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Small farm dam capacity estimations from simple geometric relationships in support of the water use verification process in the Inkomati Water Management Area

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Abstract Within the Inkomati Water Management Area in South Africa, there are a large number of small farm dams. While they are of economic value, the management of these dams raises key questions for water managers. As a result, a study to verify the storage of all farm dams has been initiated, as part of the development of an integrated river-basin-scale modelling system. The initial step towards this goal is the development of a tool to estimate the capacity of small farm dams from simple geometric relationships. The methodology used is the Geographical Information System (GIS)-based approach, with dam geometries such as the surface area, fetch and width being estimated. The results show that there is a large variation in farm dam geometries resulting in a wide range of possible storage capacities for any given surface area and that farm dam geometries tend to vary between sub-catchments.

Key words small dam capacities; Geographical Information System; Inkomati Water Management Area, South Africa

INTRODUCTION

As part of their mandate, the Inkomati Catchment Management Agency (ICMA) initiated a programme to verify all existing water users within the Inkomati Water Management Area (WMA) in South Africa. The definition of existing lawful water use (ELU), and the process of verifying the extent ELU is outlined in Sections 32 to 35 of the National Water Act (NWA) (Act 36 of 1998). These sections of the NWA make provision for the continued use of water that was lawful under previous legislation, and which was exercised during a qualifying period, until such time as the use can be authorised by a licence under the NWA. This is an important step in the process of realising the goals of the NWA.

The intention of the verification process is to collate, preferably on a Geographic Information System (GIS), information such as the registered use and the actual use in the qualifying period, in terms of volumes, crops, irrigation systems and hectares, and to determine whether any previous legislation would have limited the historical use. In support of the verification process, the present study investigated the methodology to proxy estimate the capacities of small farm dams in the Inkomati WMA, since the records compiled by the dam safety office of the Department of Water Affairs (DWA) mainly provide information only on larger farm dams, that is, with storage exceeding 50 000 m^3, and a dam wall higher than 5 m.

The Inkomati WMA features a large number of private earth dams, or farm dams, to store water for stock, domestic or commercial use (Fig. 1). These dams are generally located instream, and a series of them can occupy most of a watercourse's length. Individual storage capacities are usually small relative to the average (natural) inflow at the dam site. However, taken together across a catchment, the combined private dam storage can often be large, relative to the entire catchment (natural) streamflow. These distributed storages support a range of high-value agricultural activities such as sugarcane, fruit and vegetable cultivation. But for planners, agriculturalists and water authorities the management of these dams raises key questions, including how much water such dams intercept and when is it intercepted, and what is the reliability of irrigation water supplied from the dams to agricultural land. The questions become particularly vital when it comes to assessing how proposed new dams will affect the reliability of supply to other water users downstream.

The distributed nature of the farm dams present particular difficulties to hydrologists. Ideally, the individual characteristics of each dam would be taken into account in simulation models. This would include data such as dam volume, surface area, inflows and water use. In reality, the gathering of such detailed data is beyond the scope of most projects because there may be hundreds or even thousands of farm dams involved (Fig. 1). To address the issue, there is a need to develop an integrated river basin-scale modelling system. Such a methodology would allow reporting on spatial scales varying from the catchment scale down to individual dams. Proposed new dams could then be assessed for their effect on the reliability of supply to other water users downstream. The initial step towards this integrated basin modelling is to develop a tool to estimate the capacity of small dams from simple geometric relationships (complemented by GIS software): this is the major focus of this study.

