Sedimentation impacts on reservoir as a result of land use on a selected catchment in Zimbabwe

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Abstract:

A study was conducted to investigate sedimentation impacts on a reservoir as a result of land use during the 2009-10 rainfall season using hydrographic surveys and grab sampling methods at Chesa Causeway Dam in the Upper Ruya sub-catchment of Zimbabwe. Sedimentation analysis showed that the sediment specific yields at the dam were 774 t $km^{-2}yr^{-1}$ using the grab sampling method and 503 t $km^{-2}yr^{-1}$ obtained from hydrographic survey. The storage ratio for Chesa Causeway suggests that the dam has a very low storage ratio which implies that, at design stage, a substantial amount of available runoff has not been utilized. Projections based on current sediment loading indicate that dam will be silted up in the next 11 years, with a useful lifespan of 30 years. This could be due to alluvial gold panning activities taking place on the upstream of the dam. The study has established that both hydrographic surveys and the grab sampling methods can be used for estimating sedimentation rates in reservoirs and, hence, facilitate informed decisions for Integrated Water Resources Management (IWRM). The study concluded that the lifespan of reservoirs is strongly linked to upstream land uses.

Keywords: Land use, reservoir, sedimentation, specific sediment yield.

1.0 Introduction

Sedimentation is a process whereby particulate matter is transported by fluid flow and eventually deposited as a layer of solid particles on the bed or bottom of water[1]. Land use changes have been singled out as the main contributing factors to sedimentation of reservoirs. Sedimentation results in reduced lifespan for reservoirs. Anthropogenic activities have been identified as the main cause of land use changes and siltation in the Shiyang Reservoir in China with 43 % of woodland areas having been turned into agricultural land[2]. In Ghana a similar study to assess the impact of land use changes on the Burekese catchment was conducted. Hydrographic surveys showed a loss in reservoir storage capacity of 45 % due to siltation over a period of six years. The causes for the silting up of the reservoir were attributed to deforestation, population growth and lack of proper education of the communities in catchment management[3]. Increased demands on available resources due to, mainly, expanding population in Zimbabwe has led to the clearing of marginal lands for agricultural production and for settlement purposes. This has resulted in increased erosion, more rapid rates of sediment loading in reservoirs and reduced socio-economic benefits which they were built for[4;5].

Information on the upstream land use activities and land cover change, sediment yield within a catchment is required for controlling sediment accumulation in reservoirs[6]. In most reservoirs in Zimbabwe sediment load has exceeded normal designed expectations, thus reducing storage capacity and shortening their useful life for human benefit[7]. This has resulted in socio-economic problems which include decreased agricultural productivity, increased water supply treatment costs, decreased power generating capacity and loss of storage capacity[8]. For effective control of the sedimentation problem due to land use and land cover change a holistic approach is needed. This requires involvement of all relevant stakeholders in the water sector including the water users, government and other non-state actors in integrated catchment management.

Spatial and temporal data on land use and land cover change is required to arrive at informed decisions in integrated water management. In Zimbabwe sediment studies have only been conducted once for almost 90 % of the dams in Zimbabwe[5]. Therefore, not much data is available to establish the correlation between changes in land use and land cover with sedimentation rates in reservoirs. This has resulted in sediment loads exceeding normal design expectations in some reservoirs, thus reducing storage capacity and a shortened useful lifespan of the affected reservoirs. The objective of this research was to investigate the sedimentation impacts of upstream land use on the lifespan of reservoirs.

2. Material and Methods

2.1 Study area

The study was carried out in Mazowe catchment areas of Zimbabwe focussing on the Chesa Causeway dams (Figure 2.0). The absence of a trap dam upstream of a reservoir was the main factor considered for site selection.

2.1.1 Chesa Causeway Dam

The dam is located 2 km east of Mt Darwin Town in the Upper Ruya sub-catchment. The dam falls within the Mazowe Catchment. The dam was constructed in 1991 on the Mufure river in the hydrological subzone DM2 (S16^{o} 46.375' and E031^{o} 35.697'). The catchment area of the dam is 229 km^2 and was designed to a capacity is 1.15 $*10^6$ m^3 at full supply level. The mean annual runoff (MAR) is 129 mm from an average rainfall of 786 mm yr^{-1}. The mean annual evaporation of the dam is approximated to be 1.85 m. The dam's catchment area comprises of communal areas (Kandeya and Madziwa) and newly resettled small-scale farmers. The main purpose of the dam is to supply Mt Darwin town with water.

