

January 2015

The Impacts of Sediment Yield Estimates on a Small Reservoir in Mutoko, Zimbabwe

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I would first like to thank my research advisers, Dr. Ken Anderson and Dr. Jonathan Remo, for their insightful and dedicated assistance.

I would also like to express my gratitude to those who made the trip to Zimbabwe possible, and assisted in field work while there. Without the following individuals' unconditional support, this project would never have begun: Dr. Peter Makiriyado and family, Ellen Esling, Elle Murray, and Samuel Brittingham.

It is because of these individuals that I have discovered my mission and passion in life, without which I would be purposeless. So, although it is never enough, thank you.

Recommended Citation

Patton, Brooke, "The Impacts of Sediment Yield Estimates on a Small Reservoir in Mutoko, Zimbabwe" (2015). *Honors Theses*. Paper 375.

The Impacts of Sediment Yield Estimates on a Small Reservoir in Mutoko, Zimbabwe

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12/1/2014

University Honors Program

Abstract: Water scarcity is becoming a more widespread issue due to human modification of local and global hydrologic cycles. In developing countries, land degradation, soil erosion, and its impacts on water resources are significant issues due to ever increasing water resource demands attributable to growing human populations within these areas. Small, multiple-use reservoirs are an important source of water in rural Zimbabwe. It is imperative to develop further insights into, and an understanding of, the linkage between hydrology, land use, and water resource needs in order to develop resilient water supplies for populations living in these areas. Here, a hydrologic and sediment budget was developed to inform the management of the 265,000 m³ (215 acre feet) Katoto Reservoir located near Mutoko, Zimbabwe (155 km northeast of Harare, Zimbabwe). Assuming present hydrologic and land use conditions remain the same, the entire reservoir may be completely infilled with sediment between 160 and 940 years. However, taking into account a potential 10% decrease in precipitation totals, Katoto Reservoir could become unusable within 120-160 years. Considering other factors such as population growth resulting in increased extraction values, increased evaporation due to climate change, and higher sediment yield values due to shifting land use, the useful life of Katoto Reservoir could potentially be reduced to far below the estimated lifespan of 120-160 years.

Key Words: Geographic Information Systems (GIS); Semi-Arid; Sediment Yield; Small Reservoir; Water Management; Zimbabwe

Introduction

Water scarcity is a growing issue that currently affects 1.2 billion people globally – approximately one-fifth of the world’s population – and another 500 million are approaching this situation. Water use has been growing more than twice the rate of population growth, and is both a natural and human-caused phenomenon (UNDESCA 2014). In addition, Africa struggles with land degradation, soil erosion, and drought. This is accelerated by the land resettlement program (or Zimbabwean Agrarian Reform), which distributes land to Zimbabweans for agricultural purposes and trains locals how to manage the land in order to make a profit (Ministry of Lands and Rural Resettlement 2014). According to the government of Zimbabwe, sedimentation of reservoirs is an extremely serious problem with dire future consequences (van der Wall 1986; Mambo et al 2007). The suspected high sedimentation rates in this area are of utmost concern, as reservoirs are the main water source for communities such as this (Dalu et al 2013). One of the most effective ways of addressing these interlinked problems is to establish hydrologic and sediment budgets, which quantifies the capacity and assesses the changes in reservoir storage. In this study we evaluate Katoto Reservoir which supplies water to the people of Mutoko and the surrounding area. The study employs field observation, geospatial modeling, hydrologic analyses, and sediment yield assessment to create hydrologic and sediment budgets for the reservoir. The methods and equations selected for this study are the reasonable procedures with which to estimate inflows of water and sediment into Katoto Reservoir, given the limited data available for this region of Zimbabwe.

Study Area

Katoto Reservoir is a small reservoir ($\sim 265,000 \text{ m}^3$ or 215 acre-feet) located within northeastern Zimbabwe (Figure 1). Zimbabwe is a landlocked country bordered to the south by South Africa, to the east by Mozambique, to the west by Botswana and Namibia, and to the northwest by Zambia. In between these borders is an extensive inland plateau – Africa’s Great Plateau – dropping northwest toward the Zambezi River and south to the Limpopo River. The study area, Mutoko, lies 155 km northeast of the capital of Harare in the province of Mashonaland East (Helgren et al 1995; Figure 1).

