Evaluation of farm dam area-height-capacity relationships required for basin-scale hydrological catchment modelling

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Abstract

Farm dams form an integral part of basin-scale hydrological catchment modelling in developed regions such as the W. Cape, South Africa. In order to evaluate evaporation losses and demands supplied from farm dams, knowledge of the individual farm dam area-height-capacity relationships is required. The number of farm dams in the W. Cape water resource study total more than 4 000 with a combined storage estimated to be in excess of 120 x 10^6 m^3. In view of this large number of dams, a method was developed whereby the area-height-capacity relationships of these dams could be obtained economically, to an acceptable degree of accuracy, using a minimum of manual intervention and individual farm dam processing. This paper discusses the method used for evaluation of individual farm dam area-height-capacity relationships in the W. Cape.

Introduction

The assessment of the existing water resources and planning of further development was undertaken as part of the Western Cape System Analysis (WCSA). To perform this system analysis, monthly flow sequences are required at a range of locations along rivers in four basins comprising the study area. These are generated using a calibrated catchment model and a suite of other routines.

To calibrate the catchment model, various water demands within catchments have to be evaluated. These include consumption by forestry and irrigation, transpiration losses, evaporation and demands from standing water bodies such as farm dams and reservoirs. For this latter item, the evaluation of individual farm dam area-height-capacity relationships is required.

The number of farm dams in the four basins comprising the study area, namely the Berg, Palmiet, Riviersonderend and Eerste River basins, total more than 4 000 with a combined storage estimated to be in excess of 120 x 10^6 m^3. This is approximately equal to the combined storage of Lower and Upper Steenbras Dams and Wemmmershoek Dam. Various studies (Maaren and Moolman, 1985; Pitman and Pullen, 1989; Tarboton and Schulze, 1990) have shown that farm dams can have a significant effect on streamflow. These studies, mostly case-specific, have noted trends of larger effects in low mean annual runoff regions, significant effects in consecutive dry years, effects on streamflow variability and trends in ratios of dam surface area to catchment areas. In view of the large number of dams and their effect on streamflow, it has become necessary to devise a method whereby the area-height-capacity relationships of the dams could be obtained economically, to an acceptable degree of accuracy, using a minimum of manual intervention and individual farm dam processing. This paper discusses the method used for the evaluation of area-height-capacity relationships of farm dams in the W. Cape.

Data

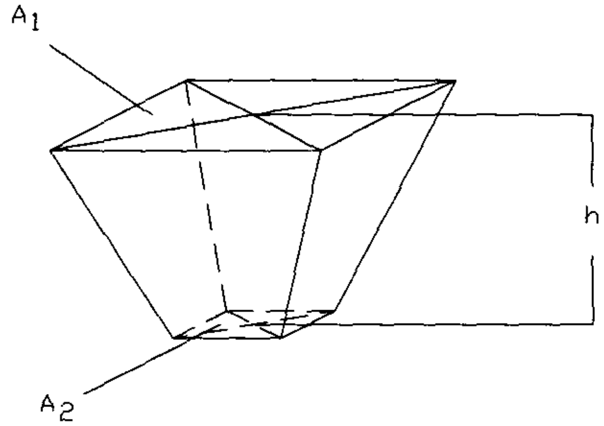
Throughout the WCSA study, aerial photographs were used extensively for measurement of land use (e.g. irrigation and afforestation areas). It was thus also decided to utilise these photographs for digitising farm dam data, and consequently to process these data to render the area-height-capacity relationship of each dam.

With the aid of 1:10 000 scaled diapositives developed from 1:35 000 scaled aerial photographs, raw data (x,y,z co-ordinates) for a digital terrain model of each dam were constructed using a stereo photographic digitiser. Aerial photographs, taken at the end of summer when dams were near empty, were used.

Each digitised farm dam was described by the following level specifications: water level (WL), two intermediate levels (where possible), full-supply level (FSL), top of dam wall level and the level of the downstream toe of the embankment.

Problem description

Using the digitised data, the farm dam area-height-capacity relationship above the WL contour was easily calculated except when the dam was full at the time of aerial photography; when the dam was not full, at least two or more contours could be recorded (e.g. the WL contour and the FSL contour). With contour averaging (Fig. 1), the areas circumscribed by these contours and the height difference between the contours allowed the farm dam volume above the water surface to be calculated reasonably accurately.



$$V = h/3\ (A_1 + A_2 + \sqrt{A_1 A_2})$$

Figure 1
Equation used for volume calculation when contour averaging

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If, however, the farm dam was near full, only the FSL contour could be digitised and contour averaging could not be used.

