sampled streams. The streams contributed approximately 372 thousands kg annum^{-1} of suspended sediments delivered to the main Okame River (Table 2).

Streamflow variation

The amount of sediments deposited in the rivers caused significant variations in the streamflow because of high deposition rates that were responsible for the reduction in the water levels and discharge. The low water levels heightened the concentration of mercury contamination in streamflow. This correlation was statistically significant ($P < 0.05$, Student's t test) from the sampled streams. However, the assessment shows a weak coefficient of determination obtained between the CSS and streamflow before Omanyi R. ($R^2 = 0.003$), Nankuke R. ($R^2 = 0.01$) and Nabewo R. ($R^2 = 0.22$) and after Omanyi R. ($R^2 = 0.001$), Nankuke R. ($R^2 = 0.07$) and Nabewo R. ($R^2 = 0.009$) gold ore washing (Fig. 5). The weakness was attributed to the repeated diversion of river channels and change of streamflow courses (Table 3).

River bed deposits

The particle size distribution of river bed deposits is an important reference for assessing the magnitude of gold mining activities (Table 4). In this regard, the study results revealed that the most predominant river bed deposits that dominated the river channel bed (before and after gold washing) from the sampled streams were fine sand (0.25 mm) and fine gravel (4 mm). The very fine sand and clay were lowest amounts of river bed deposit grain sizes. The high presence of sand-related particle size types caused a strong relationship ($R^2 = 0.88$ and 0.85) between the coarse and medium sand, respectively. The sampled streams also had a similar variation of bed deposit frequency distribution of cumulative percentage and particle size as indicated in Fig. 6. Thirty-three percent of the sieved particle sizes were less than 21.2 mm, much as the largest bed deposits weighed 6 mm. This meant that the coarse–medium sand and silt had the most significant impacts on the distribution and size of river bed deposits found in the sampled river bottoms ($P < 0.05$). The river bed deposits also played an important role in the increase in suspended sediment concentration and fluctuation of streamflow (Fig. 7).

The results showed a significant difference between coarse sand from sieved/washed sites and those that were not sieved/washed ($P < 0.05$). However, the coarse sand grains were the only statistically significant particle sizes from the sampled streams ($P < 0.05$). The significance indicated that the river bed deposit particle sizes were the

Table 2 Concentration of suspended sediments transported by the streams

	Before gold washing (kg day^{-1}) × 10^3			After gold washing (kg day^{-1}) × 10^3		
Months	Omanyi R.	Nankuke R.	Nabewo R.	Omanyi R.	Nankuke R.	Nabewo R
Jan	1.09	2.76	1.24	7.59	24.47	3.32
Feb	0.76	6.79	1.22	2.70	8.08	13.62
Mar	6.98	3.63	8.43	4.70	9.61	7.21
Apr	1.07	0.86	1.24	21.51	4.67	12.05
May	0.25	0.62	1.71	0.49	8.29	7.78
Jun	2.80	2.49	1.84	1.00	6.52	1.52
Jul	0.52	3.02	0.56	20.42	1.85	3.24
Aug	6.29	1.56	1.12	0.69	5.98	2.44
Sep	1.07	1.40	2.28	3.53	10.20	2.83
Oct	5.20	1.35	3.27	3.23	22.39	4.80
Nov	20.87	1.28	1.75	3.08	7.52	4.91
Dec	1.07	3.63	1.78	1.75	21.04	3.18
Total	47.97	29.39	26.45	70.69	130.61	66.89

Table 3 Monthly mean values of Mercury from the samples streams

Rivers/quantities	Before (mg l^{-1})	After (mg l^{-1})	Net (mg l^{-1})	R^2
Omanyi	0.0139	0.0191	0.0052	
Nankuke	0.0116	0.0163	0.0047	0.86[a]
Nabewo	0.0137	0.0158	0.0021	
Average			0.004	

[a] R^2 for the trend line of the three streams

Table 4 Comparison of P values ($P < 0.05$) from the distribution of river bed deposit particle sizes