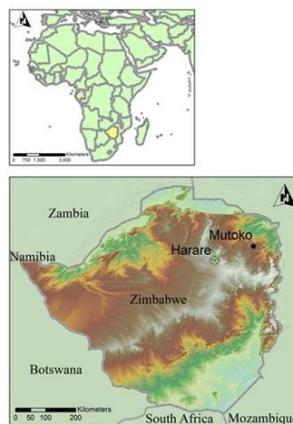


Figure 1 - An overview of Zimbabwe, and the location of Mutoko in relation to the capital of Harare (Veldhuis 2010)

The climate of Mutoko, Zimbabwe is semi-arid (615-755 mm/year rainfall) with high intensity rainfall generally occurring between November/December and February/March. Negligible amounts of rainfall occur between March and November and this time of year is considered the dry season. As a result of these hydrologic conditions, most streams in the area are ephemeral, only flowing during the wet season, and are typically underlain by a thick layer of sand (Mansell et al 2005). The geology of Zimbabwe is centered on the Zimbabwe Craton, composed of granitoids, schists, and gneisses. This basement is overlain by Proterozoic and Phanerozoic sedimentary basins in the north, northwest, and east (Treloar 1998).

Katoto Reservoir is one of few surface water bodies located within the vicinity of Mutoko. Along with small man-made reservoirs, locals rely on groundwater resources and alluvial aquifers found beneath the local ephemeral streams. These sources provide water for agricultural (cattle included) and personal use.

Methodology

Data Sources:

During the summer of 2013, an investigation into the water resources of Mutoko, Zimbabwe was undertaken. A bathymetric survey of the reservoir was conducted to measure the reservoir's current volume. The bathymetric survey was completed by measuring the depth of the reservoir on a 5 ft. by 5 ft. grid within a rowboat using a weighted tape. The X-Y location and depth were recorded within each survey grid cell and any measurement anomalies or external issues were noted. Other geospatial data employed in this study included a 1-arc-second (30 m) digital elevation model (DEM) obtained from the USGS (2014) and aerial photograph through ERIS (2014). The DEM was employed in the delineation of Mutoko Reservoir Watershed and was combined with the bathymetric data to generate a digital elevation of the reservoir.

All hydrologic parameters (i.e. evaporation, soil moisture change, groundwater runoff, groundwater storage change, and precipitation) were compiled from the literature or government sources for Zimbabwe or climatologically similar locations. The hydrologic parameters employed for the hydrologic analysis and sediment yield analysis are presented in Table 1.

Table 1 - The hydrologic parameters used in the hydrologic budget for Katoto Reservoir and sediment yield analysis for the Mutoko Reservoir Basin.

Values Used		Source Author(s)/Year
Precipitation (P)	615-755 mm/year	Mugabe, et al (2003)
Soil Moisture Change (Δ SM)	226.5 mm/year	Mugabe, et al (2007)
Groundwater Runoff (GWR)	14.35 mm/year	MacDonald, et al (2014)
Groundwater Storage Change (Δ GWS)	$-0.009 \times 10^6 \text{m}^3/\text{year}$	Love, et al (2011)
Evaporation	69.6 mm/year	Mugabe, et al (2003)

Drainage Basin Area Calculation:

