



Sedimentation and Its Impacts/Effects on River System and Reservoir Water Quality: case Study of Mazowe Catchment, Zimbabwe

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Abstract. Sediment delivery into water sources and bodies results in the reduction of water quantity and quality, increasing costs of water purification whilst reducing the available water for various other uses. The paper gives an analysis of sedimentation in one of Zimbabwe's seven rivers, the Mazowe Catchment, and its impact on water quality. The Revised Universal Soil Loss Equation (RUSLE) model was used to compute soil lost from the catchment as a result of soil erosion. The model was used in conjunction with GIS remotely sensed data and limited ground observations. The estimated annual soil loss in the catchment indicates soil loss ranging from 0 to 65 t ha yr⁻¹. Bathymetric survey at Chimhanda Dam showed that the capacity of the dam had reduced by 39 % as a result of sedimentation and the annual sediment deposition into Chimhanda Dam was estimated to be 330 t with a specific yield of 226 t km⁻² yr⁻¹. Relationship between selected water quality parameters, TSS, DO, NO₃, pH, TDS, turbidity and sediment yield for selected water sampling points and Chimhanda Dam was analyzed. It was established that there is a strong positive relationship between the sediment yield and the water quality parameters. Sediment yield showed high positive correlation with turbidity (0.63) and TDS (0.64). Water quality data from Chimhanda treatment plant water works revealed that the quality of water is deteriorating as a result of increase in sediment accumulation in the dam. The study concluded that sedimentation can affect the water quality of water sources.

1 Introduction

Sedimentation is a process whereby soil particles are eroded and transported by flowing water or other transporting media and deposited as layers of solid particles in water bodies such as reservoirs and rivers. It is a complex process that varies with watershed sediment yield, rate of transportation and mode of deposition (Ezugwu, 2013). Sediment deposition reduces the storage capacity and life span of reservoirs as well as river flows (Eroglu et al., 2010).

Sedimentation continues to be one of the most important threats to river eco-systems around the world. A study was done on the world's 145 major rivers with consistency long term sediment records and the results show that about 50 %

of the rivers have statistically a significantly downward flow trend due to sedimentation (Walling and Fang, 2003). Sumi and Hirose (2009) reported that the global reservoir gross storage capacity is about 6000 km³ and annual reservoir sedimentation rates are about 31 km³ (0.52 %). This suggests that at this sedimentation rate, the global reservoir storage capacity will be reduced to 50 % by year 2100.

Studies on some dams in Zimbabwe show that reservoir capacities are being affected by sedimentation (Sawunyama et al., 2006; Dalu et al., 2013; Chitata et al., 2014).

Water is vital for all anthropogenic activities. Water bodies have been contaminated with various pollutants due to direct or indirect interference of men causing an adverse impact on human health and aquatic life (Lawson, 2011). The quality of

2.2 Calculation of RUSLE Factors

The Revised Universal Soil Erosion (RUSLE) model was used in this study to calculate the soil that was lost from the catchment. The model predicted the long term annual loss from the basin and is given by Eq. (1; Renard et al., 1997):

$$A = R \times K \times LS \times C \times P \quad (1)$$

where: A = annual soil loss (t ha yr^{-1}); R = rain erosivity factor ($\text{MJ mm ha}^{-1} \text{h}^{-1}$); K = soil erodibility factor ($\text{t ha h MJ}^{-1} \text{mm}^{-1}$); LS = slope length and slope steepness length (m); C = land cover and crop management; P = management practice.

2.2.1 Rain Erosivity Factor (R factor)

Rainfall data was processed into average annual rainfall. Rain erosivity was calculated from the rainfall point map using Eq. (2; Merritt et al., 2003):

$$R = 38.5 + 0.35 \times P \quad (2)$$

where: R = Rain Erosivity Factor (Joule m^{-2}). P = Mean Annual Rainfall (mm yr^{-1}).

