Estimation of small reservoir storage capacities in Limpopo River Basin using geographical information systems (GIS) and remotely sensed surface areas: Case of Mzingwane catchment

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Abstract

The current interest in small reservoirs stems mainly from their utilization for domestic use, livestock watering, fishing and irrigation. Rarely were small reservoirs considered in the water resources system even though they are important in water resource planning and management. The main limitation being lack of knowledge on small reservoir capacities, for the methodologies used to quantify physical parameters of reservoirs are costly, time consuming and laborious. To address this challenge an attempt has been made in this study to estimate small reservoir storage capacities using remotely sensed surface areas. A field study on 12 small reservoirs was carried out in Mzingwane catchment in Limpopo River Basin; Zimbabwe. The depths of water accompanied with their coordinates were measured; from which area and capacity were calculated for each reservoir using geographical information system based on data acquired from the field and that from satellite images. The output data was compared and a linear regression analysis was carried out to establish a power relationship between surface area and storage capacity of small reservoirs. The Pearson correlation analysis at 95% confidence interval indicated that the variances of the two surface areas (field area and image area) were not significantly different ($p < 0.05$). The findings from linear regression analysis (log capacity–log area) show that there exist a power relationship between remotely sensed surface areas (m^2) and storage capacities of reservoirs (m^3), with 95% variation of the storage capacity being explained by surface areas. The relationship can be used as a tool in decision-making processes in integrated water resources planning and management in the river basin. The applicability of the relationship to other catchments requires further research as well as investigating the impacts of small reservoirs in water resources available in the river basin by carrying out a hydrological modelling of the catchment.

1. Introduction

People living in arid areas with highly variable rainfall, experience droughts and floods and often have insecure livelihoods (Stevenson, 2000). Water resources planning and management is the major challenge to most rural communities especially in arid areas, for they struggle securing water to cover for various uses like drinking water, domestic use, livestock watering and irrigation. However, this primarily depends on the availability of water, which is increasingly becoming a scarce resource in Zimbabwe (WRMS, 2000) and hence the need to realise the importance of water resources management in the Sub Saharan Africa as a whole (Cleaver and Schreiber, 1994). Hence, all sources of water need to be considered in the management of water resources. In this paper, small reservoirs can be defined as storage structures that store and capture runoff water.

Small reservoirs, in addition to other infrastructures of storing water are widely used for the provision of water for irrigating vegetable gardens, domestic use and livestock watering. In Limpopo River Basin, it was estimated that there are approximately 1000 small reservoirs (Zirebwa and Twomlow, 1999 and Senzanje and Chimbari, 2002), but their importance was not readily realised. This number primarily depends on data collected five years back and probably has changed over the period to date.

Thus from a hydrological point of view, the existence of a large number of small reservoirs as well as their spatial distribution and storage capacities must be known. Although, in most arid areas, small reservoirs store large amounts of water and have significant effect on downstream flows, rarely were they considered as part of water resources systems of a river basin. The absence of adequate knowledge on small reservoir storage capacities has been a constraint in decision-making processes regarding planning and management of existing water resources. Mugabe et al. (2004) cited that the sustainable use of the limited water resources is constrained by insufficient knowledge of the resources, in terms of quantity, and lack of proper water resource management. This justifies the need to establish the capacities of reservoirs using less expensive methods.

The existing techniques for estimating reservoir capacity estimates include direct (reservoir surveys) and indirect methods (use of topographical maps). Commonly used techniques to date, for instance, field survey to estimate surface areas of reservoirs, apparently are labour intensive and time consuming, and hence estimation of surface water resources of a catchment at appreciable costs. The formulas commonly used are based on the general equation for reservoir capacity given by

$$C=K*D*W*T \tag{1}$$

where C is the reservoir capacity (m^3), K is a constant, D is the maximum water depth (m), i.e. the difference in elevation between the lowest point in the reservoir bed and the spillway crest level, W is the width (m) of water surface at the spillway crest level, T is the "throwback" at the spillway crest level (m), (the throwback is the distance from the dam wall along the reservoir axis usually to the point where river enters). Volume predictions using the above equation were compared with the surveyed volumes for nine small reservoirs in Zimbabwe, covering a range of dam heights and river valley cross-section shapes (Lawrence and Lo Cascio, 2004). Based on this general equation there are a number of equations in use, such as USAID relationship (USAID, 1982), the 1/6 rule (Hudson, 1998), the Nelson relationship (Nelson, 1996) and Fowler relationship (Fowler, 1977). It was seen that on an average the USAID relationship over-predicts small reservoir volumes by 36% (Lawrence and Lo Cascio, 2004), the 1/6-rule under-predicts reservoir volumes by 43% while the Nelson and the Fowler relationships performed quite well, with an average under-prediction of 10–15% (Lawrence and Lo Cascio, 2004). This method is direct as it involves actual measurements of reservoir parameters in the field.

