Sustainable Catchment Management: Assessment of Sedimentation of Masinga Reservoir And its Implication on the Dam's Hydropower Generation Capacity

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Abstract

Masinga dam is the largest Dam of the Seven Forks Hydro-Electric Power (HEP) project with a design capacity of 1,560 million m^3*. It has a full operation surface area of 125 Km*^{2} *and was commissioned in 1981. Masinga catchment covers about 6,255 Km*^{2}*. Roles of the dam include HEP generation with an installed capacity of 40 MW, regulating water flow into subsequent dams and controlling downstream flooding. However loss of water storage capacity due to increased dam sedimentation associated with watershed activities, river characteristics, and reservoir design threatens its functionality. The research extensively utilized both primary and secondary data. Data analysis methods included the Normalized Difference Vegetation Index (NDVI), descriptive and inferential statistics. Masinga dam had lost about 215.26 M m*^{3} *(13.59 %) of its design storage capacity to sedimentation by 2011. This informed the need to develop an effective catchment management strategy to improve the dam's sedimentation regime.*

Key words: River basin, Precipitation, Stream discharge, Sedimentation, Land Cover, Land use, Land cover change, Land use change

1. Introduction

Global fresh water resources spatial-temporal distribution is erratic and unreliable (Saleh, *et al*., 2005). Consequently, man has endeavored to harness the available surface water resources by building dams to store water for use especially in times of scarcity. The volume of global water resources held by built reservoirs is about 3,400 Km^3 annually (Saleh, *et al*., 2005). Throughout human history, dams have played the essential roles of providing water for domestic and industrial uses, flood control, hydropower generation, irrigation and fisheries. Despite these functions, reservoirs are increasingly being threatened by loss of water storage capacity due to sedimentation (Walling, 2008). Reservoir sedimentation is a universal problem that is associated with agriculture. Annual loss of capacity in large reservoirs due to sediment input from agriculture is estimated to be 1% or more (Ongley, 1996). This depends on catchment activities and river characteristics, catchment land use pattern, and reservoir design (Walling, 2008). Sediment yield and loading in a river system presents an important measure of the hydrology of the rivers drainage basin and the erosion and the sedimentary processes in a given basin. High reservoir sedimentation rates affect the functionality of such facilities and sustainable use of water resources (Walling, 2008).

Hydroelectricity is the main form of renewable source of energy world over and is increasing according to Lucky (2012), the world's HEP installed capacity and output increased by over 5.3 % from the year 2009 to 2010. Currently hydropower output is about 3,427 TWH; it's about 16.1% of the global electricity consumption and 20% of the worlds' electric generation. Hydropower supplies about 50% of electricity in 66 countries and 90% in 24 countries globally (Government of India, 2004). In Africa, it's recorded that the effects of climate change are severely affecting HEP plants especially in areas that experience low annual rainfall (Bowyer, 2005).

The high population density in Kenya's Central highlands where Masinga Catchment is located has led to increased farming on steep slopes within the catchment's wet highlands (Saenyi, 2002). HEP generation energy in Kenya is increasingly vulnerable to climate variability, poor resource management and catchment degradation (GoK, 2006a). This presents complex technical and environmental challenges to water managers (International Sediment Initiative, 2005).Masinga reservoir's high sediment trap rate ranges between 75% and 98% (Jacobs, *et al.*, 2007), this resulted in an average loss of 23 million m^3 of water storage volume every year (Schneider, 2000) at its initial years. By 1988, siltation rate had tripled resulting in the loss of about 6% (this is about 93.6 of the 1560 million M^3 of the Dam'sdesign volume capacity) of the reservoir (Bobatti, 1998) during seven years of impoundment. Based on this estimates total siltation of Masinga dam would occur in less than 65 years (Watermeyer, *et al.*, 1976). This is far less than the economically viable lifespan for large dams of over 100 years (Government of India, 2004) and the design proposal of Masinga dam's economically viable lifespan of 520 years (Brown, *et al.*, 1996) respectively.

Kenya's National electricity peak demand is growing fast from 1,072 MW in 2008/2009 to 1,173MW in 2009/2010 and 1,191 MW in 2012 (GoK, 2011 &GoK, 2009). Kenya lacks sufficient power generation reserve margin to meet its ever rising national power demand. To meet its increasing energy demands, Kenya is heavily relying on diesel power. Diesel generators are both expensive and subjective to global fuel prices fluctuation, and have severe environmental effects. Due to this Kenya's electricity tariff is about 15 US cents per KWh while other tariffs in the region are at as low as 5.0 US cents per KWh (GoK, 2009) disadvantaging Kenya regionally. In the light of this background, this study was instituted to address the effects of poor catchment management activities on Masinga Dams sedimentation rates and the resultant adverse effects on hydropower generation capacity.