Furthermore, for volume calculation below the WL, contour averaging cannot be used as the depth of the dam is not known.

Thus, estimating the volume and obtaining the area-height-capacity information below the WL, and in cases where the dam was near full, posed a problem. Two approaches were attempted to resolve this :

- **The formula method**
  With this method it was assumed that every farm dam could be approximated by a geometric shape of known area-height-capacity relationship. A further requirement was to categorise farm dams into either a hilltop, a hillside or a valley dam type, based on their topographical position.
  For these shapes, formulae were established with dam volume as a function of various measurable (digitisable) variables. However, it soon became evident that the categorisation of the dams and the extraction of relevant variables involved processing large amounts of digitised data. Furthermore, it required each dam to be dealt with individually.
  In view of the large number of dams in the WCSA study this approach was abandoned in favour of a more automated approach.

- **Area-height-integration method (AHIM)**
  With this method the digitised information of any individual dam above WL was extrapolated in a rational manner to render the information below WL. Thereafter, the volume of the dam was determined by integration of a curve consisting of the digitised and extrapolated information and showing the relationship of water surface area to the height of water in the dam.
  To facilitate the extrapolation procedure, a dimensionless area-height template graph was developed from a sample of digitised dams described by four contours, namely the WL contour as indicated on the photographs, two intermediate level contours and the full supply level contour. The extrapolation procedure then consisted of superimposing the area-height data above WL of any other dam on this template graph in dimensionless form. Thereafter an averaging technique was used to extrapolate and determine a smooth curve representing the total dimensionless area-height relationship of that dam. Simply dimensionalising this curve resulted in the area-height relationship, which was integrated to establish the farm dam volume.

To ensure the highest possible accuracy in farm dam volume calculation, it was decided to evaluate the volume above WL with contour averaging (provided sufficient contour information was available) and the volume below WL with the AHIM. These were added to render the overall volume of the dam basin.

Components of the AHIM

The following two components are required for the area-height-integration method :

- the dimensionless area-height template graph (discussed above) which is used to extrapolate the area-height characteristics above WL of any other dam to include the relationship below WL; and

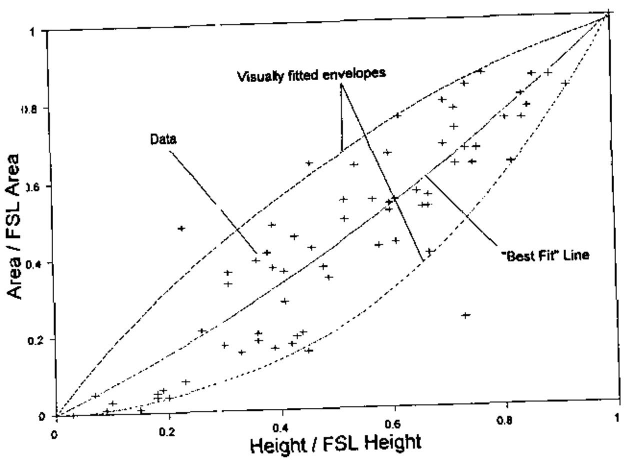

Figure 2
AHIM dimensionless area-height template graph

- a method of estimating the farm dam total depth which is required to non-dimensionalise the data, for use in the area-height template graph of the above item.

Dimensionless area-height template graph

To develop the AHIM dimensionless area-height template graph, the area and height data from a sample of 24 dams were converted to dimensionless form by :

- dividing the digitised areas at each contour level by the digitised FSL area of the dam; and
- dividing the height above dam invert of each digitised contour by the total farm dam depth (invert to FSL).

The sample of dams used in this representation comprised all dams with four digitised contours describing the dam basin.

An important requirement for the second item above was the dam invert level which, for the purpose of developing the area-height template graph, was estimated by individually scrutinising each of the farm dams in the sample.

Referring to Fig. 2, the results were plotted and a "best-fit" line was obtained through regression. Furthermore, visually fitted "envelope" lines were drawn around the data. These envelopes were subsequently approximated with a polynomial regression to allow later automation.

Data above WL from other dams could now be superimposed on this template graph. The plotting position of these data relative to the envelopes was (through an averaging technique) used to extrapolate a smooth "average" dimensionless area-height curve for a particular farm dam, from invert to full supply level. Referring to Fig. 3, if the dam was not full at the time of aerial photography, at least two digitised level contours were available to non-dimensionalise and superimpose on the template graph. The plotting position of each dimensionless data point was expressed as a ratio. This ratio represented the horizontal distance from the best-fit line to the data point, to the horizontal distance from the best-fit line to the envelope line. The ratios of all the points were averaged and the smooth "average" curve was drawn, so that any point on the curve corresponded with the calculated average ratio.