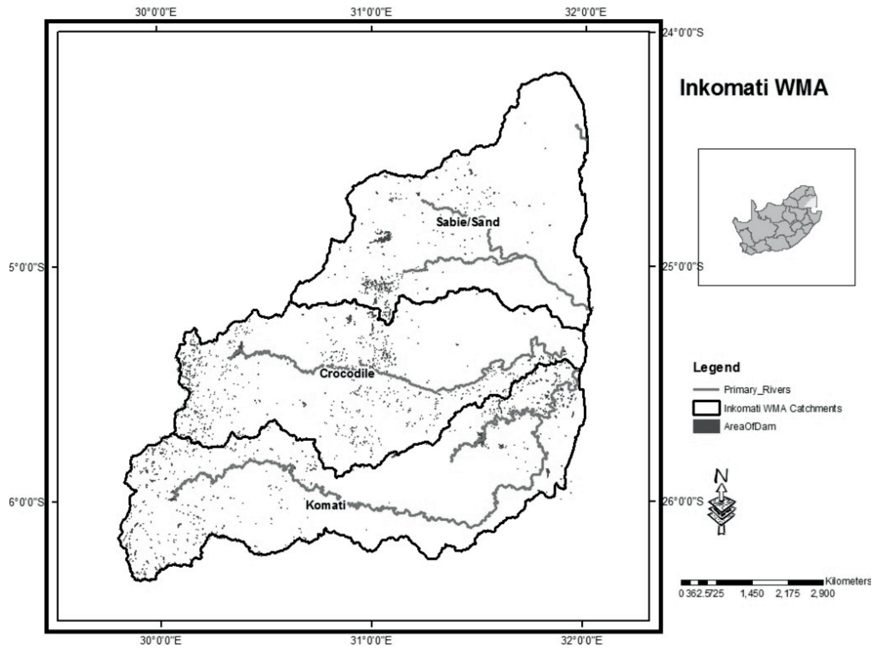

Fig. 1 Distribution of small farm dams in the Inkomati Water Management Area.

GIS-BASED APPROACH TO DERIVE DAM PARAMETERS

An approach whereby dam parameters were derived using GIS was investigated. Dams were located using 1:50 000 topographical maps, 1:10 000 orthophotos and satellite images. Satellite imagery has a great potential for the location of dams because the technique can be automated, can cover large areas and can facilitate periodic and regular updates of dam inventories (Howman, 1988). Using this method, data and information were collated for 58 000 dams located in the Inkomati catchment, including the location and surface areas of the dams at full capacity, and where possible the wall height and length, axis length (fetch) and dam shape. Some of this information was obtained from surveyed data available from archives of dams registered with the Department of Water Affairs. Dam safety office (http://www.dwaf.gov.za/dso/) and other reports were used to source the full capacity of dams for some of the registered dams. A GIS programme called ARC-VIEW 9.3 was used to estimate the surface area, the width and the fetch of the dams by digitising them using 10 m resolution Landsat Images, while the depth of dam was calculated as a function of fetch of dam and average slope. The average slope was estimated using 5 m contours by dividing distance between contour lines along a river line where the dam sits by the contour interval. However, the GIS approach has many sources of errors, which are highlighted here.

Surface area A potential source of error exists as a result of operator-subjectivity in the interpretation of the full supply level. The larger errors in the digitising can be detected during the field surveys by checking that the farm dam outline is correctly represented, and such errors can then be corrected on-screen in the office. However, even relatively small errors in determining the location of the full supply level can have a major effect on the calculation of the resulting surface area.

Maximum depth There can be significant differences between external wall height and maximum depth. The approach used to calculate maximum depth is a function of the slope (derived from 5 m contours) and the fetch of the dam. These parameters were estimated using automated software due to the large number of dams that needed to be manually digitised: there were instances where the calculated maximum depth was more than the known wall heights for registered dams.

DAM CAPACITY ESTIMATION

The establishment of a volume–area relationship is required for desktop methods of estimating the storage volume of farm dams that have been digitised from remotely-sensed data. Issues to be taken into account included a large variation in farm dam capacity–area relationships; differences between data from different sub-catchments; and varying trends in volume–area relationship over the size range. These issues presented difficulties in producing one or more capacity–area relationships that had some scientific validity, with the result that the development of the final relationship followed a disjointed path.

