1976/002

COMMONWEALTH FUND FOR TECHNICAL CO-OPERATION

COMMONWEALTH SECRETARIAT

A RECONNAISSANCE STUDY FOR MAJOR SURFACE WATER SCHEMES IN EASTERN BOTSWANA

PHASE I REPORT

MARCH 1976

SIR ALEXANDER GIBB & PARTNERS
READING and LONDON

JVS

(Alan Crutford)

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2nd April 1976

The Managing Director,
Commonwealth Fund for Technical Co-Operation,
Commonwealth Secretariat,
Marlborough House,
Pall Mall,
London SW1Y 5HX

Dear Sir,

Reconnaissance Study for Major Surface Water Schemes in Botswana

In accordance with our Agreement dated 19th December 1975, we have pleasure in submitting our Phase I report on the above study. Our Terms of Reference are reproduced in Appendix A of this report.

Following our work in Botswana and discussions there and in South Africa, 73 possible dam sites were identified which are listed in Table No. 2.1. Subsequent work in the United Kingdom on hydrological and other aspects of the study lead us to believe that selection of sites for further investigation in Phase II could be made from 26 most favourable sites, details of which are given in Table 4.1. These sites are additional to nine sites which satisfy the yield criterion set by the Terms of Reference but have been the subject of previous reports.

We look forward to receiving your instructions regarding Phase II of the study.

Yours faithfully,
for SIR ALEXANDER GIBB & PARTNERS

WTN Reeve

ACKNOWLEDGEMENTS

We wish to record our sincere appreciation of the co-operation, assistance and advice we have received from all concerned with the study. Some of the principal organisations and individuals concerned (in Botswana unless otherwise stated) were as follows:

1. The Reference Group.
2. The Secretary of External Affairs.
3. The Director of Water Affairs and his staff, particularly Messrs. Wilson (also in the Reference Group) Bjorkman, Wallander, Drake, Dewar and Wikner.
   The Assistant Director, Mapping, Department of Surveys and Lands and his staff.
5. Messrs. Jones, Mosetse, Holmberg and Gale of the Geological Survey and Mines Department.
6. The Director, Weather Bureau.
7. Mr. David Field of the Land Utilization Division, Ministry of Agriculture.
8. Professor D. C. Midgley of the University of the Witwatersrand, Johannesburg.
9. Mr. Du Plessis, Engineer Manager (Design) of the South African Ministry of Water Affairs, and members of his staff.

CONSULTANTS ASSOCIATED WITH THE STUDY

Dr. J. V. Sutcliffe of the Institute of Hydrology, Wallingford, England has been largely responsible for the hydrological aspects of the study.

Mr. K. S. Jones, of Golder Hoek and Associates advised on geological aspects of the study.

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CHAPTER 1

INTRODUCTION

1.1 Terms of Reference

The terms of reference for the study are set out in the enclosure to a letter dated 29th July 1975 from the Commonwealth Secretariat, and are reproduced as Appendix A to this Report.

Phase I of the study entails essentially the indentification from aerial photographs of likely dam sites in Eastern Botswana, and the selection from these sites of those having adequate hydrological characteristics such that they can be developed to yield at least 1000 cubic metres per day (for small rivers) and 5000 cubic metres per day(for large rivers) at the 1 in 50 year risk of failure.

1.2 Method of Study

Work in Phase 1 has involved the following personnel:

Project Engineer
Engineer
Senior Hydrologist
Hydrologist
Geologist
Consultant

(a) Work in Botswana

The Engineer started assembling relevant data including hydrological records, aerial photographs and reports in December 1975.

The Project Engineer was in Botswana from 6th to 26th January 1976 during which time he was principally engaged in the study of aerial photographs and maps at the photographic library of the Department of Surveys and Lands. Discussions were held with Government Officers. Possible sites in the vicinity of Gaborone were visited, but it was not found necessary to examine more distant sites either on the ground or from the air.

The Senior Hydrologist was in Botswana from 15th to 30th January 1976, engaged principally in the acquisition of meteorological and hydrological data in Gaborone and Francistown. Discussions were held with Government Officers and others.

(b) Work in adjoining countries

The Project Engineer visited the South African Ministry of Water Affairs in Pretoria on 27th January 1976 to discuss possible dam sites on the Limpopo and Marico Rivers and to obtain additional data.

The Senior Hydrologist had useful discussions with Professor D.C. Midgley at the University of the Witwatersrand in Johannesberg on 14th January. A large amount of meteorological and hydrological data was provided by the Ministry of Water Affairs, Pretoria.

Consideration was given to the possibility of visiting Rhodesia but discussion by telephone with the Regional Water Engineer in Bulawayo revealed that Rhodesia has no plans for developing the border rivers. Adequate meteorological and hydrological data was obtained by post and it was therefore considered that a visit was not necessary.

(c) Work in the United Kingdom

Assessment of dam site geology and catchment areas, reservoir characteristics and the main hydrological analytical work was carried out in the United Kingdom during February and March 1976.

CHAPTER 2

IDENTIFICATION OF DAM SITES

2.1 Availability of Aerial Photographs

Use was made of two series of aerial photographs:

(a) The whole of Eastern Botswana, from the desert fringes in the west to the eastern boundaries, is covered by a recently flown 1 : 50 000 scale series. Flight direction is either east to west or west to east. The series is divided into the following three blocks:

(i) Matsitama Block, covering approximately the area north of 21 degrees 30 minutes south, and west of 27 degrees east.

(ii) Motloutse Block, covering the remaining area of Eastern Botswana north of 23 degrees south.

(iii) South East Block, covering all of Eastern Botswana south of 23 degrees south.

The quality of these photographs is excellent, and only a minute proportion of the area is obscured by cloud cover.

(b) An older 1 : 10 000 series covering the Taupye, Motloutse and Thune Rivers. Flight direction is along the river. Again the quality of the photographs is excellent.

2.2 Availability of other data

A number of dam sites have been investigated in recent years. Reports prepared by BGA Lund and Partner relating to the following sites were consulted.

Tobane
Mahalapye
Timbale
Kanye
Palapye
Molepolole

A report prepared by Brian Colquhoun, Hugh O'Donnell and Partners in November 1970 gave information on dam sites near the Selkirk/Pheonix mining prospects on the Ramokgwebana, Tati and Shashe Rivers.

Our own reports relating to water supplies for Shashe and Lobatse have also been used.

2.3 Initial study of aerial photographs

The initial study of the 1 : 50 000 scale aerial photographs was made in conjunction with the 1 : 50 000 scale map series which,either in final or in some cases preliminary form, covers the whole of the area under study.

There were two possible methods of approach:

(i) Individual rivers could be studied from source downstream; this would involve transferring from one run of aerial photographs to the next as the river moved north or south away from the general direction of flights.

(ii) Each run of aerial photographs could be studied in its entirety; this would involve moving from river to river.

Both methods were tried and the second was found to be the more satisfactory; the whole area under study was therefore studied systematically starting in the north and working southwards.

The following general criteria were adopted in selecting possible sites although each site was also considered on its own merits.

(a) A natural narrowing of the river cross-section with relatively high banks would be desirable in order to limit the length of the dam and provide adequate water depth.

(b) The area upstream should ideally have a broad flat valley with steep U-shaped side slopes in order to provide good reservior basin characteristics and to reduce evaporation losses in proportion to the potential storage volume. A site just downstream of a tributary confluence has advantage in that the reservoir encompasses two sections of river valley.

(c) For the type of dam appropriate to conditions in Botswana the cost of the spillway is an important part of the whole. For this reason one bank of the river at or near to the dam site should provide a good spillway site; the presence of rock on which a simple overflow weir type of spillway can be constructed, and which will withstand corrosive forces downstream, is an important factor in reducing the cost of the structure. Advantage can sometimes be taken of an adjacent river or tributary by using the intervening saddle for a spillway site.

From this initial study of the 1 : 50 000 scale aerial photographs and maps a total of 68 possible dam sites were identified and allocated reference numbers in sequence from 1 to 68.

Subsequent study of the 1 : 10 000 scale aerial photographs revealed one further possible dam site on the Thune river near dam site No. 42 on the Lekgolwe river. As these two sites were mutually exclusive the Thune site was allocated the reference number 42A.

2.4 Discussion with reference group

The possible dam sites referred to above were plotted on a 1 : 250 000 wall map and discussed with the Reference Group. The following points were made by the Senior Hydrological Engineer, Department of Water Affairs:

(a) Although dam site No. 68 on the Marico at Derdepoort would have most of the dam and all the reservoir in South Africa it should be retained as a possibility.