As mentioned before, the above could not be achieved without knowledge of the total dam basin depth necessary to non-dimensionalise the contour-height data.

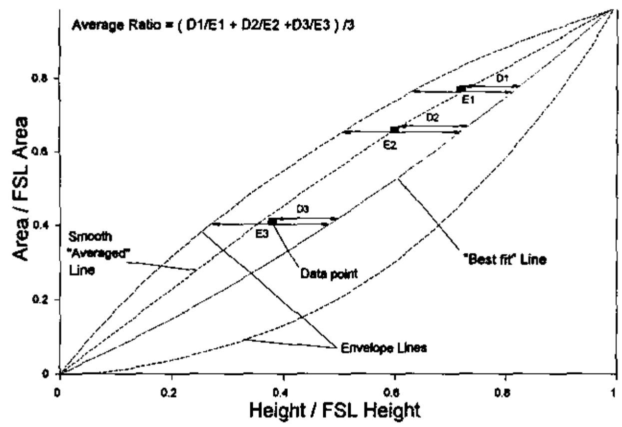

Figure 3
Superimposing data on the AHIM dimensionless area-height template graph

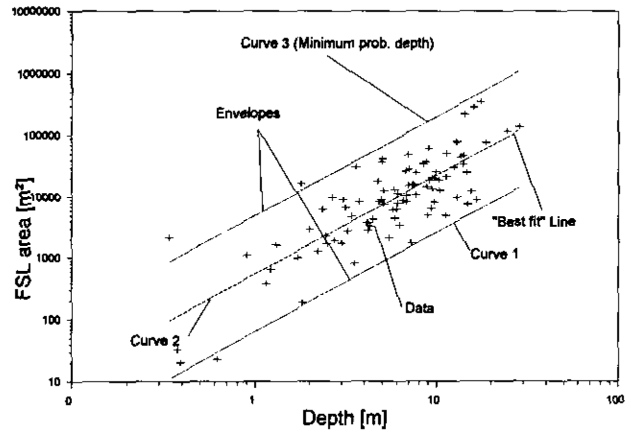

Figure 4
Area at FSL - total depth graph

Estimating the farm dam total depth

Since most farm dams contained some water at the time of aerial photography, their bed invert and consequently basin depth could not be ascertained. Thus the farm dam total depth had to be estimated, which affected the accuracy of further volume computation.

A first estimate of the farm dam total depth was taken as the height difference between the dam spill crest and dam wall toe (extracted from the digitised data). This estimate was subsequently refined if, e.g., the digitised WL was recorded to be lower than the dam wall toe, indicating excavated basins and a deeper dam.

In other cases such as excavated hilltop dams, where toe levels were generally above water surface and depth estimates were difficult to obtain, a "most probable" depth was used.

The following were thus developed to assist in the estimation of farm dam total depth :

- an area at FSL - total depth graph, to check whether the estimated farm dam total depth was within "acceptable" limits.
- a decision flow chart (Fig. 5) to assist in estimating the total depth of the dams and to classify the estimated total depth, giving an indication of depth estimate reliability.

The area at FSL - total depth graph (first item) was derived from the sample of farm dams discussed earlier and represents the relationship of FSL area to farm dam total depth. By making use of a statistical regressed "best-fit" line along with visually approximated envelope lines, the graph was used to define the "most probable" total depth (curve 2 on Fig. 4) and the "acceptable" limits (curves 1 and 3 on Fig. 4) respectively.

The estimated basin depth of any farm dam was restricted by the envelope lines (curves 1 and 3) on Fig. 4. In the case of depth estimates falling outside this acceptable range, this estimate was rejected, and the "most probable" total depth (curve 2) was used as default.

The flow chart (shown on Fig. 5) is divided into four routes, each assisting in the estimation of total depth and each giving an indication of the depth estimate reliability.

Route 1 renders the most accurate depth estimate. In this case, the recorded FSL is greater than the WL and the digitised areas at FSL and WL are not similar (more than 5% different). Furthermore, it was likely that one or two areas at intermediate contours between the WL and the FSL were digitised.

Route 2 on the flow chart renders a reasonably accurate depth estimate. In these dams, the recorded FSL is greater than the WL, but the areas at FSL and WL are similar (within 5%). Route 2 represents a farm dam which is near full, thus only areas at two contour levels are digitised (the WL and FSL).