Besides the direct methods of estimating reservoir capacities there exist other methods, which uses satellite data and topographical maps in the form of a model relationship $C = aA^b$ where, C is the capacity of the reservoir (m^3), A is the surface area (m^2), a and b being calibration constants. Meigh (1995) used 1:50,000 topographical maps, an indirect method to estimate surface areas of the small farm reservoirs in order to find the impact of small farm reservoirs on urban water supplies in Botswana. The paper concluded that area estimated from the maps would be of poor measure of the actual area because aerial photography on which the maps are based was unlikely to correspond to the times when the reservoirs are full, and because some of the reservoirs were so small that they may not be representative of the actual areas of the reservoirs. This work led to development of a power relationship by Meigh (1995) between capacity (*C*) of the reservoir and its surface area (*A*) measured from topographical maps given by

$$C = 73.8 * A^{1.25} \quad (R^2 = 0.93) \tag{2}$$

where reservoir capacity is in m^3 and surface area in m^2.

To note is that the original formula of the above equation was with units 10^3 m^3 for capacity and hectares (ha) for surface area and hence the coefficient has changed.

Similar work has been carried in Ghana in a Savannah climate (Liebe, 2002) and showed that the use of remotely sensed surface areas is indeed feasible and such information is not available in Zimbabwe. The established capacity–area power relationship by Liebe (2002), calibrated in Ghana, between capacity (*C*) of the reservoir and its surface area (*A*) measured from satellite images is summarized in the equation:

$$C = 0.0086 * A^{.44} \quad (R^2 = 0.98) \tag{3}$$

where reservoir capacity is in m^3 and surface area in m^2.

However, if the errors involved in transposing the results from site with information to another are acceptable in comparison to the uncertainty of the original estimates, then this approach has the potential to provide estimates with appreciable uncertainty for greatly reduced costs. Therefore there are indications that there is room for improvement as far as research on small reservoirs is concerned in Zimbabwe and a need to establish a model equation to estimate reservoir storage capacities of small reservoirs using their remotely sensed surface areas.

Therefore the objectives of the study reported in this paper are:

(i) To identify small reservoirs in terms of their numbers and spatial distribution in the study area from satellite images.

(ii) To develop a methodology to estimate small reservoir capacities as a function of their remotely sensed surface areas in the Limpopo River Basin.

The paper also tries to address the following hypotheses:

(i) Remote sensing is the suitable means to detect small reservoirs and adequately measure their surface areas.

(ii) There is a relationship between remotely sensed surface areas and storage capacities for small reservoirs.

2. Materials and methods

2.1. Study area

The study was conducted in the Mzingwane catchment, which forms part of the Limpopo Basin on the Zimbabwean side. The Limpopo River forms part of the northern border of South Africa, and it separates South Africa, Zimbabwe and Botswana before it enters into Mozambique and drains into the Indian Ocean. The basin is shared between four countries as shown in Fig. 1. The Limpopo River Basin is demarcated by latitude 24°S and longitude 25°E, and latitude 26°S and longitude 34°E. The average annual runoff of the Limpopo is 5500 Mm^3/year, small in comparison to other major basins, like Amazon or Nile but the river is important because of its strategic value for water to the four countries (Pallet, 1997). However, surface water resources yielded in the basin within Zimbabwe are estimated at 540 Mm^3/year, of which, 410 Mm^3/year drains to the Limpopo River at the Zimbabwe–South Africa border and 130 Mm^3/year enters Mozambique before flowing into the river (DSE, 2001). However, the Mzingwane catchment, is located in the semi-arid region of Zimbabwe, and is divided into four sub-catchments, namely, Shashe, Upper Mzingwane, Lower Mzingwane, and Mwenezi as shown in Fig. 2. While the temporal distribution of rainfall follows the general pattern of the Southern African region with wet months between November and March, the spatial distribution of rainfall is generally quite variable over the entire catchment (WRMS, 2000).