(b) There was a possibility of additional sites at the following locations:

(i) On the Limpopo River just below its confluence with the Motloutse River.
(ii) On the Motloutse River just below its confluence with the Thune River.
(iii) On the Notwani River just above its confluence with the Limpopo River.
(iv) On the Mhalapshwe River just upstream of the road bridge at Mahalapye.

(c) It was disappointing that no sites had been identified on the lower reaches of the Lotsane River.

2.5 Re-examination of aerial photographs

Following the discussion referred to above relevant aerial photographs were re-examined, leading to the identification of two additional sites at locations referred to in 2.4 (b) (i) and (ii). These were allocated reference numbers 69 and 70 respectively. Unfortunately the other locations referred to in 2.4 (b) and (c) did not appear promising.

2.6 Discussion in South Africa

Possible sites on the Limpopo and Marico Rivers were discussed with Mr. Du Plessis, Engineer Manager(Design) of the South African Ministry of Water Affairs and members of his staff with the following results:

Site No. 69 · Just downstream of the confluence of Limpopo and Motloutse Rivers. This site is known to the Ministry as the Ratho site, is considered promising and suitable for a dam about 30 metres high. No site investigations have been carried out.

Site No. 43 Just downstream of the confluence of Limpopo and Stinkwater Rivers. Known to the Ministry but not considered very promising.

Site No. 57 On the Limpopo downstream of Buffels Drift. Not known to the Ministry.

Site No. 58 On the Limpopo upstream of Buffels Drift. Not known to the Ministry.

Site No. 68 On the Marico at Derdepoort. Not known to the Ministry. However a site at Eerstepoort about 25 km. upstream was being investigated as a source of supply for the proposed new Tswana homeland capital of Bophuthaswaana. There appears to be a possibility, however remote politically, that this site, which seems more favourable than site No. 68, could be developed jointly by Botswana and South Africa, in which case it could be suitable as a source of supply for Gaborone. It has therefore been accepted as a possible site, but as it would be mutually exclusive with Site No. 68 it has been allocated reference No. 68A.

One further site on the Limpopo was suggested by the Ministry just downstream of Martins Drift, which has been allocated reference number 71.

Mr. Du Plessis was most interested in the study and offered to be of assistance in arranging access should any of the border sites be included in Phase II. There was also the possibility that South Africa would offer to share site investigation costs at a later stage.

2.7 Consolidated list of possible sites

A total number of 73 possible dam sites have been identified. Their locations are shown on Map No. 7548/1 which also indicates catchment boundaries. Table No. 2.1 gives geographical co-ordinates for each site together with the reference numbers of relevant aerial photographs and 1 : 50 000 scale maps.

The following sites have been included for completeness but had been identified prior to this study:

Site No. 1 Mosetse site proposed as a source of supply for Sua Pan Project. Report by BGA Lund & Partners (Lund).

Site No. 9 Timbale site on Tati River: Report by Lund.

Site No. 14 Lower Wolf Hills site on Tati River: Report by Brian Colquhoun, Hugh O'Donnell and Partners (Colquhoun)

Site No. 18 Shashe below Tati confluence: Report by Colquhoun.

Site No. 22 Shashe below Ramokgwebana confluence: Report by Colquhoun.

Site No. 32 Tobane site on Motloutse River: Report by Lund.

Site No. 45 Palapye site on Lotsane River: Report by Lund.

Site No. 54 Mahalapye site on Mhalapshwe River: Report by Lund.

Site No. 59 Molepolole Site: Report by Lund.

Site No. 63 Kanye Site: Report by Lund.

Site No. 64 Tsiklane Site

Site No. 65 Chawe Site

Site No. 66 Peleng Site

Site No. 67 Ramoutsa Site

Referred to in Gibb Reports on Lobatse Water Supply

TABLE No. 2.1

CONSOLIDATED LIST OF POSSIBLE DAM SITES

SERIAL NUMBER	RIVER	1:50000 MAP NUMBER	LOCATION S	LOCATION E	AERIAL PHOTOGRAPHS RUN	AERIAL PHOTOGRAPHS NUMBERS
A) MATSITAMA BLOCK						
1	MOSETSE	2026D1	20°40'	26°33'	BT3	015,016,017
2	MOSOPE	2026D3	20°59'	26°35'	BT6	217,218
B) MOTLOUTSE BLOCK						
3	TUTUME	2027C1	20°31'	27°04'		9139,9140
4	GHOSHWE	2027C1	20°33'	27°06'		9341,9342
5	MASHAWE	2027C1	20°37'	27°14'	2	9344,9345
6	SHASHE	2027C2	20°36'	27°18'	2	9345,9346
7	NTSHE	2027D1	20°42'	27°34'	4	9371,9372
8	NTSHE	2027C4	20°46'	27°30'	5	9039,9040
9	TATI	2027C4	20°52'	27°27'	6	8927,8928
10	NTSHE	2027D3	20°51'	27°31'	6	8929,8930
11	SENJA	2027D3	20°55'	27°41'	7	9925,9926
12	SHASHE	2027C4	20°59'	27°20'	8	8850,8851,8852
13	TIAYE	2027D3	20°59'	27°41'	8	8858,8859
14	TATI	2127B3	21°18'	27°36'	12	8700,8701,8702
15	RAMOKGWEBANA	2127B4	21°17'	27°53'	12	8707,8708
16	TATI TRIBUTARY	2127B4	21°22'	27°47'	13	8651,8652
17	TATI	2127B3	21°23'	27°40'	13	8654,8655
18	SHASHE	2128C1	21°34'	28°00'	15	8323,8324,8325
19	TATI	2127B4	21°29'	27°50'	15	8327,8328
20	SASAU	2127D1	21°39'	27°34'	16	8347,8348
21	SHASHANE	2127D1	21°34'	27°44'	16	8350,8351
22	SHASHE	2128C1	21°35'	28°03'	16	8358,8359

23	SHAPE	2128C2	21°37'	28°23'	16	8365,8366
24	SESWE	2127C2	21°37'	27°21'	16	8584,8585
25	SEMPAWANE TRIBUTARY	2127D2	21°44'	27°55'	18	8499,8500
26	GOBE	2128D1	21°43'	28°40'	18	8516,8517
27	SHASHE	2128D4	21°43'	28°47'	18	8518,8519,8520
28	MABOLWE	2128D4	21°47'	28°56'	18	8521,8522,8523
29	SHASHE	2128D4	21°46'	28°59'	18	8523,8524
30	SEKGOPYE	2128C3	21°49'	28°14'	19	0316,0317
31	MOTLOUTSE	2127D3	21°51'	27°44'	19	0326,0327
32	MOTLOUTSE	2127D4	21°52'	27°59'	20	9280,9281
33	MOTLOUTSE	2128C3	21°53'	28°10'	20	9284,9285
34	MOTHWANE	2128C4	21°52'	28°28'	20	0480,0481
35	METSEMASWAANE	2128D3	21°54'	28°41'	20	0476,0477
36	MMAJALE	2128D4	21°58'	28°57'	20	0470,0471
37	BOJALE	2228B2	22°00'	28°58'	21	9421,9422
38	MASHEDANE	2228B2	22°00'	28°46'	21	9426,9427
39	MOLALATAU	2228B1	22°02'	28°39'	21	9428,9429
40	MOTLOUTSE	2228B2	22°04'	28°46'	22	9718,9719
41	SELEPSWE	2228B2	22°11'	28°46'	23	9748,9749
42	LEKGOLWE	2228B1	22°11'	28°36'	24	0929,0930,0931
42A	THUNE	2228B1	22°10'	28°35'	23	9752,9753
43	LIMPOPO	2228B4	22°22'	28°58'	25	0813,0814,0815
44	MADIKEETANE	2228D1	22°32'	28°39'	28	0084,0085
45	LOTSANE	2227C1	22°33'	27°05'	29	0156,0157
46	LOTSANE	2227D1	22°36'	27°37'	29	0168,0169
47	BOLOWA	2227D1	22°44'	27°42'	31	0644,0645,0646
48	SELIPA	2226D1	22°42'	26°33'	32	0590,0591
49	KUTSWE	2226D1	22°43'	26°36'	32	0592,0593
50	SEMAKWAKWE	2227C4	22°48'	27°20'	33	0556,0557

