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ORIGINAL ARTICLE

Modeling sedimentation rates of Malilangwe reservoir in the south-eastern lowveld of Zimbabwe

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Abstract Modelling the sedimentation rates using the Wallingford (2004) equations with the aid of NDVI (remote sensing) to assess land degradation was carried out for Malilangwe reservoir catchment in the south eastern lowveld of Zimbabwe. Siltation life of the reservoir was determined from rate of incoming sediment, trap efficiency and reservoir capacity using the Wallingford method. The average rainfall of the study area was about 560 mm while runoff from the catchment ranged from 0.3 mm (minimum) to 199 mm (maximum) with an overall average runoff of 50.03 mm. Results showed that the overall mean annual sediment concentration was approximately 2,400 ppm. The reservoir capacity to inflow ratio was estimated at 0.8 with a sedimentation rate of 120.1 tkm^{-2} year^{-1}. Calculated probability of the dam filling is 26.8 %. Results also showed that the siltation life of the reservoir was >100 years according to the Wallingford method. The Normalised Difference Vegetation Index (NDVI) showed progressive decline ($p < 0.05$) of the vegetation health from 2000 to 2009. While acknowledging the limitations of techniques used, this study demonstrates in part the effectiveness of sedimentation modelling and remote sensing as a tool for the production of baseline data for assessment and monitoring levels of land degradation in the Malilangwe reservoir catchment.

Keywords Sedimentation · NDVI · Catchment · Reservoir · Degradation

Introduction

In Zimbabwe, sediment load has exceeded normal design limits in many reservoirs, thus reducing storage capacity and shortening their useful life for human benefit. According to van der Wall (1986) and Mambo and Archer (2007), Africa now stands for rapid land degradation, declining fertility, soil erosion and drought. Sedimentation of reservoirs, in the light of man accelerated erosion, is according to the Zimbabwean Government a major time bomb (van der Wall 1986; Mambo and Archer 2007). Within the framework of the development of a National Master Water Plan for Zimbabwe, a reconnaissance study in siltation and soil erosion was carried out in May 1984–January 1985 (van der Wall 1986). It has been reported that over 50 % of 132 small dams surveyed in Masvingo Province in Zimbabwe by Elwell in 1985 were silted (Khan et al. 2007).

Land use change is listed as the biggest threat to global biodiversity largely due to deforestation activities (Enters 1998). Land degradation in Zimbabwe has been caused mainly by the decline of forest areas through cutting down of trees for agriculture and fuel (van der Wall 1986; Mambo and Archer 2007). The widespread impacts of deforestation are also reflected at a national and regional level through vastly elevated soil erosion rates, sedimentation of major waterways and an increased frequency and severity of floods (Adger 1992; Ewers 2006). Of the major

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causes of soil degradation, deforestation and removal of natural vegetation account for 43 % with overgrazing, improper agricultural practices and over-exploitation of natural vegetation contributing 29, 24, and 4 %, respectively (Enters 1998). Land degradation is the most widespread and severe in communal areas which are characterized by deforested landscapes, poor quality pasture and soil infertility. The recent land resettlement programme that started in 2000 has left most of the country forests facing serious threat of deforestation increasing from 1.41 % (1990–2000) to 16.4 % (2000–2005). Degradation mostly manifests as gullies that render large tracts of land virtually unusable, threatening water supply and quality (Mambo and Archer 2007).

Recent ecological studies have highlighted the relevance of the Normalized Difference Vegetation Index (NDVI) as a tool for assessing changes in vegetation cover (Pettorelli et al. 2005). Land degradation is believed to be one of the most severe and widespread environmental problems in Zimbabwe and globally. It is, therefore, important to understand spatial and temporal distributions of vegetation in a region in order to assess changes in land cover. Remotely sensed NDVI may provide the basis for an early warning of land degradation (Scanlon et al. 2002; Wessels et al. 2004). However, the method is not without limitations and mis-registration of spectral images may lead to a considerable number of errors and unusable results (Lu et al. 2003). The calculation of NDVI values is influenced by a number of factors such as clouds, atmospheric, soil, anisotropic and spectral effects (Crippen 1990; Wessels et al. 2004). Modified indices such as Soil Adjusted Vegetation Index (SAVI) and Global Environment Monitoring Index (GEMI) have been developed indices to correct for some of the confounding factors that affect NDVI (Wessels et al. 2004). Despite its limitations, NDVI remains a valuable quantitative vegetation monitoring tool.

NDVI as a proxy for monitoring land degradation

Changes in vegetation features of terrestrial landscapes have long been used as indicators for susceptibility to degradation (Lambin and Ehrlich 1996; Mambo and Archer 2007). Vegetation cover is the commonly indicator in assessing susceptibility to degradation. Tucker et al. (1991) highlighted that vegetation cover is not a good indicator in long-term dynamics of land degradation in arid and semi-arid areas. Recent advances in remote sensing technologies have seen increased use of different spectral indices. One of the widely exploited spectral indices is the Normalised Difference Vegetation Index (NDVI) which measures “greenness” (chlorophyll content). The NDVI is a measurement of the balance between energy received and energy emitted by vegetation (Meneses-Tavor 2011). It has been observed that NDVI increases near-linearly with increasing leaf area index and then enters an asymptotic phase in which NDVI increases very slowly with increasing leaf area index (Roderick et al. 1996; Wessels et al. 2004; Jiang et al. 2006). The NDVI equation produces values in the range of -1 to $+1$. Higher values (0.8–0.9) are indicators of high photosynthetic activity linked to scrub land, temperate forest, rain forest and agricultural activity while values closer to zero means no vegetation (Crippen 1990; Weier and Herring 2000). Values in the range of -0.2 to 0.05 are indicative of snow, inland water bodies, deserts and exposed soils (Crippen 1990; Roderick et al. 1996; White et al. 1997; Bacour et al. 2006).

The use of NDVI as an indicator of degradation is based on the premise that NDVI values reflect the level of photosynthetic activity in a plant community which in turn indicate vegetation health (Barrow 1991; Mambo and Archer 2007; Meneses-Tavor 2011). Therefore, degradation of ecosystem vegetation, or a decrease in green, would be reflected in a decrease in NDVI values. The NDVI is also correlated with certain biophysical properties of the vegetation canopy, such as leaf area index, fractional vegetation cover, vegetation condition, and biomass (Meneses-Tavor 2011).