Route 3 on the flow chart does not provide an accurate estimate of total depth, the reason being that the FSL is recorded to be less than WL, which is erroneous, as the highest WL in the dam must always be the FSL. However, the digitised areas at FSL and WL in these cases are similar (within 5%). This erroneous level recording is probably the result of limitations in the stereographic digitising process.

Route 4 on the flow chart is deemed an inaccurate total depth estimate. In this case, the recorded FSL is less than the WL, which, analogous to Route 3, is erroneous. Furthermore, the digitised areas at FSL and WL are not similar (more than 5% different). An error has thus occurred in the data.

Verification of the AHIM

The verification of the AHIM was performed during stages in its development.

Conceptual verification

During the early stages of the AHIM development, various manual calculations were performed using very rough "envelope" and "best-fit" line estimates in the dimensionless area-height template graph. These early calculations proved promising, and consequently the AHIM concept was further explored.

Initial verification

Initially a comprehensive list of registered and surveyed farm dams was not available and it was decided to base the AHIM verification on the most reliable available data. This was considered to be the digitised farm dams that had four contours describing the basin, rendering area data at four different heights.

For the verification, the dam volume above WL was estimated using two methods :

- the AHIM using the area-height template graph (with averaging technique) and basin total depth estimation; and
- contour averaging.