C) SOUTH EAST BLOCK

51	MHALAPSHWE	2326B2	23°01'	26°47'		031,032
52	BONWAPITSE TRIBUTARY	2326B1	23°02'	26°34'		036,037
53	-do-	2326B1	23°01'	26°31'		037,038
54	MHALAPSHWE	2326B2	23°05'	26°50'	2	069,070
55	TAUPYE	2327A1	23°15'	27°03'	4	166,167
56	BONWAPITSE	2326B4	23°22'	26°46'	6	096,097
57	LIMPOPO	2327C1	23°36'	27°06'	9	153,154,155
58	-do-	2326D4	23°56'	26°56'	14	059,060
59	MOLEPOLOLE	2425B3	24°26'	25°31'	20	030,031
60	DITEJWANE	2425A4	24°28'	25°27'	21	096,097
61	KOLOBENG	2425D1	24°40'	25°41'	24	019,020
62	METSEMOTLHABA	2425D1	24°42'	25°32'	24	023,024
63	TSUBE	2425C4	24°49'	25°18'	26	018,019
64	MOLOPYE	2425D3	24°57'	25°39'	27	085,086
65	CHAWE	2525B1	25°01'	25°38'	28	102,103
66	PELENG	2525B1	25°11'	25°44'	31	083,084
67	NOTWANI	2425D4	24°55'	25°52'	27	090,091
68	MARICO	2426C2	24°39'	26°24'	23	237,238
68A	MARICO	2426CD*	24°52'	26°27'	Not available	

D) MOTLOUTSE BLOCK

69	LIMPOPO	2229A1	22°13'	29°02'	24	0920, 0921, 0922
70	MOTLOUTSE	2228B2	22°12'	28°57'	24	0923, 0924
71	LIMPOPO	2227D4	22°58'	27°57'	34	0439,0440

* South African series

2.8 Dam Site Characteristics

a) Catchment areas

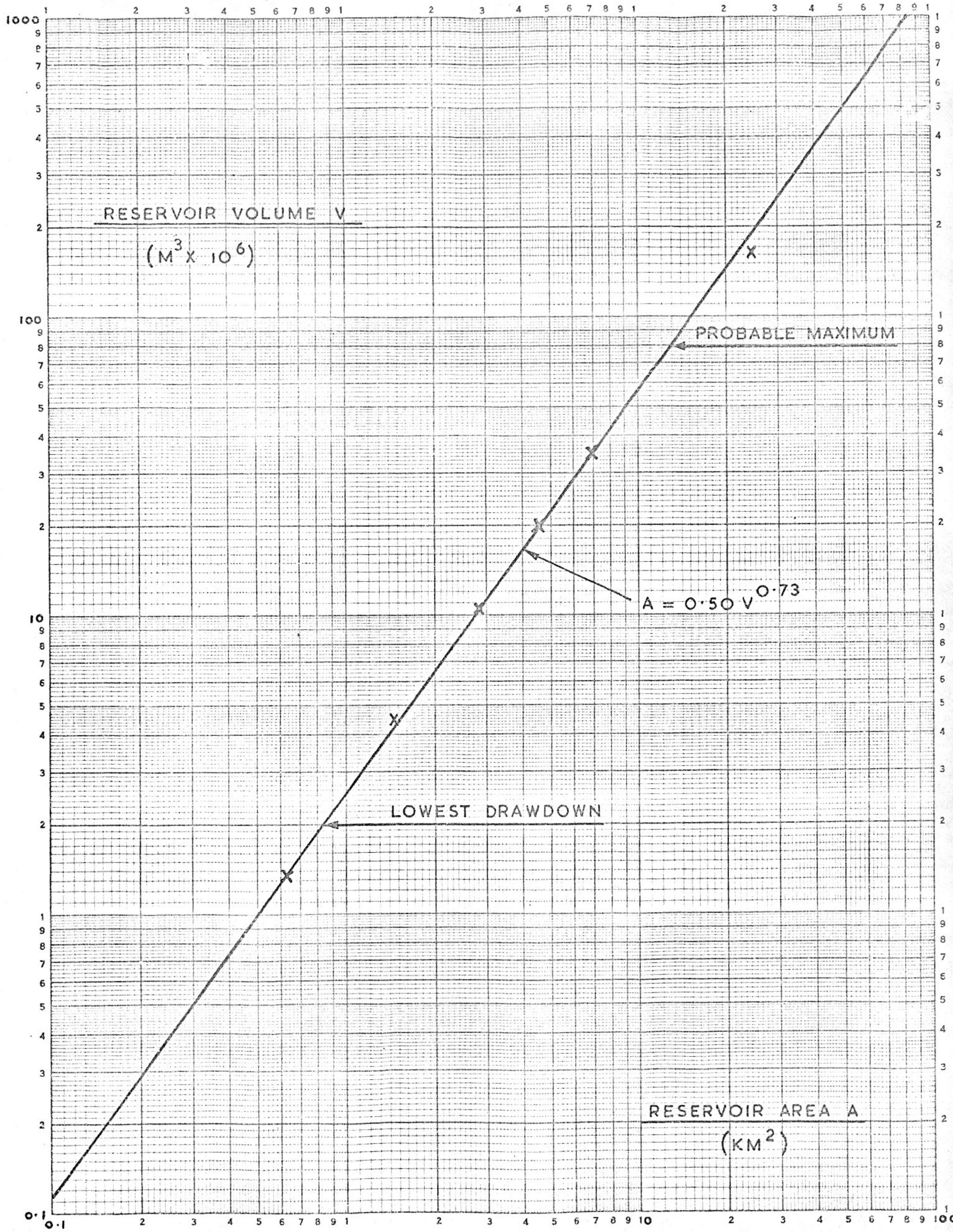
Catchment areas have been determined by planimetering from 1 : 50 000 scale maps for most of the possible dam sites. For the larger catchment areas(the Motloutse sites for instance) 1 : 250 000 scale maps have been used, and for the largest catchment areas of the Limpopo and Shashe sites it has been necessary to use 1 : 1 000 000 scale maps. We have excluded the catchment areas of the existing Shashe and Gaborone dams in the case of downstream sites.

The catchment boundaries on the desert fringes to the west are difficult to identify, and we have ignored those areas where the drainage pattern appears indistinct. The catchment boundaries shown on Map 7548/1 are not precise and are intended only to illustrate the general extent of the catchment area for each site.

b) Reservoir areas and volumes

For those sites where previous reports have been prepared the site has been surveyed and reservoir area and volume curves are available. For the other sites the information available is confined to the 1 50 000 scale maps. In most cases the contour interval is 25 feet but this increases to 50 feet for some sites. It will therefore be appreciated that only approximate reservoir characteristics can be established from these small scale maps, and this has been done by planimetering round the contours that are shown.

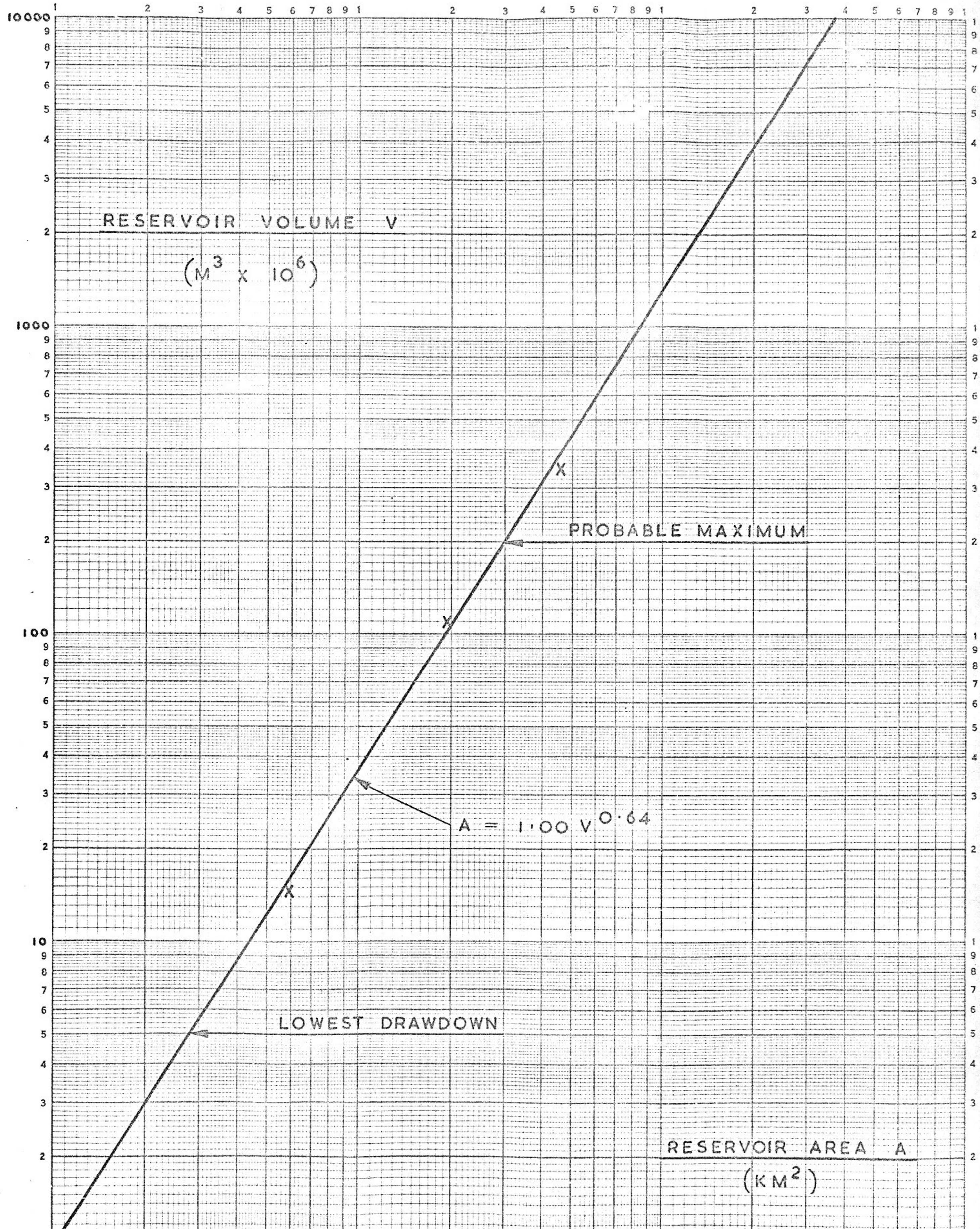
In order to make the best use of this information we have plotted reservoir area against volume on logarithmic graph paper. Typical results are given on Figures 2.1 and 2.2 showing the results for a previously surveyed site and for an un-surveyed site respectively. For the surveyed site all the points lie reasonably well on a straight line, which gives some grounds for hoping that even where only two or three points are available in the case of an un-surveyed site, the resulting line will not be too inaccurate.