Impacts of sedimentation

The effect of sedimentation in a dam is that it reduces the dam’s water holding capacity, with decline in capacity; the yield is reduced both in quantity and reliability. The relationships between reservoir yields under certain risk levels, storage ratios and the reliability of inflow, have been well established for Zimbabwe by Mitchell (1987). The deposition of eroded soil sediments in water bodies from either natural or anthropogenic impacts can result in the destruction of aquatic habitats and a reduction in the diversity and abundance of aquatic life. Diversity and population size of fish species such as *Labeo altivelis* and benthic macroinvertebrates associated with coarse substrates can be greatly reduced if the substrates are covered with sand and silt. Tomasson and Allanson (1983) showed that the growth rates of *Barbus* and *Labeo* sp. in Lake Le Roux, South Africa were greatly reduced when transparency of the water decreased due to increased sediment input in the lake. Moreover, increased turbidity decreases the water’s aesthetic appeal, human enjoyment of lake and reservoir recreational activities and interferes with disinfection of the water prior to it being pumped to the end-users. If the river cross-section is sufficiently reduced by sediment build-up, sedimentation can increase downstream flooding. In addition, some metal ions, pesticides and nutrients may combine with sediment particles and be transported downstream.

Information on upstream land use activities and land cover change, sediment yield within a catchment is required for controlling sediment accumulation in reservoirs. Presently, there have been very few studies in Zimbabwe that have looked at the problem of reservoir siltation (ZINWA 2004). Therefore, there is not much data available to establish the correlation between changes in land use and land cover with sedimentation rates in reservoirs. If this is not addressed, sediment loads could exceed normal design parameters in some reservoirs, thus reducing storage capacity and a shortened useful lifespan. The main objective of this research was to assess changes in land use and model the impacts it would have on sedimentation rates in a small reservoir.

Study area

Malilangwe Wildlife Reserve is located in the Chiredzi District of the south-eastern lowveld of Zimbabwe (20°58′21°02′S, 31°47′32°01′E) (Fig. 1). Malilangwe reservoir is an impounded reservoir formed in 1964 and is used for water supply in the reserve. It is situated on the Nyamasikana River, a tributary of the Chiredzi River which in turn flows into the Runde River. It is a gravity section masonry dam with a surface area of 211 hectares and has a maximum volume of 1.2×10^7 m^3 at full capacity, as well as a catchment of about 200 km^2. The dam wall was initially built to a height of 10 m in 1963 and the dam was filled for the first time in 1965. In 1965, the dam wall was raised to a height of 19–22 m in 1984, and finally to a height of 24 m in 1988. The dam wall was raised by an additional 1.75 m in 1999 and has a current height of 25.75 m. Malilangwe reservoir last spilled in hot–wet season of 2000 after the Cyclone Eline induced floods in 2000.

Methods

Remote sensing

Normalised Difference Vegetation Index images from different years were captured during the dry season (September) and wet season (March) of the following years: 2000, 2002, 2005, 2007 and 2009. The images were captured at the same time of the year in order to minimise

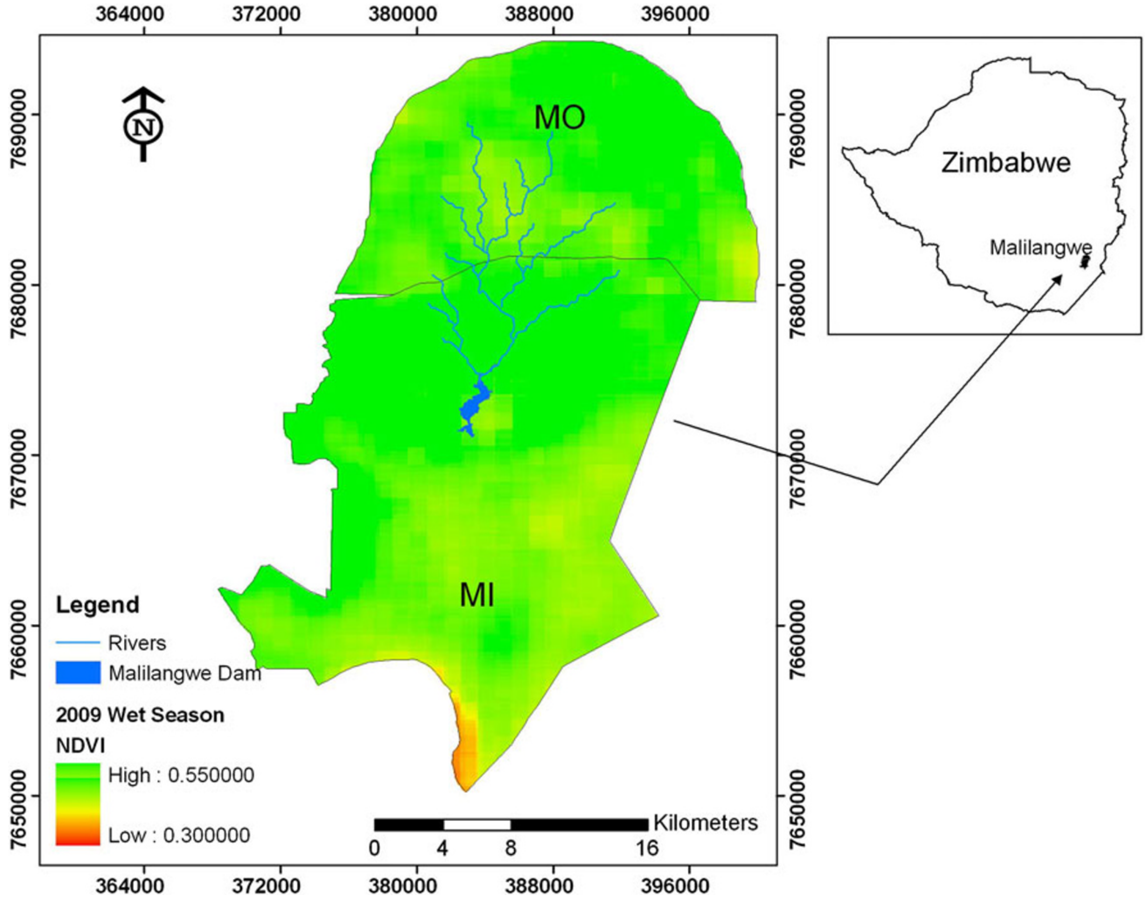

Fig. 1 Location of Malilangwe reservoir (*shaded black area*) and major water supplying rivers in the catchment (MC)

the expression of variations in such factors as light quality, geometry of the observation and variances in the state of a community over the course of a year (Mambo and Archer 2007). Images were downloaded from the United States Geological Survey (USGS), Global Visualisation Viewer (GloVis, website: www.glovis.usgs.gov). The images were processed using the Integrated Land and Water Information System (ILWIS) Version 3.3 GIS software which employed the map value function to extract NDVI values from the sample locations. Sampling points were randomly selected in the catchment area and in the reference sites with the aid of ArcView GIS 3.2a software. The points demarcated the positions of sites whose NDVI values were used for analysis. Coordinates (UTM) of each point were recorded.