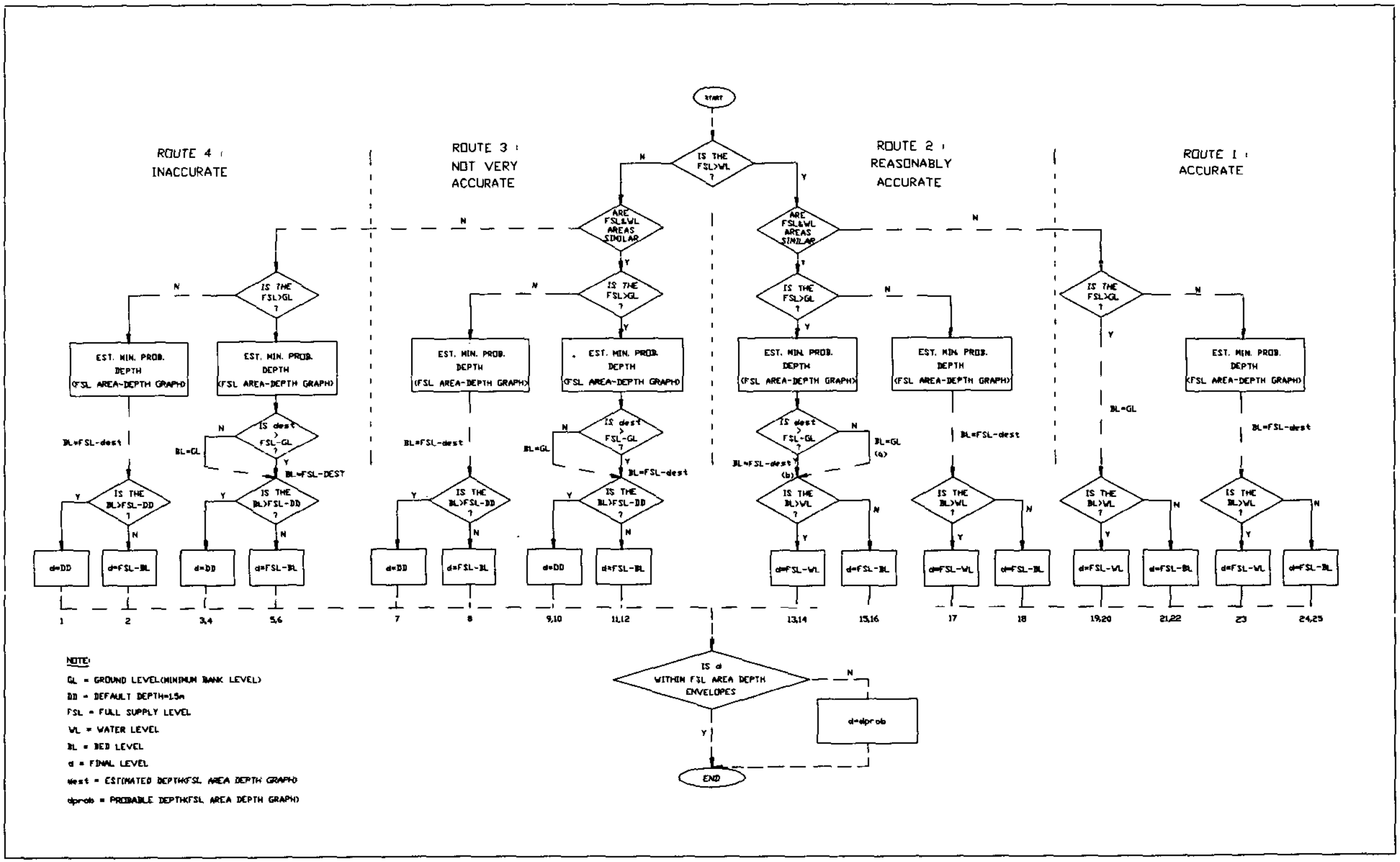

Figure 5
Decision flow chart for total depth estimation

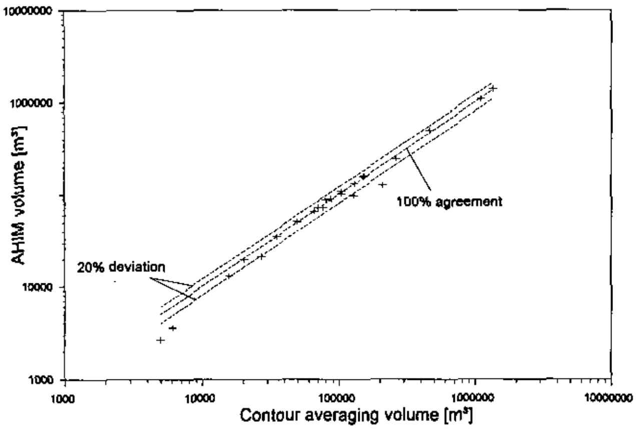

Figure 6

Initial verification : Comparison of volume calculated above WL using the AHIM and contour averaging

TABLE 1 INITIAL VERIFICATION : VALUE-ON-VALUE COMPARISON OF VOLUME CALCULATION ABOVE WL USING THE AHIM AND CONTOUR AVERAGING			
Map No.	**Dam No.**	**Volume above WL (m³)**	
		AHIM	**Contour averaging**
3418BB20	1	1 096 821	1 118 539
3418BB25	12	126 319	211 912
3419AA12	2	89 342	88 324
3419AA16	12	72 327	76 871
3419AA16	19	109 158	106 000
3419AA16	28	51 159	50 009
3419AA17	3	499 037	467 208
3419AA17	4	102 389	105 420
3419AA17	28	1 414 129	1 368 291
3419AA21	7	161 735	154 201
3419AA21	12	245 542	264 289
3419AA21	20	156 461	152 540
3419AA21	40	35 707	35 194
3419AA22	57	72 337	70 930
3419AA22	97	21 513	27 443
3419AA22	98	3 610	6 099
3419AA22	99	2 684	5 016
3419AA23	4	13 051	15 889
3419AA23	18	132 546	132 204
3419AA23	21	98 187	131 190
3419AA23	22	86 988	80 729
3419AC01	6	19 674	20 367
3419AC02	9	65 486	66 081
	Sum of volume	**4 676 213**	**4 754 759**
	% of volume	**- 1.6**	

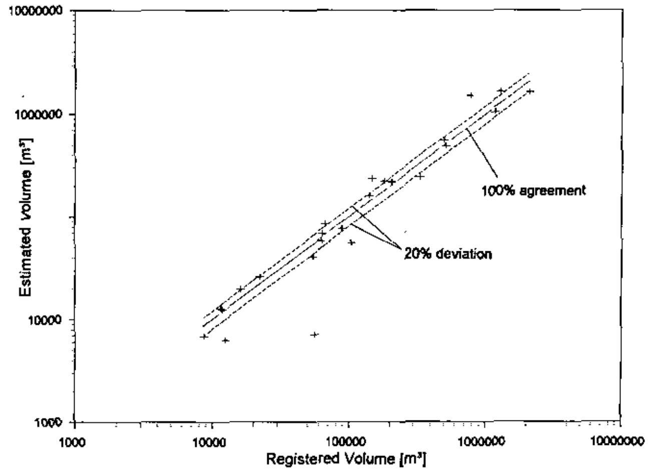

Figure 7

Final verification (using estimated total depths) : Comparison of total registered farm dam volume with calculated total farm dam volume

Figure 6 shows a comparison of volumes above the WL calculated with the two methods, while Table 1 lists the calculated volume for each dam. A regression of the calculated volumes in Table 1 resulted in a favourable R^2 of 0.995. Referring to Fig. 6, the data points are scattered about the 100% agreement line, indicating a favourable comparison. Furthermore, most of the points plot inside the 20% deviation bands giving an indication of the agreement accuracy. The value-on-value comparison in Table 1 shows that in some instances the AHIM estimate is slightly lower, while in others the reverse is true. In summary, the summed total of all the dam volumes shown in the table agrees favourably.