The Arc GIS “Fill tool” was applied to the 1-Arc-Second DEM to fill in gaps or smooth over any large errors in the DEM. Filling any errors in the DEM enables the Arc-hydro tools to realistically model various hydrologic aspects of the landscape represented by the DEM. The Flow Direction tool was then used to give the water flow a specific direction. To create an outlet point in the reservoir, or pour point, a point feature class was created and digitized at the lowest point on the spillway. The DEM was used to identify the lowest point. Next, the Flow Accumulation tool was employed to compute the accumulated number of cells (or area) that was draining to any particular cell, creating a grid and network of streams. The Snap to Pour Point function was then used to delineate the sub-basin of interest and to calculate the geometry of this basin in order to find the area. Next, break values were used to create a raster that had stream cells corresponding to a threshold area of 5 km². This created a calculation raster to define the location and approximate flow of streams. The Stream Link tool was then used to assign a unique number to each stream segment in the raster, and the Stream Order tool was used to create an order of flow between the stream segments as given by the numbers assigned using Stream Link. The Strahler Method was selected and using the Stream to Feature tool, the stream raster was converted to a polyline feature class. The Flow Length tool was used to compute the flow distance from each cell to the most downstream cell. Next, the Basin tool was used to identify which cells belonged to a specific basin, creating a drainage boundary for the basin. Finally, the Raster to Polygon tool was used to generate a polygon layer depicting the boundary of the basin and to calculate the geometry of the basin, producing the area of the watershed.

Reservoir DEM Development and Volume Calculations:

The volume of Katoto Reservoir was found first by digitizing the reservoir using the polygon tool to outline it and create a separate layer. Then, a grid was created and the bathymetric data (collected in Zimbabwe) was converted to data elevations (m) found using the DEM, and input. The reservoir was manually contoured every 0.5 m using the line tool, and the polygon tool was used to create a final basin based on localized streams that had not been digitally detected. The area of the reservoir was subtracted from this new layer, creating another separate layer. Next, the Topo to Raster tool was used to create a topographic map within this layer, and elevation points were added (Figure 2). The Surface Volume tool was then used to calculate the reservoir volume for each elevation (represented by the contour lines shown in Figure 2). The reservoir volume calculation was finalized at each reservoir water surface elevation (RWSE) using the Calculate Geometry function (Table 2).

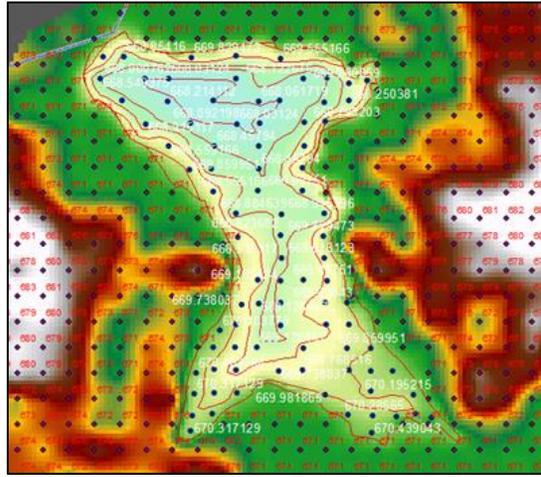


Figure 2 - A topographic representation of Katoto Reservoir (light yellow/green areas in center), with bathymetric contour lines representing RWSEs, is shown. The surrounding area (dark green/yellow/red/white) represents the topography of the final basin, with elevation points added.

Table 2 shows the reservoir volume calculated for each RWSE.

Reservoir Water Surface Elevation (m)	Reservoir Volume (m ³)
671.5	265000
671	151000
670.5	100000
670	61500
669.5	34600
669	14900
668.5	4780
668	170

Determination of Hydrologic Budget using the Water Balance Equation:

The water balance was used to determine the overland flow (OF) within Katoto Reservoir Basin (see Dunne et al 1978).

$$P = AET + OF + \Delta SM + \Delta GWS + GWR + I \quad (\text{Eqn. 1})$$

$$\text{Which implies that, } OF = P - AET - \Delta SM - \Delta GWS - GWR \quad (\text{Eqn. 2})$$