NDVI expressed as a ratio between measured reflexivity in the red and the infra-red bands was calculated as:

$$\mathrm{NDVI} = (\mathrm{NIR} - \mathrm{R}) / (\mathrm{NIR} + \mathrm{R}),$$

where NIR (in TM imagery) is near infra-red band 4; and R is red band 3 (N.B. living vegetation absorbs light in the frequency range of band 3 but shows almost no absorption in the range of band 4).

The NDVI data were first tested normally using the One-Sample Kolmogorov–Smirnov test. Since the data were normally distributed, a two-way ANOVA was carried out to test for differences in NDVI values. A Spectral Time Series analysis on SPSS 16.0 (SPSS 2007) was carried out on the NDVI data to find out whether there were any significant changes in vegetation for Malilangwe Wildlife Reserve (reference) and catchment. A two-way ANOVA was also carried out on the data set using the MYSTAT ver. 12 (Systat 2007).

In this study, Malilangwe Wildlife Reserve was used as the reference site which represents a natural functional ecosystem (Fig. 1). Reference sites are supposed to occur in similar biotic zones, in close proximity with the study site, and exposed to similar natural disturbances (Society for Ecological Restoration 2004).

Estimation of sedimentation rates

Mathematical equations from studies by van der Wall (1986), Wallingford (2004), Khan et al. (2007) and Mavima et al. (2010) were used in the estimation of sediment rates and the following procedure using several models was followed;

Gross mean annual reservoir inflow (MAI) (m^3 year^{-1}) was calculated by:

$$\mathrm{MAI} = \mathrm{CA} \times \mathrm{MAR}, \tag{1}$$

where CA is the catchment area (km^2), MAR the mean annual runoff (mm).

Annual runoff volume (ARV) (m^3) was calculated by:

$$\mathrm{ARV} = P_\mathrm{a} \times \mathrm{CA} \times 1{,}000, \tag{2}$$

where P_a is the annual precipitation (mm), CA the catchment area (km^2).

Sediment trap efficiency (S_t) as a percentage (the trap efficiency is generally assumed to be 100 % for most reservoirs were the gross storage ratio >0.1) was calculated by:

$$S_t = \left(0.1 + 9 \times \mathrm{SR_g}\right) \times 100 \text{ or } S_t = 0.1116 \times \mathrm{In}(C/I), \tag{3}$$

where C is the reservoir capacity at spillway crest level, I the inflow volume of water to the reservoir and the relationship predicts the annual sediment trapping efficiency of a dam from the ratio of the dam capacity to the annual inflow volume, $\mathrm{SR_g}$ the gross storage ratio.

Sediment concentration was calculated according to Wallingford (2004) method, since catchment characterisation was not carried out. Wallingford studies were carried out in the same region, the lowveld as Malilangwe Reservoir, and the mean annual sedimentation concentration was estimated for reservoir as highlighted below based on observation data. The method uses the description which best fitted the catchment and the Malilangwe catchment fell between two descriptions; basin with low slopes and very well-developed conservation (1,200 ppm) and basin with moderate topography and well-developed conservation (3,600 ppm). The sediment concentrations were then averaged to give the mean annual sediment concentration of 2,400 ppm (2,400 mg l^{-1}) for the catchment.

The predictive equation adopted from Wallingford (2004) and Khan et al. (2007) was used for estimation of sediment yield for the catchment of the Malilangwe reservoir with the mean annual S_y then calculated using the formula:

$$S_\mathrm{y} = X\,(\mathrm{MAR} / 1000), \tag{4}$$

where S_y is the mean annual sediment yield (tkm^{-2} year^{-1}), X the sediment concentration/density, and MAR the mean annual runoff (mm).

We used the Ministry of Lands and Water of Zimbabwe (MoLWZ) (1984) methods; to correlate the coefficient of variation (CV) of mean annual runoff with MAR, we used a fitted relationship:

$$\mathrm{CV} = (0.00139\ \mathrm{MAR})^2 - 0.7538\ \mathrm{MAR} + 154.5\ \left(R^2 = 0.87\right), \tag{5}$$

where CV is the coefficient of variance (%), MAR the mean annual runoff (mm).

The probability of a dam filling can be estimated from the coefficient of variation of annual runoff and the dam capacity to annual inflow ratio, using a procedure developed for dams in Zimbabwe described in Mitchell (1987). Mitchell argues that given the relatively short records and other deficiencies in the available data, the use of complex statistical functions is not justified, and that the Wiebul distribution can be used to represent the distribution of annual inflows to a dam:

$$P = e^{-\mathrm{km}}, \tag{6}$$

where P is the probability of a dam filling from empty, km the $(c \times V/I)^n$, V the Dam storage volume (m^3), I the annual inflow (m^3), c the constant related to CV (taken as 1.11), n the constant related to CV (taken as 0.84).

A Pearson correlation between sedimentation parameters (rainfall, runoff, sedimentation yield, Malilangwe catchment NDVI and Wildlife Reserve NDVI) was carried out using MYSTAT ver. 12 (Systat 2007) to test if year and season had an influence on parameters.

Storage capacity losses due to siltation

The proportion of the incoming sediment load that is trapped in a dam varies with the sizes of the sediments transported to the dam, the water velocities or retention time in the dam, and the proportion of the incoming flows that is passed over the spillway. The interrelationship between these parameters is too complex to be considered in the design of small dams (Wallingford 2004). Trap efficiency was assumed to remain constant at 100 % as Murwira et al. (2009) projected decreases in precipitation and runoff for the lowveld region. The loss in a dam's storage capacity over a specified time period is estimated using equation:

$$C_n = 1 - \left[n \times S_{\mathrm{y}} \times \mathrm{CA} \times S_{\mathrm{t}}/(C \times \mathrm{Den})\right], \tag{7}$$

where C_n is the proportion of original storage capacity left after n years of siltation, n the number of years, S_{y} the

