Assessment of Suspended Sediment Loadings and their impact on the Environmental Flows of Upper Transboundary Mara River, Kenya

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Abstract
This study determined the levels and constituents of the suspended sediment loading in the upper basin of Mara River and how they relate to the environmental flow requirements of the basin. The Mara River, which is an international river shared by Kenya and Tanzania, forms part of the larger Upper Nile River Basin. Flow and sediment data were collected at Nyang'ores and Amala Rivers, tributaries of Mara River from February to July 2007.
Both tributaries had similar mean monthly sediment yield ranging between 95.16 and 97.43 mg/l, which is above the allowable 30 mg/l for discharge into the environment. The iron concentration in both rivers was above the recommended Kenyan standards of 0.30 mg/l. The increased levels of sediment and metallic pollution were attributed to anthropogenic practices and settlement in forest catchment that resulted in excessive soil erosion.
The recommended normal year environmental flow of 1.00-2.00 m^3/s in the Mara was easily met and ample water was available for consumptive use. However, during a drought year the recommended reserve flows of 0.30-1.00 m^3/s and the environmental flow requirements were mostly not met.
This study recommends restoration of wetlands, stoppage of further deforestation and settlement and to encourage soil conservation and river bank protection in the catchment.

***Key words*:** Environmental Flows, Mara, Suspended Sediment, Trace Metals

1. INTRODUCTION

The Mau complex and Maasai Mara have been in both the local and international news in the recent past. The most important functions in the headwaters are efficient rainwater infiltration and soil conservation, which together ensure that there is the largest possible quantity of clean water in the river during the dry season. These functions translate into benefits to institutions and individuals in the basin such as provision of good water quality for communities, agricultural activities, tourist facilities, mining activities; maintenance of the Mara-Serengeti ecosystem, and reduction of flash floods and droughts. Further, the Mara River provides fish, indigenous plants, fertile alluvial soils and; critical habitat to people and wildlife in the basin. However, in such an arid system, the many demands for these resources are sometimes incompatible. This has made the Mara basin vulnerable to erosion thereby distorting the river hydrology (Mati *et al.*, 2008).

In recent years, the capacity of the river to support these activities has been diminished during the dry season when flows become very low. There is little systematic monitoring of water quality, especially sediment pollution in the Mara River Basin. Sediment transport is a carrier of nutrients, heavy metals and pesticides that adversely affect the water quality in rivers (Machiwa, 2001). The study of river suspended sediments is becoming more important, nationally and internationally because of the increasing need to assess fluxes of nutrients and contaminants to lakes, oceans and across international boundaries.

This research was therefore aimed at assessing the impact of suspended sediment on environmental flows and identifying elements in the sediment of the upper Mara River basin.

2. METHODODLOGY

2.1. Field Measurements and Data Collection

The two tributaries, Amala and Nyang'ores Rivers, drain the forested Mau escarpment in a south-westward direction as shown in Figure 1. Sampling for suspended sediment loads was done at two rivers gauging stations (RGS): site 1, Amala RGS 1LB02 (longitude 35.438, latitude-0.897) on Kapkimolwa bridge and site 4, Nyang'ores RGS 1LA03 (longitude 35.330, latitude-0.780) located 1 km from Bomet town on the Nyang'ores River bridge. The site 1 at Amala River and sites 2 and 3 were used for the Environmental Flow Assessment. Baseline and reconnaissance surveys of the Mara basin were carried out and historical data collected from the Ministry of Water and Irrigation. Rainfall data was collected from the Kenya Meteorological Department. Data from the routine river flow measurements that were carried out during the study was analyzed for any relationships between the discharge and sediment loading. The river discharge gauging and sediment sampling were done over a period of 6 months from February to July 2007.

