Spatial and Seasonal Dynamics of Total Suspended Sediment, Total Dissolved Solids and Turbidity of a Lacustrine Reservoir in the Magoye Catchment, Southern Zambia

Manoah Muchanga and Henry M. Sichingabula

ABSTRACT

Dissolved and suspended sediment that form part of the Total Sediment Load (TSL) affects the quality of water making it unsuitable for selected aquatic invertebrates and livestock. The study aimed at determining spatial and seasonal dynamics in the concentration levels and distribution of selected physical parameters in a small lacustrine system whose main problem was punctuated by rapid deposition of clastic and none-clastic sediment. Water sampling was done during the rainy and cool-dry seasons across the reservoir using sampling bottles and DGPS. Laboratory analysis was done to determine variations in concentration levels of the parameters over time and space. Distributions of selected parameters across the reservoir were analysed using 3D Spatial Analysts Tool, Inverse Distance Weighted (IDW) in ArcGIS 10.2. Using paired T-Test at 0.05 level of significance, the study found statistically significant differences ($p < 0.001$) in the concentration of TDS, TSS, and turbidity between the rainy season and cool-dry season. With exception of TDS, TSS and turbidity were higher in the rainy season than in the cool-dry season. Rainfall was the main control variable regarding seasonality influence on TDS, TSS, and turbidity. The study concluded that although lacustrine reservoirs may be closed systems, they still experience variations spatially and temporally in terms of concentration of TDS, TSS and turbidity. The study recommends implementation of integrated catchment-wide management of anthropogenic activities so as to minimize excess generation, transportation and deposition of sediment, which punctuate elevated levels of TDS, TSS and turbidity.

Keywords: Invertebral biodiversity, Lacustrine Reservoir, Livestock, SDG14, Total Dissolved Solids, Total Suspended Sediment, Turbidity, Water Quality.

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Manoah Muchanga*

Geography and Environmental Education
Section, University of Zambia, Zambia.
(e-mail: mmuchanga@unza.zm)

Henry M. Sichingabula

Geography and Environmental Studies,
University of Zambia, Zambia.

**Corresponding Author*

I. INTRODUCTION

Although sedimentation may be a natural process, in many places worldwide, it is enhanced by anthropogenic activities such as deforestation, mismanagement of riparian areas and poor farming practices especially near lacustrine systems. Sedimentation is recognized as a problem in Zambia accelerated by long history of sedentary agriculture and the large herds of cattle kept by local people especially in southern Zambia. Neglect of catchments usually punctuates reservoirs' sedimentation due to high levels of erosion, transportation, and deposition [1]. Chemical effluents and metals that are usually part of the Total Sediment Load (TSL) affect the quality of water, especially in highly managed catchments. The most obvious visual effect is that of increasing turbidity. This often affects light penetration resulting in extensive loss of lacustrine reservoir productivity [1]. Sediment may be contaminated with excessive levels of nutrients from urban and agricultural

landuse [2]. Studies on water quality are broadly documented especially from outside Zambia and Africa in general [3]-[5]. Physical parameters such as TSS release heavy metal pollutants such as Lead and Cadmium, pesticides, and nutrients such as phosphorus into lacustrine systems. Others release cholera-causing bacteria, which may render water unsuitable for aquatic microphytes and livestock [6], [7]. The opacity punctuated by TSS affect the ability of aquatic organisms to catch food due to reduced transparency and visibility. Sometimes TSS and turbidity clog fish gills and decrease their resistance to diseases as well as ability to recolonize. Excess TSS may also settle in rocky habitats thus, taking up the spaces for laying of eggs and eventually, productivity [7]. Although it is generally believed that physical characteristics of water in a lacustrine system are generally uniform, this study suggests that such a perspective is not concrete universal considering the variations, which were spatial-temporally observed in the study. Generally, the study aimed at understanding the

spatial-temporal dynamics of total suspended sediment, total dissolved solids, and turbidity of a lacustrine reservoir in the Magoye River Catchment. The study hypothesized that the concentration of TDS, TSS and turbidity significantly differed from one season to the other at 95% level of confidence.