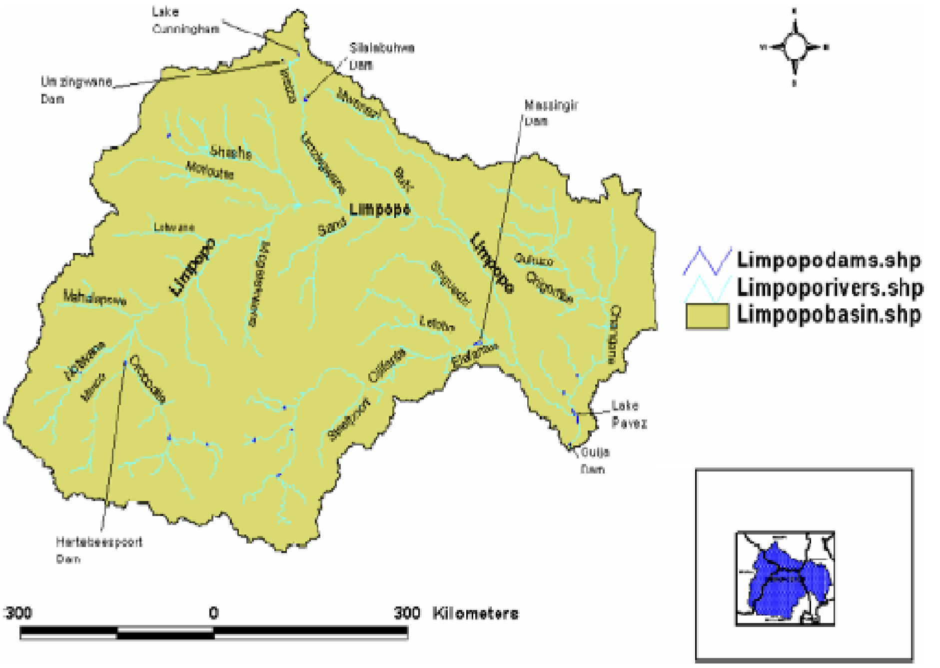


Fig. 1. Map of Limpopo Basin.

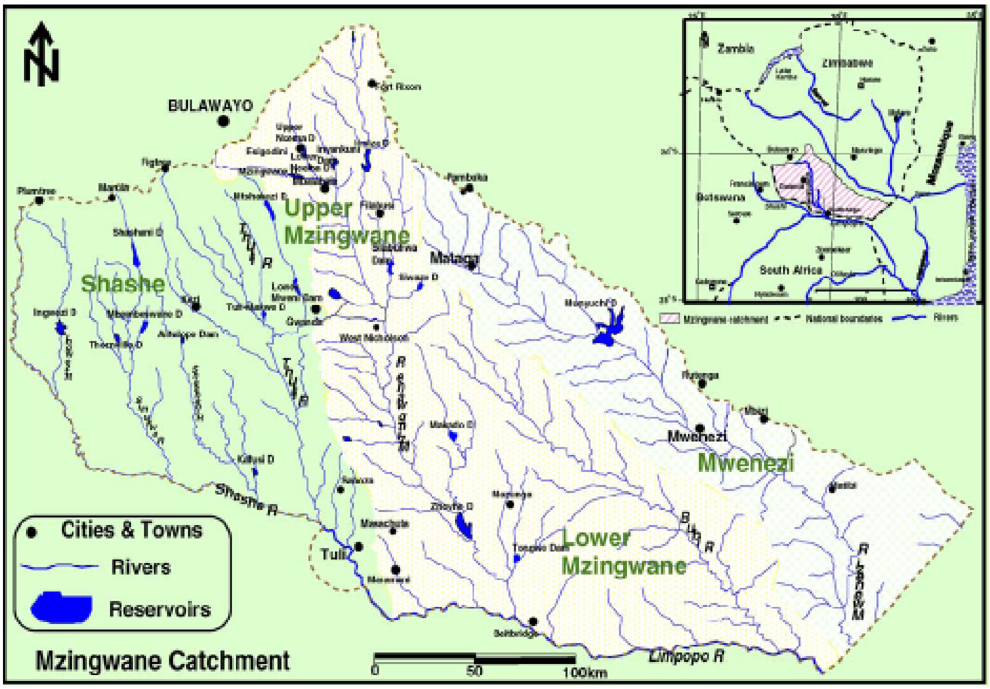


Fig. 2. Mzingwane catchment.

2.2. Reservoir surveys and remote sensing for surface areas and storage capacities

For most of small reservoirs in the catchment, no data was available on their physical characteristics. In order to model them it was necessary to have estimates at least of the following for each reservoir: the surface area and storage volume, and the reservoir depths.

2.2.1. Collection and processing of field data

The estimates of surface areas and volumes of reservoirs were carried out in Insiza District, in Mzingwane catchment. The equipment used includes the following:

Boat, GPS, Theodolite, Stadia rod and rope, 1:50,000 maps, Tripod, Level, Tape measure (50 m), vehicle, and notebooks. Reservoir depths were measured using telescopic stadia rod (5 m). It was measured from surface of water level at least 20 m apart to allow creation of contours from which surface area was derived. Each measurement was accompanied by its GPS (error of <5 m) coordinate and/or interpolated coordinates based on measurements from the theodolite to locate its position within the reservoir. For depths exceeding 5 m a rope was used to extend to greater depths.

2.2.2. GIS application

Arc View 3.2 GIS package with Spatial Analyst, plus Surface Areas and Ratios from elevation Grid extension was used, to automate surface area calculations and to provide surface area statistics. Interpolation was carried out using Spline interpolator that fits a minimum curvature surface through the input points. In order to establish the volume of the reservoir, the triangulated irregular network (TIN) model for the reservoir was calculated using derived surface area. The field data was collected in a manner that was scheduled according to the acquisition of images. The reservoir field surveys provided a basis for an assessment of the quality of a method that was used to derive the extent of small surface water bodies from images.