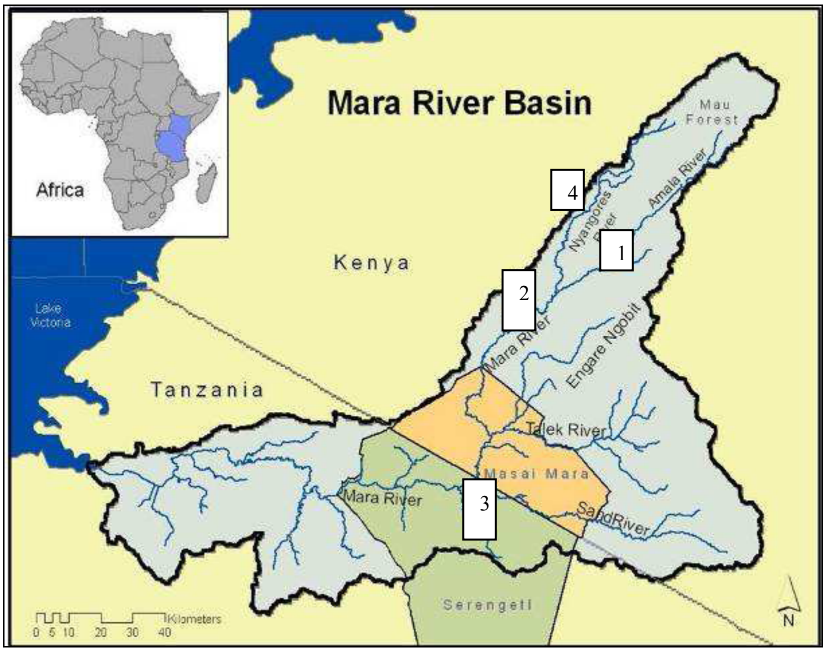

Figure 1: Location of sediment sampling sites and sites for EFA during the study period.

2.2. Flow and Sediment Sampling Procedures

The suspended sediment sampling was carried out using USDH-59 sampler suspended on a cable controlled by the bridge crane or boat during floods or mounted on the current meter- wading rod (Figure 2). A depth-integrating sampler traverses the complete depth of the stream and back at a uniform rate and collects a sample, which has a concentration equal to the average concentration in the vertical (Garde and Raju, 1995).

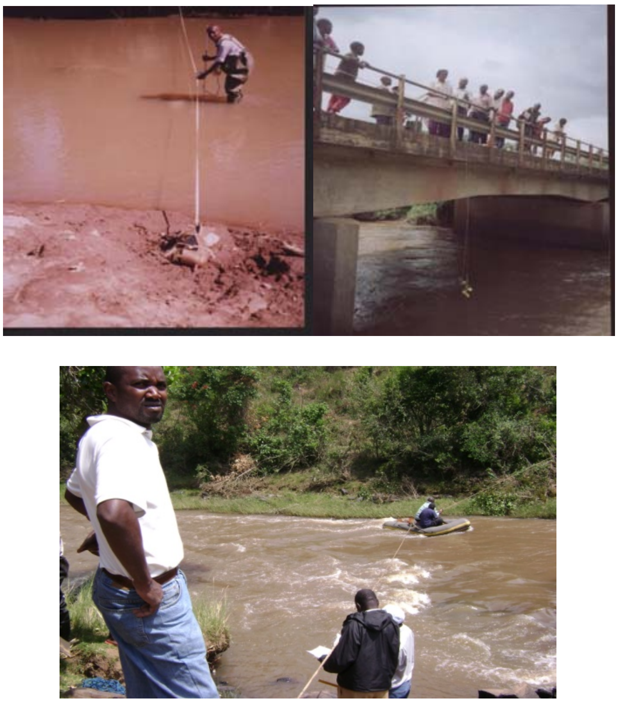

Figure 2: Wading, bridge crane and boating at Nyang'ores River.

River flow discharges were computed from measurements of velocity and depth at a cross section near the recorder downstream of the bridge (Linsley, 1988). The Mid-section method that was used assumes that the mean velocity for the vertical *i* represents the mean velocity in the cross section, from half-way to the preceding vertical (i-1) to halfway to the next vertical (i+1). The verticals for suspended sediment samples were located according to standard procedures by Garde and Raju (1995). The velocity was measured at vertical sections spaced at 1 m interval across the river using the SEBA current meter. The velocity in each vertical was observed at 0.6 of the depth from the surface. At a third of the distance from the banks and in the midpoint, a depth-integrated sample was taken using a 400ml bottle: noting the transit time required by the nozzle of the sampler.

Each of the three verticals had a different depth and velocity and hence the time to lower and lift the sampler varied with each vertical sampled. The 400 ml sampler bottle was filled according to standard procedures (Guy and Norman, 1970). Since coarser particles tend to have lower concentrations of metals, nutrients and organic micro pollutants, samples were collected of fraction less than 63 µm with which most metals tend to be associated (Bartram and Ballace, 1996). All sampling bottles were acid-cleaned, rinsed twice with distilled water and rinsed twice with sample water prior to collection. The three samples were composited to one daily sample and put into a single 1 litre HDPE bottle and labeled at the site and taken for determination of total suspended solids in the laboratory.