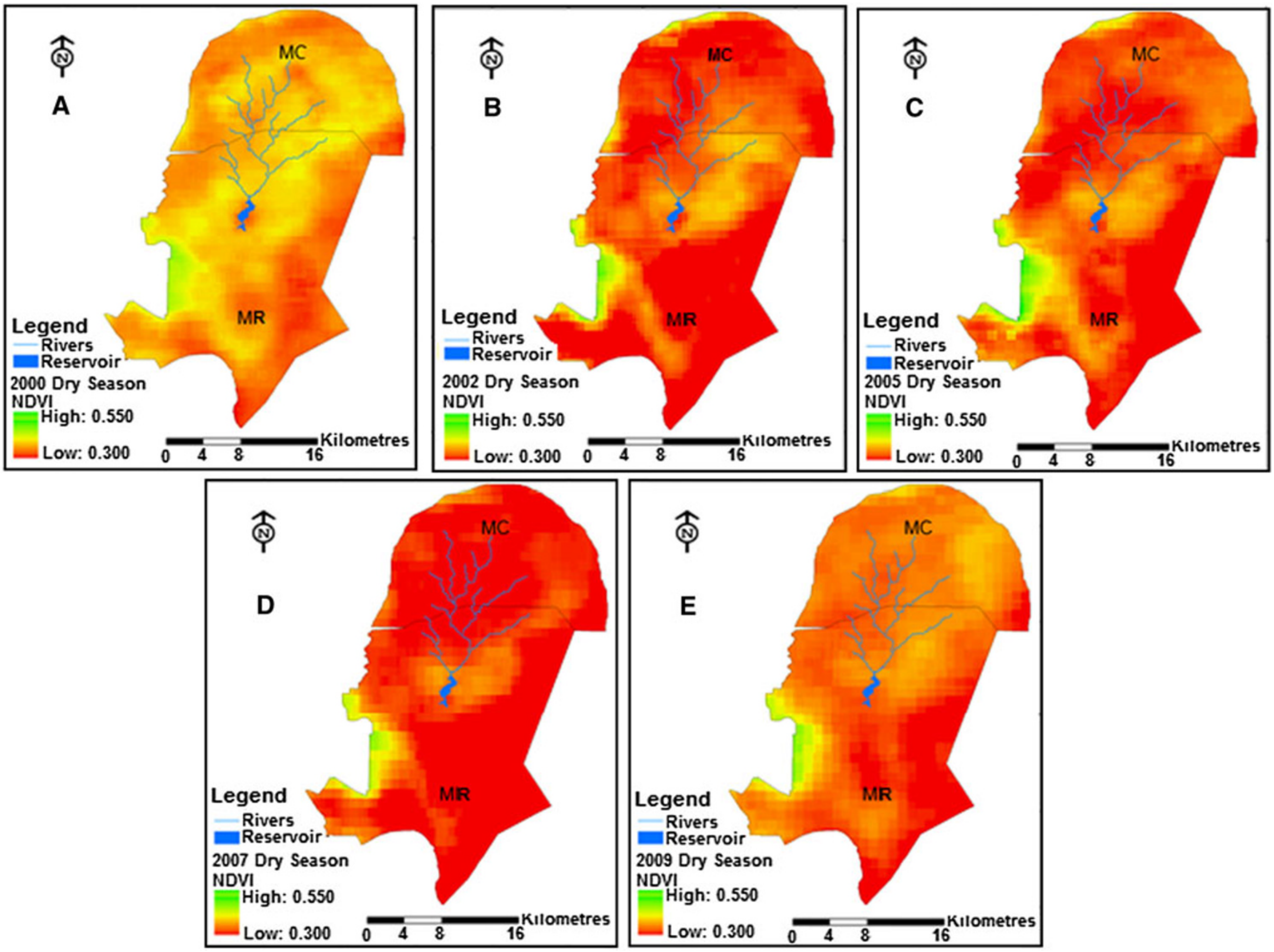

Fig. 2 Colour composite Landsat satellite images covering Malilangwe study area in the dry season for **A** 2000, **B** 2002, **C** 2005, **D** 2007 and **E** 2009 overlaid with degraded areas mapped by National Land Cover (NLC). Map units are in kilometres, Universal Transverse Mercator (UTM) zone 36 South based on WGS 1984 spheroid