2.2.2 Soil Erodibility Factor (K factor)

The soil erodibility factor (K Factor) was calculated using Eq. (3) with the parameters obtained from the soil map (Teh, 2011).

$$K = \frac{(1.0 \times 10^{-4}(12 - OM^{1.14} + 4.5(F - 3) + 3.0(P - 2))}{100} \quad (3)$$

where K = Soil Erodibility; M = (% fine sand + %fine sand)] \times (100 - %clay) O = % of organic matter; F = Soil Structure; P = Permeability.

2.2.3 Land Cover and Crop Management Factor (C factor)

The C factor was calculated using the Normalized Difference Vegetation Index (NDVI), which is a tool for assessing changes in vegetation cover (Pettorelli et al., 2005; Gusso et al., 2014). NDVI was calculated from the bands using Eq. (4; Deering, 1992).

$$\text{NDVI} = \frac{(\text{NIR} - \text{Red})}{(\text{NIR} + \text{Red})} \quad (4)$$

where NIR = band 3 for landSat images 1 to 7 and band 4 for landSat 8. Red = band 4 for landSat 1 to 7 and band 5 for landSat 8.

The calculated NDVI was then used to calculate the C factor from Eq. (5)

$$C \text{ factor map} = 12708 \times \text{NDVI} + 02585 \quad (5)$$

2.2.4 Management Practice Factor (P Factor)

The P factor reflects the control of conservation methods on soil loss. P values range from 0.01 to 1, with the value 0.01 being given to areas of maximum conservation support and the value 1 being given to areas with minimal or no conservation practices (Renard et al., 1997). The P values were derived from the land use map of the study area. Different values were assigned to each type of land use as guided by literature and the P factor map was produced (Jang et al., 1996).

2.3 Quantifying the sediment yield in the Catchment

The estimated soil loss was calculated from Eq. (6).

$$A = R \times K \times LS \times C \times P \quad (6)$$

where A = Average Soil Loss (t ha yr^{-1}); R = R factor map; K = K factor map; LS = LS factor map; C = C factor map; P = P factor.

Soil loss from the catchment cannot be taken as sediment contribution to a river flow system since it does not account for deposition that occurs along the path (de Vente et al., 2011). Therefore the estimated soil loss was multiplied by the sediment delivery ratio (SDR) to obtain the sediment yield of the catchment. Sediment delivery ratios represent the fraction of the total soil loss that is washed into rivers and was calculated from using Eq. (7; USDA, 1972).

$$\text{SDR} = 05656\text{CA}^{-0.11} \quad (7)$$

where SDR = Sediment Delivery Ratio; CA = Watershed Area, km^2 .

After determination of the sediment delivery ratio, the average sediment yield was determined using Eq. (8), by Wischmeier and Smith (1978)

$$\text{SR} = \text{SDR} \times A \quad (8)$$

where: SR = Sediment yield (t ha yr^{-1}); SDR = Sediment delivery ratio; A = Average soil loss (t ha yr^{-1}).

2.4 Sediment yield from field measurements

Seven out of the thirteen functional ZINWA gauging stations were selected for collection of sediment concentration samples, (Fig. 2). Water samples were collected from various flow gauging stations for the period November 2014 to March 2015 using grab sampling method. An average of 20 samples was collected from each gauging station. The samples were analyzed in a laboratory using the weighing and filtration method in order to determine the sediment concentration in mg L^{-1} . The sediment load was determined by multiplying the sediment load at a particular gauge by the area of influence.

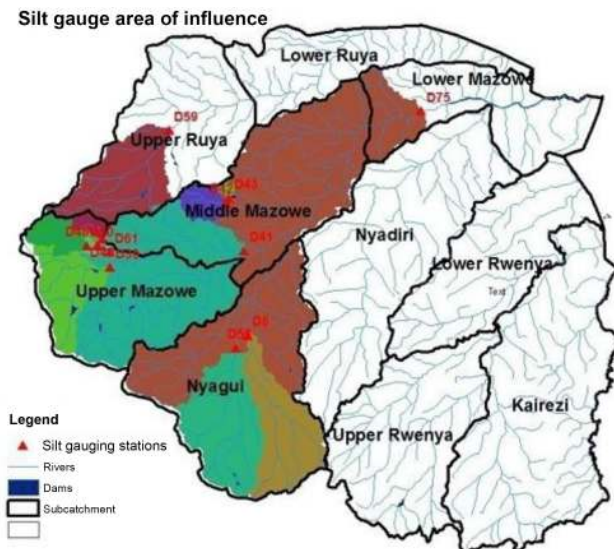


Figure 2. Gauges in the catchment and areas of influence.