All Samples for this study were transported and analysed at Jomo Kenyatta University of Agriculture and Technology for Total Suspended Solids (TSS). Measurements were done once a week or within 24 hours during the rains. 132 samplings were done making 44 composite samples (22 samples per river) over the period and recorded in standard hydrological sheets. The concentration of suspended sediment in the water samples was determined in the laboratory using the method described in Bartram and Ballace (1996) and APHA methodology No. 2540D (A.P.H.A, 1995). The sand concentration was negligible and not required separately, so a known volume of raw water was filtered through a pre-weighed 0.45 µm pore diameter filter paper.

A Statistical Analysis of flow and total suspended solids was carried out by Instat for Windows®. According to Bartram and Ballace (1996), discharge measurements, Q, and suspended sediment concentration (C) can be used to calculate suspended sediment load (SSL) in tonnes per day as shown in equation 1:

$$\mathbf{SSL} = \boldsymbol{Q} \times \mathbf{C} \times \mathbf{0.0864} \qquad (1)$$

2.3. Assessment of the Heavy Metals in Suspended Sediment Solution

The fundamental parameter method as described by Sparks (1978) was used. For each river, two dried samples were analyzed when flow increased, two when it reached a peak, and then two when it decreased. The concentrations of trace metals from 12 dried sediments products were analyzed using an X-Ray Fluorescence spectrometer in the University of Nairobi. Energy-dispersive XRF spectrometry (EDXRF) analyzed trace elements present from Beryllium (Be) to Uranium (U) and beyond at trace levels up to 100 %. EDXRF includes special electronics and software modules to take care that all radiation is properly analyzed in the detector and therefore provide a lower cost alternative for element analysis as compared with such techniques as atomic absorption spectrophotometer (AAS). The emission of the characteristic radiation can be induced either by the impact of accelerated particles such as electrons, protons, α- particles and ions or by x-ray photons emitted by a radioactive source on an x-ray machine. In this study, ^{109}Cd source was used. Laboratory analysis began with the optimization of the x-ray fluorescent system. During optimization, setting of the optimum bias voltage, shaping the time constant at which best detector resolution is achievable and setting the optimum irradiation time for the loaded filters were done. A setting of 2000 seconds was found appropriate.

2.4. Environmental Flow Assessments

As more countries invest in water resources infrastructure such as dams and canals, there is an increasing need to assess the water requirements of river reaches and lakes to ensure that they continue to provide resources for human use (ILEC, 2005). The assessment of flows and suspended sediment pollution was done as part of the Environmental Flow Assessment (EFA) exercise concurrently with partners from GLOWS and Worldwide Fund for Nature (WWF) (EFA-MRB, 2008). The reserve required to satisfy basic human needs for all people who are or may be supplied from the water resource is defined as a minimum of 25 l/day/person and was compared with historical runoff in the upper Mara River system (EAC 2009, Hoffman *et al.* 2009).

The Building Blocks Methodology (BBM) as described by King *et al.* (2000) was adopted as the best choice because it uses structured, science-based approaches to determine how much water must be left in the river to protect the aquatic ecosystems and meet Resource Quality Objectives (RQOs). Site selection for environmental flow assessment (EFA) was done through geomorphological surveys that classified the river into three uniform macro-reaches based on gradient, channel pattern and bed structure. During initial field visits, a representative site for each of macro-reach was chosen. Consultations on the ability of the site to resist disturbance and capability to recover from disturbance were held at the site. Fish species were also characterized according to their environmental guild, a classification system that groups species that respond similarly to changing hydrology and geomorphology (Welcomme *et al*., 2006). Fish were sampled in these surveys after a standardized period of time of 6 hours, the nets were hauled and data was collected on number and abundance of species, length and weight of individuals, and reproductive condition using gillnets placed in the river at each study site.

Site 1, Kapkimolwa Bridge (1860 m a.s.l) represented the upper Mara Basin. The land around this site was dominated by small-scale settlement with the main land use practices being subsistence farming and cattle rearing. Amala River joins the Nyang'ores River downstream of Site 1 to form the Mara River (Figure 3).

1 2 3

Figure 3: The Macro-reaches for EFA at the Upper Mara River for Locations 1, 2, and 3.

Site 2 at Mara Safari Club (1687 m a.s.l) at the boundary of Maasai Mara Game Reserve represented the Middle Mara River. The land outside the reserve was a mixture of large-scale irrigation farming, wildlife ranching and tourism. Site 3 at the New Mara Bridge (1470 m. a.s.l); at the Kenya-Tanzania border between the Maasai Mara game reserve and Serengeti National Park represented the lower reach. Because this site is within the two major protected areas of Kenya and Tanzania, the only land use in the vicinity was wildlife rangeland and the only economic activity was tourism. At each of the 3 EFA sites, a 65-75-meter straight stretch of the river was marked that included runs, pools and riffles, in order to capture the variability in habitat types and hydraulic regimes. The geometry of each transect was carefully surveyed in each site.