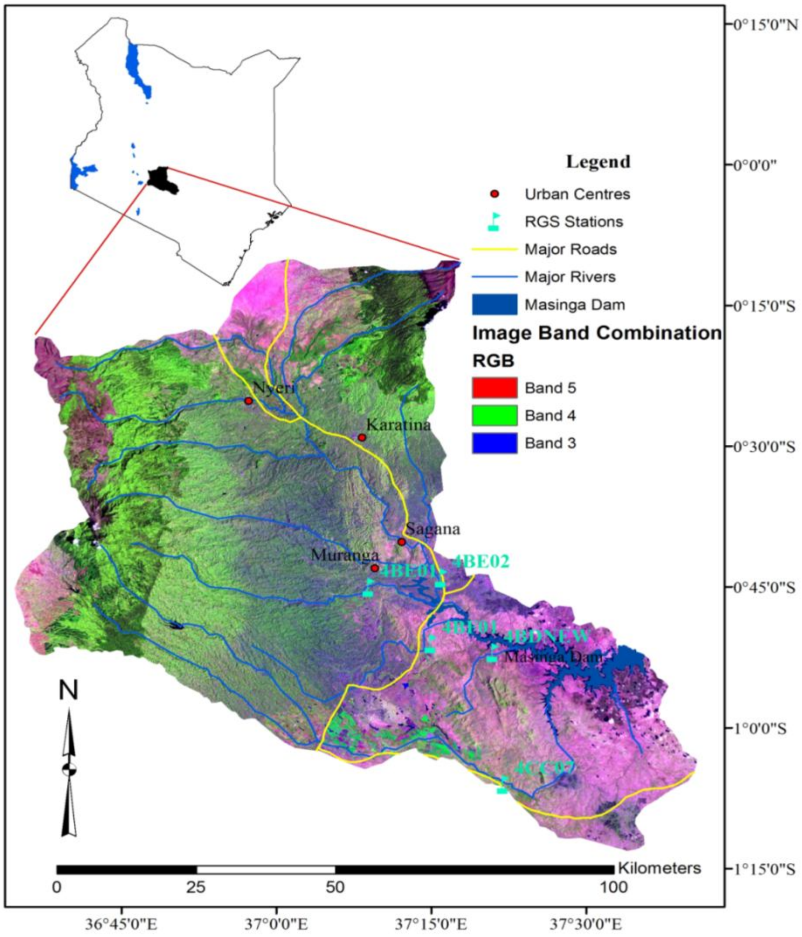
2. Materials and Methods

2.1. Area of study

Tana River basin covers nearly 21 % of the total national landmass of Kenya, and has an aerial coverage of about 126,927 km^2 (Agwata, 2006; NEMA, 2004). Masinga catchment lies in the upper Tana catchment and it covers an area of about 6,255 Km^2 (Mutua&Klik, 2007). Masinga catchment lies between latitudes $00^0$17' and $01^0$22' south and longitudes $36^0$58' and $37^0$68' east (WRMA, 2010). Masingareservoir is located at latitude $00^0$89' south and longitude $37^0$59' east. Masinga catchment forms part of the source of Tana River (Ongweny, 1979). The catchment drains nine counties: Murang'a, Nyandarua, Kirinyaga, Kiambu, Laikipia, Machakos, Kitui, Nyeri and Embu (WRI, 2011).

Masinga dam is the largest reservoir of the Seven Forks HEP project and therefore most important in controlling the Tana River system (NEMA, 2004; Pacini, Harper, &Mavuti, 1998). The dam has a full operation surface area of about 125 Km^2 that extends about 45 Km upstream head to head (Jacobs, *et al.*, 2007). Because of its strategic location and function, it is more subjected to catchment activities that hasten soil erosion and sedimentation; this reduces the reservoir's storage capacity.

FIGURE 1: MasingaCatchment in Kenya's Context



(Source: WRI and ILRI, 2011)

2.2. Topography

The main topographic features in the area are Mt. Kenya and the Aberdare ranges; this constitutes the upper Tana basin highlands. The catchment uplands have an average altitude of about 3,500 m but this rises to about 5,200 m towards the peak of Mt. Kenya (Droogers*et al.*, 2006; Ongweny, 1979). Masinga reservoir receives its headwaters from the central highlands of Kenya, specifically from the southern slopes of Mt. Kenya and the eastern slopes of the Arberdare ranges (Agwata, 2006). The main rivers that drain into Masinga Dam are: Thika, Mathioya, Sagana and Maragua (Ongweny, 1979). Towards Mt. Kenya and the Aberdare ranges, the topography is rugged and sloping towards the Tana basin allowing for construction of hydroelectric dams. The slopes in the catchment are characterized by deeply dissected ridges and valleys which vary in altitude between 1,500m up to 2,400m, these dissections are further eroded by the rivers and runoff through erosion forming parallel valleys and ridges (Kareri, 2012).

2.3. Geology

Masinga catchment has a broad range of soil types with varying water retention ability (Wilschut, 2010). On average, soils in the area consist of Andosols in the upper elevations, Nitosols in the mid-elevations and Vertisols in the lower elevations of the catchment (Kareri, 2012; Mutua&Klik, 2012; Jacobs, *et al.*, 2007).

2.4. Climatic set-up

The Climate ofMasinga catchment ranges from semi-arid in the east to humid near the western watershed (Saenyi, 2002). Generally, the area has a bimodal rainfall pattern as a result of the inter-tropical convergence zone (Wilschut, 2010).

The two distinct rain seasons appears fairly well distributed in the months of March to June and September to December. The rainfall is strongly influenced by orographic effects (Saenyi, 2002). Averagely the area receives about 600 mm in the east to 2,000 mm of rain in the humid western boundary (Mutua&Klik, 2007). The maximum and minimum mean annual temperature varies between 25.5 – 31.0^0C and 21.0 – 24.0^0C respectively (Mutua&Klik, 2007). The climate is favorable for a wide range of vegetation (Ongweny, 1979), dairy and subsistence farming. Catchment evapotranspiration is about 500 mm in the summit region. All areas below the forest zone have a rainfall evapotranspiration deficit. Thus, the high elevation forest and moorland zones provide most of the discharge of the rivers in the dry periods (Wilschut, 2010).