2.5 Assessing the current sedimentation levels of Chimhanda Dam

A bathymetric survey was carried out at Chimhanda dam to determine the siltation level of the dam. The survey was conducted using a SonTek River Surveyor system and a theodolite to come up with a basin survey map. The plotted map was digitized to get the surface area between contours. The area was then multiplied by the contour interval to get the volume of each contour using Simpson's formula.

$$V_{\text{contour}} = \frac{A_1 + (A_1 \times A_2)^{1/2} + A_2}{3} \quad (9)$$

where V_{contour} = contour Volume (m^3); A_1 = Area₁ (m^2); A_2 = Area₂ (m^2).

The calculated volumes for each contour were accumulated to get the new capacity of the dam.

2.6 Water quality trend from sedimentation

Water quality historical data from six selected water sampling points were obtained from the Environmental Management Agency records. The points were selected basing on the consistency of the data and less gaps. The trend for the selected water quality parameters, TSS, DO, NO_3 , pH, TDS and turbidity for the corresponding predicted sediment yield years were analysed. The water quality parameters were compared with the Environmental Management Agency, Effluent and Solid Waste Disposal Regulations Statutory Instrument number 6 of 2007 (EMA, 2007) shown on Table 1. Water quality data for Chimhanda water supply treatment plant from the Zimbabwe National Water Authority was also related to the change in level of sedimentation of Chimhanda Dam.

2.7 Investigation the relationship between sedimentation and water quality

Selected water quality parameters were correlated with the corresponding sediment yield to determine the relationship between sediment yield and water quality. Pearson Correlation was used to estimate the strength of relationship between sediment yield and some physical water quality.

3 Results and discussions

3.1 Results of the RUSLE factors

The erosivity map (R factor) depicts rainfall energy in the various areas within the catchment. The rainfall erosivity ranges between 200 and 500 ($\text{MJ mm ha}^{-1} \text{h}^{-1} \text{yr}$). A greater part of the catchment is averaging a rainfall erosivity value of $276 \text{ MJ mm ha}^{-1} \text{h}^{-1} \text{yr}$. Highest rainfall erosivity values are in the Kairezi sub-catchment of the study area. Erodability (K factor) values range from 0 to $0.5 \text{ t ha}^{-1} \text{yr}^{-1} \text{MJ}^{-1} \text{mm}^{-1}$. Some parts in the south west of the catchment have high values of erodibility, the highest K value is dominated by very fine sand with silt particles which give rise to higher soil erodibility (Kamaludin et al., 2013). Highest slope length steepness (LS) values of 16 m were found in the eastern part of the catchment. The northern part of the catchment experiences average LS values of 7 m.

Cover Management and Practice (C factor) ranges from -1 to 1 . The C factor is depicted by NDVI which is a function of photosynthesis. The C factor is high in the eastern highlands area, some parts of Kairezi sub-catchment and along the Mufurudzi area. This is possible because the Kairezi area experiences high rainfall while Mufurudzi being a game park, has more vegetation. High C values were observed with high vegetation cover (Pettorelli et al., 2005). The P value of 1 was observed in Lower Mazowe and Upper Rwenya subcatchment areas respectively. Areas like Mufurudzi and parts of Kairezi experienced an average P value of 0.8.

3.2 Soil loss from the catchment

The average annual soil loss for the different years are shown on Fig. 3 and the temporal variation of actual soil loss is tabulated on Table 2.

The estimated soil loss from the catchment ranges from 0 to 203 t ha yr^{-1} . The estimated average soil loss is 54 t ha yr^{-1} . The highest soil loss is being experienced in Middle Mazowe and Nyagui sub-catchments. High soil loss in Middle Mazowe sub-catchment can be associated with high gold panning activities in the Mazowe valley whilst in Nyagui sub-catchment, this can be associated with high crop farming activities in the area. When the soil is made loose, its structure is altered hence increase in erodibility.