II. MATERIALS AND METHODS

The targeted study area is found in the Magoye Catchment in Njola area, east of Monze Town in southern Zambia. It is specifically located between 16°14'08.4" South to 16°15'06.8" South and 27°40'52.8" East to 27°42'49.8" East with surface area of about 76,437.11 m² (Fig. 1). It has been in existence since 1940 and, so far, is the oldest anthropogenic lacustrine system in the Magoye Catchment and whose subbasin areal extent is 5 km² [8]. It is agro-ecologically located in Zone-IIa with a mean annual rainfall of ≤815 mm and a maximum temperature range of 33 to 36°C [9]. Geologically, it is underlain by the Zambebian belt and pedologically by, lithosols, chromic-luvisols, vertisols, orthic ferralsol and nitosols [10]. Southern miombo is common [11] and, pastoral farming is a common anthropogenic activity [12]. The population of households in the catchment is over 474 of which, 77% are dependent on pastoral and crop farming [12]. By 2016, there were over 10,000 heads of cattle that depended on the lacustrine system under consideration [13].

Fig. 1. General location of the study area in the Magoye Catchment.

A. Sampling Process

In order to sample the Lacustrine Reservoir, various types of snowball sampling techniques were used, namely, Exponential Non-Discriminative Snowball Sampling (ENDSS) and Exponential Discriminative Snowball Sampling (EDSS) [14]. During a reconnaissance survey, a listing of 96 reservoirs was generated using ENDSS. EDSS was used to separate 10 small lacustrine reservoirs of medium size, useful to the host communities and, which were suitable for rainy season camping. The 10 reservoirs became the final target population from which Makoye Lacustrine System was selected using Simple Random Sampling Technique (SRST) [15]. Fig. 2 summarizes the sampling process used.

Fig. 2. Sampling framework applied in the study.

B. Data Collection Process

The research team comprising the principal investigator and two research assistants camped on the site for the whole 2015/2016 rainy season, November 2015 to March 2016. The team identified transects and points across the reservoir surface from where water samples were collected. Water was sampled across the reservoir on 3 March 2016 when the reservoir was at bankful, but before it spilled over. Samples were collected at 10 different points with the aid of an inflatable boat, Differential Global Positioning System (DGPS), and a note pad for taking coordinates. In all instances of water sampling, all bottles of water samples were clearly labelled in order to avoid mixing them up prior to laboratory analysis.

C. Data Analysis

To determine concentration levels of selected physical and chemical parameters, laboratory analysis was done, thereafter, results were summarised using tabular matrices [15]. Standard deviations and means with the aid of Excel Spreadsheet were also used to determine variations in concentrations of TDS, TSS and turbidity from each other and from the Maximum Permissible Limits for livestock as prescribed by FAO. In order to visualise how the concentration levels of selected physical parameters varied across the reservoir, 3-D Spatial Analysts Tool, specifically IDW Raster interpolation tool in ArcGIS 10.2 was used [16]. The input data into the GIS ArcMap interface included sampling points' coordinates in Universal Transverse Mercator (UTM), measured concentration of TDS, TSS and turbidity and wetted perimeter of the lacustrine system.

III. RESULTS

Although lacustrine reservoirs are almost fully closed systems in terms of concentration of physical parameters, the study found that even such closed systems experience moderate to significant variations in the concentration of physical parameters. Total Suspended Sediment was the most variable within the target system especially during the rainy season (November-April) than during the cool-dry (May-July) season. On average (2,805 mg/l), TSS widely varied above the maximum permissible limit (1,000 mg/l) for livestock by 70%, which represented a significant departure from the normal. Like TSS, turbidity was also highly variable from one point of the reservoir to the other and from one season to the other. On average, that is, 1,714.4 NTU, and it varied above the prescribed standard (1000 NTU) by 40%. The average variation of Total Dissolved Sediment (TDS) was quite moderate and most stable, but intra-spatial variations were still notable from one point to the other. However, this did not imply that variations were not notable. On average, the study found TDS (50.8 mg/l) to be within acceptable concentration levels compared to permissible limits (1000 NTU) with CV of 170% (1.7). Table I shows results on concentration levels of physical parameters across the small lacustrine system.