2.5. Research Methodology

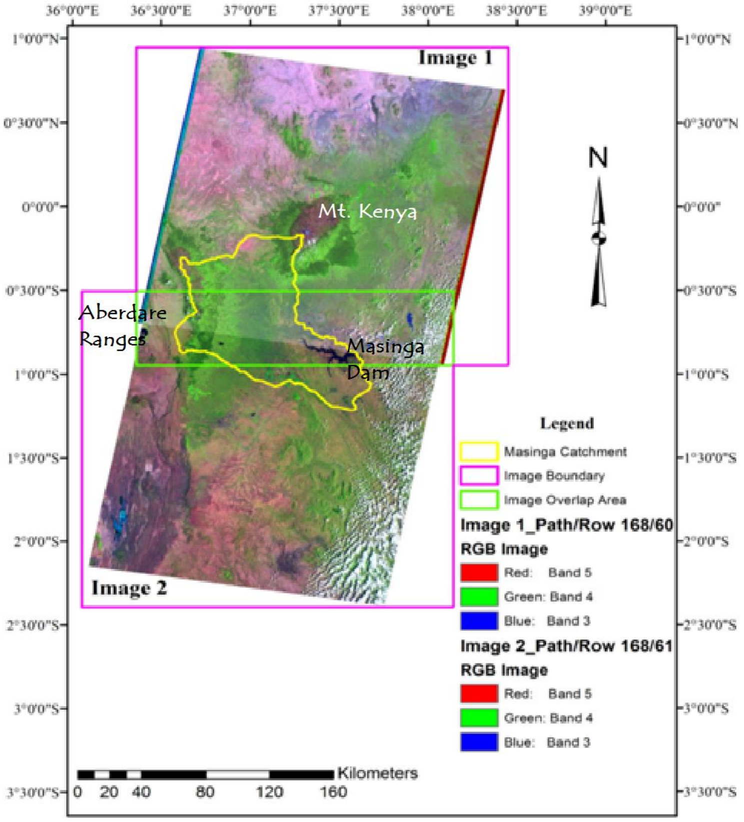
This research utilized both primary and secondary data to address research objectives. Varied categories of data were collected. Secondary data included LANDSAT satellite images which were obtained from Glovis (Global Visualization) website of the USGS - EROS. The images used to generate NDVI images of the catchment for the years 1986, 1995, 2001 and 2011 and the false color land-use image of 1976.Topographic maps provided background information about the areas administrative units, topography and land use. Digital Elevation Model (DEM) and the area’s population distribution maps were obtained from the World Resource Institute (WRI). This data formed vital input into image interpretation and classification of aspects that affect catchment erosion and Masinga sedimentation regime.

Information on the reservoir inflow rate data from functional WRMA River Gauging Stations (RGS), formerly operated by the Ministry of Water and Irrigation was used alongside the KENGEN inflow rate data determined from the dam levels to determine the variation in reservoir inflow trends, its relationship with sediment loading into the dam and how it affects HEP generation capacity of the Masinga Dam. Consideration was given to the average reservoir inflow vis-à-vis the base flow required to generate adequate dam head for power generation.

This research used both descriptive and inferential statistics for data analysis. The quantitative data was analyzed using correlation and trend analysis using SPSS and Microsoft Excel soft-wares. To assess the presence and health of vegetation cover, the Normalized Difference Vegetation Index (NDVI) computation was used to determine vegetation cover change. Quantitative data on catchment forest cover change was obtained from secondary sources including district development plans, Endeleo NDVI project website and calculated from classified land-use land-cover image maps of the study area.

The study area traverse two LANDSAT image scenes defined by path/row 168/60 and 168/61 in this order for images captured by Thematic Mapper (TM), Enhanced Thematic Mapper (ETM) and Enhanced Thematic Mapper Plus (ETM+), this formed the bulk of images. But in the Multi-Spectral Scanners (MSS) images the study area extended into three scenes identified by path/row 179/60, 180/60 and 180/61. The classes used in the classification are: artificial surfaces, bare or lightly vegetated surface, water bodies, cropland, grassland, moorland, scrub and scrubland and forest cover (Ministry for Environment, 2007). Trend analysis was conducted based on the variation in sedimentation trends in relation to forest cover change, dam inflow variations and mean annual rainfall trend between 1981 and 2010.

FIGURE 2: Footprint of images used for the study area



(Source: Glovis, 2012; WRI, 2012 and ILRI, 2011)

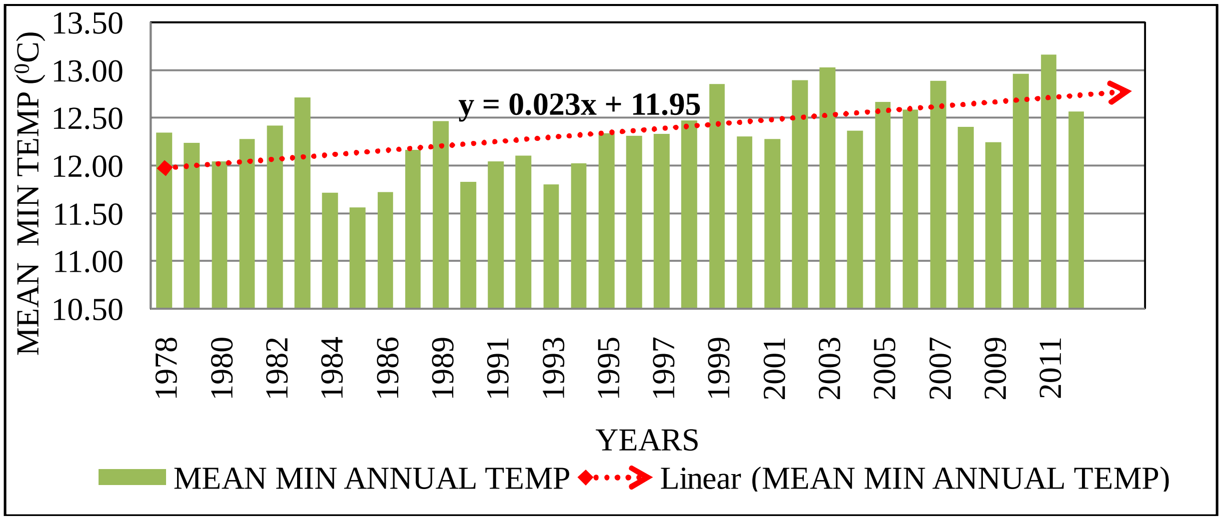
Sediment inflow data for Masinga reservoir was obtained from different sources including KENGEN records, past research reports and bathymetric survey report. Other important reports that provided data on sediment loading rates are the appraisal survey report and research findings by Bobatti (1998), Schneider (2000) and Saenyi (2002). The generalized alluvial rivers and reservoirs computer model (Yang, Simões, Huang, &Greimann, 2005); GSTARS 2.1 model was used to determine sediment loading into Masinga dam as a function of dam recharge using bathymetric data from Tana and Thika arms water temperature, sediment data and dam levels.