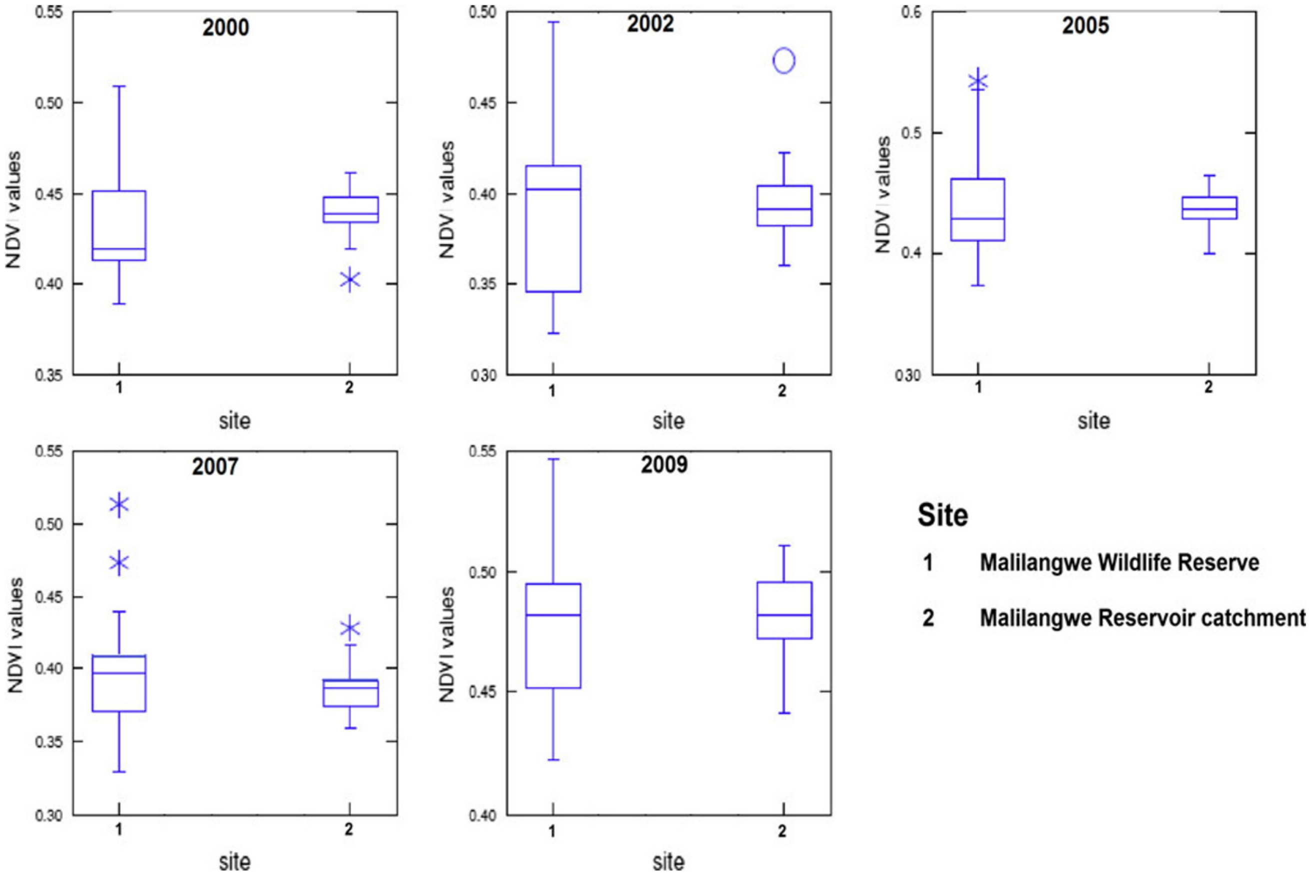

Fig. 3 Boxplots of NDVI values for Malilangwe catchment and Malilangwe Wildlife Reserve (2000, 2002, 2005, 2007 and 2009)

catchment sediment yield (tkm^{-2} year^{-1}), CA the catchment area (km^2), S_t the sediment trap efficiency, C the dam's original capacity at full supply level (m^3), and Den the settled density of dam sediment deposits (taken as 1.2 tm^{-3}).

Results

NDVI analysis

Geographical Information Systems (GIS-NDVI) images were used for monitoring vegetation changes in the Malilangwe catchment (MC). Figures 2, 3 and 4 show vegetation change in the catchment and Malilangwe Wildlife Reserve (MR) from 2000 to 2009. The catchment showed progressive decline in NDVI values as shown by the decrease in cover especially along the Malilangwe Wildlife Reserve boundary meaning that vegetation was being cleared or greenness of plants was decreasing. The catchment showed a more extensive decrease in vegetation cover than the reserve in areas along major rivers supplying Malilangwe reserve. From the NDVI images and values, all sites in the wildlife reserve and the catchment between the years 2000 and 2009 consisted of sparse vegetation as a range of 0.1–0.5 represent sparse vegetation and >0.6 represent dense vegetation. In 2002 and 2007 vegetation had decreased in both the reserve and catchment as seen by low NDVI values (Figs. 2, 3, 4). In 2009, the catchment and reserve were still covered by sparse vegetation except for the southern tip of the reserve which had little patches of vegetation (Figs. 2, 3, 4).

The ranges of NDVI values are shown in Figs. 2 and 5. Mean NDVI values were generally higher for the catchment compared to the wildlife reserve. Mean NDVI values for Malilangwe Wildlife Reserve (MR) for 2000 were 0.4322, indicating that healthy vegetation mainly consisting of woodland as 2000 was a cyclone year. The other different colour tones identified, with lower NDVI values (from 0.3229 to 0.3973) indicate high moisture, given the low NDVI reflectance of moisture and also given the similarity of the tones to water bodies. These areas were characterized by open savanna grasslands. There was a decrease in 2002 (NDVI = 0.3229) and 2005 (NDVI = 0.3729) and 2007 (NDVI = 0.3973) before increasing in 2009 (NDVI = 0.4411) (Fig. 5). Tones indicating moisture patterns, as identified in 2002, 2005 and 2007, have completely disappeared in 2009. Overall mean NDVI value

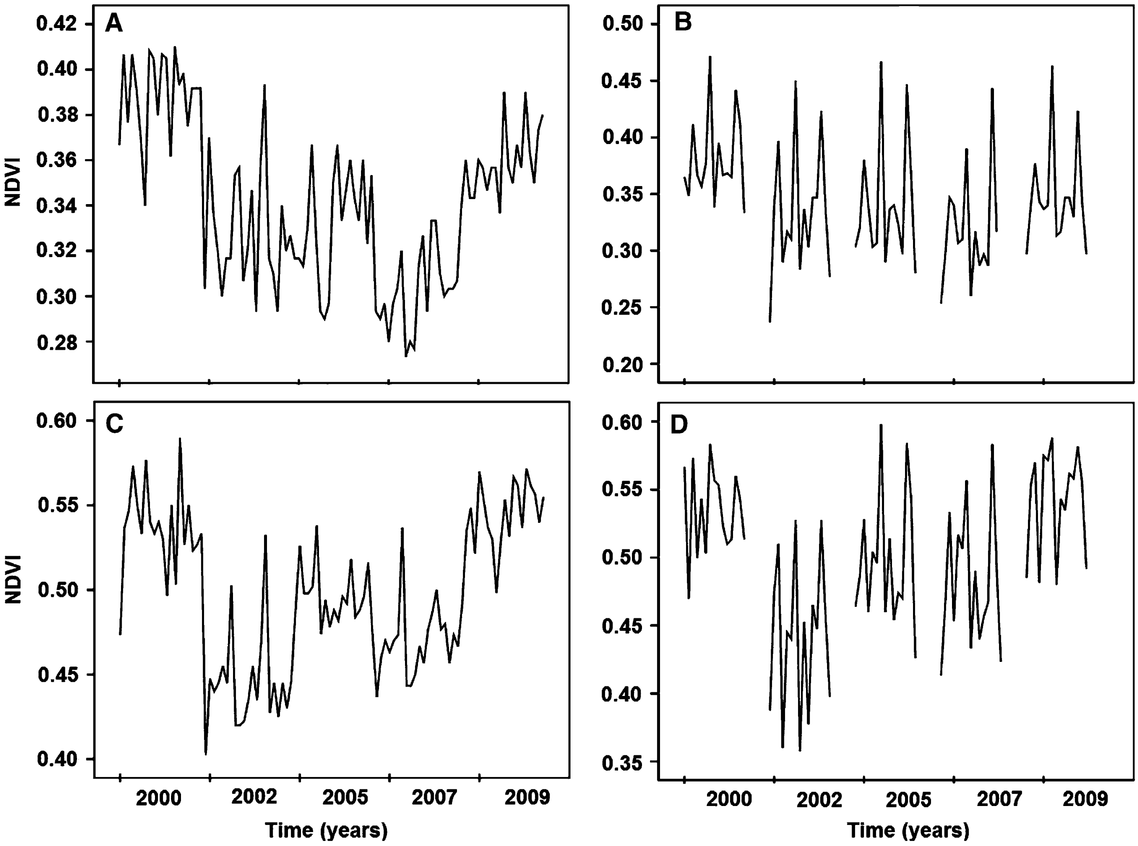

Fig. 4 Spectral time series analysis for the dry (**A, B**) and wet (**C, D**) season for the Malilangwe catchment (**A, C**) and Wildlife Reserve (**B, D**)