However, a concerted effort was made to present the reasoning behind the final recommendation in a logical sequence. It is important to note that the results presented here are based on filtering the data from small dams of a capacity of less than 1 hm^3 and of less than 12 m deep. It was assumed that for values greater than these, this approach would introduce huge uncertainties. Maaren & Moolman (1985) developed algorithms for dam capacity for different shaped dams, and developed a generalised relationship for all shapes which can be expressed as: $A = 7.2C^{0.77}$, where A is surface area (m^2) and C is the capacity (m^3). However, the use of generalised relationships has been generally discouraged in the verification of dam volumes, since different dam shapes and sizes give different results. Thus either simple in-field measurements or desktop derived parameters are used to estimate dam capacities. In the guidelines for the verification process, DWA (2006) recommended the use of approximation equations to estimate dam capacity. Thus the approximate equations shown in Fig. 2 were used in this study for the estimation of the capacity of small farm dams. Moolman & Maaren (1985) also provided a list of approximation equations. The capacities of the dams were calculated using two approximation approaches based on geometric relationships. The first method is a function of depth, width and fetch of the dam, whilst the second approach was a function of surface area and depth. Both of these methods have huge uncertainties associated with them. As first order screening, the dams were firstly grouped according to the catchment to which they belong (e.g. Crocodile, Komati, Sabie-Sand), as shown in Table 1, and then according to surface areas (dams less than 5000 m^2 were excluded as it was assumed that GIS approach will not be suitable to assess small dams of such sizes).

In the first approach, an automated GIS approach was used to derive fetch (dam-axis length) and width due to time and budget constraints, leading to major uncertainties in the fetch of the dam, where the dam either did not align with any river at all or where the river network (1:50 000) was inaccurate as it did not intersect the dams or contours in some instances. The second approach was negatively affected by inaccuracies in digitising the full supply surface areas of the dams from Landsat imagery. The results of the two approximation methods are presented in Table 1 and the percentage difference in estimates of the two approaches. The widely scattered points plotted in Fig. 3 show that the correlation between the two methods of deriving capacities of small dams is very weak, and that it is difficult to determine which of the two methods gives the best estimates, unless the results are validated using surveyed dam parameters from a few sampled dams in the sub-catchments. However, due to budget and time constraints this validation was not done. To validate using registered small dams could not be done because most of the registered small dam parameters from the Dam Safe Office are also incorrect, except the parameters of the large dams.