3. Results and Discussions

3.1. Masinga catchment's mean monthly and annual temperatures

Between the year 1981 and 2011, the mean monthly and annual temperatures in Masinga catchment shows an increasing trend. Both the minimum and maximum annual average trend-lines indicate that the catchment temperatures are increasing at indices of 0.026 and 0.015 respectively. Based on this, the mean minimum and maximum catchment temperatures will rise with a value of about 0.26^{0}C and 0.15^{0}C respectively after every decade.

FIGURE 3: Annual Mean Minimum Temperatures in Masinga Catchment



(Source: KMD, 2012 - Based on Embu station)

The increase in catchment temperature is a complex phenomenon which can be attributed to both natural processes and anthropogenic activities. From the past research findings it has been proved that temperature change influences the areas hydrological cycle because it affects both evapotranspiration and soil moisture changes. Arnel and Reynard (1993) study findings on the potential evapotranspiration scenarios indicated that based on temperature increase only, evapotranspiration would increase by over 10% in England and Wales by 2050. The temperature increase in Masinga catchment causes a broad range of issues associated with the reservoir inflows and sedimentation such as augmented evaporation, low precipitation, season shift, extreme whether like floods and droughts become more frequent and with greater magnitude over the whole region, biodiversity imbalance and loss of biomass vital in stabilizing soil to reduce erosion during rainy seasons thus exacerbating catchment sediment discharge. Increasing catchment temperatures trend-lines conforms to global warming effects which occur as a result of climate change, among other effects this results in increasingly unpredictable weather patterns.

The dry spell of between January and March has high mean maximum temperature for the entire study period of 26^{0}C and 27^{0}C. Since this follows the wet season it results in rapid depletion of water resources. This increases the possibility of soil erosion occurrence during the rainy seasons as soil is left bare and vulnerable. Increased reservoir sedimentation lowers the reservoir capacity which is vital for HEP. The catchment temperature rise as indicated by Arnel and Reynard (1993), McCarthy (2001), and Yang and Sivapalan (2011); is one of the main climatic variables affecting catchment water balance and vegetation. Therefore, increasing catchment temperature trends will in the long-run affect the catchment's rain pattern and intensity, and vegetation health and intensity. This affects HEP generation in two ways, first the reservoir inflows declines and increased sediment loading reduces the reservoir's storage capacity directly impacting long-term HEP generation output.

3.2. Masinga catchment precipitation trends

Precipitation is a key factor controlling the hydrology of the catchment. Precipitation, runoff and sediment yield presents the most intricate hydrological trend due to immense spatial variability of catchment uniqueness and rainfall patterns. Masinga catchment average annual precipitation based on Nyeri weather station indicates that the amount of precipitation between 1981 and 2011 is gradually but steadily declining. Masinga catchment precipitation is decreasing by 3.93 mm annually, therefore for a period of 30 years (1981 to 2011) the annual average precipitation has dropped by 117.9 mm on average. Decreasing catchment precipitation adversely affects both the reservoir sediment loading trend and river base-flows especially during the dry spells.It is notable that Masinga catchment mean precipitation fluctuates between 587 and 1,622 mm per annum. Even though the average shift in rainfall pattern in the area may not seem significant, the change in precipitation pattern endangers the water resources. Catchment temperature rise yields increased evapotranspiration in the catchment and sporadic rain pattern.

The annual catchment rainfall range of 1,035mm suggests that the rainfall is sporadic in nature, meaning the catchment will be subjected to more frequent flash floods which increase runoff wash effects yielding greater sediments that further endanger the dam's storage capacity and HEP production capacity through increased catchment sediment discharge into the dam.

Masinga precipitation decrease as calculated over three decades is significantly high at 3.93mm on average, this accompanied by the rise in catchment temperatures by an average index of about 0.027^0Cmakes the dry seasons even drier drastically reducing vegetation cover. This trend corresponds to the US Geological Survey Report (2010), in which it was argued that rains received between March and June in central Kenya had declined by more than 100 mm from 1970s. This was linked to the warming of the Indian Ocean. Increase in catchment temperatures as precipitation declines may adversely affect the area's vegetation cover on annual aggregation. Low vegetation cover reduces the catchment water retention capacity as the release rates are accelerated, this hastens erosion.