3. RESULTS AND DISCUSSION

3.1. The Suspended Sediments in Nyang'ores and Amala Rivers

The mean daily sediment concentration of Nyang'ores River at ILA03 was 95.16 ± 12.68 mg/l and that of Amala River at 1LB02 was 97.43 ± 12.46 mg/l while the medians were almost the same at 84.5 mg/l and 85 mg/l respectively. The highest sediment concentration observations were 268.5 mg/l in Nyang'ores River and 258 mg/l in Amala River.

The sediment concentration for Nyang'ores ranged from 35.5 mg/l to 268.5 mg/l. while the sediment loading for the Amala River ranged from 26.4 mg/l to 258 mg/l. Suspended sediment load (SSL) were calculated from the discharge measurements (Q) and suspended sediment concentration (*C*) (equation 1). From the results of the 44 samples, Nyang'ores River had a mean loading of 128.47 ± 20.15 tonnes/day while Amala River had 131.70 ± 38.56 tonnes/day. This level of sediment loading shows that Mara River is still near pristine conditions compared to other Kenya Rivers. For example, in a study in the Tana Estuary between 2001 and 2003, it was reported that total daily sediment load varied from 2796 tonnes/day during the dry season to 24,322 tonnes /day during the rainy season (Kitheka *et al*., 2003). Comparing the sediment loads during the study period with the historic data, there is a general increase in sediment yield in the upper catchment (Republic of Kenya, 1992; WREM, 2008).

The sediment loading decreased to a minimum in the dry period from February to March before the long rains and then remained at mean discharge in April- May before reaching a maximum in June. The trend of sediment loading could be expected to repeat the April-May-June cycle and have another peak in October-November as this area has bimodal rainfall. There is some July-August rain from the west due to the Congo air mass. The higher sediment yield in the Nyang'ores River could explain the increasing problem of siltation in the Tenwek dam (Terer, 2005), 15 km upstream of Site 4 and associated increase in river turbulence suspending bed load sediment.

The high concentration of suspended material at Amala Site 1 in June was caused by an increase in erosion. A visit made upstream of Kapkimolwa Bridge (1LB02) as far as Matecha Gauging Site in Mau Forest revealed sediment pollution even at the uppermost reach of Amala River. This was attributed to increased agricultural activities and commercial centres along the rivers. Of the eleven rivers draining into Lake Victoria, the Mara River with a mean turbidity of 130 NTU is the second major source of sediment transport and the sediment concentrations in the lake (Swallow et al., 2003).

The riverbanks, upstream of Site 4 and Site 1 sampling points, showed some degree of terracing, along with the presence of areas prone to intermittent flooding. Both sites also had active channel banks and in-stream sandbars, indicating the occurrence of active processes such as erosion and sediment deposition (Figure 4). There was evidence of soil and gully erosion in the farms and along cattle tracks near the town (Figure 5). The main cause of soil erosion was surface runoff from within and outside the farms, and steepness of the farms. There was evidence of substantial quantities of sediment on the riverbeds which is available to be taken into suspension due to turbulence in the event of increased flow. This could explain the high sediment concentrations after a storm preceded by dry period.

Figure 4: Evidence of terracing and sediment deposition on the upper right and left banks and sandbars (foreground) near Matecha Bridge, upstream of Site 1.

Figure 5: Gully formation and soil erosion along access road to Bomet Town, upstream of Site 4.

3.2. Sediment Rating Curves at the Upper Mara River

The trend in total suspended sediment presented a simple linear relation Log discharge with a coefficient of determination (R^2) of 0.5887 showing little variation of sediment concentration in Nyang'ores River in Figure 6 and Amala River in Figure 7. The goodness of fit for Amala River represented by R^2 was 0.5112. The fitted equations within the sampled range are equations 2 and 3:

Nyang'ores Sediment Concentration (mg/l) = 19.77 + 22.42 *Log Discharge, (m^3/s) **(2)**

And for Amala, Sediment Concentration (mg/l) = 28.182 + 31.007*Log Discharge) (m^3/s) **(3)**

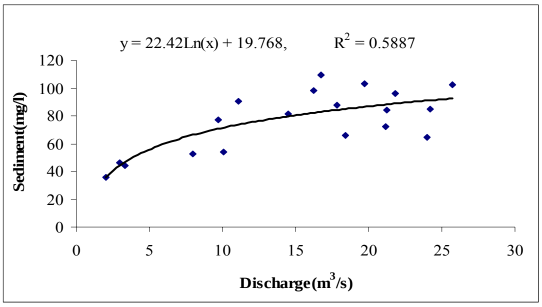

Figure 6: Nyang'ores River sediment Rating Curve.