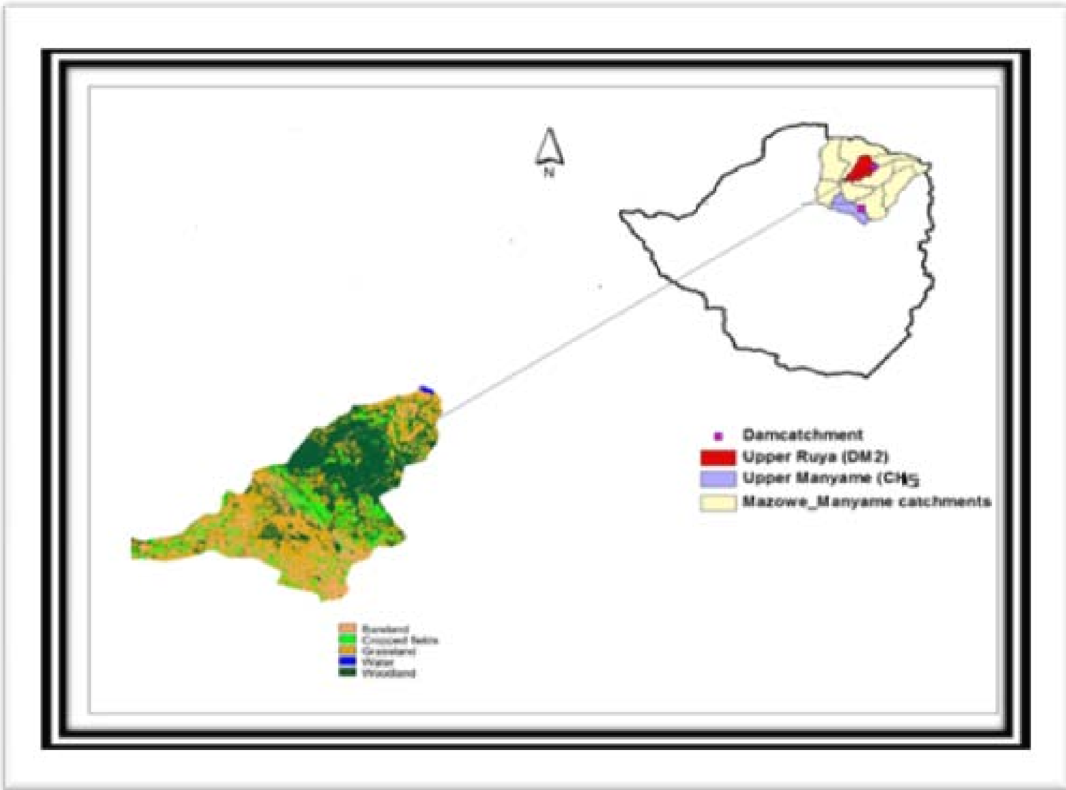

Fig. 2.0: Study Area

2.2 Sedimentation issues in the study area

2.2.1 Chesa Causeway Dam

The dam has been in operation for 19 years now and sediment accumulation has been witnessed over this period. The main drivers for sediment accumulation in the reservoir include lack of enforcement of environmental laws, alluvial gold panning activities taking place within the main tributary of the dam and poor farming methods such as stream bank cultivation[7]. Indications are that the dam is almost silting up now[7]. At commissioning stage, this dam met 80 % of Mount Darwin town's water requirements. The loss of storage impacts on water supplies to the town whose population is now estimated to be 15000.

2.3 Quantification of sedimentation rates

Two methods were used to quantify the sedimentation rates of the study areas. The methods used were the grab sampling and hydrographic survey methods.

2.3.1 Grab sampling

Water samples were taken by scooping (using a 500 ml plastic sampling bottle) at a sampling point. The water samples were taken at a depth of 300 mm below the water surface. Scooping below the water surface has an advantage of getting the best estimate of average sediment load as sediments are concentrated more beneath the water surface.