Table 1. Effluent and solid waste disposal regulations.

PARAMETER	BANDS					Test Methods
	Blue		Green	Yellow	Red	
	Sensitive	Normal				
DO % saturation	> 75	> 60	> 50	> 30	> 15	SAZS 573
Nitrates NO ₃ mg L ⁻¹	< 10	< 10	< 20	< 30	< 50	
PH	6.0–7.5	6.0–9.0	5–6, 9–10	4–5, 10–12	0–4, 12–14	SAZS 483
TDS	< 100	< 500	< 1500	< 2000	< 3000	SAZS 576,
Turbidity (NTU)	< 5	< 5				SAZS 478
TSS mg L ⁻¹	< 10	< 25	< 50	< 100	< 150	SAZS 478

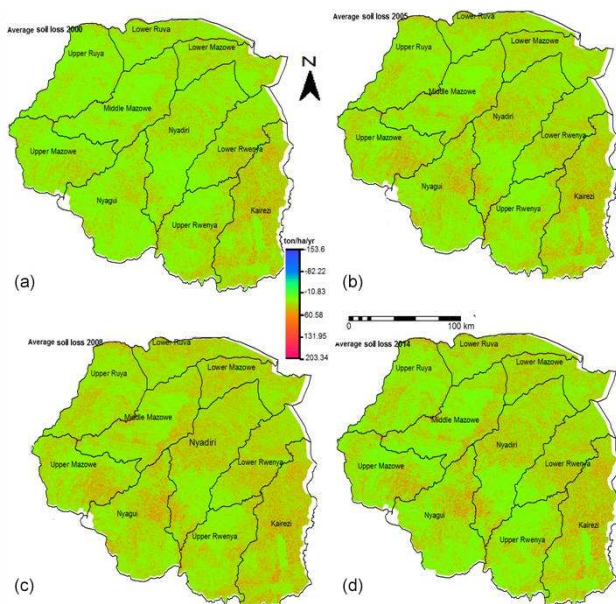


Figure 3. Estimated Average Soil Loss for 2000, 2005, 2008, and 2014.

The average soil loss value of 54 t ha yr⁻¹ concurred with other studies that were carried out in the country. Whitlow (1986) found that 76 t of soil is lost per hectare per year through soil erosion in most parts of the country. Another study by Mutowo and Chikodzi (2013) “Erosion hazards mapping in the Runde Catchment”, concluded that most of the areas in the catchment fall in the category range of 0–50 t ha yr⁻¹. Makwara and Gamira (2012) reported that the most serious type of erosion being sheet erosion, is estimated to remove an average 50 t ha yr⁻¹ from Zimbabwe’s communal lands.

There is no uniform trend in the soil loss over the study period. In year 2000, the soil loss was 54 t ha yr⁻¹. The increase of soil loss in 2005 from the 2000 figure can be explained by the land reform programme which started in year 2000 and

Table 2. Temporal Variation of Estimated Soil Loss.

Year	Average Soil Loss (t ha yr ⁻¹)
2000	54
2005	65
2008	36
2014	62

was at its peak around 2003. There was a lot of deforestation as new farmers were clearing land for agricultural purposes (Mambo and Archer, 2007). Some areas which were meant for animal rearing and forest were also converted to crop agricultural areas. In 2008 the soil loss rate decreased to 36 t ha yr⁻¹. The reduction can be attributed to a number of factors. Year 2008 experienced low erosivity as a result of low rainfall, which could also lead to low annual soil loss. The economy of Zimbabwe was almost at a stand-still during the period 2007 to 2009, with an inflation rate record of over 231 million percent in July 2008 (Hanke and Kwok, 2009). As a result there was less farming activities during that period.

The soil loss rate almost doubled in year 2014 as compared to 2008. This can be explained by the increase in the number of small scale gold miners in the catchment and alluvial gold panning in streams and rivers. Mining within the catchment is not only limited to the river beds and banks, miners are also targeting the inland areas of the catchment such as the Mazowe Valley and Mufurudzi Game Park and as a result, soil erodibility is also increasing. Increase in rate of unemployment caused by low capital investment and continuing closure of industries in Zimbabwe has resulted in the population resorting to other sources of income such as illegal gold mining and alluvial gold panning. A study that was carried out in the Lower Manyame sub – catchment along Dande River, on the analysis of the implications of cross- sectional coordination of the management of gold panning activities

Table 3. Measured sediment Load from flow gauges for the period December 2014 to March 2015.