DAM SITE No. 14 ON RIVER TATI AT WOLF HILLS

(TYPICAL PREVIOUSLY SURVEYED SITE)

FIGURE No. 2.1



DAM SITE No. 17 ON RIVER TATI

(TYPICAL UN-SURVEYED SITE)

FIGURE No. 2.2

From the graph an equation relating area to volume has been determined for each site in the form:

$$A = C\,V^{N}$$

where A = reservoir area in square kilometres

V = reservoir volume in million cubic metres

and C and N are constants.

The maximum water depth D_1 for any volume V_1 can be determined from the expression

$$D_1 = \frac{V_1^{(1 - N)}}{C\,(1 - N)} \text{ metres}$$

These characteristics have been used in the determination of reservoir yield described subsequently in Chapter 3.

For any site the lowest drawdown level and maximum possible capacity are of importance. For the lowest drawdown we have assumed a minimum depth of water of 3 to 4 metres, in order to make some allowance for future siltation and to facilitate intake construction. At some sites a natural feature such as a saddle suitable for the spillway will limit the maximum capacity, but at others there may be no limitation apart from the likely cost of the dam in relation to the likely yield. However, for all sites we have made an approximate estimation of maximum capacity bearing all relevant topographical factors in mind as far as is possible at this early stage of design. There may also be a hydrological restraint affecting the maximum capacity, and this aspect is considered in Chapter 3.

Table 2.2 shows catchment areas, the derived reservoir constants C and N, and our estimate of maximum capacity and the corresponding maximum water depth resulting from the consideration of topographical factors for all the sites, which are arranged in descending order of catchment area.

TABLE No. 2.2

DAM SITE AND RESERVOIR CHARACTERISTICS

Dam Site Reference Number	River	Catchment area (Sq. km)		Reservoir Characteristics		
					Probable Maximum Capacity	
				N	Volume of water ($m^3 \times 10^6$)	Maximum water depth (m)
69	Limpopo	135 000 (1)	4.25	0.43	2 000	31
43	Limpopo	117 000 (1)	0.88	0.57	200	26
71	Limpopo	86 000 (1)	0.58	0.75	500	33
57	Limpopo	59 000 (1)	2.10	0.60	1 000	19
58	Limpopo	42 000	0.81	0.73	1 000	30
29	Shashe	14 400 (2)(3)	1.40	0.47	300	28
27	Shashe	13 800 (2)(3)	0.55	0.54	150	40
70	Motloutse	13 100	0.66	0.70	500	33
68	Marico	9 600	0.82	0.67	1 000	36
40	Motloutse	9 200	0.50	0.72	200	31
68A	Marico	8 200	0.95	0.66	1 000	32
33	Motloutse	6 700	1.20	0.60	150	15
22	Shashe	6 100 (2)(3)	0.56	0.73	300	31
32	Motloutse	6 000	0.67	0.71	80	18
46	Lotsane	5 700	0.60	0.72	200	26
18	Shashe	4 000 (2)	0.60	0.81	160	23
31	Motloutse	3 700	0.53	0.72	200	30
19	Tati	2 600	0.60	0.67	150	26
45	Lotsane	2 500	0.74	0.77	50	14
42A	Thune	2 400	0.43	0.70	40	23
17	Tati	2 400	1.00	0.64	200	19
67	Notwani	2 200	1.90	0.52	200	14
14	Tati	1 740	0.50	0.73	80	24
15	Ramokwebana	1 700 (3)	1.00	0.60	75	14
56	Bonwapitse	1 540	0.50	0.73	50	21
12	Shashe	1 450	0.87	0.65	125	18
1	Mosetse	1 310	1.60	0.58	500	20
2	Mosupe	1 030	1.70	0.55	300	17
50	Semakwakwe	1 000	0.75	0.73	100	17
54	Mhalapshwe	880	0.56	0.69	50	19
64	Molopye	870	0.47	0.68	20	17

(1) Excluding catchment area of existing Gaborone Dam

(2) Excluding catchment area of existing Shashe Dam

(3) Excluding catchment areas of existing Madabe and Ingwezi Dams

Table No. 2.2 (cont'd)

Dam Site and Reservoir Characteristics

Dam Site Reference Number	River	Catchment area (Sq. km)			Reservoir Characteristics — Probable Maximum Capacity: Volume of water ($m^3 \times 10^6$)	Maximum water depth (m)
62	Metsemotlhaba	800	0.92	0.50	60	17
55	Taupye	660	0.57	0.67	50	19
42	Lekgolwe	475	0.37	0.75	20	23
51	Mhalapshwe	440	0.51	0.65	50	22
10	Ntshe	440	0.40	0.68	50	27
9	Tati	380	0.28	0.80	25	34
8	Ntshe	375	0.35	0.73	50	30
63	Tsube	330	0.43	0.74	10	16
24	Seswe	290	0.53	0.72	25	17
65	Chawe	255	0.52	0.67	15	14
7	Ntshe	240	0.42	0.65	50	27
37	Bojale	235	0.52	0.66	20	16
41	Selepswe	230	0.38	0.56	20	22
3	Tutume	210	0.40	0.80	20	23
66	Peleng	205	0.32	0.71	10	21
30	Sekgopye	205	0.40	0.71	15	19
35	Metsemaswaane	185	0.63	0.63	20	13
36	Mmajale	175	0.48	0.72	15	16
47	Bolowa	170	0.74	0.54	30	14
61	Kolobeng	165	0.36	0.59	20	23
34	Mothwane	150	0.48	0.60	15	15
6	Shashe	115	0.53	0.76	20	16
38	Mashedane	93	0.40	0.71	10	17
59	Molepolole	89	0.17	0.66	2	22
13	Tiaye	86	0.37	0.78	20	24
28	Mabolwe	86	0.24	0.73	20	35
39	Molalatau	86	0.56	0.63	10	11
4	Ghoshwe	75	0.52	0.66	10	12
25	Sempawane tributary	69	0.66	0.57	10	9
49	Kutswe	69	0.36	0.67	5	14
48	Selipa	60	0.29	0.70	5	19
20	Sasau	56	0.50	0.69	10	13
26	Gobe	52	0.35	0.73	10	20

Table No. 2.2 (cont'd)

Dam Site and Reservoir Characteristics

Dam Site Reference Number	River	Catchment area (Sq. km)	Reservoir Characteristics			
					Probable Maximum Capacity	
					Volume of water ($m^3 \times 10^6$)	Maximum water depth (m)
16	Tati tributary	51	0.58	0.62	7.5	10
11	Senja	46	0.60	0.60	15	12
60	Ditejwane	38	0.25	0.67	5	21
5	Mashawe	34	0.85	0.54	8	7
44	Madikeetane	33	0.22	0.70	1	15
23	Shape	26	0.38	0.60	5	13
53	Bonwapitse tributary	26	0.26	0.73	5	22
21	Shashane	24	0.43	0.62	7.5	13
52	Bonwapitse Tributary	18	0.48	0.67	5	11

CHAPTER 3

HYDROLOGY

3.1 Objective

The purpose of this hydrological study has been to use all the information currently available to make a reasonable estimate of the mean run-off and the variability of run-off at any site in Eastern Botswana, in order to assess the yield of potential reservoirs of a given volume at a number of sites. The method of estimate must be indirect in most cases and must therefore be based on a relationship between rainfall and runoff, and thus depends not only on the volume and reliability of available information but also on the uniformity and predictability of this relationship.