Where P = precipitation, OF = overland flow, ΔSM = soil moisture change, ΔGWS = change in groundwater storage, GWR = ground water runoff, and I = interception. All parameters were calculated in mm/year, and I was presumed to be negligible due to land cover within the semi-arid Katoto Reservoir Basin. The change in groundwater storage (ΔGWS) of $-0.009 \times 10^6 \text{ m}^3/\text{year}$ was also considered negligible (see Table 1). The parameters used in the water balance equation were compiled from literature which used remote sensing and/or field method techniques to determine the values for these parameters either from East Zimbabwe, or semi-arid climates and geographic settings similar to that

found in Katoto Reservoir Basin (Table 1). According to Shahin 2002, actual evapotranspiration (AET) values were found to be approximately equal to evaporation (E) values in semi-arid African environments. Due to a lack of available actual evapotranspiration data for East Zimbabwe, evaporation data was used, yielding the following equation:

$$OF = P - \Delta SM - \Delta GWS - GWR - E \quad (\text{Eqn. 3})$$

Sediment Yield and Reservoir Storage Estimation Methods:

The number of years the reservoir would take to silt in at each Reservoir Water Surface Elevation (RWSE) was found by dividing the total reservoir volume by the average annual sediment volume, or sediment yield (Sy). The RWSE refers to the contoured elevations within Katoto Reservoir (Figure 2), along with the corresponding volume. A range of values was used for the sediment concentration, producing a high, low, and average Sy value (Eqn. 4; Tables 4-9). The Wallingford Method (Dalu et al 2013) was used to calculate sediment yield:

$$Sy = Cs \times \frac{OF}{1000} \quad (\text{Eqn. 4})$$

Where Sy = sediment yield (t/km²year), Cs = sediment concentration (g/L) and OF = overland flow (mm/year). A range of Cs values (22.5 to 115 g/L) was applied here to confine sediment yield estimates using likely upper and lower bounds of sediment concentrations for Katoto Reservoir Basin. The range of Cs values used was taken from a case study in Sedbou, Algeria (Bisantino et al 2011), which has a similar climate to the study area in Zimbabwe.

Results

Using the GIS analysis described above, the area of Katoto Reservoir Basin was estimated to be 7.6 km². Next, the upper and lower bounds of average annual precipitation were used to confine the likely inflow of water (discharge) into Katoto Reservoir. Using Equation 3 the lower bound for annual discharge into Katoto Reservoir was estimated as follows:

The lower bound of annual runoff depth (or OF) for Katoto Reservoir Basin is:

$$OF = 615 \frac{\text{mm}}{\text{year}} - 69.6 \frac{\text{mm}}{\text{year}} - 226.5 \frac{\text{mm}}{\text{year}} - 0 \frac{\text{mm}}{\text{year}} - 14.35 \frac{\text{mm}}{\text{year}} = 305.6 \frac{\text{mm}}{\text{year}}$$

The upper bound of annual runoff depth (or OF) for Katoto Reservoir Basin is:

$$OF = 755 \frac{\text{mm}}{\text{year}} - 69.6 \frac{\text{mm}}{\text{year}} - 226.5 \frac{\text{mm}}{\text{year}} - 0 \frac{\text{mm}}{\text{year}} - 14.35 \frac{\text{mm}}{\text{year}} = 444.6 \frac{\text{mm}}{\text{year}}$$

The lower bound of the annual runoff volume for Katoto Reservoir Basin is:

$$OF = 7,600,000 \text{ m}^2 \times 0.31 \frac{\text{m}}{\text{year}} = 2,356,000 \frac{\text{m}^3}{\text{year}}$$

The upper bound of the annual runoff volume for Katoto Reservoir Basin is:

$$OF = 7,600,000 \text{ m}^2 \times 0.45 \frac{\text{m}}{\text{year}} = 3,420,000 \frac{\text{m}^3}{\text{year}}$$

Table 3 – The overland flow (OF) and annual runoff volume values calculated, in relation to the lower and upper bounds of average precipitation used in this study.

Precipitation (mm/yr)	Overland Flow (m/year)	Annual Runoff Volume (m ³)
615 (lower bound)	0.31	2356000
755 (upper bound)	0.45	3420000

Sediment Yield Calculations:

Here the sediment yield (S_y) was calculated for likely upper and lower bounds of sediment concentration in Katoto Reservoir Basin using the Wallingford Method (Eqn. 4; see Dalu et al 2013). The range of C_s values used (22.5 to 115 g/L) was taken from a study of the Sedbou, Algeria area which has a similar climate to Katoto Reservoir Basin (Bisantino et al 2011).