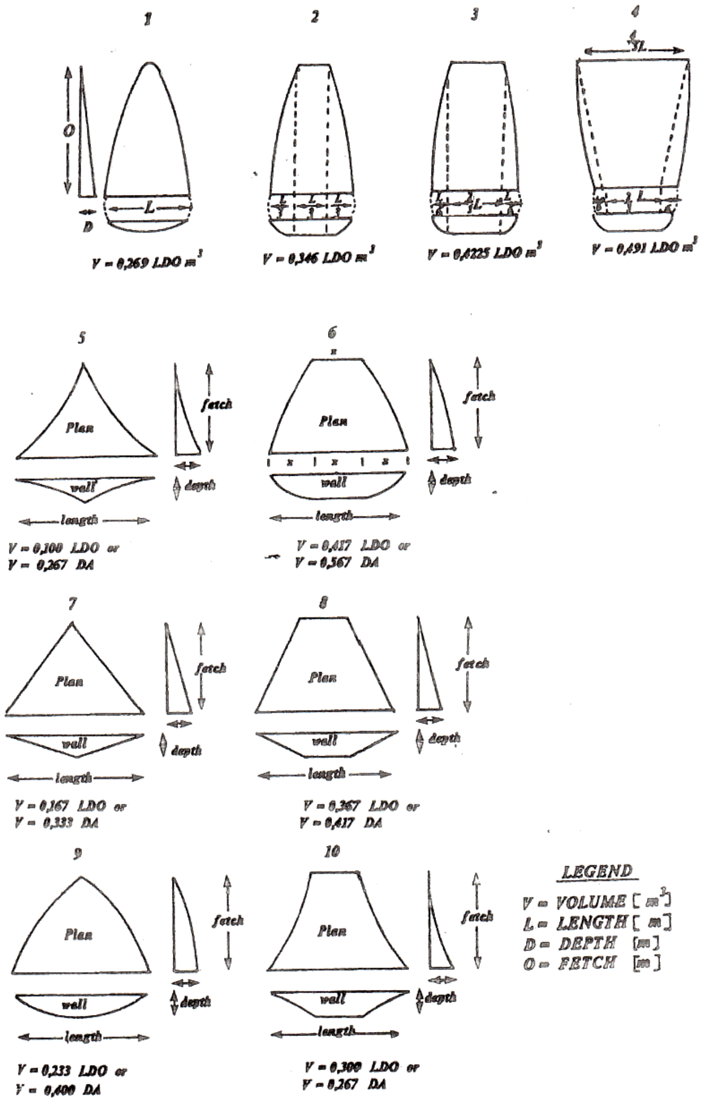

Fig. 2 Approximation equations to estimate capacities of small dams of different shapes (DWAF, 2006).

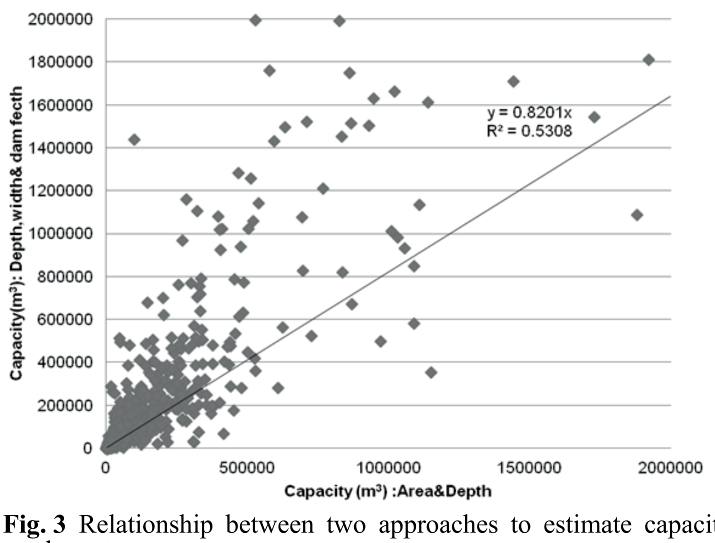

Fig. 3 Relationship between two approaches to estimate capacities of small farm dams in all sub-catchments.

Table 1 Comparisons of two approximation methods and the percentage differences in capacities estimated.

Catchment	Dam ID	Capacity: 1st Method (m^3)	Capacity: 2nd Method (m^3)	% Difference
Crocodile	1727	19937.41	22545.19	13.08
Crocodile	1209	12713.42	14359.12	12.94
Crocodile	2237	39457.09	44526.09	12.85
Komati	379	6461.33	7286.46	12.77
Komati	1497	101012.03	113730.57	12.59
Komati	652	75867.70	85376.76	12.53
Sabie/Sand	3366	1543099.36	1726619.82	11.89
Sabie/Sand	3339	404539.49	417871.93	3.30
Sabie/Sand	3362	932.85	808.68	–13.31

The second method is more practical to use since full supply surface areas can be accurately estimated from orthophotos instead of Landsat imagery. Figure 4 shows the relationship between surface area and depth, illustrating clearly that it is not possible to use a single geometric relationship to derive the capacities of small dams, since for any given depth it can result in different surfaces areas depending on terrain slopes. There is therefore need to group dams by topographical location.

Figures 5 and 6 are scatter plots of capacity *versus* depth, and capacity *versus* surface areas power-law relationships respectively. The wide scatter of points plotted in these figures implies that for any given depth or surface area there is a wide range of possible capacities. This confirms that a volume–area relationship is not a suitable instrument for estimating the capacity of individual farm dams, although there is frequently no practical alternative.