change for the wildlife reserve from 2000 to 2009 was 0.045. NDVI values decreased from the year 2000 up to 2007 for the catchment compared to the wildlife reserve. For the Malilangwe catchment (MC), mean NDVI values showed a generally declining trend although they fluctuated between the years. In 2000, mean NDVI was 0.4381; 2002 (NDVI = 0.3950); 2005 (NDVI = 0.4354) and 2007 (NDVI = 0.3855). The general reduction in NDVI values indicated a possible reduction in healthy vegetation across the catchment, but the area to the north of the catchment falling under woodland class shows high NDVI values. Similar to the wildlife reserve, there was an increase in NDVI values in 2009 (NDVI = 0.4812) (Figs. 2, 5). The overall mean NDVI value change for the catchment from 2000 to 2009 was 0.043.

The available NDVI data were not enough for a comprehensive time series analysis to be carried out on the data. It was necessary to identify if there had been any significant changes in vegetation cover over the years and also if there were any differences in terms of NDVI between the catchment and reference sites. ANOVA revealed significant differences between the years and sites ($p < 0.05$). However, for the years the trend implied by these differences could not be established. Two-way ANOVA test showed a significant ($p < 0.05$) effect of seasons on NDVI years with the interaction effect also present (Table 1). This showed higher NDVI values within the wet season, and the significant ($p < 0.05$) interaction also showed higher NDVI values in wet season than dry season (Fig. 6).

Sedimentation rates and reservoir capacity–inflow ratios

The sedimentation rates, capacity inflow ratios are presented in Table 2. The reservoir capacity or volume was 1.2×10^7 m^3 and inflows were determined from the long-term data collected over a 60-year period. The reservoir capacity to inflow ratio was estimated at 0.8. The calculated gross storage ratio was 4 for the reservoir, and the sediment trap efficiency was assumed to be 100 % as the reservoir has no outlet for water. The catchment sediment yield was estimated at 120.1 tkm^{-2} $year^{-1}$ with a mean annual sediment concentration of 2,400 ppm (Table 2). Using the relationship developed by Mugabe et al. (2007), the Malilangwe catchment area is about 200 km^2 and with mean annual rainfall of 562 mm, runoff was calculated at 50 mm and the coefficient of variance of mean annual runoff was 120.3 %. The runoff coefficient for the catchment was calculated as 0.1 (Table 2). The probability of the dam filling with water was calculated at 26.8 %.

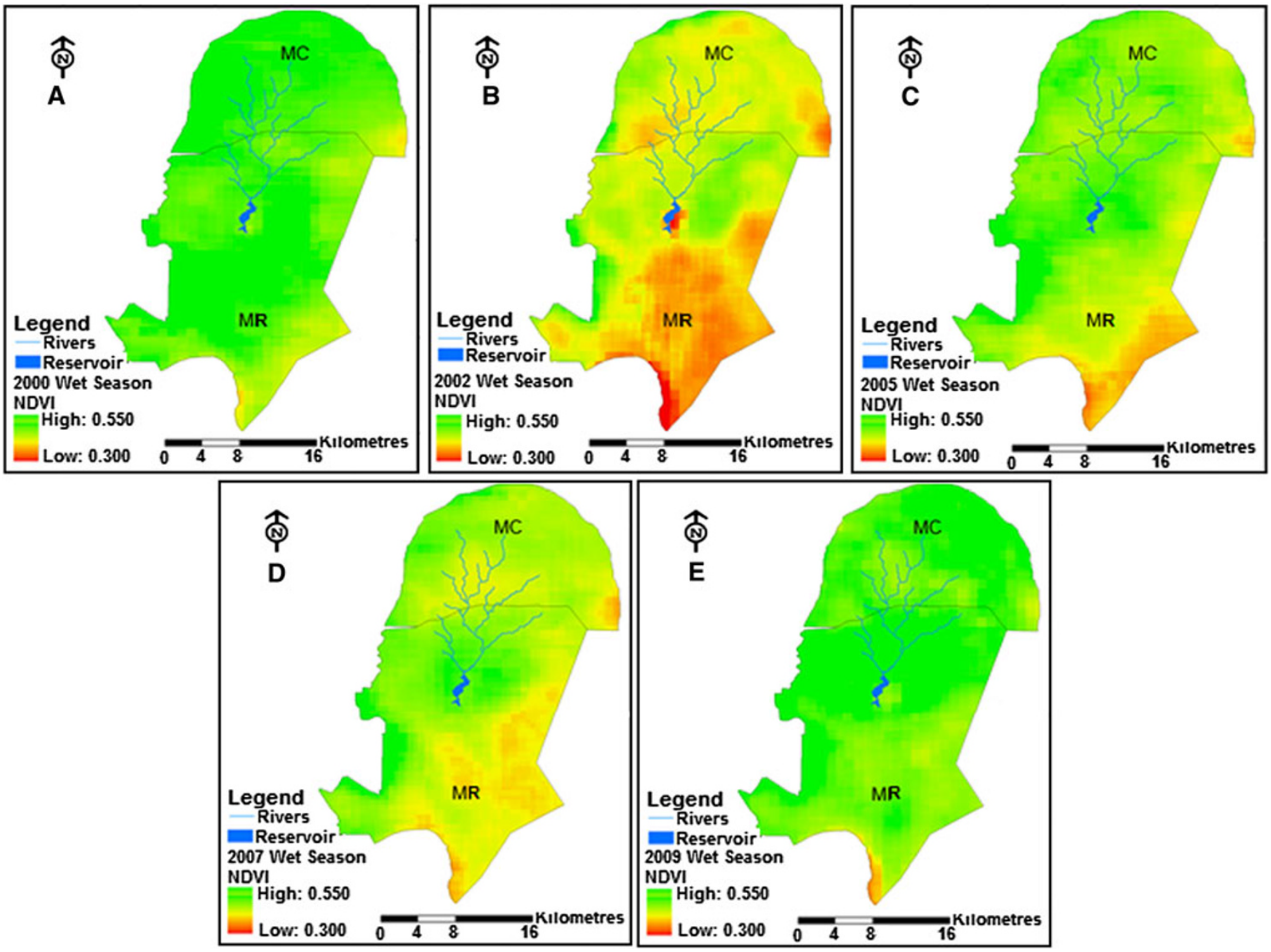

Fig. 5 Colour composite Landsat satellite images covering Malilangwe study area in the wet season for (**A**) 2000, (**B**) 2002, (**C**) 2005, (**D**) 2007 and (**E**) 2009 overlaid with degraded areas mapped by National Land Cover (NLC). Map units are in kilometres, Universal Transverse Mercator (UTM) zone 36 South based on WGS 1984 spheroid