3.3. Masinga reservoir inflow trends

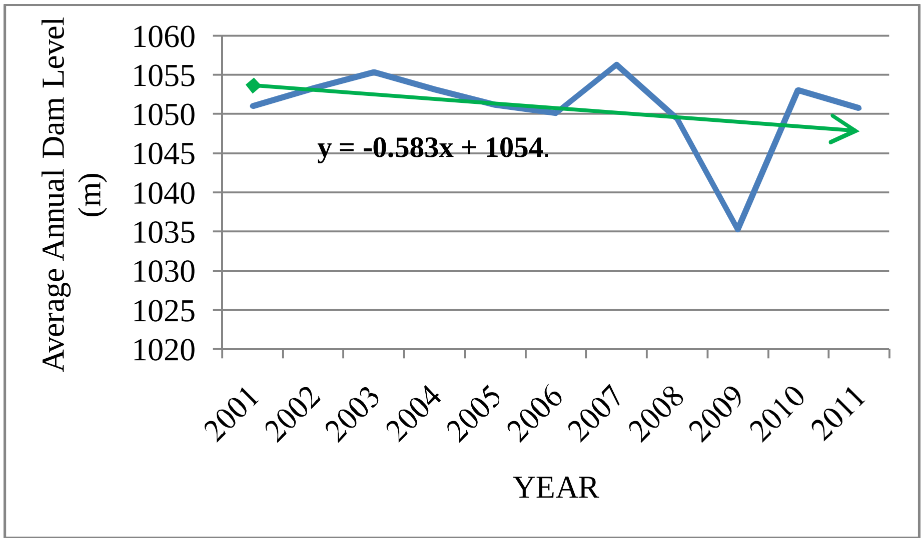
Masinga reservoir inflow data is based on the dam test flows in cumecs, this data was obtained from KENGEN. The inflow rates are determined based on daily dam levels. Trend analysis indicates a steady decline in the reservoir inflow rates. Dam inflow is the medium of sediment transfer from the dam's catchment. Sediment loads per cubic meter is greatly influenced by catchment's anthropogenic activities. During the rainy season more sediment loads into the dam due to increased stream flow volume and runoff wash effects of the exposed soils.Based on the trend line equation $y = - 0.736x + 81.85$, the annual average dam inflows are declining at the rate of 0.736 annually. This means the dam inflows are declining at the rate of 0.736 cumecs per year, for a period of 30 years (1982 to 2011) the reservoir inflow rates have depreciated by 21.344 cumecs in aggregation. Lowest annual reservoir inflow rates have occurred within the last one decade in 2001 and 2009 of about 32.0 and 24.3 cumecs respectively. Further reduction in reservoir inflows directly threatens the HEP generation future of the Seven Forks Project, because Masinga reservoir plays regulatory functions which include storing and releasing water to subsequent plants to sustain optimal power generation especially during low inflows, flood control and sediment trapping as a more recent function.

The reservoir's range of the annual mean inflows between 1982 and 2011 is 134.7 cumecs. Certainly the variations in inflows are brought about by alternating scarce and abundant rainfall pattern. During the year of abundance preceded by rain scarce year, this usually finds most biomass dry providing limited cushion against soil erosion. Low inflow rate is already a course to worry about for water resource and energy sectors. Decreasing annual inflow averages into Masinga dam is echoed by the dam levels between 2001 and 2011. This threatens the dam's storage capacity directly affecting the Tana HEP project.

3.4. Masinga dam level variations

The average overall dam level between 2001 and 2011 is 1,050.85 meters above sea level (m a.s.l). This is about 6.1 m below the dam's Full Surface Level (FSL) which is approximately 1,095.5 m a.s.l. Within this period the annual average dam levels sharply dropped to 1,049.5 m and 1,035.2 m in 2008 and 2009 respectively. Based on monthly average dam levels, the lowest dam level recorded in a span of 10 years (2001 – 2011) is 1,023.6 m a.s.l recorded in August 2009. This was far below the required dam level to generate power at Masinga Dam of 1,035 m a.s.l (Oludhe, 2011) by 11.4 m.

FIGURE 4: Annual average levels of Masinga dam



(Source: KENGEN, 2012)

Figure 4 shows an annual average dam levels trend-line equation as y = - 0.583x + 1054. This means on average the dam level is decreasing by 0.583 m annually, on aggregate 5.83 m after 10 years (2011 to 2001). The higher the dam level the greater the dam head efficiency and thus the lesser water is used to generate a single unit of energy. The higher the dam levels the greater the reservoir's surface area and thus higher water storage capacity. Subsequently any drop in the dam levels adversely affect power generation especially during dry seasons where inflows are minimal. Based on the trend of the average annual dam levels trend-line equation, Masinga dam level will reach the minimum operation level of 1,035 ma.s.l in about 33 years. After which power generation at Masinga power generators will cease, this is far less than the dam's lifespan.

3.5. Masinga catchment land-use/ land-cover change

Masinga catchment forest cover has substantially varied in the duration of 1976 and 2011. The catchment recorded maximum forest loss on the years between 1976 and 1984, by 53.37 % based on forest cover of 1976 as the pedestal year. In 36 years Masinga catchment has lost about 21,180.87 hectares of its forest cover, this is about 62% loss based on 1976 forest cover.Previous research findings have indicated a correlation in hydrologic response to land cover change, catchment forest cover change in the long-run affects the areas evapotranspiration, total annual water yield, quick flow and base flow rates (Cao, Bowden, Davie, & Fenemor, 2008).

TABLE 1: Masinga catchment forest cover change

YEAR	Forest Cover in Hectares	Inter-Data Forest Cover Variation (Percentages)	Percentage Forest Cover (Based on 1976 forest cover)
1976	34,165.8 Ha.	***	***
1984	15,930.72 Ha.	- 53.37 %	- 53.37 %
1995	17,751.51 Ha.	11.43 %	- 48.04 %
2001	11,162.88 Ha.	- 37.12 %	- 67.33 %
2011	12,984.93 Ha.	16.32 %	- 61.99 %

Where: *** it is the base year from which comparison is drawn (Source: Glovis, 2012)

Forest cover change impacts on water resources are complex depending on the affected aerial extent. Catchment vegetation cover change affects water cycle processes like water interception, evapotranspiration and soil moisture levels (Cao, *et al.*, 2008; Calder, 1992). As indicated below, the catchment forest cover is decreasing at the rate of 528.7 hectares per year.