2.2.3. Use of remote sensing

The procedure used to estimate surface areas from satellite images follows acquisition of images (LANDSAT 5, bands 5, 4 and 2). Using Red–Green–Blue channel, water bodies were depicted in colours ranging from blue to almost black. Reservoirs were uniquely identified from satellite images as shown in Fig. 3. This procedure was applied for all reservoirs studied in this research work.

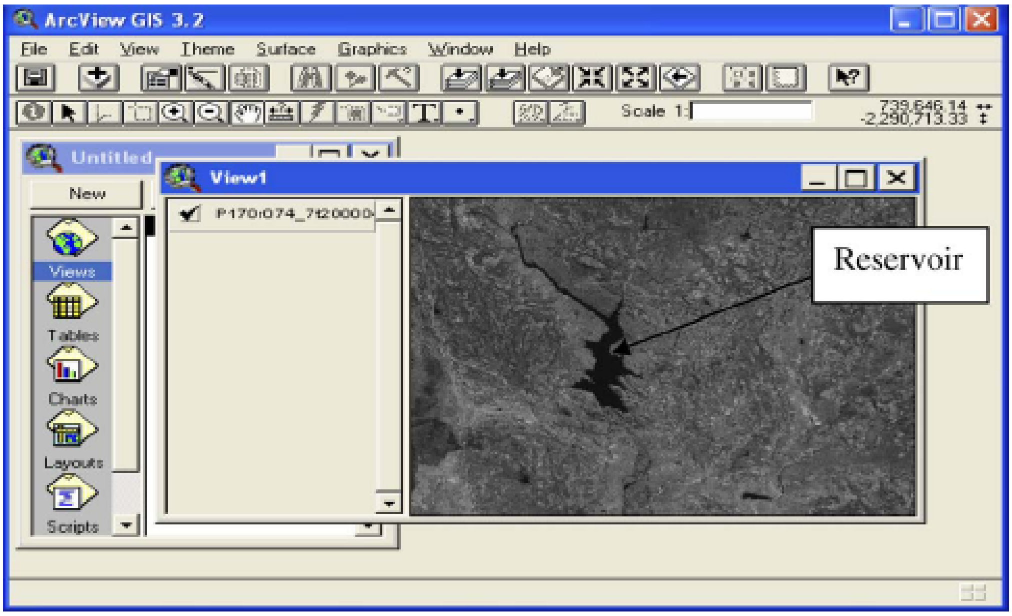


Fig. 3. Reservoir identification from satellite image.

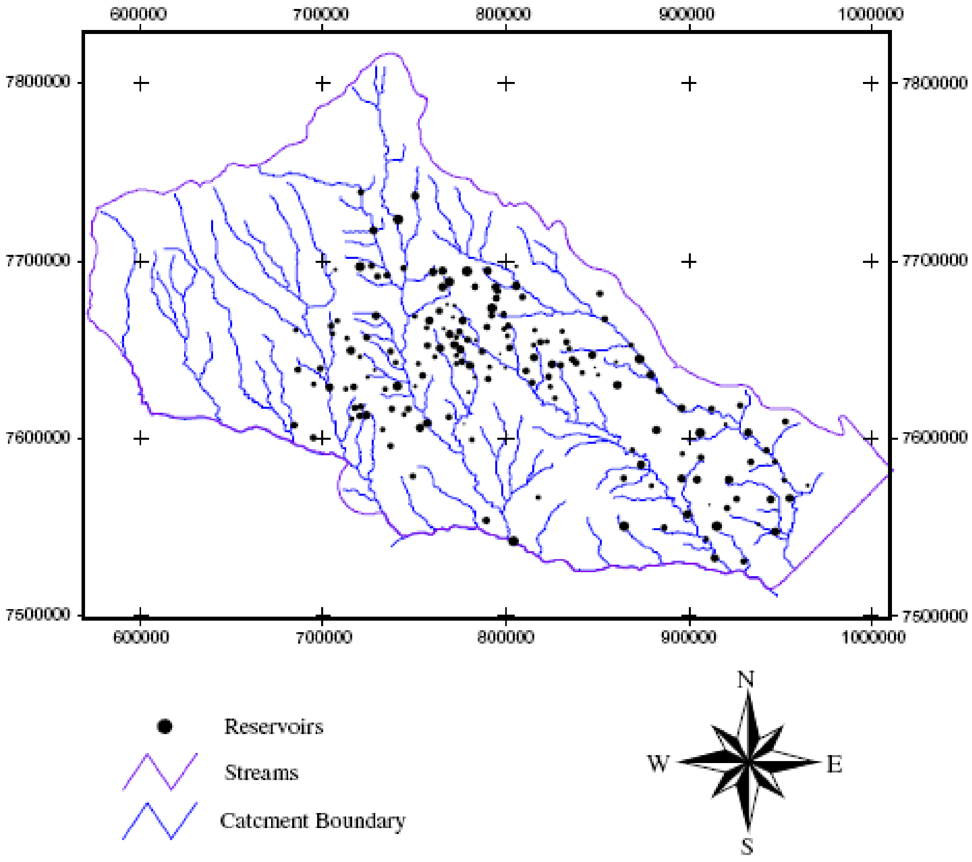
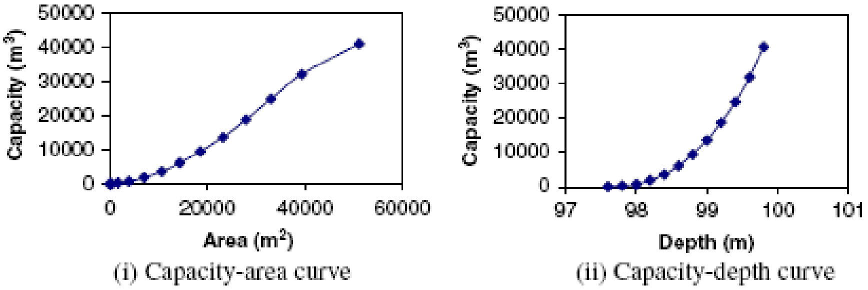