However, none of the catchment-derived regression equations were considered suitable as a "universal" volume–area relationship. The weak correlations $R^2 < 0.80$ confirm that the volume-area relationship is not a suitable instrument for estimating the volume of individual farm dams, despite being the only practicable alternative. The R^2 values of over 0.70 (Fig.6) indicate artefacts of existence of some medium to large dams and this could have been worse if only small dams were considered.

A simple exercise using power-law relationships was used to determine whether or not dam capacities can be estimated. This exercise indicated that a catchment-derived power-law regression equation (Fig. 6) might be suitable as a volume–area relationship for some individual catchments.

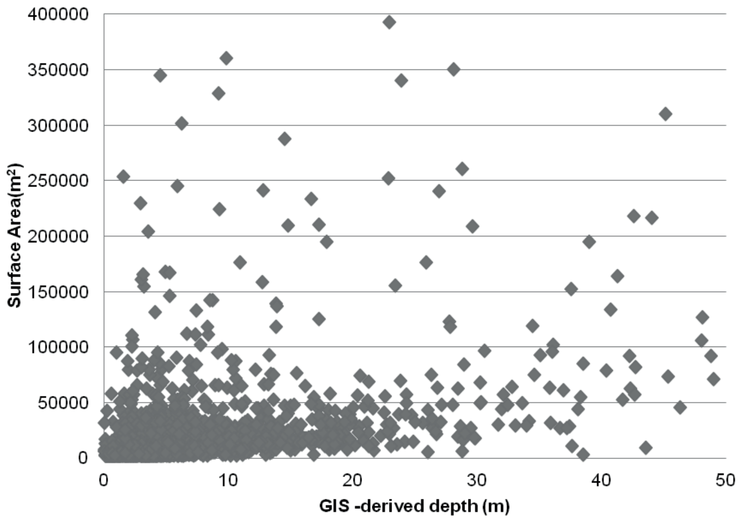

Fig. 4 Relationship between surface area and depth for all dams in all sub-catchments.

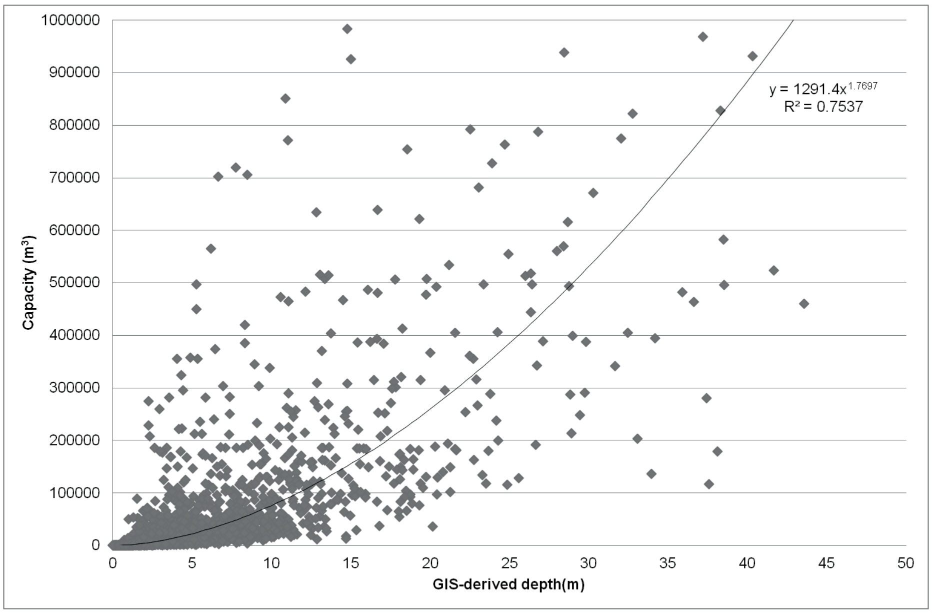

Fig. 5 Relationship between capacity and depth.