Final verification

Using estimated depths

At a later stage of the AHIM development, the data of a sample of registered and surveyed farm dams became available for further verification. In this verification, the total farm dam volume was estimated using :

- contour averaging for volume calculation above water level; and
- AHIM for volume calculation below water level.

The sum of the above items represents the total volume which was compared with the registered volume. In this verification, the total farm dam depth was estimated using the techniques described earlier. Figure 7 shows a comparison of the calculated and registered volumes, while Table 2 lists the calculated volumes, digitised FSL areas and estimated total depths along with the registered data. A linear regression of calculated on registered volumes produced an R^2 of 0.851. Despite the favourable impression of this technique given by the R^2, it was recognised that :

- some of the farm dams differed with respect to the digitised and registered FSL areas (areas differed by more than 10%); and
- some of the estimated farm dam depths differed significantly from the registered depths.

Using recorded depths

As a sensitivity test of the above verification, the calculation was repeated omitting farm dams where the FSL areas differed

TABLE 2 FINAL VERIFICATION (USING ESTIMATED TOTAL DEPTH) : COMPARISON OF TOTAL REGISTERED FARM DAM VOLUME WITH CALCULATED TOTAL FARM DAM VOLUME						
Farm dam name	**Calculated**			**Registered data**		
	Total volume (m^3)	**Digitised FSL area (m^2)**	**Total depth (m)**	**Total volume (m^3)**	**FSL area (m^2)**	**Total depth (m)**
3419AA21027V	58 345	14 683	14.01	62 900	13 767	8.42
3419AA21015T	12 801	5 232	3.48	11 500	4 309	4.27
3419AA21017H	19 725	6 209	4.22	16 100	7 150	4.46
3419AA21051V	220 412	41 617	13.47	206 300	41 419	12.00
3419AA21052V	557 510	157 344	12.51	502 400	140 307	7.63
3419AA16012T	76 871	12 827	8.05	89 100	13 076	13.88
3419AA16027V	67 834	12 445	12.05	64 100	12 392	10.52
3419AA16034T	491 855	55 181	11.45	517 600	54 746	14.64
3419AA16068V	6 798	4 760	7.76	8 700	4 830	3.78
3419AA16002T	12 508	7 119	3.22	11 970	5 286	3.65
3419AA22008V	56 026	13 149	14.52	103 600	20 052	13.00
3419AA22068V	225 705	28 149	17.77	181 100	26 315	15.10
3419AA22088V	1 532 355	206 478	18.05	769 900	206 895	15.25
3419AA22090V	7 136	13 945	3.22	56 500	15 363	6.10
3419AA22029T	41 125	13 144	5.03	54 400	15 211	7.00
3419AA22045V	1 057 943	176 601	11.78	1 178 200	167 786	13.72
3419AA22057V	84 522	12 114	19.31	66 900	12 470	10.60
3419AA22058H	6 305	2 459	7.36	12 500	4 679	3.50
3419AA17028V	1 648 580	137 337	28.58	2 095 500	158 202	29.15
3418BB20001V	1 667 554	350 352	17.46	1 272 200	345 447	15.25
3418BB25011V	243 459	87 996	10.00	334 600	116 777	8.20
3419AA23011H	25 980	6 628	9.41	22 300	6 766	7.70
3419AA23018V	161 728	30 510	12.53	141 600	28 405	9.45
3419AC02006V	235 357	33 5556	14.73	147 800	30 492	10.67
Totals	**8 518 447**	**1 429 844**		**7 927 870**	**1 452 153**	
Averages	**354 935**	**59 576**	**11.7**	**330 327**	**60 506**	**10.3**
% deviation	**+7.4**	**-1.5**				

significantly and using registered depths instead of estimated farm dam depths throughout.

Figure 8 shows only a slight improvement in the agreement between the calculated and registered volumes. A linear regression of calculated on registered volumes produced a slightly improved R^2 of 0,883. Table 3 shows that some of the estimated volumes are higher while others are lower than the registered volumes. However, in terms of total volume and area of the sample of farm dams, favourable agreement is observed.

Generally, because of the high correlations and good comparisons with registered volumes, the AHIM, along with contour averaging, was deemed an acceptable method of establishing farm dam area-height-capacity relationships for basin-scale hydrological modelling purposes.