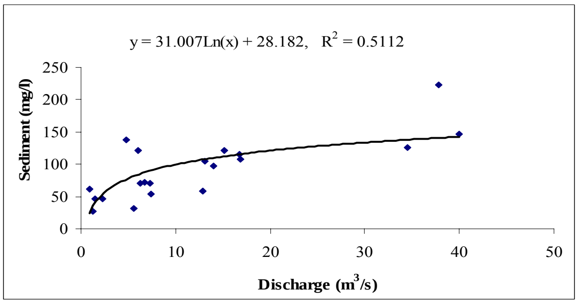

Figure 7: Amala River Sediment Rating Curve.

These series of discharge and sediment measurements indicate a constant sediment concentration increase, reaching a peak (close to the mean and the median) at a flow of 15 m^3/s. The weir reservoirs act as effective sinks for suspended matter resulting in reduced suspended matter quantities and depleted nutrients (UNEP, 1991). This could be the phenomenon interfering with flows at the river gauging station at Bomet Bridge (1LA03). However, when these results are used to estimate mean annual sediment yield, the errors in sediment rating tend to compensate and satisfactory results are obtained for sufficiently long record (Linsley, 1988).

3.3. Sediment and Turbidity Relationship

Figures 8 and 9 show the Sediment-turbidity relationship in Nyang'ores and Amala Rivers respectively. The regression analysis for Nyang'ores River produced a good equation ($R^2 = 0.9341$) in equation 4:

Turbidity (NTU) = 32.62 + 0.7558 *Sediment (mg/l) **(4)**

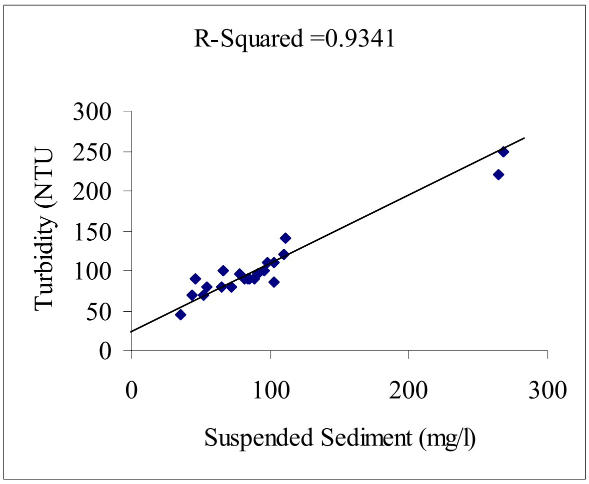

Figure 8: Sediment-Turbidity Relationship for Nyang'ores River

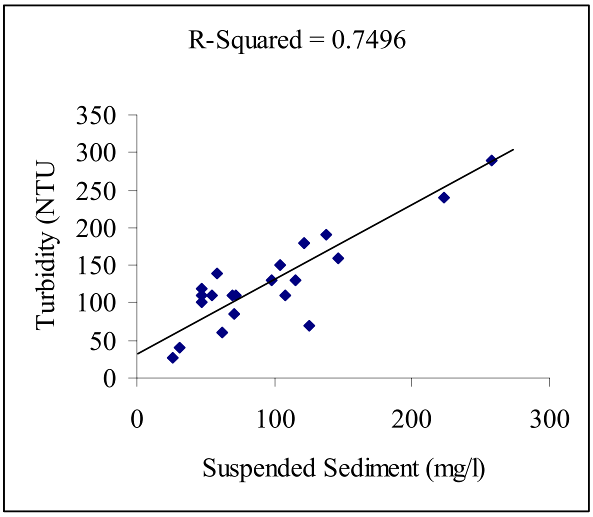

Figure 9: Sediment-Turbidity Relationship for Amala River.

and for Amala River, the fitted equation 5 also had a linear relationship with $R^2 = 0.7496$:

Turbidity (NTU) = 40.32 + 0.9126 * Sediment (mg/l) **(5)**

The water is more turbid in Amala River than at Nyang'ores River. Since it is easier to measure turbidity at the Bomet station, these relationships can be used to estimate suspended sediment concentration.