Sediment samples were obtained to determine the sediment bulk density. The average sediment concentration for the three months of study was determined using the weighing and filtration method. At Chesa Causeway dam a total of ten samples were collected in December (2), January (3), February (3) and March (2) and the samples were averaged for each month. Sampling after storm events increases the probability of coinciding with peak sediment concentrations. The sediment concentration was obtained by averaging the monthly sedimentation rates. A graph showing the average concentrations for each month is shown on figure 3.0. The following procedure was followed for sediment quantification.

$$\text{MAI} = CA * MAR \qquad \text{Equation 2.1}$$

Where: MAI is the gross mean annual reservoir inflow ($m^3\ yr^{-1}$)

CA is the catchment area (km^2)

MAR is the mean annual runoff ($mm\ yr^{-1}$)

$$SRg = \frac{DC}{MAI} \qquad \text{Equation 2.2}$$

Where SRg is the gross storage ratio

DC is the gross dam capacity

$$T_n = (0.1 + 9 * SRg) * 100 \qquad \text{Equation 2.3}$$

Where T_{η} is the trap efficiency (%)

In general, the trap efficiency is assumed to be 100 % for most reservoirs were the gross storage ratio > 0.1

$$S_Y = \frac{MAI * S_C}{1000} \qquad \text{Equation 2.4}$$

Where S_Y is the mass of sediments in the inflowing river in $t\ yr^{-1}$ (Sediment yield),

S_C is the sediment concentration

$$SS_Y = \frac{S_Y}{A} \qquad \text{Equation 2.5}$$

Where SS_Y is the specific sediment yield which gives a measure of mass of sediments per unit area per given time (measured in $tkm^{-2}\ yr^{-1}$) and A is the area of the catchment in km^2

2.3.2 Hydrographic surveying

Control pegs were set up, traversed, levelled and tied up to a local grid reference using the spillway level as the reference. Spot shots were taken above the water edge 2 m above the full supply level. Points of plumbing were marked along the dam for distances of between 50 m to 150 m and less on bends or curvatures. The points were surveyed and levelled up to the main traverse. A graduated tag line was stretched on opposite points and 20 litre sealed plastic containers tied to it so that it remained floating. The motorised boat was used to navigate along the tag line. Depth sounding was then done at 10 m to 25 m intervals along the line. The sounding was done by dropping a weight attached to a string to the riverbed so as to measure the depth of water up to the surface of water. The depth was then subtracted from the water level reading. The spillway level was taken as the common datum to get the levels underneath the water, which were also related to land survey. Figure 2.1 shows depth sounding on a dam profile.

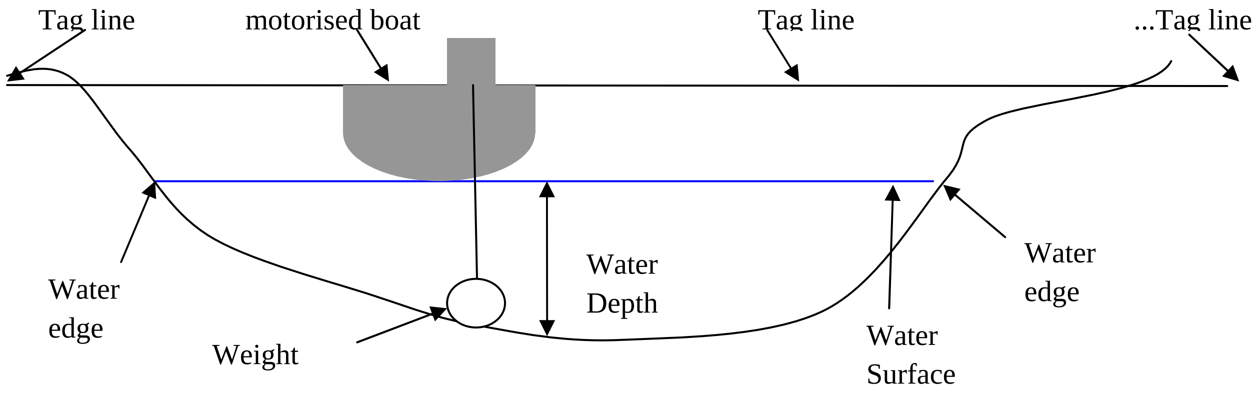

Figure 2.1: Depth sounding

When all the points had been taken, they were then reduced using the spillway as the datum and then plotted using a plotting set on a scale of 1:2000. Contour lines were then drawn on the map at 1 m interval. The lines were drawn from the lowest points on the bed up to 2-3 m above the spillway level. The points were reduced to get levels for both study areas and contour maps for the dams were then drawn. Areas between contour lines were then digitised using a plannix. The formula below was used to calculate the volumes for each contour.

$$V_{contour} = \frac{A_1 + (A_1 * A_1)^{1/2} + A_2}{3}$$

Where: $V_{contour}$ is the contour volume

A_1 = Area 1; A_2 = Area 2

Equation 2.6

Volumes for each contour were then calculated using Equation 2.6 and accumulated to get the total capacity. Area/Capacity curves for both dams were plotted as shown in figures 3.1 and 3.3.