Silt Gauge	Name or River	Area of Influence (km ²)	Sediment load (t km ⁻²)	Load (t)
D75	Mazowe	20 380	1.4	28536
D50	Nyamasanga	13	0.24	3
D42	Mupfurdzi	163	1.92	313.56
D41	Mazowe	3300	0.86	2836
D6	Shavanhowe	1166	0.51	589.65
D58	Nyagui	98.3	24.25	142.93
D48	Mwenje	399	0.36	33.4

Table 4. Summarized Results from the silt survey.

	1988	2003	2015
Capacity at FSL ($\times 10^6$ m ³)	5.2	3.470	3.194
Loss Of Storage (%)	0	33.3	38.6
Dam Surface Area (Ha)	93.00	74.00	64.04

and its impacts (Zwane et al., 2006), identified river bed gold panning activities as a cause of degradation of river channels and banks as well as accelerated erosion and siltation in many areas of Zimbabwe.

3.2.1 Sediment Yield

Figure 4 shows the sediment yield distribution map. Sediment yield ranges from less than 1 t ha yr⁻¹ to a maximum of 24.5 t ha yr⁻¹ with an average value of 6.04 t ha yr⁻¹ over the catchment area. The highest sediment yield is in the Middle Mazowe sub catchment area with an average of 6.72 t ha yr⁻¹ and a maximum of 24.5 t ha yr⁻¹. The high value can be associated with high gold panning activities in the Mazowe valley. The lowest value is in the Lower Ruya sub-catchment with an average of 4 t ha yr⁻¹. The results are almost in line with a study by Rooseboom and Engineers (1992) that estimated the average sediment yield in the nine defined sediment regions in Southern Africa to vary between 30 and 330 t ha yr⁻¹ with an average of 15 t ha yr⁻¹. A study which was also carried out in the catchment area of Pahang River basin in Malaysia gave a sediment yield ranging from 0–13.79 t ha yr⁻¹ (Kamaludin et al., 2013). The total sediment yield for the catchment was calculated to be 6.3 million t yr⁻¹.

3.2.2 Measured Sediment Loads

Results from the measured sediment loads were highest at D75 which is along Mazowe River, in the Zambezi valley. D41, located in Middle Mazowe sub catchment recorded a relatively high sediment load of 2836 t. D58 and D6 are both in Nyagui Sub-catchment recorded 142.93 and 589.65 t re-

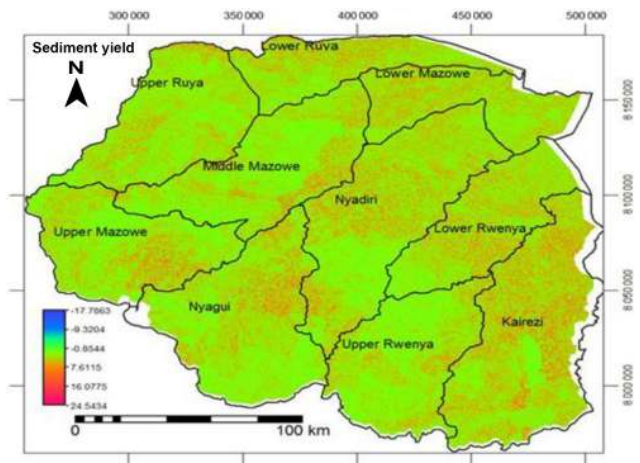


Figure 4. Sediment Yield within the Catchment.

Table 5. Results for the correlation between sediment yield and water quality parameters.

	Sediment	Ave Turbidity	Average TSS
Sediment	Pearson Correlation	1	.647
	Sig. (2-tailed)	.366	.353
	N	28	28

spectively. D50, which is in Upper Mazowe sub catchment, recorded a low figure of 3 t. The results are concurring with those from RUSLE model, where high sediment yields were recorded from Middle Mazowe and Nyagui sub catchments respectively.