The sediment yield for the lower bound of annual precipitation and sediment concentration was estimated to be:

$$S_y = 22.5 \frac{\text{g}}{\text{L}} \times \frac{305.6 \text{ mm/year}}{1000} = 6.9 \text{ t/km}^2/\text{year}$$

The sediment yield for the upper bound of annual precipitation and sediment concentration was estimated to be:

$$S_y = 115 \frac{\text{g}}{\text{L}} \times \frac{444.6 \text{ mm/year}}{1000} = 53.1 \text{ t/km}^2/\text{year}$$

The lower bound for the volume of soil being delivered to Katoto Reservoir was calculated to be:

$$6.9 \text{ t / km}^2/\text{year} \times 7.6 \text{ km}^2 \times 1.6 \text{ t/m}^3 = 83.9 \text{ m}^3/\text{year}$$

The upper bound for the volume of soil being delivered to Katoto Reservoir was calculated to be:

$$53.1 \text{ t / km}^2/\text{year} \times 7.6 \text{ km}^2 \times 1.6 \text{ t/m}^3 = 645.7 \text{ m}^3/\text{year}$$

Converting the calculated S_y values above to cubic meters per year results in a possible range of sediment yield values from a low value of 83.9 m³/year to a high value of 645.7 m³/year, averaging 364.8 m³/year. Using these sediment yields and the volume of Katoto Reservoir, estimates for the rate of sedimentation were calculated. Tables 4 through 6 present the estimated rates on the infilling of Katoto Reservoir.

Table 4 - The number of years calculated for the reservoir to completely silt in for each RWSE and reservoir volume. The low bound for overland flow and sediment concentration were used.

Reservoir Water Surface Elevation (m)	Reservoir Volume (m ³)	Sediment Yield (m ³ /year)	Number of Years
671.5	265000	83.9	3158.5
671	151000	83.9	1799.8
670.5	100000	83.9	1191.9
670	61500	83.9	733
669.5	34600	83.9	412.4
669	14900	83.9	177.6
668.5	4780	83.9	57
668	170	83.9	2

Table 5 - the number of years calculated for the reservoir to completely silt in for each RWSE and reservoir volume. The upper bound for overland flow and sediment concentration were used.

Reservoir Water Surface Elevation (m)	Reservoir Volume (m ³)	Sediment Yield (m ³ /year)	Number of Years
671.5	265000	645.7	410.4
671	151000	645.7	233.9
670.5	100000	645.7	154.9
670	61500	645.7	95.2
669.5	34600	645.7	53.6
669	14900	645.7	23.1
668.5	4780	645.7	7.4
668	170	645.7	0.3

Discussion

Sedimentation is a major concern for Mutoko specifically and Zimbabwe as a whole. The rate of sedimentation for Katoto Reservoir was calculated at half meter increments from the maximum water surface elevation to nearly the maximum depth of the reservoir. Using these values, water resource managers have an estimate of the future losses in Katoto Reservoir's storage capacity. This information will allow them to better allocate the water from this reservoir and assess the need to develop new water resources to offset future water storage losses. A range of Sy values were applied here to provide managers an estimate, while accounting for possible error due to uncertainties in the amount of rainfall (mm), rainfall intensity, land use and antecedent conditions. The average values for the estimated lifespan of Katoto Reservoir reflect the annual variation in water elevation as a result of the semi-arid climate (Table 6). According to the local population, RWSE's of 669 – 671.5 m are most common, and RWSE's of 668-668.5 m do not yet occur during the dry season. In order to more accurately reflect actual water level variations in the reservoir, two average values were calculated – one including all RWSE values, and one excluding surface elevations of 668 m and 668.5 m. The second average will be used in evaluating the life-span of the reservoir unless otherwise noted.