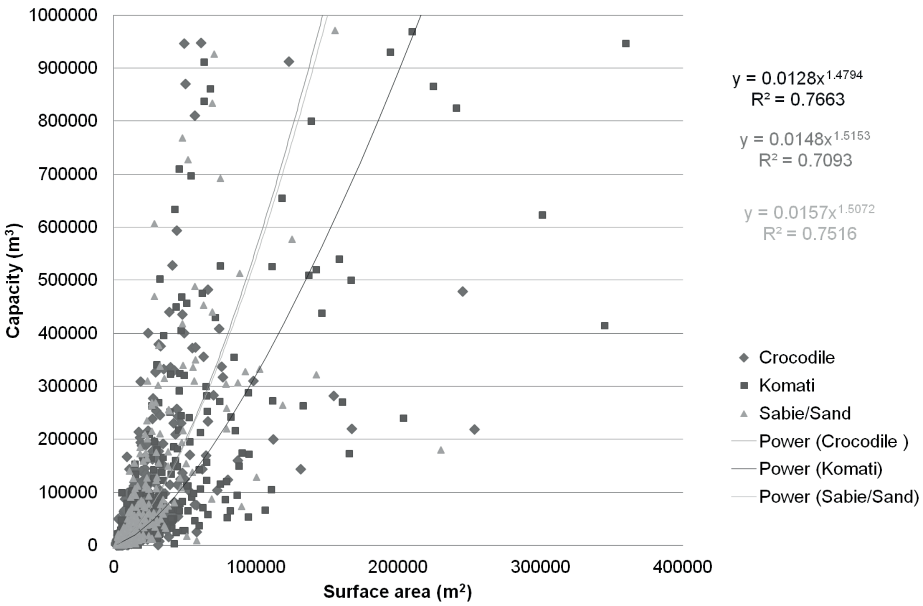

Fig. 6 Power-law regression equations for each sub-catchment showing trends between sub-catchments.

DISCUSSION AND RECOMMENDATIONS

The results of the investigation show that there is a large variation in farm dam geometries resulting in a wide range of possible storage capacities for any given surface area. There is also evidence in the data to indicate that farm dam geometries tend to vary between sub-catchments. A capacity–area relationship is not, therefore, a good instrument for estimating the storage volumes of individual farm dams. However, a statistical advantage can be assumed when a capacity–area relationship is used to estimate the combined volume of a reasonable number of farm dams, say within sub-catchments, as is the case with hydrological modelling.

This study shows that the volumes of dams can be estimated from remotely digitised shape of the water surface and the contours/digital elevation models can be used to estimate the slope and hence depth of the dam. However, these methods only estimate the volume stored at the time of the satellite overpass. While images can be selected for periods where dams may have been closer to full supply, this is not always possible. It is therefore important to use these data only to indicate possible unlawful impoundment of water, and to confirm these estimates with site visits. It can be concluded that if one wishes to establish a local relationship between area and volume there is a need to survey a sample of dams or alternatively, all new (and even old small dams) registered dams should be surveyed by the owners and the results be lodged with Department of Water Affairs and Inkomati Water Management Agency.

The uncertainty associated with use of GIS approach to determine the parameters used to estimate volumes of small dams is well documented (Tarboton & Schulze, 1992; Sawunyama *et al*., 2006). The use of satellite imagery has several problems which exist due to similar reflectances from substances other than water bodies and the low resolution of imagery. Hughes & Mantel (2010) also noted that there will be always high degree of uncertainty on the impacts of small dams, largely due to lack of appropriate data.

It is recommended that as part of any detailed hydrological study in areas where farm dams are considered an issue, the most significant farm dams are surveyed, at least with the rapid field assessment method. This will provide a reasonable estimate of the storage capacity of these farm dams, and permit the suitability of a volume–area relationship to be determined and used to estimate the volume of the remaining farm dams. It is important that the costs of these surveys are incorporated into the project budgets at the planning stage.

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