The records which are available comprise about 55 rainfall stations whose length of record is up to 60 years, a fairly sparse network in view of the size of the area; a few meteorological stations where evaporation can be estimated; and a small number of river flow gauging stations, currently 13 including reservoir sites, with periods of records from 3 to 13 years. The mean annual rainfall and the evaporation appear to vary fairly steadily with position, so that the number of point values is probably sufficient to determine the main feature of the mean annual values, except perhaps in the lower and drier areas near the Limpopo - Shashi confluence and near isolated hill features. On the other hand, the variable incidence of individual storms and probable variation of rainfall/run-off response with geology, topography, soils and vegetation mean that run-off is more variable in time and space and would require more stations with longer periods of records for a reliable assessment.

The records from Eastern Botswana have been supplemented by records from adjacent areas of Rhodesia and South Africa. These include rainfall records which are summarised in the form of isohyetal maps, evaporation records and a number of run-off records.

Method of Analysis

The hydrological analysis was based on the production of an isohyetal map showing the distribution of mean annual rainfall in Eastern Botswana and adjacent areas, the assessment of mean annual run-off at sites where measurements have been made, and the deduction of a series of curves relating mean annual run-off to mean annual rainfall. These curves are largely based on investigations by Professor D.C. Midgley in South Africa, but the choice of regional curve is based on local records. The mean annual run-off at an ungauged site, such as a reservoir site, can be deduced from region, catchment area and mean annual rainfall.

The gross yield of a reservoir, or the sum of supply (or net yield) and evaporation losses, depends not only on mean annual run-off and the volume of the reservoir, but also on the variability of run-off from year to year; the net yield depends on the evaporation during the design drought and therefore on the reservoir area. Because the period of flow records is short, these records require extension before the drought flows of a given frequency can be deduced. In Phase I , the time available for analysis after the receipt or calculation of flow records has been short, and reliance has been placed on dimensionless flow frequency curves derived from adjacent South African records: it is intended to supplement this analysis in Phase II by using a rainfall run-off model to extend selected run-off series. The reservoir evaporation has been estimated for a selection of sites by the methods described in Midgley and Pitman (1969) and dimensionless relations between net yield and reservoir capacity have been expressed in terms of mean annual run-off. The ratio of reserve or dead storage to mean annual run-off appears to be the main factor in controlling the dimensionless relationship reducing gross yield to net yield, and because the dead storage cannot be reliably estimated without survey, a single graph can be used at this stage to estimate net yield of 1 in 50 year frequency as a percentage of mean annual run-off.

Reliability of results

It is necessary at this stage to stress the preliminary nature of the assessments of run-off and yield at ungauged sites. The number and length of available flow records is not yet adequate to provide a sufficient number of estimates of mean annual run-off to derive a reliable relationship between mean annual rainfall and run-off.- It is fortunate that Midgley's analysis of South African flow records includes a number of sites adjacent to Eastern Botswana; nevertheless in choosing the boundaries of regions, in which different curves are assumed to apply, we have had to adopt a hypothesis which seems in line with presently available facts. In the future more records will become available and different conclusions will doubtless prove necessary. This is particularly likely in South East Botswana, where flow records are particularly short and where we have had to calculate inflows from reservoir level records which are not ideal for this purpose.

3.2 Rainfall Records

Where run-off has to be deduced at ungauged sites, an isohyetal map showing mean annual rainfall is an important tool. Such maps have been produced in the course of previous investigations (e.g. Gibb 1968, UNDP 1972), but for this study we used previous estimates of mean annual rainfall at various stations to provide a map on 1 : 1 000 000 scale. Because the rainfall estimates (Pike 1971) were fairly recent and based on the period 1939-69, we did not consider it necessary to revise them, but we corrected some apparent minor anomolies after discussion with the Weather Bureau. (The adjusted average for Tshesebe and Sedibeng must be incorrect, and the positions given for Leupane and Sedibeng are not correct.)

The isohyets for Rhodesia and South Africa were taken from maps published in 1969 and 1957 respectively (Mean monthly and annual rainfall in Rhodesia, 1916-66; Normal annual rainfall in South Africa, 1921-50) with some necessary slight adjustments near the borders with Botswana. The isohyets for Botswana were redrawn from the rainfall averages, taking account of topography, and were discussed with the Weather Bureau. The composite map is shown as Map No. 7548/2 and forms the basis for subsequent analysis.

Monthly rainfall statistics were obtained for the whole available period for the long-term stations in Eastern Botswana - Dikgatlong, Francistown, Gaborone, Kalamare, Kanye, Leupane, Lobatse, Mahalapye, Masama, Mochudi, Molepolole, Palapye, and Serowe. These records could be used to extend run-off records using a relationship between rainfall and run-off.

Because the method of Midgley and Pitman (1969) for assessing reservoir yields suggests the subtraction from evaporation of mean monthly rainfalls derived from all years in which annual rainfall was less than average, these average 'dry year' rainfalls were extracted and are given in Table 3.1 for typical northern, central and southern stations.

TABLE 3.1

Mean monthly rainfall during years in which annual rainfall was lower than average (mm)

	Francistown	Mahalapye	Gaborone
Oct	15.0	21.6	31.4
Nov	44.4	55.5	56.1
Dec	64.6	59.2	70.8
Jan	71.3	61.2	62.6
Feb	54.4	57.5	52.4
Mar	37.4	50.6	54.8
Apr	20.3	20.8	41.0
May	6.2	8.1	11.8
Jun	1.8	1.1	2.4
Jul	0.2	0.7	2.2
Aug	1.5	1.7	1.9
Sep	3.1	6.3	7.5
Total	320.2	344.3	394.9

TABLE 3.2

Mean monthly open water evaporation (mm) (After Pike, 1971)

	Francistown	Mahalapye	Gaborone
Oct	215.5	197.5	196.1
Nov	204.4	198.5	200.7
Dec	201.2	203.8	210.9
Jan	208.3	212.8	214.1
Feb	177.9	181.6	179.5
Mar	179.8	165.3	160.7
Apr	135.5	123.9	112.6
May	104.9	91.4	80.2
Jun	78.4	68.0	58.5
Jul	85.0	77.6	69.0
Aug	124.1	109.8	100.9
Sep	171.1	154.9	148.4
Total	1886.1	1785.1	1731.7

3.3 Evaporation

Previous estimates of open water evaporation have been made for Francistown, Mahalapye, and Gaborone (Pike 1971; UNDP 1972) using the Penman energy balance approach. These estimates were based on the period 1958-68, and vary from 1886 mm at Francistown to 1785 mm at Mahalapye and 1732 mm at Gaborone. Because evaporation is fairly conservative with position and period, these estimates (Table 3.2) are adequate for estimating reservoir evaporation except perhaps at the lower Limpopo sites.

3.4 Run-off Records

Much of the time spent on this investigation has involved the collection of flow records, discussion of their reliability, and the filling of gaps in the record, and the computation of reservoir inflow estimates from records of levels within the reservoir and above the spillway. Therefore the results of this work are given in some detail.

Botswana Records

The problems of measuring river flows in Eastern Botswana are considerable. The annual rainfall is a small fraction of the potential evaporation, and surface run-off is infrequent and caused by heavy storms of high intensity which exceeds infiltration either on areas of limited soil cover or over a wider area. The number of floods per year is small and recession is rapid. Thus it is not easy to establish stage-discharge relationships, while gauging weirs tend to accumulate sand upstream. The early level readings were based on pressure recorders, and there were a number of instrument failures in these records; since 1968 float recorders have been installed, but the inlet pipes are liable to blocking by sand.

Thus there are a number of gaps in the records; because the records are short we have estimated flows during these gaps by comparison with nearby flow records or rainfall records, by interpolation during periods of recession and other methods. The results may be somewhat subjective but should give more reasonable estimates of the runoff regime than incomplete records. These records are therefore given in detail in Appendix B.