P values	Sieve particle sizes (mm)							
Sieve size	4	2	1	0.5	0.25	0.125	0.063	<0.063
Grain type	FG	VCS	CS	MS	FS	VFS	Silt	C
R^2	0.65	0.83	0.88	0.85	0.76	0.72	0.83	0.79
Overall ANOVA	0.72	0.06	0.01*	0.03*	0.24	0.41	0.05*	0.16
Sampled rivers	0.95	0.02*	0.09	0.13	0.43	0.30	0.69	0.14
Months	0.08	0.48	0.01*	0.01*	0.04*	0.03*	0.02*	0.01*
Treatment	0.63	0.81	0.04*	0.77	0.92	0.68	0.82	0.77
River and months	0.93	0.13	0.03*	0.48	0.38	0.69	0.90	0.64
River and treatment	0.96	0.85	0.28	0.14	0.29	0.45	0.09	0.75
Months and treatment	0.90	0.01*	0.03*	0.93	0.66	0.99	0.01*	0.84

Soil type: *FG* fine gravel, *VCS* very coarse sand, *CS* coarse sand, *MS* medium sand, *FS* fine sand, *VFS* very fine sand, *S* silt, *C* clay. Treatment: sampled sites before and after gold washing

* Significant ($P < 0.05$)

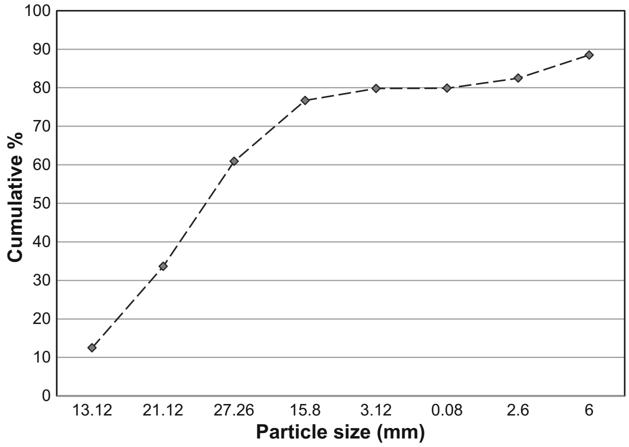

Fig. 6 Sediment frequency distribution of bed deposits from the sampled streams

major determinants of streamflow fluctuations and mercury contamination.

Discussion

This study reveals that the continued extraction and washing of gold ore in the tributaries of the Okame River throughout the year explains why human-induced sediment loading had a much higher impact on the concentration of suspended sediments (CSS) and distribution of river bed deposit particle sizes. This caused significant variations in the streamflow than surface rainfall run-off from the sampled streams. The findings are also in agreement with the observations made by Milliman (2001) and Walling (2006) that the main drivers of increased sediment loads include mining activities and land clearance for agriculture. Houben et al. (2006) also noted that the human factor was the major driving force of sediment production and redistribution in streams. In addition, Syvitski et al. (2005) also reported that humans have simultaneously increased sediment transport by global rivers through soil erosion (by 2.3 ± 0.6 billion metric tons per year), yet reduced the flux of sediment reaching the world's coasts (by 1.4 ± 0.3 billion metric tons per year) because of retention within reservoirs.

On average, about 35 thousands kg of particle grains (gold ore) are washed in each accessible stream on a daily basis. The sampled streams (Omanyi R., Nankuke R., Nabewo R.) contributed approximately 372 thousands kg annum^{-1} of suspended sediments in the Okame River, which is one of the major tributaries of the Malaba River. This is also responsible for the profound effects on the fluctuation of the Malaba river overall streamflow (Barasa et al. 2013). This finding relates to Dearing and Jones (2003) who argued that the human-induced sediment loading increases typically five to tenfold following a

Fig. 7 Nature of gold pits (**a**), pounded gold (**b**) ore ready to be washed in the streams and human-induced sediment loading process (**c**) and diversion of the river channels (**d**). Gold ore is mined from both the upland and river bottoms and pre-processed manually (pounding or grinding of the rock ore) into granules. The granules are sieved with mesh to separate the particles with gold using mercury to amalgamate small particles of gold

major human impact that causes drastic changes in the fluctuation of streamflow.