3.3 Sedimentation in Chimhanda Dam from Bathymetric Survey

Table 4 summarizes the results of the silt survey for Chimhanda Dam.

The capacity of the dam decreased from the original 5.200×10^6 to 3.470×10^6 and 3.194×10^6 m³ in years 2003 and 2015 respectively. There was 33.3 % loss in stor-

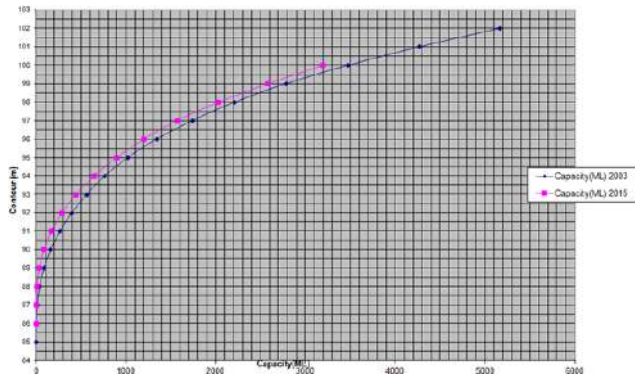


Figure 5. Chimhanda Dam Capacity comparison over the years.

age up to 2003 and a storage loss of 38.6% up to 2015 in reference to the design capacity. Figure 5 shows reservoir capacity changes over the years.

Results from the 10 samples of river inflows collected gave an average sediment concentration of 39 mg L^{-1} . There was a decrease in trend in the sediment concentration as the rainfall season was progressing. The sediment accumulation in the reservoir was found to be 330 t yr^{-1} and the specific sediment yield was $226 \text{ t km}^{-2} \text{ yr}^{-1}$. The usefulness of Chimhanda Dam has reduced from the initial design life of 50 to 37 years. A study by Godwin et al. (2011) on Chesa Causeway Weir in the same catchment gave a specific yield of $510 \text{ t km}^2 \text{ yr}^{-1}$. The usefulness of the dam was reduced from the initial design life of 50 to 25 years.

Generally the results support the existing literature that most of the small to medium dams are being affected by high rates of sedimentation in Zimbabwe (Sawunyama et al., 2006; Godwin et al., 2011; Dalu et al., 2013; Chitata et al., 2014).

3.4 Water Quality Trend from Sedimentation

Figures 6 to 10 show the results for the historically measured water parameters for the years 2000, 2008, 2010 and 2014.

3.4.1 Turbidity

Results for the years did not meet the permissible turbidity of 5 NTU. The highest turbidity values were recorded in 2000 and 2005 respectively. High values in 2005 corresponds to the high soil loss of 65 t ha yr^{-1} that was recorded during that particular year. The high values in 2000 can be explained by high rainfalls that were experienced during that particular year as compared with the other years (Met, 2005). Low turbidity values were recorded during the year 2008, the same year recorded the lowest soil loss of 36 t ha yr^{-1} . High Turbidity levels are associated with poor water quality, (Adekunle et al., 2007). WHO (2008) highlighted that high turbidity waters can facilitate the formation of nuclei, where gastrointestinal disease pathogens can attach. If that water

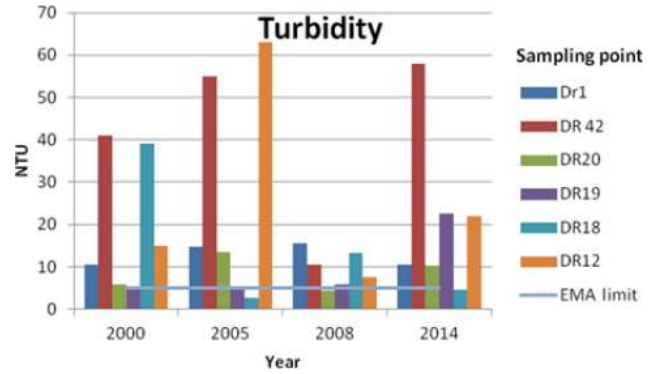


Figure 6. Turbidity variation among sampling points.