Table 1 Two-way ANOVA test on the effect of seasons and years on NDVI values

Treatment	*df*	*F* value	*p* value
Year	4	57.14	0.00
Season	1	1643.99	0.00
Site	1	0.33	0.57
Year × season	4	10.49	0.00
Year × site	4	1.06	0.38
Season × site	1	0.00	0.98
Year × Season × site	4	0.21	0.93

Predicted capacity storage losses for the Malilangwe reservoir calculated using the Wallingford (2004) method is shown in Table 3. It is predicted that the dam will lose 16 % of its storage capacity over 100 years at current levels of sedimentation (120.1 tkm^{-2} year^{-1}). The reduction in water yield over the same period is expected to be larger than 16 %. It is also projected that 32 % of the storage capacity will be lost over a 100-year period with double the sedimentation (Table 3).

A Pearson correlation of sedimentation parameters with season and year showed that season and year was significantly correlated with rainfall, runoff, sedimentation yield, catchment and Wildlife Reserve NDVI. Thus, season and year was significantly negatively correlated with rainfall ($r = -0.754$), runoff ($r = -0.754$), sedimentation yield ($r = -0.754$), catchment ($r = -0.917$) and Wildlife Reserve NDVI ($r = -0.933$).

Discussion

Remote sensing was used to assess changes in vegetation cover in the study area in a period covering almost a decade. The interpretation of the NDVI data pointed

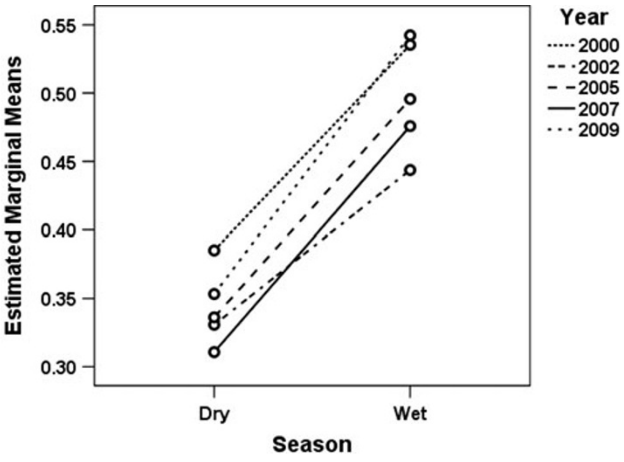

Fig. 6 Interaction plot showing the effect of seasons and year on NDVI values

Table 2 Results of sedimentation rates for Malilangwe reservoir

Reservoir volume	m^3	1.2×10^7
Annual runoff volume	m^3	1×10^7
Mean annual runoff (MAR)	mm	50.0
Sediment trap efficiency	%	100.0
Runoff coefficient		0.1
Mean annual sediment concentration	ppm	2400
Catchment sediment yield	tkm^{-2} year^{-1}	120.1
Probability of the dam filling	%	26.8
Coefficient of variance of MAR	%	120.3
Capacity–inflow ratio		0.8

Table 3 Projected capacity storage losses (%) for Malilangwe reservoir for 0, 10, 25, 50, 80 and 100 years for different sediment yield rates

Years	Sedimentation storage loss of reservoir in percentage				
	120.1	150.1	180.1	210.1	240.2
0	0	0	0	0	0
10	1.6	2	2.4	2.8	3.2
25	4	5	6	7	8
50	8	10	12	14	16
80	12.8	16	19.2	22.4	25.6
100	16	20	24	28	32

Sedimentation rate increases 120.1 tkm^{-2} year^{-1}—0 %, 150.1 tkm^{-2} year^{-1}—25 %, 180.1 tkm^{-2} year^{-1}—50 %, 210.1 tkm^{-2} year^{-1}—75 % and 240.2 tkm^{-2} year^{-1}—100 %

toward a progressive decline in vegetation cover in the Malilangwe catchment particularly in areas close to the reserve boundary. We employed NDVI values as a surrogate for the assessment of vegetation (deforestation) change rates in the catchment. Vegetation change thus showed a general decline in the catchment for the period 2000–2009 with a mean yearly change of 0.043 NDVI values whilst the wildlife reserve showed a slight increase in NDVI values of relatively 0.045 NDVI units. The mean NDVI value, observed in 2002 and 2007, decrease in both the wildlife reserve and the catchment could be attributed to the severe droughts in those years that significantly reduced vegetation cover. In contrast, NDVI increases observed in 2005 and in 2009 in both the wildlife reserve and the catchment) could be attributed to good rainfall during the 2 years. Therefore, climatic factors have an important role in determining vegetation patterns. This variable is of great concern as this can be linked to protected climatic changes for the region where dry areas are expected to get less and less rainfall.

The use of statistical tools to analyse NDVI values for the 2000–2009 period, identified a large vegetation change in the catchment closer to the boundary with the communal areas. The catchment vegetation is facing serious anthropogenic impacts such as deforestation, veld fires and vegetation clearing for farmland and firewood which change the vegetation structure resulting in it being different from that of the wildlife reserve. There was a significant difference found between catchment and wildlife reserve with the latter having higher vegetation cover. It is evident that the catchment is slowly being degraded from the spectral time series analysis ($p < 0.05$) of 2000–2009, though influenced by stochastic setbacks such as cyclone, drought and human-induced anthropogenic events which are resulting in runoff and soil erosion changes in the catchment. Deforestation had a significant effect on the runoff and sediment discharge from Malilangwe catchment because it brought about a number of interferences such as increased surface runoff in streams and rivers and soil erosion which resulted in sedimentation of rivers and the reservoir as shown by significant correlations as suggested also by Dinor et al. (2007). The study also showed a strong relationship between sedimentation parameters as highlighted by Murwira et al. (2009) that found a strong positive and significant correlation between rainfall and runoff in the Save mega-basin. They noted that an increase in rainfall has a simultaneous increase in runoff and the inverse is also true and they also found a decreasing but not significant trend in the rainfall and runoff over the years. A deficit of over 5×10^4 mega litres of water in certain subcatchments of the Save basin was projected given the worst case scenario of decreased rainfall that was observed (Murwira et al. 2009).