The study also reveals that the less than 50 percent of the variance of CSS could not be explained by streamflow. This low variation was attributed to the intensive loading of human-induced sediments in the face of low stream power, changing climate and stream morphology. Syvitski and Milliman (2007) also noted that climatic factors (precipitation and temperature) account for an additional 14 percent of the variability in global patterns of sediment load, while the anthropogenic factors account for an additional 16 percent of river loads. This clearly demonstrated how the human impact contributes more to sediment load than rainfall run-off. The relatively high concentration and trend of soluble mercury from the sampled rivers ($R^2 = 0.8$) were caused by gold ore washing along the rivers.

The coarse and medium sand and silt had the most significant contribution to the distribution of particle sizes that were found on the sampled river channel beds. This was attributed to increased sediment supply (Jayne and Mossa 1999). The re-washing of river bed deposit materials (gold ore) in the endless search for gold caused incision of channel beds (Kondolf et al. 2002), channel enlargement, shrinking and metamorphosis (Gregory 2006). However, the transport of river bed deposits was governed by higher slope-sensitive capacity limits (Moss and Walker 1978).

Nevertheless, the rates of sediment deposition were higher in the dry season than in the rainy season. This was because the artisanal miners diverted to crop farming during the rainy season since the active mining pits were filled with water. This is in agreement with the findings of Hinton et al. (2011) who supplemented that most of artisanal and small-scale mining activities in Uganda are informal and unlicensed and in many cases undertaken seasonally to supplement agricultural livelihoods. The high amount of sediments deposited in the streams results into stream course diversion, reduced water levels, colonization of stream banks by vegetation, which slowed down streamflow. Gradziński et al. (2003) also found out that the riparian vegetation stabilizes channel banks and slows down the water flow.

The magnitude of gold mining land use increased exponentially in the catchment as noted earlier; the mined area expanded from 4.5 to 19.9 km^2 in 2013 and 2008, respectively. This rampant growth in the number of mined pits was largely attributed to livelihood diversification, the customary land tenure system, local and international demand for gold, weak enforcement of environmental and mining policies and bureaucracy in the acquisition of mining permits and licences. This is similar to the findings of Hilson (2009); Siegel and Veiga (2009); Banchirigah and Hilson (2010); Bryceson and Jønsson (2010) and Maconachie (2011) who noted that livelihood diversification in rural sub-Saharan Africa is focusing primarily on the growing economic importance of artisanal and small-scale mining in the region. In addition, Foster (1996) and Jønsson and Bryceson (2009) also found out that the spread of artisanal gold mining activities is spurred by the availability of gold as a highly valued commodity in the region and worldwide. Moreover, this study is also in conformity with the view that almost one-third of all active mines in the world are found in sensitive watersheds (Millennium Ecosystem Assessment 2005).

Conclusion

This study reveals that human-induced sediment loading has a higher impact on the concentration of suspended sediments and fluctuation of discharge than sediments from rainfall/stream bank run-off from the sampled streams. This has caused significant variations in the streamflow than surface rainfall run-off from the sampled streams. This impact was generally high in the dry months than when the catchment was wet. From the studied streams, the main contributors of human-induced sediments were Nankuke, Omanyi and Nabewo Rivers. This has resulted into stream course diversion, reduced water levels, colonization of stream banks by riparian vegetation, which slowed down streamflow. A significant concentration and trend of soluble mercury contamination from the sampled rivers is attributed to gold ore washing along the rivers. Unlike most sediment loading studies in East Africa, which were normally carried out at the lake level, the present study has bridged the knowledge gap at the river or tributary level (Kishe and Machiwa 2003), where sediment point sources are not clearly defined (Kimwaga et al. 2012).

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