3.4. EDXRF analysis for Nyang'ores and Amala Rivers

Examples of the spectrum produced by the computer analyzer for Nyang'ores sediment at Site 1 is shown in Figure 10.

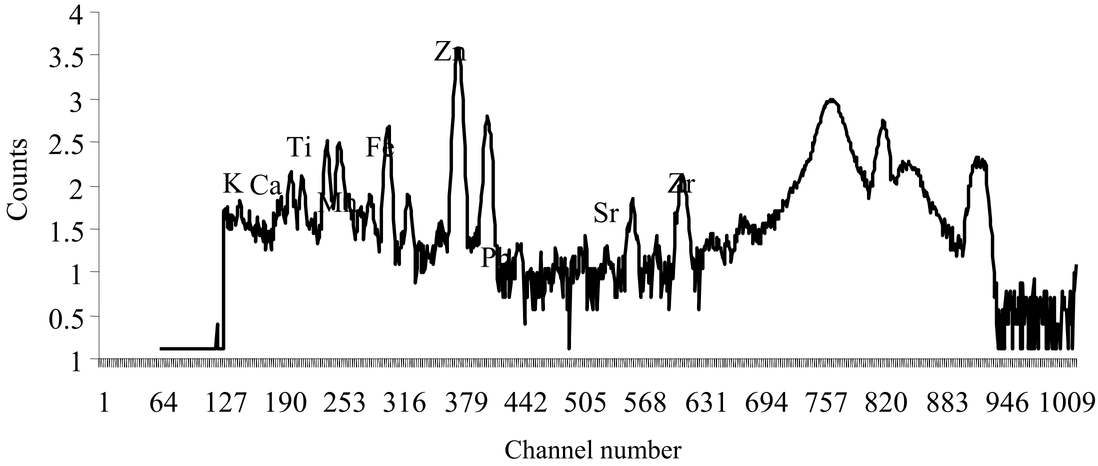

Figure 10: Typical XRF spectrum for sample 10N5 from Nyang'ores River.

Each element, represented by the channel numbers, has a unique electronic configuration and produced two peaks. The emitted secondary radiation (peak) is a characteristic of that element. Zinc (Zn) and Iron (Fe) had the highest counts while lead (Pb) had the lowest in Nyang'ores samples. The second process on the right (after channel No.631) was scattering of the incident photons in all directions after collision with atoms. The scattering photons have either a longer wavelength or the same wavelength and therefore producing a similar curve (Sparks, 1978). Just like in Nyang'ores River, the main elements in Amala were Iron (Fe); Zinc (Zn), and Manganese (Mn).

3.5. Trace metal concentration in the Upper Mara River

The iron concentrations of samples in Figure 11 were above the WHO maximum allowable level of 0.30 mg/l for drinking water (Chapman, 1996) but within the Kenya guidelines for irrigation water (1.0 mg/l) and discharge to the environment (10 mg/l).

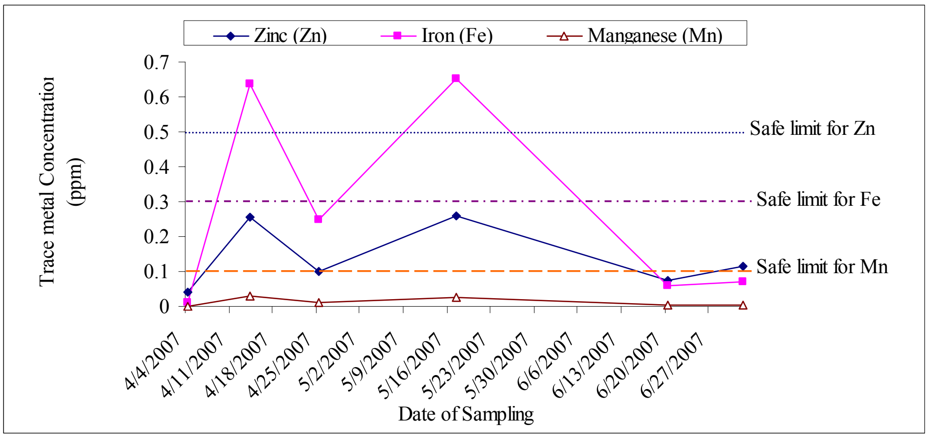

Figure 11: Concentrations for Zinc, Iron and Manganese at Nyang'ores River on different sampling dates.

Above the 0.30 mg/l level, the water is objectionable due to yellow colour and a bitter taste and in fact some countries set the limits at lower levels. The limit is 0.2 in EU while in Russia it is 0.1 mg/l (Pearce, 1999). Therefore considering the downstream use of Mara River include tourism hotel industries; the allowable limits of pollutants for such significant rivers should be reviewed.