Further evidence regarding how the concentration of TSS, TDS, and turbidity varied across the lacustrine system is presented in Fig. 3 (a-f). They all show visual impressions of unstable equilibrium in the concentration of parameters with seasonal changes in rainfall events as a major driving factor. The study found that TDS was significantly higher in the cool-dry season than in the rainy season ($p<0.001$). TSS

and turbidity were very significantly higher in the rainy season than in the cool-dry season at 0.05 significance level. This suggests the significant influence of seasonal rainfall in the spatial-temporal variations of TDS, TSS and turbidity. During the rainy season, the lacustrine reservoir was still receiving surface off from rainfall, which meant high rate of sediment entry compared to the rate at which the system could homogenously mix the parameters. The turbulences due to frequent storm events in the rainy season could have also slowed sediment settling rate and possibly scoured and resuspended already settled sediment, hence increasing TSS and eventually turbidity in the rainy season. In the cool-dry season, no surface runoff enters the system, hence, most of the TSS, which predominantly influence turbidity would have already settled to the bed thereby drastically reducing TSS and turbidity. Given the lacustrine nature of the system, TSS could have had a long residence time in water (between March and July) such that, part of it further got dissolved and hence, high TDS in cool-dry season than rainy season. Generally, rainfall was the main influencing factor within the context of seasonal change.

TABLE II: SIGNIFICANCE OF THE DIFFERENCE IN CONCENTRATION OF THE PHYSICAL PARAMETERS BETWEEN RAINY AND COOL-DRY SEASONS

Description	T-Test Results for TDS	T-Test Results for TSS	T-Test results for Turbidity
Paired sample	10	10	10
Df	9	9	9
t Stat	23.75	11.45	10.47
P-value	0.0000000009	0.0000005	0.000001
t Critical one-tail	1.83	1.83	1.83
Confidence Level	95%	95%	95%

TABLE I: CONCENTRATION LEVELS OF PHYSICAL PARAMETER ACROSS THE MAKOYE RESERVOIR (3/3/2016)

Sample No	X	Y	TDS (mg/l)	TSS (mg/l)	Turbidity (NTU)
1	574803.07	8203961.3	44	3850	2252
2	574855.45	8203855.4	56	2240	1868
3	574736.68	8203846.7	42	1800	1174
6	574591.94	8203949.4	42	2040	1265
7	574695.22	8204061.5	42	3050	1807
8	574641.14	8203921.7	40	2950	1927
9	574750.68	8204137.6	41	3100	2130
10	574880.2	8204081.8	68	2100	1794
11	574823.71	8204131.2	43	4120	2254
12	574723.08	8203972.9	90	2800	673
Average concentration			50.8	2805	1714.4
FAO/ OETZEL (MPL)			1000	1000	1000
Mean for Samples and MPL			525.4	1902.5	1357.2
Standard Deviation for Samples and MPL			671.2	1276.3	505.2
Coefficient of Variation, Sample mean and MPL (%)			130	70	40
Coefficient of variation among sampling points (%)			32	28	30

Fig. 3. Spatial-seasonal variations in the concentration of TSS during (a) Rainy Season (3/3/2016) and (b) cool-dry season (17/7/2017), Turbidity (c-d), and TDS (e-f) during Rainy Season (3/3/2016) and cool-dry season (17/7/2017).

IV. DISCUSSION

Premised on the pieces of evidence provided in the previous section, the study argues that, although lacustrine reservoirs are generally closed systems, they experience variations in the concentration of TDS, TSS, and Turbidity. On average, the TDS was within MPL for livestock watering, wide spatial variations in its concentrations were noted and could be attributed to divergence in the character and solubility of mineral sediment deposited in the lacustrine reservoir. A similar scenario was earlier noted in another study although it was focusing on mobile hydrological systems [17]. The current findings further suggest that seasonal changes in terms of rainfall during wet season and lack of rainfall in the cool-dry season have a significant influence on the variations in concentration of TDS in non-perennial lacustrine water bodies with the lowest concentration likely to be recorded at the peak of rainy seasons and highest during the cool-dry seasons. The long residence time of sediment in the lacustrine system meant long exposure of sediment particles to water molecules and hence, a high dissolving rate resulting in high TDS in cool-dry season. Further spatial-temporal analysis revealed that none-perennial lacustrine reservoirs in the tropical region are likely to have a highly variable concentration of TDS with the highest concentrations near the bottom-set during the rainy seasons and conversely in the top-set zone during the cool-dry season. Based on the adopted methodological guideline [18], at 0.05 level of significance, TDS was significantly higher and more stable in the cool-dry season than during the rainy season ($p < 0.001$). This could be attributed to the large influx of water into the reservoir in the rainy season than during the