2.4 Land use and land cover changes.

Landsat TM images for both sites in the years 1991, 2003, 2009 for the month of April were downloaded from the USGS website. The images were classified using the supervised classification into five land cover classes (cropped land, woodland, water, grassland and bareland) based on the maximum likelihood method. Training samples were then taken from the field using a GPS based on the five land cover classes. The classified images were then crossed with the catchments of the two dams to get the land cover specific to the areas. The statistic function in ILWIS GIS software was used to calculate the area of each land cover for the different years. The area of different land cover classes was then used for statistical analysis. Ground truthing was also conducted for the study site to complement Landsat TM images.

3 Results and Discussion

3.1Quantification of sedimentation rates

The results for both methods used are presented as follows:

3.1.1 Grab sampling method

Figure 3.0 shows the trend in the monthly average sediment concentrations for Chesa Causeway dam for the 2009-2010 rainfall season.

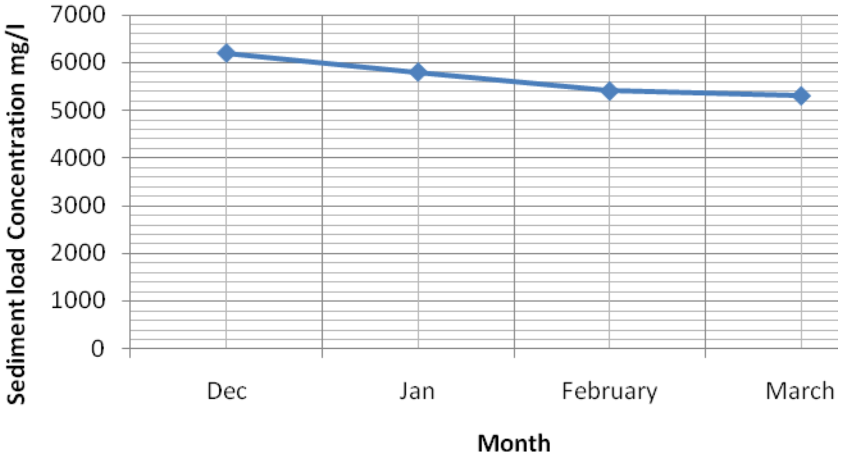

Figure 3.0: Average monthly trends of sediment concentration at the study site during the 2009/2010 rain season.

According to[5], sediment concentrations below 3000 mg/l indicate a well conserved catchment while ranges of 3000-10000 mg/l indicate catchment prone to erosion through, mainly, poor conservation and steeper slopes. Concentrations above 10000 mg/l indicate catchments which are highly susceptible to erosion.

From the classification presented above, Chesa Causeway dam had a seasonal average of 5660 mg/l and it fell in the category of a catchment prone to erosion due to poor conservation practices following the Zimbabwean catchment classification.

The sediment concentrations were found to be decreasing as the rainfall season progressed for both study areas. This is due to the fact that at the onset of the rainfall season the soil particles will be loosely attached to each other hence more erodible therefore high chances of detachment and transportation into the reservoirs, resulting in high sediment concentrations being recorded at the sampling points. As the rainfall season progresses the sediment concentration decreases as the soil particles become aggregated and less erodible therefore presenting low values for the sediment concentration recorded at the sampling points.

3.1.2 Hydrographic Survey

Using the hydrographic survey method the following results were found:

Surface Area/capacity curves for the dam after digitising the contour map is shown in figures 3.1 and 3.2.

- **Chesa Causeway Dam**

Figure 3.1 shows a plot of the Surface Area/Capacity curve when the dam became operational in 1991 and Figure 3.2 shows Surface Area/Capacity curve for 2010.