The shortage of flow records in South East Botswana has been remedied as far as possible by estimation of inflows to Nuane and Gaborone reservoirs. Daily reservoir levels are available for most of the period since the construction of these reservoirs, and because the inflows are short in duration they can be deduced from changes in reservoir storage and evaporation can be neglected during inflow periods. However, when the reservoirs spill, water level gauge readings provide only an approximate estimate of the flow over the long spillways, especially at moderate flows. Because of the importance of these sites, we have converted the level readings to flows, but because of the lack of continuous records of level and the insensitivity of the spillway calibration we recommend that recorders should be installed, that consideration should be given to the construction of a gauging weir downstream of each reservoir to measure spillage more reliably, and that computation of these inflows should be carried out on a routine basis.

We have not attempted to estimate the inflow to Notwani reservoir because the small storage volume means that spillage is more frequent and, although the gauging weir downstream might provide a check on Gaborone inflows, the catchments are of similar extent and little additional information would be provided.

We have also used level records at the Shashe Dam to extend the Shashe Siding record after the construction of the dam; the same reservations apply as at the other sites, but this was necessary to provide a synthetic record for Shashe Weir during the year 1973-74 when the inlet pipes to the recorder appear to have been blocked.

A very small catchment has been gauged with a compound weir in a gully west of the Athlone Hospital, Lobatse, which drains an area of 0.1457 km^2. Flows have at present been computed for the three seasons 1970/1, 1971/2, and 1972/3; totals are 7 273, 17 409, and 585 m^3. (The first two figures are taken from Jennings, 1974, Table 31; the third is from Robins 1973). These totals correspond to 49.9, 119.4 and 4.0 mm in years when Lobatse rainfall was 620.6, 682.1 and 469.8 mm against the 1924-75 average of 564.1 mm. The average rainfall for the nearby Geological Survey raingauge is 554.7 (Robins) but the catchment rises steeply towards Sokwe Hill from this gauge. These records provide interesting evidence of the behaviour of a small steep catchment, but are evidently not representative of the Nuane and Gaborone catchments.

The monthly discharges are given in Appendix B with notes on their derivation. Summaries of the annual discharges are given in Tables 3.3 and 3.4, expressed in million cubic metres and in millimetres over the catchment.

Rhodesian and South African flow records

Run-off records for the Nata and Shashe tributaries were obtained from the Hydrological Branch, Ministry of Water Development, Salisbury, and from published hydrological yearbooks. Monthly discharges are available, but annual summaries are given in Tables 3.3 and 3.4, expressed in million cubic metres and in millimetres of run-off.

Monthly run-off records for the South African gauging stations on the Limpopo and its tributaries were obtained from the Department of Water Affairs, Pretoria, and from records published in 'Hydrological Survey Publication No. 8 - Monthly flow records of gauging stations up to September 1960'. Annual discharges are also given in Tables 3.3 and 3.4 in volumes and in depths.

3.5 Calculation of Mean Annual Run-off at Gauging Stations

The monthly and annual river flows for Botswana rivers are given in Appendix B, and were summarised in the last section; the Rhodesian and South African flow records were also given in the last section.

Because these records cover varying periods, and run-off is particularly variable in this region, it is essential to derive or adjust estimates of mean annual run-off for a uniform period if comparisons with mean annual rainfall are to be meaningful.

For Botswana, where the records are particularly short, the flows of the Nata, Mosupe at Matsitama, Shashe Siding/Dam, and the Motloutse at Tobane, were adjusted to the period 1962-75 by direct ratio with the flows at Shashe Weir during the common period of record. Although some of these stations were rather distant from the Shashe, the relationship between the Shashe and the Tati and Inchwe (Ntshe) annual flows is reasonably close and it seemed preferable to make this adjustment. In the south, however, there was a reasonable relationship between the computed inflows to Nuane and

TABLE 3.3 SUMMARY OF RUNOFF (million m^3)

	1948-49	1949-50	50-51	51-52	52-53	53-54	54-55	55-56	56-57	57-58	58-59	59-60	60-61	61-62	
Rhodesia															
A12													2.480	0.194	
A47															
A48															
A55															
B5			55.512	158.317	207.589	42.052	427.930	75.795	61.808	96.938	73.361	0.843	73.804	6.359	
B7			19.056	20.152	177.782	51.326	631.135	56.399	34.909	83.224	88.047	0.432	87.311	19.337	
B9															
B12				10.294	74.358	28.800	201.748	29.417	19.930	35.238	45.475	0.453	36.788	2.281	
B26								3.230	0.812	5.226	2.571	0.021	6.140	0.114	
B31											268.195	10.923	243.153	43.729	
South Africa															
A2M19				19.280	47.577	20.243	252.752	(57.576)	124.677	136.960	(84.360)	35.438	51.478	16.904	
A2M20				48.053	156.686	22.032	(427.604)	128.577	75.676	52.423	32.195	18.567	169.095	6.414	
A2M21								147.319	82.443	21.760	68.831	16.251	78.407	9.853	
A2M25												58.302	(276.998)	24.045	
A3M07										(42.176)	25.530	27.856	195.288	44.445	
A4M02	38.289	27.076	(33.354)		49.097	62.456	233.757	159.770	80.710	18.680	60.547	21.888	88.842	14.435	
A5M01&4		[271.495			501.881	121.781]		85.054	25.644	31.138	93.758	27.984	93.346	1.587	
A5M02&5										73.087	130.198	85.493	191.257	10.842	
A5M03&6												128.446	1114.931	25.830	
A6M07													260.665	17.791	
A6M09													233.031	14.983	
A7M04								1645.947	2019.763	2199.024	2843.582	139.840	2226.948	191.853	11266.957

) Incomplete record

TABLE 3.3 SUMMARY OF RUNOFF (million m^3)

Botswana	1962-63	63-64	64-65	65-66	66-67	67-68	68-69	69-70	70-71	71-72	72-73	73-74	74-75	Longterm Average	Average from 62
M3 (Nata)								52.176	64.142	805.299	9.348	773.958	79.873	297.466	278.735 (1)
M22 (Mosetse)									37.801	97.786	2.816	71.979	8.993	43.875	36.799 (1)
M32 (Matsitama)									8.951	14.991	0	12.278	2.977	7.839	6.575 (1)
L16 (Shashe)	85.252	14.059	19.742	108.950	141.267	49.557	102.426	34.906	57.66	196.19	10.209	135.3	71.690	79.016	79.016
L22 (Tati)	27.933	5.566	6.562	29.188	26.064	18.047	14.883	7.577	24.798	136.488	0.740	71.065	37.048	31.228	31.228
L25 (Inchwe)	18.912	3.629	6.981	25.493	41.556	6.803	19.680	7.345	19.712	127.93	5.713	82.423	41.106	31.329	31.329
L17 (Shashe Siding/Dam)									75.724	249.62	14.0	169.1	82.7	118.229	99.161 (1)
L12 (Shashe below Tati)									144.138	650.1		216.152	194.231	301.155	206.545 (1)
L31 (Motloutse)								10.897	83.553	242.208	29.005	128.980	212.880	117.921	110.495 (1)
L44 (Lotsane)								0.311	46.717	13.278	0	18.583	17.195	16.014	16.014
L55 (Mahalapshwe)						0	3.19	1.611	48.986	6.901	0.189	12.548	15.757	11.148	11.148
Gaborone Resr.				87.648	177.471	13.899	2.706	0.246	9.348	43.698	11.439	68.901	16.203	43.156	43.156
Nuane Resr.				9.517	16.954	0.191	0.436	0.264	0.880	2.193	0.996	3.627	0.474	3.553	3.553
Lobatse Weir									0.007273	0.017409	0.000585			0.0084	