Table 6 shows each Sy value used, along with the average number of years of useful life for the reservoir. *Due to current water level variations, plane heights 668 m and 668.5 m were disregarded in the calculation depicted in the third column.

Sediment Yield (m ³ /year)	Average Number of Years	Average Number of Years *
83.9	941.5	1245.5
645.7	122.4	161.9

Based on current climate and land use conditions Katoto Reservoir will become completely infilled with sediment within the next 160 to 940 years (Tables 4-6). As mentioned, the reservoir does not currently exhibit RWSE's of 668 m and 668.5 m, giving validity to column three (Average Number of Years*) as an approximate low value. As the reservoir silts in, resulting in a reservoir volume and area decrease, column two (Average Number of Years) will become more valid (Table 6).

From 1933 to 1993, it has been shown that national mean minimum and maximum ambient temperatures have risen by approximately +0.8 degrees Celsius. Over the next 100 years, it is predicted that the mean temperature will rise 1 degree Celsius (Waylen and Henworth 1996). This temperature increase will result in increased evaporation rates. If increased evaporation rates are not matched by an increase in precipitation rate, portions of Zimbabwe could shift from semi-arid to arid, making water management more difficult. Climate change has also been modeled based on past and current variations due to the El-Niño Southern Oscillation, the cyclic warming and cooling of the ocean surface of the central and eastern Pacific (Waylen and Henworth 1996). This modeling has indicated a potential 10% decrease in precipitation totals expected by 2090 (Unganai 1996).

Sediment yield is not simply used in the modeling of reservoir lifespans, but is also a useful indicator for assessing current land use changes, affecting current rates of erosion (Bisantino 2011). The variation in precipitation rates in semi-arid environments enhances the role of infrequent flood events (Soler et al 2007), which deposit the suspended sediment load on the banks of rivers. As a consequence, suspended sediment concentrations in semi-arid rivers remain high, resulting in problems for small reservoir water management efforts (Bisantino 2011).

Sediment yield is a useful indicator for assessing current land use changes (Bisantino 2011). Katoto Reservoir has been silting in due to its semi-arid environment, causing high suspended sediment concentrations in streams, as well as land degradation upstream from the point of deposition. Land degradation in Zimbabwe has been caused mainly by deforestation as the country continues to develop (van der Wall 1986; Mambo and Archer 2007), causing an increase in erosion rates and sedimentation in waterways throughout the nation. Land degradation and deforestation is the most widespread in communal areas, where large tracts of land are dedicated to agriculture and cattle grazing, causing soil infertility (Dalu et al 2013). Recently, due to the land resettlement program (or Zimbabwean Agrarian Reform) – in which land is distributed to Zimbabweans for agricultural purposes (Ministry of Lands and Rural Resettlement 2014) – deforestation in Zimbabwe has increased from 1.41% (1990-2000) to 16.4% (2000-2005). This increase in deforestation has resulted in enhanced soil erosion, rendering large tracts

of land virtually unusable. This threatens water capacity of reservoirs throughout the country (Mambo and Archer 2007).

Due to a predicted decrease in precipitation yields, it is necessary to further evaluate Table 4, showing a sediment yield of 83.9 m³/year. This OF value was calculated using a low annual precipitation yield estimate and, therefore, more accurately showcases predicted future circumstances. To more accurately reflect the variation in RWSE, an emphasis was put on the average values calculated (Table 6). Compared to values associated with an OF value of 645.7 m³/year, the average number of years until the reservoir becomes unusable is lower due to a decrease in precipitation and, consequently, a decrease in the reservoir's maximum capacity. Here, "unusable" refers to the point in time at which Katoto Reservoir becomes an intermittent water source, rather than a perennial water source. The range of values then changes from 160-940 years to 120-160 years (Table 6). However, taking into account other factors such as population growth resulting in increased extraction values, predicted increases in evaporation (Unganai 1996), and higher sediment yield values due to land degradation (Dalu et al 2013), the lifespan of the reservoir could fall below the estimated 120-160 years.