In Ivory Coast, deforestation increased surface runoff and sediment yield by 50–1,000 times compared to the forested areas. Similar effects of deforestation have been reported from East Africa, Kenya where sediment yield from agricultural and grazed catchments was significantly more than from partially or forested catchments. Li et al. (2007)

found that deforestation increased both surface and subsurface runoff by about 20 % because some of the water that was formerly intercepted by vegetation and evaporated became overland flow. They also observed that about 80 % of the increase was due to an increase in subsurface drainage of soil moisture that would have been transpired by plants in the control experiment.

Field studies should be carried out to determine the actual amounts of sediments in the catchment and reservoir so as to provide the actual rate of sedimentation related to land use change in the catchment. While acknowledging the limitations of the techniques applied, this study demonstrates in part the effectiveness of remote sensing as a tool for the production of baseline data for assessment and monitoring of land degradation in the Malilangwe catchment. Field studies measuring sedimentation and erosion rates must also be carried out to aid remote sensing data.

The annual catchment sediment yield for Malilangwe reservoir was calculated at 120.1 tkm^{-2} year^{-1}. The value of sediment yield (120.1 tkm^{-2} year^{-1}) obtained is similar to studies done by van der Wall (1986) where about half of the basins observed in Zimbabwe yielded more than 100 tkm^{-2} year^{-1}. The sediment yields for the Malilangwe reservoir of 120.1 tkm^{-2} year^{-1} were compared to that of Chikwedziwa (45 tkm^{-2} year^{-1}) which is in the same geographic region and area (van der Wall 1986). This could be attributed to little land degradation and low population density per unit area (70 inhabitants' per km^2) in Chikwedziwa at that time (1987), but the sediment rate for this area is expected to be higher than 45 tkm^{-2} year^{-1} at present. In the study area, high rates of degradation and population increase are estimated at 2.68 and 2.2 % per year, respectively (Lorup et al. 1998). Population growth and the poorly organised land resettlement since the year 2000 have been cited major factors contributing to the deterioration of the environment in the catchment (Mambo and Archer 2007).

The ratio of reservoir capacity to inflow indirectly provides an index of residence time of sediment laden water in the reservoir (Reddy 2005). Most sediment enters reservoirs during high inflow periods and ideally if the capacity–inflow ratio is small, much of it will be discharged over the spillway (Reddy 2005). If the capacity–inflow ratio is large, much of this water is retained in the reservoir resulting in high sediment trap efficiency (Reddy 2005). The capacity–inflow ratio for the dam was 0.8 which is higher than the recommended ratio of 0.3 for long economic life of the dam. In highly degraded catchments, where large sediment yield is expected, the capacity to inflow ratio of about 0.5 is mostly recommended (Wallingford 2004). With such a high capacity–inflow ratio for the dam, the reservoir is expected to have high siltation and shorter economic life.

The calculated gross storage ratio for Malilangwe reservoir was greater than 0.1 (calculated = 4): according to Khan et al. (2007), a gross storage ratio of greater than 0.1 means the sediment trap efficiency is 100 %. Thus, with a sediment trap efficiency of 100 %, all sediments that enter the reservoir are retained and trapped in the reservoir. A total depth of about 8.6 m or 33.1 % of storage capacity has been lost due to the sediment accumulation in the reservoir over a 48-year period (1963–2011) with the current estimated maximum depth at 15.4 m from a previous of 25.75 m. The Save River catchment in Zimbabwe loses an estimated 2.6×10^8 m^3 year^{-1} of its storage capacity annually (Marshall and Maes 1994). At current sedimentation rates, the reservoir is projected to lose 16 % of its storage capacity in 100 years. With increase in land degradation in the Malilangwe reservoir catchment, the reservoir estimated life span of over 100 years will be drastically reduced unless drastic measures are taken to address the problem. Khan et al. (2007) showed that the bigger the reservoir and catchment, the better is the siltation life. All projections on storage capacity showed that the reservoir will not lose over 50 % of capacity in 100 years.

The coefficient of variation for mean annual runoff was calculated at 120.3 % with a capacity–inflow ratio of 0.8 which indicates a probability of filling of 26.8 %. This is less than the 80 % sometimes adopted as a target value for conventional water supply and irrigation systems (Wallingford 2004) as this would probably be acceptable as it is customary to retain some water in the dam at the end of the dry season (carry-over) to provide insurance against low rainfall in the following year. Since the probability of the dam filling (>26.8 %) is considerably less than the recommended levels, hence measures must be put in place to conserve much of the water in the reservoir. Other factors such as environmental factors (temperature, rainfall and evaporation rates), changes in catchment activities such deforestation, poor agricultural methods and water use and demand will be major determinants of the reservoir lifespan.

The annual runoff volume of 1×10^7 m^3 indicates that a storage volume larger than $0.8 \times 1 \times 10^7 = 8 \times 10^6$ m^3 is required, meaning that an 11 m dam height from the current 15.4 m dam height should be selected as this gives the best ratio of volume of water stored at any given year. O'Connor (2007) calculated runoff volume 6.2×10^6 m^3 for Malilangwe reservoir which was lower than the calculated runoff volume of 1×10^7 m^3 in this study. Magadza (2002) projected that mean annual runoff of some major rivers in southern Africa is estimated to decline by as much as 20–45 % within the next 50 years meaning that the rate of erosion and rate of sedimentation also is strongly related to runoff and rainfall.

Many benefits might be obtained from improving the management of the Malilangwe reservoir catchment so as to reduce siltation rates in the reservoir. These include addressing poor land practices leading to low soil productivity and the value of wood and non-wood products to be obtained from increased tree planting and improved management of natural forest areas. It is strongly recommended that Malilangwe must be geared for increased variability in the water availability in the reservoir with an increased frequency of droughts and floods as projected by Murwira et al. (2009). This calls for the use of more dams and groundwater sources (boreholes) within the wildlife reserve to reduce the negative effects of increased water fluctuations in the Malilangwe Reservoir. This sedimentation problem can only be solved through wider soil conservation technologies that are readily understood and implemented by locals and is within their financial reach. These measures require limited labour and require no foregone benefits but lead to substantially increased benefits within catchment populations.

The study provided an indication of degradation hot spots within Malilangwe catchment, where interventions to prevent further change and where practices for mitigating the associated degradation should be targeted. The generated data will be useful for managers of the Malilangwe Reservoir, environmental organisations, government and local communities in helping curb land degradation and aid in the coordination of mitigation.

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