(1) Average adjusted by comparison with Shashe Weir to period 62-75

Rhodesia	1962-63	63-64	64-65	65-66	66-67	67-68	68-69	69-70	70-71	71-72	72-73	73-74	74-75	Longterm Average	Average from 62
A12	0.450	0	0.713	3.931	1.757	0.049	0	0.021	0.212	6.998				1.293	1.285
A47					2.805	0.097	0.195	0.090	1.025					0.842	(4)
A48						0.360	0.075	0.026	1.369					0.458	(4)
A55									3.105	79.806				41.456	(4)
B5	64.547	6.344	13.674	58.779	134.323	1.712	20.356	1.347	33.646	73.167	8.321	138.467		76.458	46.224
B7	56.473	0.130	15.252	102.039	111.500	3.994	46.519	1.409	180.356	110.844	5.564	316.283	293.976	100.538	95.718
B9					641.012	10.582	56.072	62.203	187.642	369.798	11.008	759.988		262.288	262.288
B12	29.439	1.806	6.175	62.460	55.211	2.703	9.663	0.747	10.343	22.383	1.912	77.207		33.253	23.337 (1)
B26	1.810	0.375	0.388	6.873	20.978	0.766	2.249	0.301	1.105	7.210	0.434	3.998		3.400	3.874
B31	169.969	15.235	56.820	274.277	378.761	12.084	115.101	1.568	78.956	145.954	6.922	520.551	609.745	173.644	183.534
B35			647.140	1731.077	6580.992	112.248	1481.156	621.840	1737.339	3394.70	80.597	3319.418		1970.651	1970.65
B64					(35.238)	5.057	26.699	1.270	7.821					15.217	15.582 (2)
B69					63.023	0.894	45.113	19.578	33.501	51.425	2.041			30.796	30.796
B71						3.727	8.108	0		20.351	0			6.437	6.467 (2)
B73							0.148	0.007	0.462	0.737	0	37.139		6.416	6.416
B77								(0.734)	9.166	19.519	0.972	70.410		20.160	20.160
B78								(0.013)	1.177	2.864	0.940	6.797		2.358	2.358
B85										135.681	14.762	922.694		357.712	292.470 (3)

) Incomplete record

(1) Flows for 69-74 are sum of B77 and B78, averages include these flows
(2) Averages adjusted by comparison with Shashe Weir to period 62-75
(3) Averages adjusted by comparison with B 31 to period 62-75
(4) Records too short

TABLE 3.3 SUMMARY OF RUNOFF (million m^3)

South Africa	1962-63	63-64	64-65	65-66	66-67	67-68	68-69	69-70	70-71	71-72	72-73	73-74	74-75	Longterm Average	Average 62-73
A2M19	2.222	3.154	12.651	7.957	150.003	10.237	(14.330)	13.090	23.475	(36.443)	(15.625)			51.656	26.290
A2M20	2.261	3.973	65.912	30.999	(652.445)	4.707	6.502	1.543						100.298	96.043
A2M21	12.954	24.439	37.101	7.745	401.507	(32.323)	(40.753)	(21.899)	(90.923)	148.035	(23.094)	118.1		72.828	76.434
A2M25	4.574	16.118	102.715	15.466	1311.164	40.090	65.033	25.371	248.231	338.013	(38.456)			183.184	200.476
A3M07	13.265	9.359	12.116	(54.135)	(344.448)	10.537	3.861	0.684	38.946	(77.517)	7.903			56.754	52.070
A4M02	(11.866)	13.033	7.122	2.397	129.749	22.509	36.281	24.629	153.642	(130.509)	(28.846)	122.9	(290.4)	71.646	50.962
A4M04	3.023	3.710	4.485	0.465	121.259	6.989	7.660	29.968	78.767	76.614	(5.503)			30.768	30.768
A4M05	(48.152)	17.748	(20.708)	(0.882)	(437.021)	(31.639)	53.269	47.645	382.689	299.580	29.592	315.453	(625.156)	177.656	124.448
A4M06	2.987	0	0.879	0											
A4M07	1.256	0	0.039	1.488	(34.545)	(0.159)			(3.138)					5.804	5.804
A4M08			4.263	0.428	158.668	15.703	11.398	(13.915)	132.415	96.695	9.109			49.177	49.177
A5M01&4	9.466	9.560	22.094	11.184	134.336	6.396	38.510	46.608	32.908	81.117	9.644			42.241	36.529
A5M02&5	34.404	8.302	37.842	21.444	(275.429)	6.104	106.981	89.197	(67.032)	222.118	8.279			85.500	79.739
A5M03&6	68.763	7.701	(114.973)	198.186	3513.966		92.808	131.979	732.846	523.430	0.038	419.08		505.213	538.469
A6M07	36.106	6.623	42.442	8.297	165.116	0.097	58.122	47.938	30.976	101.092				64.605	49.681
A6M09	63.174	(4.128)	(49.729)	20.144	265.328	0.025	79.853	39.727	55.532	(134.600)				80.021	71.224
A7M04	1038.722	34.383	404.640		(6916.420)	78.780	(784.944)	92.541	(1675.686)	(2220.808)	73.186			1446.298	1332.011

Composite record for Limpopo at Beit Bridge

	SA	SA	R	R	R	R	R	R	R	R	R	R	32046.569 ÷ 19	
A7M04/B35	1038.722	34.383	647.140	1731.077	6580.992	112.248	1481.156	621.840	1737.339	3394.70	80.597	3319.418	= 1686.661	1587.920 (1962-73)

) Incomplete record

Sum 1965-74 19059.367 (9)
Salisbury data 415.356 (9)
Ratio x mean = 36.76 mean for Salisbury (1955-74)

TABLE 3.4 SUMMARY OF RUNOFF (mm)

	1948-49	1949-50	50-51	51-52	52-53	53-54	54-55	55-56	56-57	57-58	58-59	59-60	60-61	61-62
Rhodesia														
A12													34.0	2.7
A47														
A48														
A55														
B5			56.2	160.4	210.3	42.6	433.6	76.8	62.6	98.2	74.3	0.9	74.8	6.4
B7			10.5	11.1	98.1	28.3	348.1	31.1	19.3	45.9	48.6	0.2	48.2	10.7
B9														
B12				15.5	111.8	43.3	303.4	44.2	30.0	53.0	68.4	0.7	55.3	3.4
B26								17.1	4.3	27.7	13.6	0.1	32.5	0.6
B31											64.7	2.6	58.7	10.6
South Africa														
A2M19				3.1	7.7	3.3	40.9	9.3	20.2	22.2	13.7	5.7	8.3	2.7
A2M20				10.4	33.8	4.8	92.3	27.7	16.3	11.3	6.9	4.0	36.5	1.4
A2M21								19.8	11.1	2.9	9.2	2.2	10.5	1.3
A2M25												2.7	12.9	1.1
A3M07										4.9	3.0	3.2	22.7	5.2
A4M02	21.7	15.4	18.9		15.8	35.5	132.8	90.8	45.8	10.6	34.4	12.4	50.5	8.2
A5M01&4		438.7	811.1		196.8			137.4	41.4	50.3	151.5	45.2	150.9	2.6
A5M02&5										31.2	55.6	36.5	81.7	4.6
A5M03&6												1.3	11.4	0.3
A6M07													28.9	2.0
A6M09													15.5	1.0
A7M04								8.2	10.1	10.9	14.2	0.7	11.1	1.0

TABLE 3.4 SUMMARY OF RUNOFF (mm)