Fig. 4. Spatial distributions of small reservoirs in the Mzingwane catchment.

3. Results and analysis

3.1. Quantifying small reservoirs

In this paper, from the inventory carried out using satellite images approximately 1000 small reservoirs were identified from Insiza District only, which forms part of Mzingwane catchment and the distribution of the reservoirs is shown in Fig. 4. Having established the spatial distribution of small reservoirs in the study area in question, their capacity–area relationships became a cause for concern. The graphs in Fig. 5 represent the relationships between three ‘parameters’ ‘depth’, ‘surface area’ and ‘capacity’ of small reservoirs as obtained from field survey. The graphs showing capacity–area and capacity–depth relationships depict the general shapes expected for small reservoirs as derived.



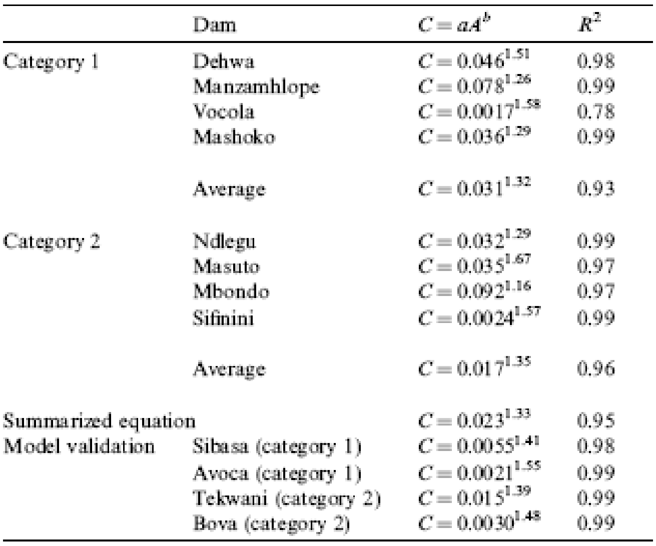
(i) Capacity-area curve (ii) Capacity-depth curve

Fig. 5. Graphs showing general relationships between capacity, area, and depth for small reservoirs.

3.2. Data analysis

The data for both capacity and surface area were transformed into log equations and corresponding R^2 value for each reservoir calculated, and the capacity–area relationships are shown in Table 1. Focusing on log capacity–log area correlation; a mean storage capacity was sought for each area-step. This is achieved by averaging the reservoir capacities of corresponding area-steps in base 10 notations. The regression equations for log capacity–log area were classified into two separate categories, depending on the general shape of the reservoir, and the length of throw back. The first category (category 1) resembles oval shaped reservoirs with a fairly short throw back. On the other hand, the second category (category 2) resembles triangular shaped reservoirs with a fairly long throw back. The power relationship expected is expressed as $C = a * A^b$ as shown in Table 1, C is the capacity of the reservoir (m^3), A is the surface area (m^2) and a and b are constants. These categories and their equations are further explained in Section 3.3.

Table 1
Capacity–area relationships and the coefficient of determination (R^2) values for the studied small reservoirs



	Dam	$C = aA^b$	R^2
Category 1	Dehwa	$C = 0.046^{1.51}$	0.98
	Manzamhlope	$C = 0.078^{1.26}$	0.99
	Vocola	$C = 0.0017^{1.58}$	0.78
	Mashoko	$C = 0.036^{1.29}$	0.99
	Average	$C = 0.031^{1.32}$	0.93
Category 2	Ndlegu	$C = 0.032^{1.29}$	0.99
	Masuto	$C = 0.035^{1.67}$	0.97
	Mbondo	$C = 0.092^{1.16}$	0.97
	Sifinini	$C = 0.0024^{1.57}$	0.99
	Average	$C = 0.017^{1.35}$	0.96
Summarized equation		$C = 0.023^{1.33}$	0.95
Model validation	Sibasa (category 1)	$C = 0.0055^{1.41}$	0.98
	Avoca (category 1)	$C = 0.0021^{1.55}$	0.99
	Tekwani (category 2)	$C = 0.015^{1.39}$	0.99
	Bova (category 2)	$C = 0.0030^{1.48}$	0.99

Note: From the table the average R^2 value for all the reservoirs is 0.95.