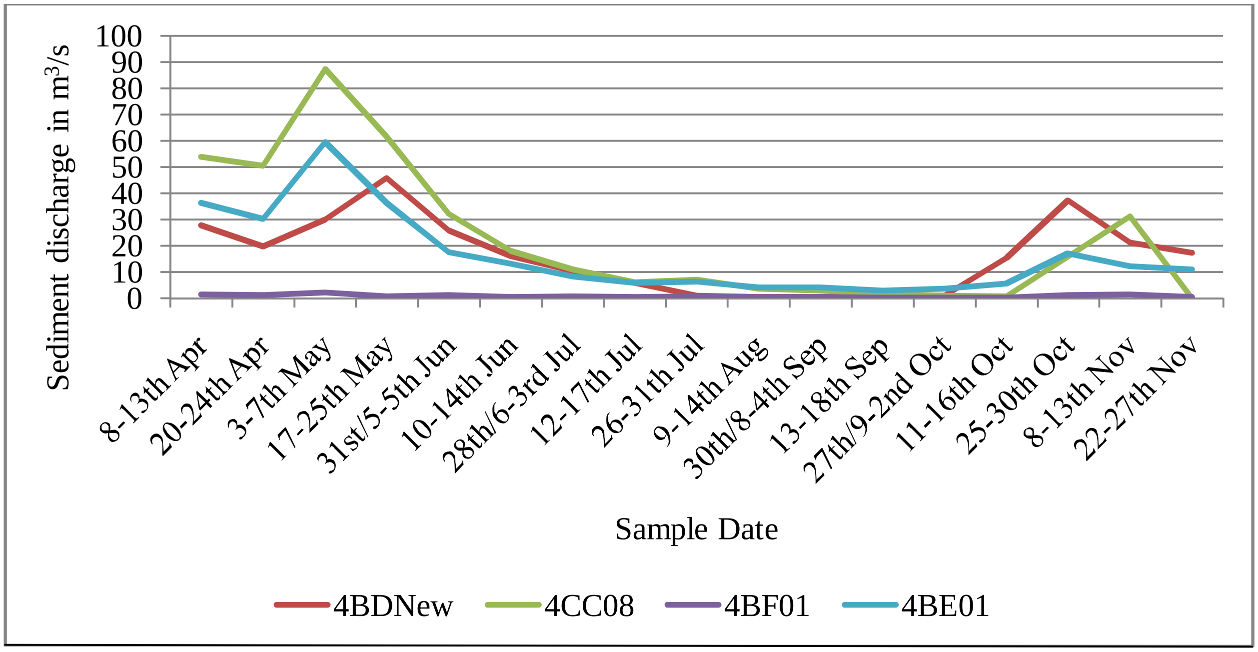
If this trend persists, the hydrological and catchment sediment yielding trends are likely to persist threatening the ability of Masinga dam to store adequate water for power generation throughout the year.

The forest loss trend threatens the vital remaining indigenous forest ecosystems on Mt. Kenya and Aberdare forests. Native forests are usually associated with high flows even during the dry seasons of the year (Cao, *et al.*, 2008; Smakthin, 2001). Forest depletion therefore adversely affects stream recharge rates, thus threatening hydropower generation especially during low dam inflows or when the dam inflows and discharge yields a water deficit function.Comparison of the catchment images utilized the 1976 LANDSAT MSS to generate a false land-use color image which provided the base forest cover extent. NDVI, a GIS function that utilizes the chlorophyll present in plants leaves was used to compute vegetation cover change in subsequent years.

3.6. Masinga Reservoir Sedimentation Rates

Different rivers have varied sediment loading levels as indicated by four RGS, sampled in 2010 by WRMA. Sediment concentrations in milligrams per liter (mg/l) vary from one river to another. However the sediment discharge in kilograms per liter (kg/s) varies from the sediment concentration of the same river because of the soil type and nature (clay, loam or sand) and catchment human activities.The samples collected between 8^{TH} April, 2010 and 11^{TH} December, 2010 covered both the short (March – June) and long (September – December) rain seasons. This means each sub-catchment had varying sediment discharge rates based on both natural and artificial actors like the area's geological setup, and intensity and land-use types respectively.

FIGURE 5: Variations in sediment discharge in kg/s between April and December 2010



(Source: WRMA Bathymetric Survey Report, 2010)

For the sampled RGS stations 4BDNew, 4CC08, 4BF01 and 4BE01 indicates broad discrepancies in sediment routing between the short and long rains and across the year. The long rains in the catchment between March and June also doubles as the main planting season, meaning soil cover is altered during land preparation exposing soils to erosion. For the last three decades, Masinga Dam sediment loading data's trend-line equation ($y = 0.063x + 5.931$) indicates that on average the annual dam sediment loading is increasing by an index of 0.063 M m^3. This is equivalent to 63, 000 m^3 annual increment in the loss of Masinga reservoir storage capacity. Based on the average RGS flows and sediment loading based on 17 samples collected in 2010 are: 4BE01 – 11.7 m^3/s and 100mg/l; 4BF01 – 3.6 m^3/s and 27mg/l; 4BE02 – 144.4m^3/s and 100mg/l; and 4CC07 – 17.2 m^3/s and 3mg/l respectively. Masinga reservoir sedimentation rates, gross sediment inflow and the sediment budget for the reservoir included the 2010 bathymetric survey approximation of the reservoir's full storage capacity.

Based on this Masinga reservoir sedimentation rate is estimated at about 5.45 M m^3/year, meaning the reservoir has lost about 10.1% of its capacity over 30 years. This however is below the aggregate value of annual sediment loading into the dambased on KENGEN data (1981 – 2011) which is about 215.26 M m^3. This is equivalent to loss of about 13.8% loss of Masinga Dam storage capacity of 1,560 M m^3. This means Masinga would totally be filled in 187 years to come, but owing to high population growth in the region as indicated by population census report where population grow at the rate of 13.6% between 1969 and 2009 and the increase in dam sediment loading at 0.063 M m^3/yr, the duration may greatly be reduced for the total dam siltation.