cool-dry season. The concentration levels of TDS (significantly below 1000 mg/l) were not just favorable for livestock watering, but also suitable for optimum distribution and abundance of aquatic invertebrates that are adaptive to aquatic environments with low TDS [19].

On average, TSS was found to be significantly high in the rainy season as demonstrated by its wide departure from the MPL. Unlike TDS, TSS tended to be higher around the boundaries of the lacustrine system irrespective of the season. This could be attributed to little volumes of water that are found within this zone and rapid deposition of sediment from agricultural fields [20]. The other possible explanation for higher concentrations of TSS around the boundaries could be attributed to livestock that loosened the bank soils as they drank water around the bank such that loosened sediment found itself into the water body [21]. Moreover, as livestock especially cattle reach out for clean water towards the centre of the water body, they scour the bed and agitate the settled sediment and resuspend it into these shallow zones, hence, the high concentration of TSS. At all seasons, TSS was highly variable, but the highest magnitude of variability was observed during the rainy season. This points to large scale influx of sediment with different gravities and whose settling rates could have been influenced by variations in the volumes of water at different points of the lacustrine reservoirs and hence, the drastic changes in the levels of concentration. As of the third day of March 2016 when sampling was done, the rainfall was at its peak such that the level of water (1.29-1.89 m) [20] in the incoming stream was on the rising limb of the hydrograph, during which mobilisation and replenishment of sediment into the channel and eventually the reservoir take place [3]. The exact opposite was the case during the cool-dry season

as the streams and lacustrine reservoir's water levels (1.04 m) [20] were already on the falling limb of the hydrograph with little or no cascades of new allochthonous sediment. At 95% level of confidence, the study found statistically significant elevated levels of TSS in rainy season than in the cool-dry season. This suggests a very slow settling rates sediment particles compared to its influx rate in rainy season and vice versa for the cool-dry season. Sediment particle size analysis across the reservoir actually revealed the sediment particle size of 0.02 mm across the reservoir bed and within 50 cm vertical profile [8]. The elevated levels of TSS in the rainy season also points to a highly managed and eroded subbasin of the lacustrine system under consideration. Since lacustrine systems are almost perfectly closed [17], [21], the mixing process of TSS tends to be slow and hence, the spasmodic changes in the observed concentration of TSS. The finding implies that water in such lacustrine systems as Makoye may not be very safe for animal watering during rainy seasons because of elevated levels of TSS.

Although TSS and turbidity are almost always inextricably linked with high turbidity suggesting high TSS [21], this study observed a converse scenario at one of the sampling points during the rainy season (refer to point 12, Table 1). At this point near the entry point of incoming sediment, turbidity was found to be the lowest, but with elevated concentration level of TSS. This is quite unusual, but there are three possible explanations for this phenomenon, firstly, it could be attributed to sediment that easily coagulates to each other under the presence of jelly-like algae plankton of cyanobacteria family, which was physically present in the lacustrine reservoir. Secondly, it could be that, at the time of sampling, the incoming sediment was clastic with little or no refined non-clastic sediment particles that could have easily changed the water opacity at the point of entry. An earlier study [22] suggests the same although its main focus was on how the two variables predict each other. Thirdly and possibly the most probable explanation could be that none-clastic and fine-grained allochthonous sediment had already been washed away from the sources, transported into the lacustrine reservoir long before the medium to coarse clastic sediment, which could be the reason why the main lacustrine reservoir had higher turbidity levels than the entry point or the edge of the throwback. Unlike some studies [23]-[25] that suggest outright linearity of the relationship between turbidity and TSS, this study suggests a reconsideration of linearity given that, in some instances, turbidity may not necessarily be linearly related to TSS depending on the character of sediment and turbidities.