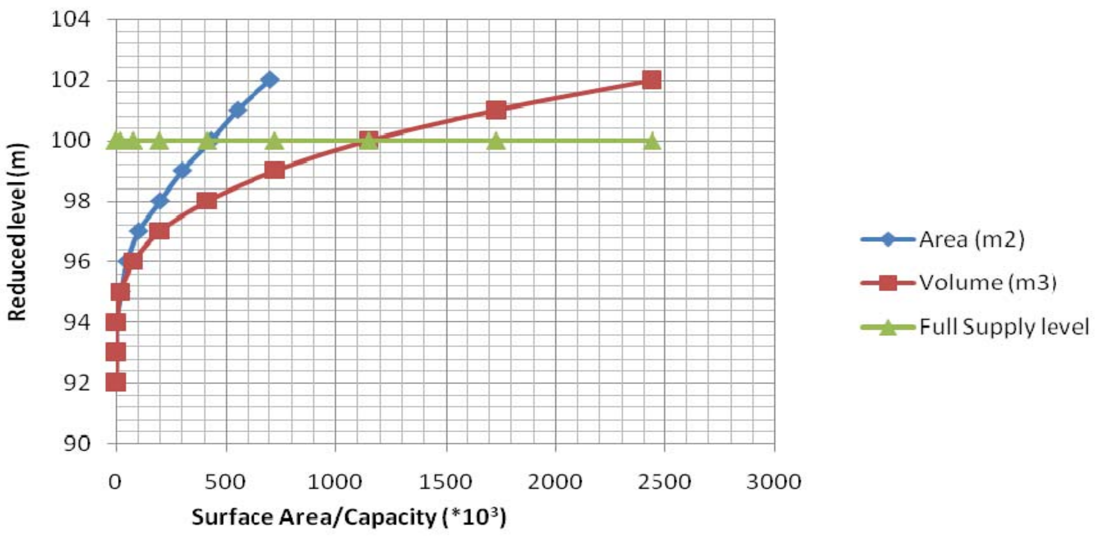

Figure 3.1: Chesa Causeway Dam 1991 Surface Area/Capacity curve (Adopted from Dam design 1991)

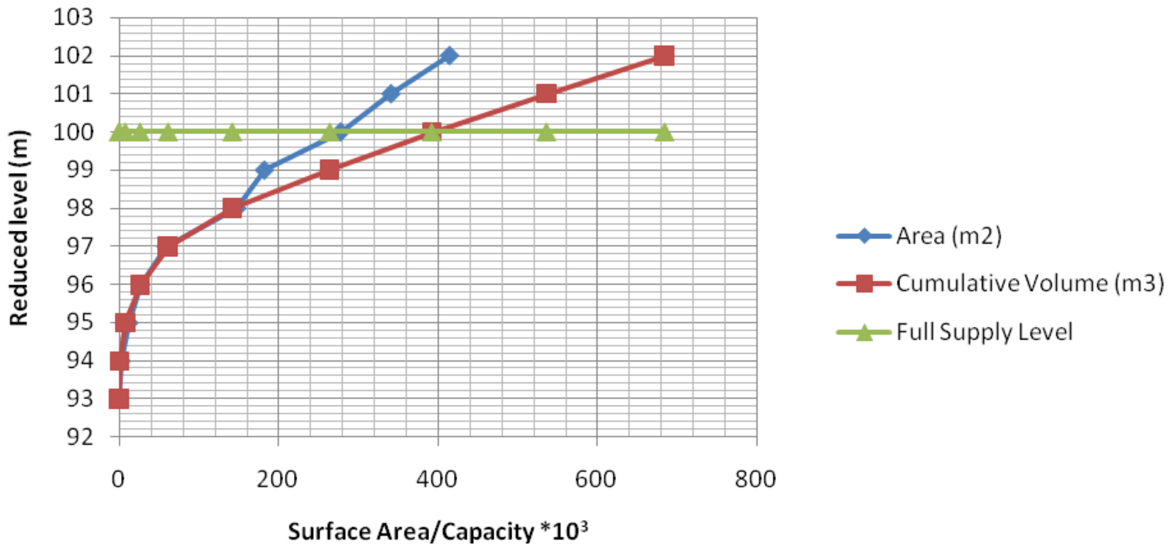

Figure 3.2: Chesa Causeway Dam 2010 Surface Area/Capacity curve

From figure 3.2, in 2010 at full supply level the dam has a storage capacity of 392 $*10^3$ m^3 as compared to 1 150 $*10^3$ m^3 when the dam became operational in 1991 as shown in figure 3.2. This represents a 67 % loss of storage from the original storage capacity. The Surface area curve is not smooth for 2010 as compared to the design surface area curve of 1991. This can be attributed to the non-uniformity of sediment deposition across the dam surface area (from 98 m to 99 m reduced levels).

3.1.3 Capacity changes of Chesa Causeway Dam over the years

A plot of volume changes over the years is shown in figure 3.4. The 1991 volume is the original and the volumes from subsequent years found through hydrographic surveys. The full supply was at a reduced level of 100 m for all the years.