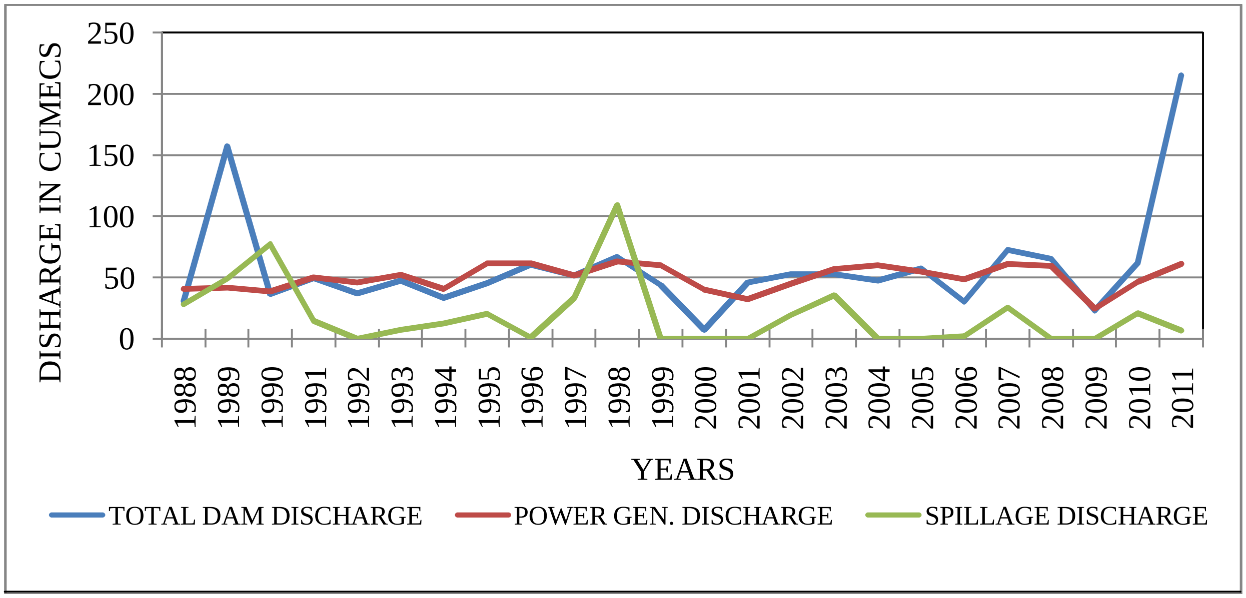
About 25% of the sediment yield in Masinga Catchment is contributed by uncontrolled run-off along roads, loosened earthworks and culvert discharge into unprotected lands. Also about 10% of total sediment yield is attributed to run-off generated from urban centers, institutions and homesteads without rainwater harvesting structures or soil and water conservation systems. Thus, anthropogenic activities are increasingly contributing to catchment sediment discharge. The quantity of sediment that is retained in the reservoir has been estimated using observed relationships like those of Brune, 1953 (Dam trap rate verses ratio of capacity to annual inflow) and Churchill, 1948 (Desilting basins and semi-dry reservoirs) curves. Based on this, the trap rates of Masinga reservoir is estimated at 100% for sand, 99% for silt and 2% for clay all with a weighted mean of 84% (WRMA, 2010). The extremely low clay trap rate at Masingareservoir accounts for the turbid water discharge from Masinga dam through its spill way as in Plate 1. This arises because the clay fraction of sediment that loads into Masinga reservoir does not settle.

PLATE 1: Masinga dam spilling turbid water

(Source: WRMA, 2010)

The spillage trend of Masinga dam indicates that from 1999 spillage occurs after an average of 2 – 3 years. However, from 1988 the frequency of no spillage years is on the increase. This essentially indicates years when the dam operates below its storage capacity; the dam's FSL does not attain the maximum height. Increased frequency of operating below capacity of the dams' HEP generation puts national energy source at stake. Masinga reservoirs objective was to impound and store flood waters to regulate release in the HEP dam cascade.In dealing with large reservoir sedimentation issues like Masinga, there is need to devise a good prediction scheme of sedimentation process, to better understand the reservoir behavior. Sloff (1997) provided a general view of how fine sediments in a homogeneous flow and turbidity currents tend to behave in large river fed dams. Sediments may damage power generation ways and machines if not well managed and thus the need to seek for comprehensive catchment management strategies to retain the sediments at the source as the only best option. The Pearson's correlation coefficient statistics of Masinga sediment inflow and catchment precipitation and temperature indicates that there are significant relationships between reservoir sediment inflows with catchment mean temperature, reservoir inflow rates and catchment precipitation at 0.14, 0.54 and .076 respectively. This means a change in any of these variables directly affects the reservoirs sedimentation regime and thus they should be factored in during catchment management planning.