Rate and amount of Iron concentration increase immediately after the drier period was higher than the

Iron increase due to increased discharge in the middle of the rainy season. Comparison was done between the two peaks of each of the graph and the respective flows and rainfall patterns for days before and during sampling for 5 main rain gauge stations in the upper Mara catchments.

3.6. Iron Concentration in the Upper Mara River

It was evident that Iron increased during the rising limb of flow in the hydrograph. Low metallic concentrations were observed in the drier periods and after a prolonged period of flooding (Figure 12).

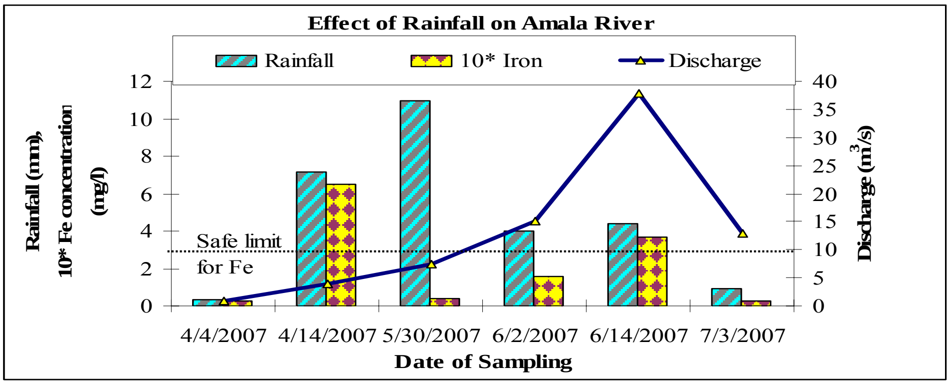

Figure 12: the Impact of rainfall to Iron concentration in Amala River.

The iron pollution could be attributed to soil erosion in the study area and high organic matter in the swamps upstream. The Andosols in the agricultural zone upstream of Site 4 and Site 1 have high silt content and susceptible to serious erosion problems (Muchena *et al.*, 1988). These soils are susceptible to mass movement (slump and landslide) especially where thin soil layers are resting on unconsolidated volcanic ash deposits. The increased iron concentration could be related to geological and anthropogenic influence, soil erosion and run-off from point sources like rusted metallic articles at the shopping centres, scrap metal dump sites and any sludge lagoons upstream.

Comparing this range of concentration with the Mara Baseline water quality dataset, the level of Iron pollution in 2004 was ≤ 0.10 mg/l .Thus the iron pollution has increased in the recent past. Water treatment would therefore be necessary before consumption of Mara River water. Excessive iron can be toxic, because free ferrous iron reacts with peroxides to produce free radicals, which are highly reactive and can damage DNA, proteins, lipids, and other cellular components. Excess iron consumption causes vomiting, diarrhea, and damage to intestines and if consumed over a long period of time may damage coronary arteries (Merck& Co, Inc., 2003).

Figure 13 shows that soil erosion and shopping centres upstream of the gauging sites could be the possible sources of trace metal pollution.

Figure 13: Intensively cultivated and degraded area upstream of RGS at Bomet Bridge

3.7. Discussions on suspended sediment at Amala and Nyang'ores Rivers

The study shows that the water quality at the two regular gauging stations had a TSS of more than 30 mg/l, the maximum figures recommended by Kenya for domestic use and effluent discharge into the environment (Republic of Kenya, 2006). EPA (2003) has recommended the removal of at least 80 % of total suspended solids (TSS) from polluted runoff to control heavy metal, phosphorus and other pollutants. The turbidity at the two RGS was more than 5 NTU recommended by WHO (Chapman, 1996) for drinking water and 50 NTU for aquatic life and recreational waters in Kenya (Republic of Kenya, 2006). The methods used for discharge computation gave sufficiently accurate results which can be used by water managers.

3.8. Environmental Flows in Drought Years (Flows below normal)

During drought years (Figure 14), the recommended reserve (EFR) was a minimum of 0.30 m^3/s in January, March, April, June and July while a maximum value of 1.00 m^3/s was recommended for September. It is clear that the EFR was not being met during several months of the year at Kapkimolwa RGS 1LB02, Macro-reach Site 1. The environmental flow was met only in the month of September.