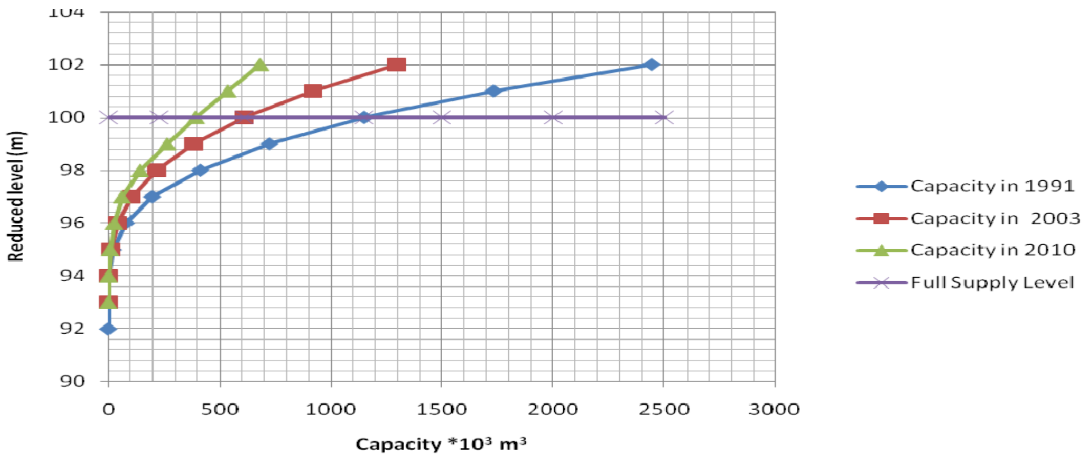

Figure 3.3: Chesa Causeway Dam volume comparison over the years

From figure 3.3 the reservoir basin has reduced in elevation by 1m from the original (where the original starting contour was 92 m) this can be attributed to the current high sediment specific sediment yields of 503 tkm^{-2} yr^{-1} being deposited into the reservoir. This has resulted in the dam capacity decreasing by 46 % over a period of 12 years (1991 - 2003); from 2003-2010 there is a 33 % decrease and the overall decrease in storage volume over 19 years calculated as 67 %.If no interventions are put in place to reduce the specific sediment yields assuming constant rate of deposition the reservoir would be completely silted up in the next 11 years which is 20 years less the designed lifespan.

A summary of the results for the calculated key parameters for both study areas are shown in Table 3.1:

Table 3.1: Summary of Hydrographic survey results for both study areas

	Chesa causeway
Design Storage Capacity ($*10^3m^3$)	1 150
Current Storage Capacity ($*10^3m^3$)	393
Gross mean annual Inflow ($*10^6$ m^3 yr^{-1})	29.5
Designed Lifespan (years)	50
Current Lifespan (years)	30
Design trap efficiency (%)	46
Calculated % Trap Efficiency for 2010	19
Design Storage ratio	0.04
Storage Ratio for 2010	0.01
Specific Sediment yield (tkm^{-2} yr^{-1})	503

From Table 3.1 the calculated trap efficiency has decreased by 27 % from 1991 when the dam became operational. A decrease in the trap efficiency is a result of an increase in sediment accumulation in the reservoir. The lifespan of the dam has reduced by 20 years from the initial predicted of 50 years this could be attributed the sedimentation taking place in the reservoir. Assuming a constant rate of specific sediment yield the results show that Chesa causeway dam has lost 67 % of storage in 19 years of operation for Chesa Causeway dam. The design ratio of the dam is much smaller than the recommended in Zimbabwe of not less than 0.1[7]. A larger dam could have been designed at Chesa Causeway to optimise the storage of the available runoff

3.1.4 Comparison of results from sediment quantification methods used

A comparative table for the calculated key parameters from the sediment quantification methods used are shown in Table 3.2:

Table 3.2: Summary of key parameters calculated from sediment quantification methods

	Chesa Causeway Dam
Grab sampling	
Estimated % storage lost to sediment deposition (2009 – 2010 rain season)	9
Specific Sediment yield ($tkm^{-2}\,yr^{-1}$)	774
Hydrographic Survey	
Estimated % storage lost to	3.5
sediment deposition annually	
Specific Sediment yield ($tkm^{-2}\,yr^{-1}$)	503

The estimated annual percentage storage lost due to sediment deposition and specific sediments yield values are within range of ± 270 $tkm^{-2}\,yr^{-1}$ using both methods. This difference could be attributed to the nature of the methods used in the study. The grab sampling is a point method of measuring sediments in a dam, as opposed to the hydrographic survey method which involves surveying the whole dam basin to estimate the two parameters. The grab sampling method shows seasonal variability as opposed to the hydrographic survey which assumes a constant rate of deposition over a given period of time and therefore the rates do not take into account the seasonal variability hence the differences in magnitude of values for both parameters using both methods.