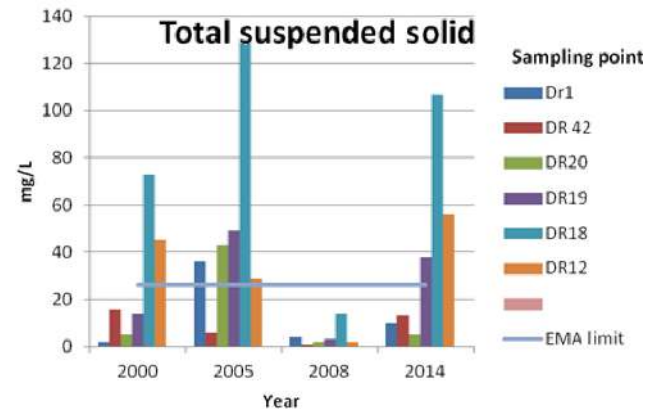


Figure 7. Total Suspended Solids variation among sampling points.

is consumed improperly treated, it can cause diseases. High turbidity levels also render the treatment of water expensive.

3.4.2 Total Suspended Solids

2008 values were below the recommended limit of 15 mg L^{-1} as shown on Fig. 7. High values were recorded during year 2000, 2005 and 2014. The high values are in agreement with the high soil loss that were recorded in those particular years. Total suspended solids are closely related to sedimentation (Chapman, 1996). When these suspended particles settles at the bottom of a water body they become sediments. Suspended solids consist of inorganic and organic fractions. Part of the organic fractions is bacterial and that might be detrimental to human health if the water is consumed without adequate treatment (Hoko, 2008).

3.4.3 Dissolved Oxygen (DO)

Dissolved Oxygen was above the lower limit for EMA at all the stations for all the years. Year 2000 and 2005 recorded % saturation of 125 and 100 respectively. Oxygen levels can be higher due to excess aquatic plants in the water which

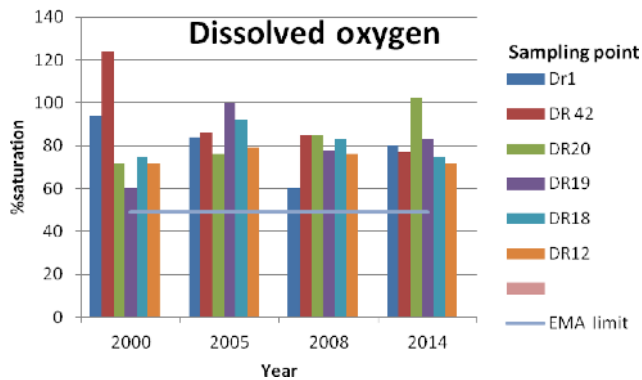


Figure 8. Dissolved Oxygen variation among sampling points.

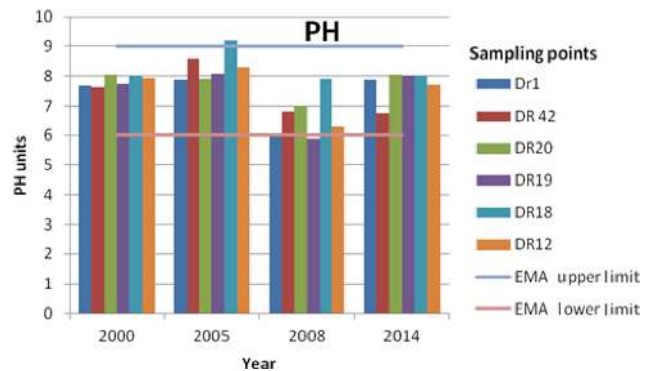


Figure 10. pH variations along sampling points.