In addition to the data collected in this investigation, other figures used in these calculations were taken from multiple sources which represent the scale of Katoto Reservoir and its surrounding climate. This potential source of error adds to the uncertainty of the calculated estimates concerning the projected useful life of the reservoir. It is also important to note that current evapotranspiration rates were not accounted for in the methods selected. Future trends, such as an increase in temperature and evaporation rate (Waylen and Henworth 1996), population growth resulting in increased extraction values, and higher sediment yield values (Dalu et al 2013), were also not considered. These will have a significant effect on the useful lifespan of the reservoir. As future investigations are conducted and additional hydrologic measurements in and around the reservoir are collected, less reliance on general information sources will occur and the reliability of future calculations will improve.

Katoto Reservoir is considered a multiple-use small reservoir, and is currently used for laundry, bathing, drinking water (for residents and cattle), agricultural irrigation, and the watering of small local gardens. Other sources of water in the area include local streams during the rainy season, wells, and alluvial aquifers during the dry season. Of the few wells that are available, one is briny and, therefore, unusable. These limited water sources are a buffer during the dry season. Though the community is vaguely aware of the reservoir's limitations, management efforts are hindered by inadequate knowledge of actual water consumption from the reservoir; future rainfall, temperature, and evaporation predictions; and the effect of an increasing population, on the volume of the reservoir throughout the year. As a short-term solution, raising the height of the spillway could increase the capacity of the reservoir. In the future, the harvesting of rainwater during the rainy season should be evaluated as a viable supplemental water source, as well as the more communal use of alluvial aquifers of non-perennial rivers (Hamer et al 2008).

Future studies in this area should include an investigation of the factors controlling groundwater flow in the sandy beds of ephemeral streams, as well as further analysis regarding the intake and outflow of the reservoir. Additionally, rather than only focusing on hydrologic factors, Mutoko's

reservoir extraction outtake should also be studied and adjusted according to positive population trends (therefore increasing the community's outtake). The relatively small size of this reservoir increases the impact that these non-hydrologic factors have on the volume of water present at any given time and, therefore, on the lifespan of the reservoir.

Conclusions

The human modification of local and global hydrologic cycles continues to expand the serious issue of water scarcity. Increases in the human populations of developing countries, land degradation, and soil erosion result in ever increasing demands on the water resources in these areas. Due to the reliance on small, multiple-use reservoirs as a primary water source by residents in rural Zimbabwe, it is imperative to develop further insights into, and a greater understanding of the linkage between hydrology, land use, and water resource needs in order to develop resilient water supplies in these areas. Here, a hydrologic and sediment budget was developed to inform the management of the 265,000 m³ (215 acre feet) Katoto Reservoir located near Mutoko, Zimbabwe (155 km northeast of Harare, Zimbabwe).

Assuming present hydrologic and land use conditions remain the same, the entire reservoir may be completely infilled with sediment within 160-940 years (Table 6). However, taking into account a potential 10% decrease in precipitation totals expected by 2090 (Unganai 1996), Katoto Reservoir could become unusable within 120-160 years (Table 6). Considering other factors such as population growth resulting in increased extraction values, increased evaporation due to climate change (Unganai 1996), and higher sediment yield values due to shifting land use (Dalu et al 2013), the lifespan of Katoto Reservoir could potentially be reduced to far below the estimated lifespan of 120-160 years.

Although this is a simplistic estimation, it may be used as a baseline for future water management efforts in the area. With a potential lifespan of less than 120 years, Katoto Reservoir must be managed in order to be able to sustain the livelihoods of the thousands of residents who use it. Raising the height of the spillway, taking advantage of alluvial aquifers, and developing methods of harvesting rainwater during the rainy season are a few actions that may be taken to lengthen the lifespan of the area's main water resource. More research must be completed in order to determine the reservoir's absolute lifespan, and design a water management plan accordingly. Additionally, an increase in the education of local villagers concerning the monitoring and tracking of real time data (e.g. precipitation totals, population growth, etc.) would improve the accuracy of information needed for future studies.

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