3.2 Land cover and land use

Figures 3.4 to 3.6 show the changes in land cover patterns for Chesa Causeway dam catchment from 1991 (when the dam was constructed), 2003 (when a hydrographic survey was conducted for the dam) and 2009. The Landsat images were taken for the month of April of each year. Figure 3.7 shows land cover changes for different classes for 1991, 2003 and 2009 for Chesa dam catchment area.

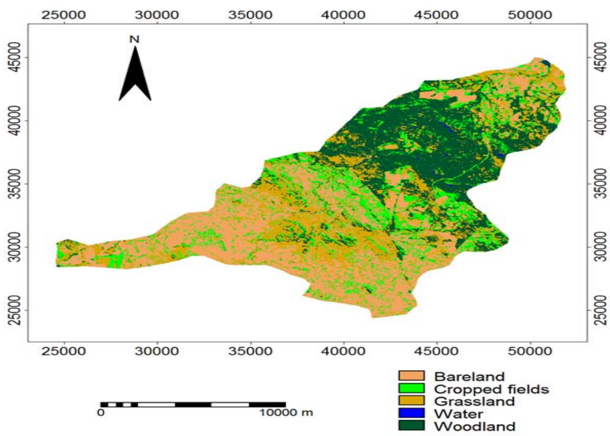

Figure 3.4 Land cover pattern in 1991 for Chesa

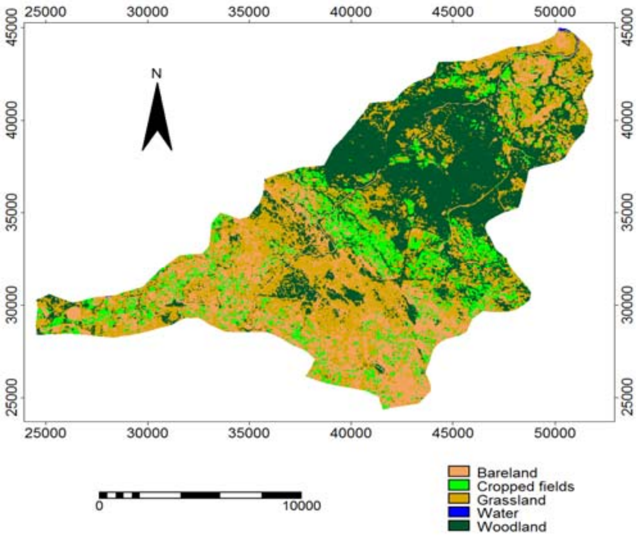

Figure 3.5 Land cover pattern in 2003 for Chesa dam catchment area

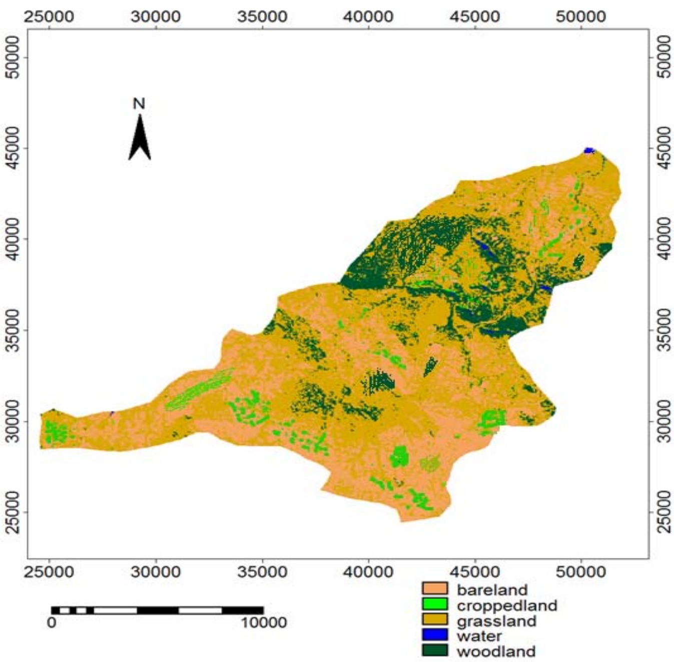

Figure 3.6: Land cover pattern in 2009 for Chesa dam catchment area

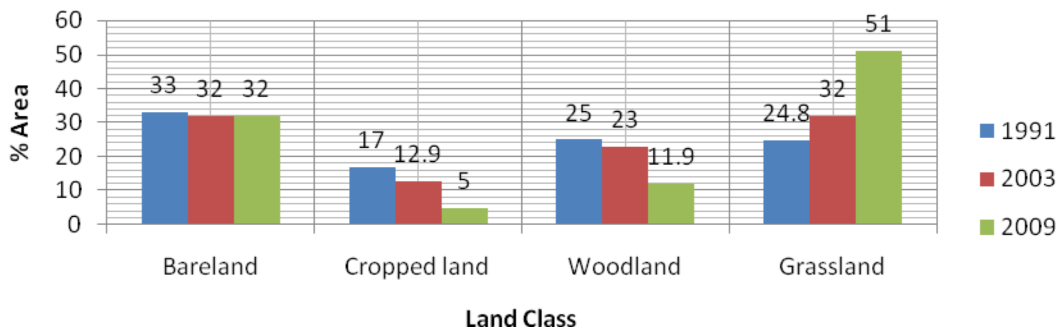

Figure 3.7: Land cover changes for different classes for 1991, 2003 and 2009 for Chesa dam catchment area.

From figure 3.7 above percentage areas for bareland have not changed much over the years with only a percentage decrease from 1991 to 2003. For cropped land and woodland there is a general trend where the percentage area is decreasing for both land classes over the years grassland cover is rising sharply from 25 % to 51 % over the years.

Up to 2000, the catchment area was predominantly a commercial farming area before the Zimbabwean resettlement programme began. The commercial farming area within the catchment area was then subdivided into 20 hectare plots commonly known as A1, where indigenous farmers were allocated the plots. This has resulted in the decrease of cropped land from 17 % to the current 5 % as much of the land is not being utilised to its maximum potential due to a number of reasons which include financial constraints, rainfall variability and lack of proper education to the farming community on the choice of crops to grow which suit the climatic conditions experienced in the area. Much of the land which used to be cropped before 2000 is now being left fallow, which has led to an increase in grassland from 24.8 % in 1991 to 51 % in 2009. Lack of enforcement of environmental by-laws by the local rural district council regarding deforestation has led to uncontrolled cutting down of trees within the catchment and much of the woodland has now become grassland area. From ground