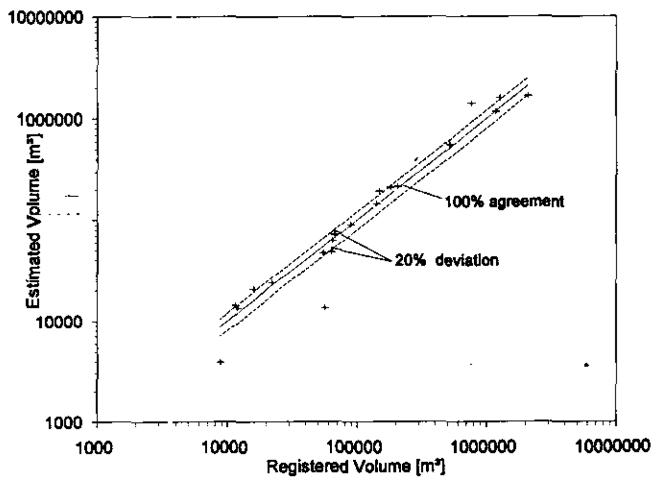

Figure 8
Final verification (using recorded total depths) : Comparison of total registered farm dam volume with calculated total farm dam volume

Problems experienced

The primary source of problems experienced during the development of the AHIM was the digitised data. These problems were either due to human error or to physical/photographic limitations.

The human errors included incorrect height recordings during

TABLE 3
FINAL VERIFICATION (USING RECORDED TOTAL DEPTHS) : VALUE-ON-VALUE COMPARISON OF TOTAL REGISTERED FARM DAM VOLUME WITH CALCULATED TOTAL FARM DAM VOLUME

Farm dam name	Calculated			Registered data		
	Total volume (m^3)	Digitised FSL area (m^2)	Total depth (m)	Total volume (m^3)	FSL area (m^2)	Total depth (m)
3419AA21027V	48 024	14 683	8.42	62 900	13 767	8.42
3419AA21015T	14 182	5 232	4.27	11 600	4 309	4.27
3419AA21017H	20 290	6 209	4.46	16 100	7 150	4.46
3419AA21051V	214 490	41 617	12.00	206 300	41 419	12.00
3419AA21052V						
3419AA16012T	89 845	12 827	13.88	89 100	13 076	13.88
3419AA16027V	62 123	12 445	10.52	64 100	12 392	10.52
3419AA16034T	560 160	55 181	14.64	517 600	54 746	14.64
3419AA16068V	3 956	4 760	3.78	8 700	4 830	3.78
3419AA16002T	13 475	7 119	3.65	11 970	5 286	3.65
3419AA22008V						
3419AA22068V	211 081	28 149	15.10	181 100	26 315	15.10
3419AA22088V	1 407 861	206 478	15.25	769 900	206 895	15.25
3419AA22090V	13 492	13 945	6.10	56 500	15 363	6.10
3419AA22029T	46 852	13 144	7.00	54 400	15 211	7.00
3419AA22045V	1 170 549	176 601	13.72	1 178 200	167 786	13.72
3419AA22057V	71 979	12 114	10.60	66 900	12 470	10.60
3419AA22058H						
3419AA17028V	1 654 814	137 337	29.15	2 095 500	158 202	29.15
3418BB20001V	1 598 444	350 352	15.25	1 272 200	345 447	15.25
3418BB25011V						
3419AA23011H	23 520	6 628	7.70	22 300	6 766	7.70
3419AA23018V	144 445	30 510	9.45	141 600	28 405	9.45
3419AC02006V	193 506	33 555	10.67	147 800	30 492	10.67
Totals	**7 563 099**	**1 168 895**		**6 974 770**	**1 170 336**	
Averages	**378 155**	**58 444**	**10.8**	**348 738**	**58 516**	**10.8**
% deviation	**+8.4**	**-0.1**				

digitising, resulting in severely inaccurate farm dam depth estimates and consequent volumes. These errors were corrected by editing the digitised data files.

The inherent errors resulted from the physical limitations of the photographic digitising process. A typical example of such an error is the recording of a digitised FSL area being slightly less (5%) than the digitised WL area. However, these errors became apparent and were dealt with, according to the depth estimate flow chart (Fig. 5).