The regression analysis provided a regression line, which gives a formula from which; knowing surface areas of reservoirs by remote sensing the reservoir capacity for each reservoir can be estimated. The coefficient of determination (R^2), shows the amount of explained variance, that is the variance in the y-values (in this case reservoir capacity) that can be accounted for by x-values (surface areas). Having established the surface areas and corresponding capacities of reservoirs, a comparison for the set of reservoirs studied was made using t-test distribution. The deviation area index (D_{AI}) was used for comparison of surface areas and is given as

$$D_{\mathrm{AI}}=((A_{\mathrm{f}}-A_{\mathrm{s}})/A_{\mathrm{f}}) \tag{4}$$

where D_{AI} is the deviation area index (dimensionless), A_{f} is the area estimated from field survey (m) and A_{s} is the area estimated from use of satellite images (m).

The values obtained from this equation would range from −1 to 1 and reservoirs with values close to 0 have the best match between A_{s} and A_{f} while moving to both extremes stand for increasing deviations between surface areas.

3.3. Reservoir capacity–area relationship

The information from the general relationships between capacity and area provided the basis for linear relationships between capacities and surface areas of reservoirs. The plots shown in Fig. 6 (log capacity–log area plots) depict the basic principle for area-based estimation of small reservoir capacities. The regression equations were transformed to storage capacity–area relationship using basic logarithmic principles. Thus for the category 1 reservoirs, as in Fig. 6a, established equation as deduced from logarithmic equations to relate capacity to area is given by

$$C=0.031*A^{1\ldots31} \tag{5}$$

Then for the category 2 reservoirs, as in Fig. 6b, the established equation is as follows:

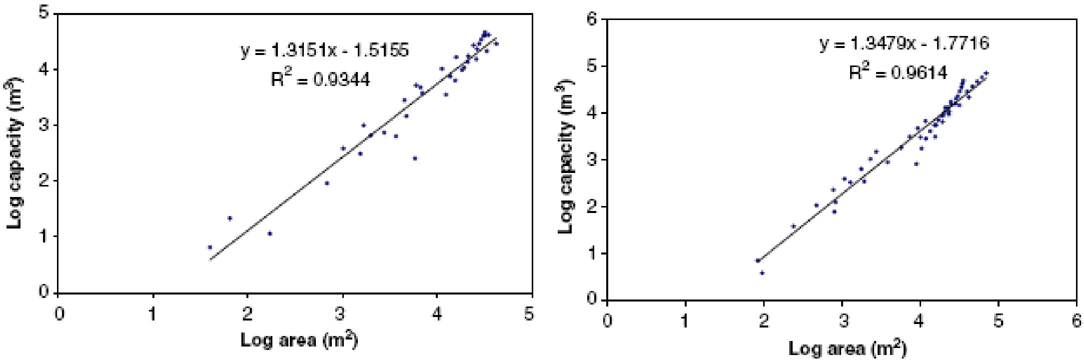
$$C=0.017*A^{1.35} \tag{6}$$

The assumed general characteristics of the reservoirs in terms of their size, maximum depths, geology and topography therefore led to one general equation to be used to estimate reservoir volumes based on their remotely sensed surface areas in

Mzingwane catchment. The best-fit capacity–area relationship as shown in Fig. 6c obtained for small reservoirs surveyed is given by

$$C = 0.023 * A^{1.33} \quad (R^2 = 0.95) \tag{7}$$

where C is reservoir capacity is in m^3 and A is surface area is in m^2, for Eqs. (5), (6) and (7).



a For category 1 reservoirs.

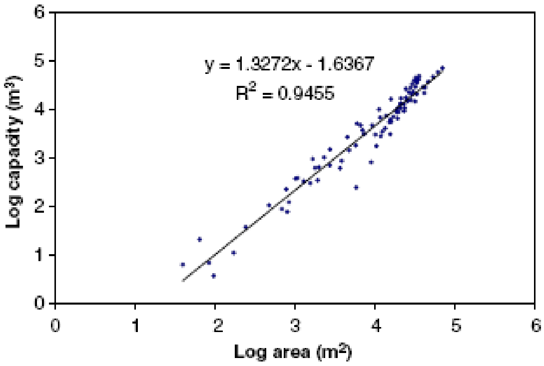
$C = 0.031 * A^{1.31}$

(R^2=0.93)

b For category 2 reservoirs.

$C = 0.017 * A^{1.35}$

(R^2=0.96)



c Summarized regression equation for small reservoirs.

$C = 0.023 * A^{1.33}$

(R^2=0.95)

Fig. 6. Log capacity–log area relationships for small reservoir categories.