truth data, alluvial gold panning activities are taking place within and along the main tributary of the dam which is Mufure river. A similar study conducted in Ghana noted a similar trend whereby siltation of reservoirs was mainly attributed to deforestation and lack of proper education of the communities in catchment management[3]. This resulted in high (calculated) specific sediment yields therefore reduced useful lifespan of the dam as shown in Tables 3.0 and 3.1. This shows that land use activities influence the lifespan of reservoir and, in this case, the less conserved Chesa Causeway dam catchment which is characterised by alluvial gold panning activities resulting in a much less useful life than predicted from the initial dam design.

4.0 Conclusions

Both methods had specific sediment yields within the range of ± 270 $tkm^{-2}yr^{-1}$ if each other with the grab sampling method having a higher value than hydrographic method. The higher specific sediment yields obtained from both methods helps in confirming the reason why Chesa Causeway dam has lost more than half its storage capacity (66 %) in its 19 years of operation. Also larger dam could have been designed at Chesa Causeway to optimise the storage of the available runoff. Land use activities also influence the lifespan of reservoir and, in this case, the less conserved Chesa Causeway dam catchment which is characterised by alluvial gold panning activities will have a much less lifespan of 30 years than the 50 years predicted during the design stage.

5.0 Recommendations

The study has established that both hydrographic surveys and the grab sampling methods can be used for estimating sedimentation rates in reservoirs and, hence, facilitate informed decisions for IWRM. Also more similar studies using both methods are recommended, to determine the correlation between them, in quantifying reservoir sedimentation rates.

The study recommends all catchment councils adopt and enforce comprehensive catchment management plans as outlined in the 1998 Zimbabwe Water Act 20:24 subsection 12, so as to ensure sustainable management of the dam catchment.

6.0 Acknowledgements

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7.0 References

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