Farm dams evaluated in the WCSA study

During the initial evaluation of dams in the basins of the WCSA study, all farm dams in the Riviersonderend and the Palmiet River basins were digitised irrespective of their size. The area-height-capacity relationships of these dams were calculated. Subsequent ranking in ascending order of capacity and graphing the number of dams vs. cumulative total volume (Fig. 9) showed that 80% of all the ranked farm dams contributed to only 20% of their summed total capacity in these two basins. Considering the costs of the photographic

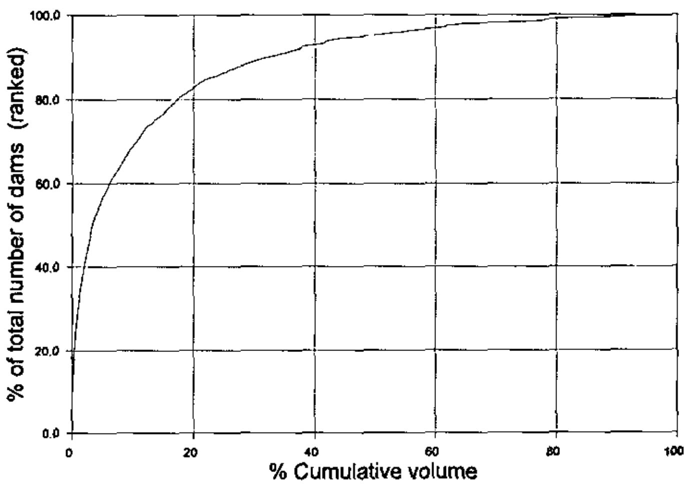

Figure 9
Ranked farm dams in the Riviersonderend and Palmiet River Basins

TABLE 4
SUMMARY OF TOTAL FARM DAMS EVALUATED IN THE WCSA

Details	Berg * River basin	Eerste River basin	Palmiet River basin	Riviersonderend River basin	Total
Tot. vols. (m^3)	45 468 129	22 786 754	24 198 113	11 506 908	103 959 904
Tot. area (m^2)	12 541 468	5 216 356	5 749 316	3 544 272	27 051 412
Av. vol. (m^3)	93 172	122 509	60 646	26 452	30 278 188
Av. area (m^2)	25 699	28 044	14 409	8 147	7 630 122
Av. height (m)	7,20	8,23	6,42	4,18	2 603
No. dams	488	186	399	435	1 508

*Represents the larger 20% of the number of farm dams in the basin.

digitising process and the large number of farm dams in the remaining Berg and Eerste River basins, it was decided to digitise only the larger dams (20% of the total number in the basin) and to factor the volumes accordingly. This resulted in considerable savings in both time and costs. Table 4 lists the total areas and capacities for each basin and for the total study area.

For the hydrological catchment modelling, the resulting area-height-capacity relationship of each individual farm dam was converted to yield the areas and capacities assuming the dam was at a range of percentages of the FSL volume, namely 0%, 25%, 50%, 75% and 100%. These data were subsequently stored on a geographic information system (GIS).

Based on the assumption that the dams generally fill and empty at a similar rate, the areas and capacities at 0%, 25%, 50%, 75% and 100% of the FSL volume of all farm dams in a particular sub-catchment were extracted from the GIS database and summed. The result was assumed to represent the area-capacity relationship of a single (equivalent) dam at 0%, 25%, 50%, 75% and 100% of the FSL volume. This was consequently approximated with a power curve, the coefficients of which were required for input into hydrological modelling programs.

Subsequent to the implementation in the WCSA, this technique of evaluating farm dam area-height-capacity relationships has been used to support basin-scale catchment modelling of the Algoa water supply region, the Upper Kei basin and the Amatole water supply system.

Conclusions

- Through verification tests, the AHIM, along with contour averaging, was found to be an acceptable method of evaluating farm dam area-height-capacity relationships. This method gave favourable results when compared to surveyed registered farm dam data.
- The AHIM is expected to be more reliable when there are a number of digitised contours describing the basin of the farm dam (i.e. three or four contours).
- The AHIM along with contour averaging was highly suitable to automation and could thus be incorporated in computer software. In view of the large number of farm dams in the WCSA study area, this proved beneficial.
- Most of the problems encountered were related to the digitised data. These errors were easily detected.

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References

MAAREN, H and MOOLMAN, J (1985) The effects of farm dams on hydrology. *Proc. 2nd S. Afr. Natl. and Hydrol. Symp.*, Pietermaritzburg.

PITMAN, WV and PULLEN, RA (1989) The impact of minor dams on the water resources of the Upper Olifants River Basin. *Proc. 4th S. Afr. Natl. and Hydrol Symp.*, Pretoria.

TARBOTON, KC and SCHULZE, RE (1990) Impacts of increased afforestation and farm dams on water resources of the Upper Mgeni Catchment. *Proc. 22nd Natl S. Afr. Inst. of Agric. Eng. Symp.*, Cape Province.