Turbidity was generally spatially variable in the rainy season and on average, above the MPL. The opposite scenario was the case during the cool-dry season. Further analysis showed that at 0.05 level of significance ($p < 0.001$), turbidity was significantly higher during the rainy season than during the cool-dry season. This implies that water of a lacustrine system in a highly managed catchment could be safer for livestock watering during the cool-dry season than during the rainy season because, during the cool-dry season, much of the TSS is deposited to the bed, but during the rainy season, TSS transportation is more prevalent than deposition

[21]. According to [10], surface water whose turbidity goes beyond 1000 NTU is susceptible to chlorine-resistant pathogens such as *Cryptosporidium*, which cause animal diseases such as diarrhea. The Zambia Ministry of Livestock and Fisheries 2016 livestock census confirmed that some cattle in the catchment suffered from reduced immune system and diarrhea partly due to poor quality of water leading to death and reduction in the population of cattle between 2015 and 2016 [13]. Generally, the findings have implications on the biological safety of water for animals and even people alike given the unstable nature of the variables which were studied especially TSS and turbidity. Aquatic invertebral biodiversity is also under threat because of the dynamic nature of the concentration of TDS, TSS, and turbidity. If these are not frequently monitored and assessed, they are a deterrent to successful and localized implementation of SDG 14 concerning sustainable life under waters of non-perennial lacustrine systems. Hence, an understanding of geophysical processes such sediment fluxes and deposition is critical in the management of threatened lacustrine systems and generally, life underwater. Continuous assessment of the status of concentration of physical parameters in general and particularly their possible implications on livestock and aquatic biodiversity is useful in exploring new ways of increasing benefits from chemical sediment in lacustrine reservoir whilst reducing any detrimental effects. Understanding the physical characteristics of lacustrine reservoirs could be a perfect scanning tool to determine the nature of landuse across the whole catchment and may help in devising the best catchment management strategies that are community engaged and are responsive to climate action for sustainable integrated water resources management and adaptive landuse [26].

V. CONCLUSION

Based on the findings of the study, it can be concluded that small lacustrine reservoir with highly managed basins experiences elevated levels of TSS and Turbidity, during the rainy season than cool-dry season. Both spatial and temporal variations are common in small none-perennial lacustrine systems, which inspired the conclusion that seasonal and geospatial changes have influence on the concentration of TDS, TSS, and turbidity. Seasonal changes in terms of rainfall have a statistically significant influence on the variations in the concentration of TDS, TSS, and turbidity. Although some studies have concluded about strong linearity of the relationship between TSS and turbidity, this may not always be the case for all hydrological systems because geophysical and landuse processes vary from one space to the other. This study focused on a singular non-perennial lacustrine reservoir, notwithstanding that, the findings may well have a bearing on other lacustrine systems with homogenous characteristics as the one studied. The findings raise important theoretical issues that have a bearing on the realization of sustainable water resources management, life underwater, livestock management and aquatic invertebral biodiversity. Hence, the need for further research and implementation of sustainable catchment management practices that do not only reduce excess

sediment production, transportation and deposition to where they are least desirable, but also ensure that communities are educated to participate in the implementation of the control measures against excess siltation for sustainable water resilience amidst the changing climate.

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COMPETING INTERESTS

The authors have no competing interests to declare.

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Manoah Muchanga is a Doctor of Philosophy in Fluvial Geomorphology earned from the University of Zambia School of Natural Sciences in 2020. His PhD was sponsored by the Southern Africa Science Service Centre for Climate change and Adaptive Land Management (SASSCAL) under Task 109. He holds a Masters Degree with emphasis on Climate Change and Learning also awarded by the University of Zambia in 2011. His meritorious bachelor's degree with Geography Major was obtained in 2008 at the same institution. Dr. Manoah Muchanga holds advanced certificates in Research Methodology from Rhodes University-South Africa, Geographical Information System & Hydrological Modelling from DELFT IHE in the Netherlands, Project Management from WESSA-South Africa. He is currently a researcher and lecturer at the University of Zambia. His current research interest is in water and sediment; water education, environment and learning, climate change; social hydrology and river restoration, strategic planning, and research methodology. He is also the founder and Executive Director of Widelogic Consultancy and Training specialised in sediment and water research.