This capacity–area relationship was validated using four independent reservoirs from those used to obtain the constants of the equation, namely Sibasa, Avoca, Tekwani and Bova in the catchment. The data on the surface areas estimated from both field survey and remote sensing was statistically compared. This was mainly to investigate the correlation between surface areas obtained from the field survey to that estimated from satellite images. From t-test, Pearson correlation at 95% confidence interval ($p < 0.05$) it showed that surface areas are correlated. In addition, the deviations (error) in the data obtained using difference area index (D_{AI}), which weights deviations and express the relation between the area measurements from the field data and the satellite image classification provided a range of error from −0.23 to 0.15 and these results are shown in Table 2. The results are quite comparable; with error close to 0 giving better match between remotely sensed surface areas and areas obtained from field survey. The storage capacities also provided the same magnitude of error for respective reservoirs after a similar comparison was made using remotely sensed areas.

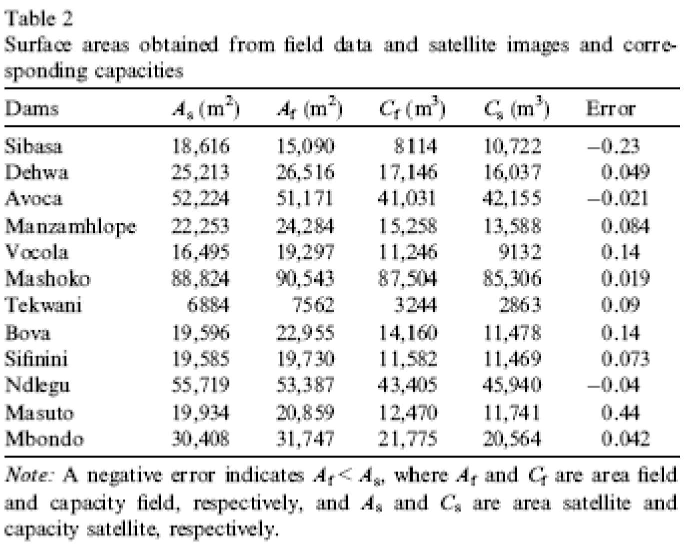


Table 2
Surface areas obtained from field data and satellite images and corresponding capacities

Dams	A_s (m^2)	A_f (m^2)	C_f (m^3)	C_s (m^3)	Error
Sibasa	18,616	15,090	8114	10,722	−0.23
Dehwa	25,213	26,516	17,146	16,037	0.049
Avoca	52,224	51,171	41,031	42,155	−0.021
Manzamhlope	22,253	24,284	15,258	13,588	0.084
Vocola	16,495	19,297	11,246	9132	0.14
Mashoko	88,824	90,543	87,504	85,306	0.019
Tekwani	6884	7562	3244	2863	0.09
Bova	19,596	22,955	14,160	11,478	0.14
Sifinini	19,585	19,730	11,582	11,469	0.073
Ndlegu	55,719	53,387	43,405	45,940	−0.04
Masuto	19,934	20,859	12,470	11,741	0.44
Mbondo	30,408	31,747	21,775	20,564	0.042

Note: A negative error indicates $A_f < A_s$, where A_f and C_f are area field and capacity field, respectively, and A_s and C_s are area satellite and capacity satellite, respectively.

4. Discussion

4.1. Reservoir numbers

The inventory of small reservoirs in Insiza District that forms part of Mzingwane catchment was obtained through remote sensing with little labour and less cost incurred on counting small reservoirs in the district. The estimated number of small reservoirs when this study was conducted is 1000 in Insiza District as depicted from satellite image and they are quite evenly distributed in the entire catchment as displayed in Fig. 4. However, from previous work conducted by FAO approximately 826 small reservoirs were identified in the Insiza District and approximately over 2500 small reservoirs were identified in the Mzingwane catchment (Sugunan, FAO 1997). These values are comparably far much higher than 1000 small reservoirs that were identified for the whole of Limpopo Basin (Zirebwa and Twomlow, 1999 and Senzanje and Chimbari, 2002). This included small reservoirs in both communal lands and resettlement areas, which means an update baseline data of reservoirs was obtained by use of remote sensing. The method of using satellite information to estimate the number of small reservoirs keep an update of small reservoir database current and hence a better method for use by water managers and water institutions in water related studies. The difference in the number of small reservoirs' records maybe is through construction of small farm dams over recent years by some commercial farmers privately without prior approval from the water authorities

4.2. Reservoir capacity–area power relationship

The general shapes of the reservoir curves as shown in Fig. 5 represent the expected curves for small reservoirs as indicated by designs common for small reservoirs (Lawrence and Lo Cascio, 2004). This is so because reservoirs, in particular, vary considerably in their shape, depth and nature. Thus, from the regression analysis carried out the generalized equation obtained for small reservoirs, 95% of the variation in the storage capacities of small reservoirs in the catchment is due to their surface areas, with about 5% being due to other factors and hence fairly a strong relationship exist, refer to Eq. (7). This compares well with the coefficient of determination ($R^2 = 0.93$) obtained by Meigh (1995), see Eq. (2), on the analysis for small farm dams in Botswana where a relationship between capacity and surface area was also established. The relationship also matches closely with Liebe's (2002) equation; refer to Eq. (3), with R^2 value of 0.98 obtained in Ghana for estimating storage volumes for small reservoirs. The variation in constants between all these relationships is mainly due to different climatic conditions the studies were taken. Thus the commonality in the established equations is that surface areas of small reservoirs can be obtained from satellite data and topographical maps and still give a better estimate of reservoir capacities without necessarily carrying out a field survey.