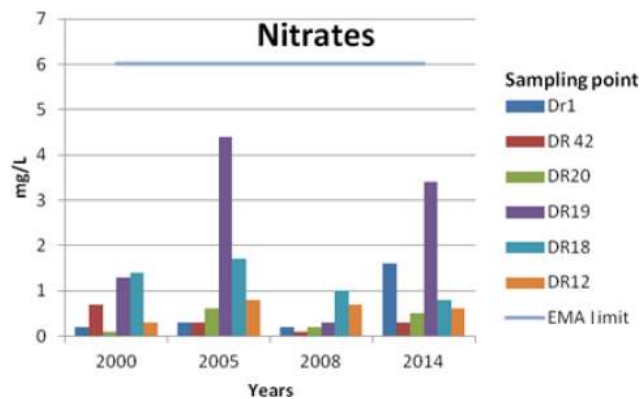


Figure 9. Nitrates variation along sampling points.

produce oxygen. Most living organisms require oxygen for their basic metabolic processes.

3.4.4 Nitrates (NO_3)

Results for nitrates for the years under consideration were all below the recommended EMA levels of 6 mg L^{-1} . Nitrates are washed by runoff from agricultural lands into water bodies. High concentration of nitrates in water bodies cause eutrophication, resulting in competition for oxygen by aquatic organisms and high water treatment costs (Dike et al., 2010).

3.4.5 PH

pH values for all the years were within the normal limits category according to EMA upper and lower limits of 6 and 9 units respectively. Year 2005 had one sampling point that had a value slightly lower than the recommended. Bhadja and Vaghela (2013) indicated that activities in the water shed such as increased leaching of soils, soil erosion and heavy precipitation affects the pH levels downstream. pH levels as high as 9.0 and as low as 5 affects the life span of aquatic organisms (Addo et al., 2011). Low pH values do not have direct effect to human health, but can have indirectly effect

since it causes leaching of metal ions such as copper, zinc and lead into the water (WHO, 2008).

3.5 Relationship between sedimentation and river water quality

Pearson correlation was used to determine the relationship between two water quality parameters and sediment yield. The parameters are related to sediment yield and these are turbidity and suspended solids, (Bhadja and Vaghela, 2013). The results are shown on Table 5.

There is a close positive relationship between turbidity and sediment yield of 0.63. Total Suspended Solids have a positive relation of 0.64. The results show that the two water quality parameters can be indicators of sedimentation. Higher values of total suspended solids and turbidity indicate higher values of sediment yield in water bodies.

3.6 Variation in reservoir water quality

The variation in two selected reservoir water quality indicators, turbidity and pH was determined. A significant variation in turbidity was noted for the years 1988 to 2014 with a p -value of 0.02, which is less than 0.05. The mean value of turbidity for 1988, 2003 and 2014 are 15.6, 34.4 and 41.7 NTU respectively. The values show an increasing trend in turbidity which may be as a result of anthropogenic activities occurring upstream of the dam which has resulted in increased soil erosion hence more sediment on the reservoir. pH results showed that there is no significant change between 1988 and 2014 (p -value > 0.05). This might be because pH is a chemical parameter that is determined by the type of sediments that are carried into the river not the sediment load.

4 Conclusions and recommendations

4.1 Conclusion

The objective of the study was to analyze sedimentation and its impact on river system and reservoir water quality in Mazowe Catchment, Zimbabwe. The study's major findings are,

The catchment is generally experiencing moderate soil loss, however there are some pockets under high and extreme soil loss which gave rise to siltation and water quality deterioration of available water bodies.

There is reduction in capacity of reservoirs within the catchment due to sedimentation. Chimhanda Dam capacity has been reduced by 38.6% from the initial design capacity as of April 2015, reducing the usefulness of the dam to 37 years from the initial design life of 50 years due to siltation.

Sediment deposition in rivers affects water quality and water quality parameters can be used as an indicator for sedimentation.

4.2 Recommendations

In order to curb erosion and sedimentation in rivers and reservoirs, there is need to develop and implement an integrated water resources management plan by all stakeholders.

In order to maintain the lifespan of Chimhanda dam, best land management practices such as contour ploughing and re-forestation should be employed around the catchment area of the Dam and this is an area that could be considered for further research.

Data availability. The main data used in the research is rainfall data that was obtained from the meteorological department, water quality data obtained from Environmental management Agency as well as sediment Data from Zinwa. The data can be obtained from these departments.

Competing interests. The authors declare that they have no conflict of interest.

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