The results of this EFA should be monitored to reveal whether the required reserve levels are lower than originally prescribed. However, the recommended reserve of 0.3-1.0 m^3/s is close to the figure suggested by a study done in Great Ruaha Catchment in Tanzania, where a flow of 0.5-1.0 m^3/s was recommended to sustain the environment in the park during the dry season for Great Ruaha River (Kashaigili, 2005).

Reduced infiltration rates and excessive runoff caused by loss of ground cover (Terer, 2005) in the drainage basin of the Mara River have resulted in flashy flow regimes and flooding in downstream sections of the river. Sometimes the trend toward higher peak flows may be an indicator of urbanization (Haan *et al.*, 1994). Silt loads carried by the river have increased, confirming previous baseline survey data (Singler and McClain, 2006). Rainfall has decreased over the last 30 years but sediment loading has increased 5 times. Deforestation can raise suspended matter in a river more than 100 times (UNEP, 1991). This is likely to be the case in this catchment. National policies and laws need to recognize the importance of providing for environmental flows (ILEC, 2005).

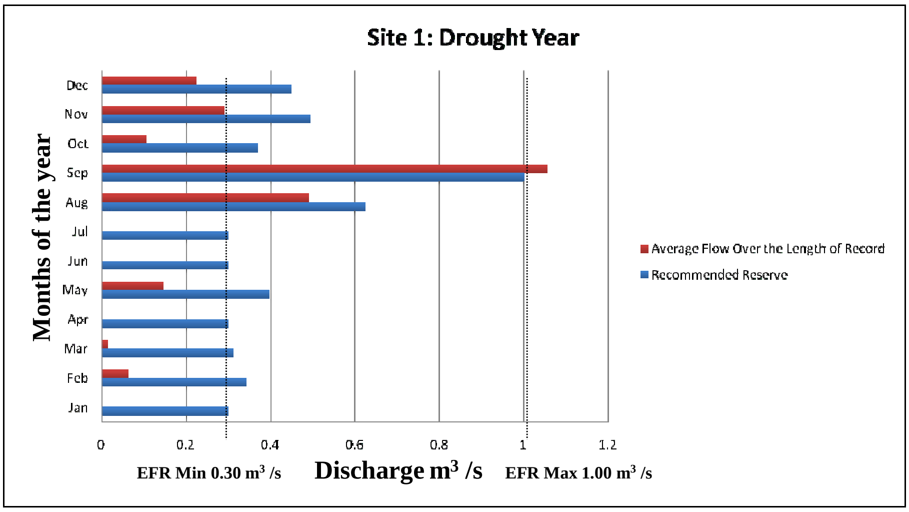

Figure 14: Environmental Flow Recommendation for Drought year at Macro-reach Site 1.

4. CONCLUSIONS AND RECOMMENDATIONS

4.1. Conclusions

1. Suspended Sediment concentrations in the Mara River were above allowable Kenyan standards (30 mg/l) for domestic uses and effluent discharge into the environment. This high sediment pollution in the upper reach was attributed to increased agricultural activities and settlement in forest catchment.
2. The stage-discharge rating curves showed good coefficient of determination (R^2) at 0.84 and 0.85

for Nyang'ores and Amala Rivers respectively. The relationship between turbidity and sediment concentration indicated a higher level of linearity than the logarithmic discharge-sediment relationship. The developed sediment rating can be recommended as sediment monitoring tools to give an indication of sediment load.
3. The high level of Iron concentration at 0.638 and 0.652 mg/l at RGS 1LA03, Nyang'ores River, and 0.650 mg/l at RGS 1LB02, Amala River, were above recommended standards of 0.30 mg/l. Other pollutants included Zinc, Manganese and Lead. The source was likely geological and overland storm runoff.
4. The recommended reserve flow levels in the two rivers for maintenance years were between 1.00-2.00 m^3/s and ample water is available for extractive uses. However, during the drought years, the environmental flow recommendation of 0.30-1.00 m^3/s exceeded the available flow in almost all months.
5. EFA using Building Blocks Methodology has been successfully applied in Mara and the need to employ integrated Watershed Management strategies in transboundary river basins where all stakeholders are involved.

4.2. Recommendations

1. There is need to stop further deforestation, settlement in catchment and encourage soil conservation, planting of environmentally friendly trees, storm water management and prohibit destruction of the river banks.
2. Although serious contamination was observed during the beginning of wet season only with Iron, yet Zinc, Manganese and Lead results also warrant further consideration and follow-up actions due to bioaccumulation and biomagnifications.
3. Further research on dissolved metal pollutants, climate change and watershed modeling is recommended to influence decisions on policy direction, land and water development activities.

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