The *t*-test and Pearson correlation analysis at 95% confidence interval indicated that the variances of the two surface areas (A_f and A_s) are not significantly different ($p < 0.05$) meaning the surface areas are correlated. This is the case because the time from which fieldwork was conducted corresponds to the dates when images used to estimate surface areas were taken. This enabled the established relation; see Eq. (7) to be used to estimate the capacities of reservoirs using remotely sensed surface areas in Mzingwane catchment. Thus, from the comparison of remotely sensed surface areas and surface areas obtained from field survey errors ranging from −0.23 to 0.14, as shown in Table 2, for all surveyed reservoirs were obtained. It was likely because some areas covered with water might have been classified as vegetation and errors in pixel counting also existed contributing to the errors. Cater (1980), discusses the similar problem of estimating areas by counting pixels in Landsat imagery in which perimeter cells with mixed spectral signature occur. On the other hand, during classification, shallow water areas covered by floating vegetation were classified as wetlands but where aquatic vegetation was submerged the area was classified as water, which might have also contributed to the error. The other thing might be the coarse spatial resolution (30 m) that was used, given that some reservoirs are so small to be picked up, giving rise to errors in imagery data. Thus the study suggest better spatial resolution (10 m or less) to be used to detect small reservoirs and cost implications should be considered as well in using these higher resolution images. However, for the purposes of having a general understanding of water resources assessments the use of 30 m resolution is justifiable to water managers with little costs. The method is quite easy to use and less time consuming as compared to other methods commonly used to estimate reservoir capacities. The method performs well like Fowler and Nelson relationships see Eq. (1) for the general equation that estimates reservoir capacities within 10% or 15% under predictions (Lawrence and Lo Cascio, 2004).

4.3. Reservoir management

The information of reservoir capacities is quite essential with regards to management of the small reservoirs, and storage capacities. More so, European Space Agency (ESA) Earth Observation at WSSD (2002) meeting indicated that it would provide free satellite to water managers and water institutions in order to facilitate water resources planning and management as well as flood mitigation measures. Thus with time, based on the time of image acquisition and considering rainfall, abstractions and siltation, storage capacities will vary. Hence a necessity of using satellite images in conjunction with GIS tools to monitor and manage water levels for small reservoirs. Thus a clear picture of what a reservoir can hold at any given time will therefore be deduced. Moreover, decision on allocation of water in larger reservoirs based on a number of small reservoirs scattered around its catchment area can be made possible. If small reservoirs have larger storage capacities say by April than water in larger reservoirs, then water in large reservoirs can be allocated to say winter wheat, since people will have adequate for primary uses and vegetable watering. On the other hand, if small reservoirs are almost empty by April, water in large reservoirs is allocated to vegetable watering, thereby substituting for primary purposes. In addition, most of the reservoirs were used to capture water for dry season irrigation of gardens among other uses in the community. With the capacities known, planners and water managers will quickly make decisions on how to utilize and manage the available water given the various competing uses. Thus from the findings of this paper conclusions can be made that reservoir storage capacities of small reservoirs can be estimated using remotely sensed surface areas.

5. Conclusions and recommendations

Remote sensing was found to be a suitable means to detect small reservoirs and accurately measure their surface areas, from the inventory obtained based on satellite images. This means the majority of small reservoirs, for which detailed information is lacking, can be included in the capacity–area power relationship in Mzingwane catchment without the need to carry out extensive field surveys. The relationship provides a tool to quantify water available in small reservoirs given that it explained 94.6% of measured variance and hence enabling planners to have a clear picture of water resource system in the river basin. However, a limitation to the relationship is that it does not apply to very deep valley cross-sections, which for example assume a rectangular section. In addition, the period for which the relationship is valid requires further research.

The applicability of the relationship to other catchments should be looked at in future as well as the need to carry out a hydrological modelling to investigate the impacts of small reservoirs in water resources available in the basin. However, also lacking in this paper is the assessment of sediment yield, because of its complexity due to temporal and spatial variability of the bulk densities in the reservoir storage. In general the paper provided a leeway to which a water manager will in case of flooding is able to predict the likelihood of floods and hence putting in place remedial actions to ensure the community is not at risk. However, it is worth noting that the need for good information on the existing distribution of small reservoirs is perhaps questionable given that the future development has shown a trend from a large number of small reservoirs to a smaller number of large reservoirs.

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