FIGURE 6: Masinga dam discharge through generation and spillage

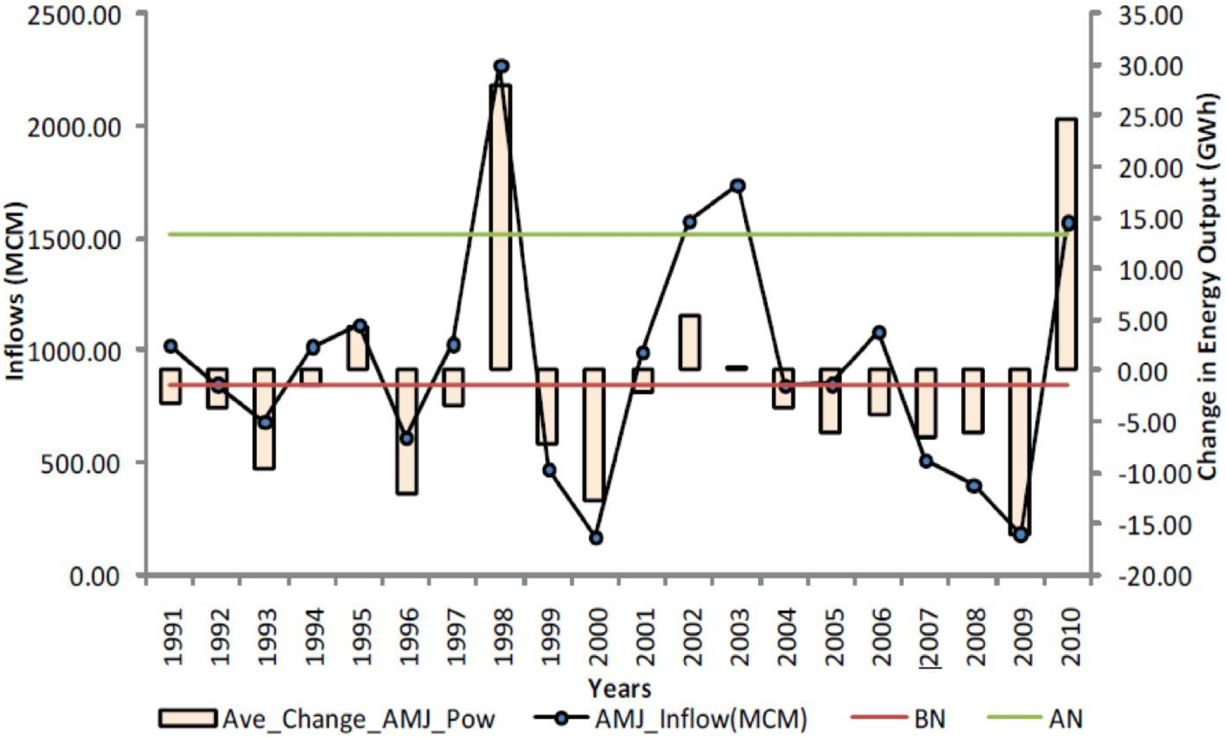


(Source: KENGEN, 2012)

3.7. Effects of Masinga Reservoir Sedimentation on Hydropower Generation

Sediment laden water wears the water ways components by its abrasive effect, increasing maintenance costs and thus the cost post of per unit power generation. The wear of the water ways reduces the plant performance. This leads to loss of energy production efficiency of the machines, this result in increased loss in energy margins and later economic costs to meet repair and maintenance charges. Sediments may also block the plants cooling system leading to rise in temperature in oil coolers for bearings and generator air coolers. The high temperatures results in unit isolation leading to decreased plant power generation capacity.

FIGURE 7: Average variation in power generation at Masinga dam during the long rains



(Source: Oludhe, 2011)

Because of the magnanimous size of Masinga dam, most sediment deposition occurs near the river mouth. Eventually levees and silt banks may form as dictated by reservoir basin morphology restricting the flow within the main river channel. However reservoir sedimentation trends may most likely vary during the flood season. Masinga reservoir has had only two instances in 1998 and 2010 when the dam's average change during the long rain seasons when average change in power exceeded above normal production margin of about 13.5 GWH per year. Average change in power output for most of this duration operates below capacity by up to about 16 GW Hour per year, this may be attributed to the dam operating with water far below FSL/ maximum water head height of 49 m. Though the Turbines water flow rate may be sustained at or above its normal rate of 45.9 m^3/s for the period of 1988 and 2011 as indicated by the power generation discharge curve in Figure 8, the dam power generation efficiency is below its power production potential of 350 GW Hours per year at water head of 49 m. Further sedimentation may render the reservoir ineffective especially during low flows during dry spells.

4.0. Conclusion and Recommendations

4.1. Conclusion

Masinga Catchment Rivers and Masinga Dam are jointly affected by varied catchment parameters, including but not limited to catchment precipitation, temperatures, vegetation cover and anthropogenic activities as the drivers of change. The basic sediment management principle for large reservoirs is to alleviate reservoir sedimentation. This can be achieved through varied methods depending mainly on the reservoir topographic features, riverbed characteristics before dam construction, and local morphology greatly determines the methodology to be adopted. Sediment management can be achieved by catchment rehabilitation, sediment flushing, sediment removal and disposal, or sediment routing (Boroujeni, Accessed 2012). But for Masinga dam which has a head to head length of about 45 km and full volume surface area of about 125 km^2 (Jacobs, *et al.*, 2007) makes dredging or flushing unpractical, as most dense sediments settle near the dam tail which renders flushing ineffective.

Dredging is impractical also due to lack of a place to store material removed from the reservoir, and Masinga dam is the largest compared to the other four dams' in a cascade (Kamburu, Gitaru, Kindaruma and Kiambere). Thus flushing must work for all the dams for it to be effective or it would adversely affect lower dams which are smaller but have higher HEP capacity (Masinga 40 MW, Kamburu 94.2 MW, Gitaru 44 MW, Kindaruma 225 MW &Kiambere 156 MW).

Individual catchment rivers, runoff and sediment load are irregularly distributed based on spatial temporal basis. Highest sediment loading into the catchment rivers and ultimately into Masinga Dam is more pronounced during rainy season and increases with rain intensity and duration. Sediment loading is most during the long rain season (March – June) as compared to the short rain season (September – December). Since water is the medium of sediment loading, there is a strong correlation between catchment precipitation trends and sediment loading into the dam. The greater the rain intensity is the higher the quantity of sediment that loads into the dam. For instance sediment loading in River Thika has the highest rate of 87.38 m^3/s in the month of May during the long rain season of 2010 and least in October just before the onset of short rains in the same year at 0.85m^3/s.

4.2. Recommendations

The choice and formulation of catchment sediment management strategy should assume a multi-disciplinary approach. For Masinga catchment it draws on board a broad spectrum of stakeholders including KENGEN, WRMA, TARDA, KFS, Water Resource Users Associations (WRUAs), land owners and Community Forest Associations (CFAs) in the area, Local Authorities within the basin, Central Government and the local community including farm owners in the catchment. The strategy should be based on a compromise among the stakeholders whose activities directly or indirectly affect land resources like water resources and catchment sedimentation regime.Catchment management strategy should ensure reservoir sustainability to adequately reduce catchment sediment discharge. The strategy includes soil erosion conservation measures, terracing and contour building on steep slopes, and sediment retention in the catchment by use of check dams, forest conservation and protection of riverine and vegetated wetland areas.

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