	1962-63	63-64	64-65	65-66	66-67	67-68	68-69	69-70	70-71	71-72	72-73	73-74	74-75	Longterm Average	Average from 62
Botswana															
M3 (Nata)								2.3	2.8	35.2	0.4	33.8	3.5	13.0	12.2 (1)
M22 (Mosetse)									34.7	89.7	2.6	66.0	8.3	40.3	33.8 (1)
M32 (Matsitama)									17.3	29.1	0	23.8	5.8	15.2	12.7 (1)
L16 (Shashe)	34.7	5.7	8.0	44.3	57.4	20.1	41.6	14.2	23.4	79.8	4.2	55.0	29.1	32.1	32.1
L22 (Tati)	49.0	9.8	11.5	51.2	45.7	31.7	26.1	13.3	43.5	239.5	1.3	124.7	65.0	54.8	54.8
L25 (Inchwe)	23.6	4.5	8.7	31.9	51.9	8.5	24.6	9.2	24.6	159.9	7.1	103.0	51.4	39.2	39.2
L17 (Shashe Siding/Dam)									20.7	68.4	3.8	46.3	22.7	32.4	27.2 (1)
L12 (Shashe below Tati)									18.5	83.2		27.7	24.9	38.6	26.4 (1)
L31 (Motloutse)								1.8	14.0	40.6	4.9	21.6	35.7	19.8	18.5 (1)
L44 (Lotsane)								0.1	11.8	3.4	0	4.7	4.3	4.0	4.0
L53 (Mahalapshwe)						0	4.3	2.2	66.2	9.3	0.3	17.0	21.3	15.1	15.1
Gaborone Resr.				20.4	41.3	3.2	0.6	0.1	2.2	10.2	2.7	16.0	3.8	10.0	10.0
Nuana Resr.				40.5	72.1	0.8	1.9	1.1	3.7	9.3	4.2	15.4	2.0	15.1	15.1
Lobatse Weir									49.9	119.4	4.0			57.8	57.8
Rhodesia															
A12	6.2		9.8	53.8	24.1	0.7	0	0.3	2.9	95.9				17.7	17.6
A47					15.2	0.5	1.1	0.5	5.6					4.6	(4)
A48						2.4	0.5	0.2	9.1					3.1	(4)
A55									3.7	93.9				48.8	(4)
B5	65.4	6.4	13.9	59.6	136.1	1.7	20.6	1.4	34.1	74.1	8.4	140.3		77.5	46.8
B7	31.1	0.1	8.4	56.3	61.5	2.2	25.7	0.8	99.5	61.1	3.1	174.5	162.1	55.5	52.8
B9					110.7	1.8	9.7	10.7	32.4	63.9	1.9	131.3		45.3	45.3
B12	44.3	2.7	9.3	93.9	83.0	4.1	14.5	1.1	15.6	33.7	2.9	116.1		50.0 (1)	35.1 (1)
B26	9.6	2.0	2.1	36.4	111.0	4.1	11.9	1.6	5.8	38.1	2.3	21.2		18.0	20.5
B31	41.0	3.7	13.7	66.2	91.4	2.9	27.8	0.4	19.1	35.2	1.7	125.6	147.1	41.9	44.3
B35			3.3	8.8	33.6	0.6	7.6	3.2	8.9	17.3	0.4	17.0		10.1	10.1
B64					49.5	7.1	37.5	1.8	11.0					21.4	21.9 (2)
B69					27.9	0.4	20.0	8.7	14.8	22.8	0.9			13.6	13.6
B71						17.6	38.2	0	(48.2)*	96.0	0			30.4	30.5 (2)
B73							0.2	0	0.5	0.9	0	43.1		7.4	7.4
B77								1.4	17.0	36.2	1.8	130.6		37.4	(4)
B78								0.3	24.0	58.4	19.2	138.7		48.1	(4)
B85										17.7	1.9	120.2		46.6	38.1 (3)
South Africa															Average 1962-73
A2M19	0.4	0.5	2.0	1.3	24.3	1.7	2.3	2.1	3.8	5.9	2.5			8.4	4.3
A2M20	0.5	0.9	14.2	6.7	140.8	1.0	1.4	0.3						21.6	20.7
A2M21	1.7	3.3	5.0	1.0	53.9	4.3	5.5	2.9	12.2	19.9	3.1	15.8		9.8	10.3
A2M25	0.2	0.8	4.8	0.7	61.2	1.9	3.0	1.2	11.6	15.8	1.8			8.6	9.4

(1) Flows for 1969-74 are sum of B77 and B78; averages include these flows
(2) Averages adjusted by comparison with Shashe Weir to period 1962-75
(3) Averages adjusted by comparison with B31 to period 1962-75
(4) Records too short
( )* Incomplete record. Not used for average

TABLE 3.4 SUMMARY OF RUNOFF (mm)

South Africa	1962-63	63-64	64-65	65-66	66-67	67-68	68-69	69-70	70-71	71-72	72-73	73-74	74-75	Longterm Average	Average 1962-73
A3M07	1.5	1.1	1.4	6.3	40.1	1.2	0.4	0.1	4.5	9.0	0.9			6.6	6.1
A4M02	6.7	7.4	4.0	1.4	73.7	12.8	20.6	14.0	87.3	74.1	16.4	69.8	165.0	40.2	29.0
A4M04	2.7	3.4	4.1	0.4	109.9	6.3	6.9	27.2	71.4	69.5	5.0			27.9	27.9
A4M05	12.8	4.7	5.5	0.2	116.6	8.4	14.2	12.7	102.1	79.9	7.9	84.1	166.8	47.4	33.2
A4M06	6.6	0	1.9	0											
A4M07	3.4	0	0.1	4.0	93.3	0.4			8.5					15.7	15.7
A4M08			8.7	0.9	322.6	31.9	23.2	28.3	269.2	196.6	18.5			100.0	100.0
A5M01&4	15.3	15.4	35.7	18.1	211.8	10.1	60.7	73.5	51.9	127.9	15.2			67.5	59.0
A5M02&5	14.7	3.5	16.2	9.2	117.4	2.6	45.6	38.0	28.6	94.7	3.5			36.5	34.1
A5M03&6	0.7	0.1	1.2	2.0	35.8		0.9	1.3	7.5	5.3	0	4.3		5.2	5.5
A6M07	4.0	0.7	4.7	0.9	18.3	0	6.4	5.3	3.4	11.2				7.2	5.5
A6M09	4.2	0.3	3.3	1.3	17.7	0	5.3	2.6	3.7	9.0				5.3	4.7
A7M04	5.2	0.2	2.0		34.4	0.4	3.9	0.5	8.3	11.1	0.4			7.2	6.6

Gaborone reservoirs, but the flows of the Lotsane at Palapye and the Mahalapshwe at Madiba did not appear to be related to these and therefore there was no choice but to take the arithmetic averages. In the case of the Lotsane this may give too low an average by comparison with Gaborone. On the other hand the Mahalapshwe record is dominated by the very high run-off in 1970-71, most of which followed the exceptional storm of 19-22 December 1970 (UNDP, 1972, Tech. Report 1, p.118) which was aligned along and slightly to the north of this catchment; the average derived for this basin is probably too high, which is most unfortunate as this gauge is the only example on the southern part of the Basement Complex.

Two sites appear to be unusual and are not included in comparison of rainfall and run-off. The Nata catchment is covered by Kalahari Beds in its middle and lower reaches, and it appears that most of the run-off is generated by the areas of exposed Basement Complex north of a line from Tutume to Figtree; if the run-off is expressed as millimetres over this smaller area it is comparable with the other rivers. The very small steep catchment of the Lobatse Hospital weir provides interesting information but is atypical.

The average flows for the Rhodesian rivers have been taken from 1962 only in order to coincide with the period of the Shashe record to which the northern flows have been adjusted. Station B12 has been extended to cover the period 1962-74 by adding together B77 and B78 for the later years. Stations B64, B71 and B85 have been adjusted by ratio with the Shashe Weir flows.

Because the evidence of the South African flows is particularly useful in comparing the flows of the main Limpopo with those of the South African tributaries, the longest common period of 1962-73 has been chosen to estimate mean annual run-off. A record for the Limpopo at Beit Bridge based on both Rhodesian and South African Records provides an average for this period without the gaps of either record alone. Some of these records are affected by upstream dams (A1?, B73, A2M19) and are omitted from comparison with rainfall.

3.6 Relationship between rainfall and run-off

The estimates between mean annual run-off derived in the previous sections are compared in Table 3.5 with estimates of mean annual rainfall over their catchments, deduced from the isohyetal map. It is evident that the Rhodesian records are comparable with the flows in North East Botswana, from the Mosetse to the Motloutse. On the other hand, the small number of stations in South East Botswana, the Notwani at Gaborone Reservoir and the Nuane at Nuane Reservoir, correspond with the stations on the Marico and Krokodil tributaries of the Limpopo; the flows of the lower tributaries of the Limpopo, especially the Mokolo and the Palala, are higher.

Rainfall/run-off relationships in this type of climate, with floods deriving from rare storms of high intensity,must be controlled by surface infiltration rates, and thus by soils, relief and vegetation. It is interesting to note that surface run-off must also be increased by overgrazing. Midgley (1952) has found that natural vegetation, being a result of climate, geology, soils and slope is the most useful single indicator of rainfall run-off zones. The main vegetation boundary in Eastern Botswana is between mixed Mopane bushveld and mixed Acacia/Combretum tree savanna; this is shown by Field (1975) as occurring between Palapye and Mahalapye. Perhaps the most fundamental difference between the northern and southern regions is a geological difference between the Basement Complex rocks in the north and the more recent Karroo and Waterberg Series, with intrusive igneous rocks, to the south (Geological Map of Botswana, 1 : 1 000 000, Lobatse 1973). This generalisation is complicated by the Karroo Series to the west of the Basement Complex rocks and by the Kalahari sands which overlie them and which reach well to the east between Mahalapye and Gaborone.

However, the most reasonable hypothesis appears on present information to be as follows. There is a region of Basement Complex basins in the north of the study area where the rainfall/run-off regime corresponds with the Rhodesian rivers on similar rocks. There is another region in the south of more varied geology, with some drift cover, which corresponds with the Marico and Krokodil tributaries of the Limpopo. The high run-off from the Mokolo and Palala coincides with the Waterberg area, which is treated

TABLE 3.5 COMPARISON OF MEAN ANNUAL RAINFALL AND RUNOFF AT GAUGED SITES

No	Station River	Station Site	Area km²	Mean annual rainfall mm	Mean annual m³x10⁶	runoff mm	Remarks
Botswana							
M3	Nata	Nata Bridge	(22900)		278.735	12.2	see text
M22	Mosetse	Mosetse	1090	454	36.799	33.8	
M32	Mosupe	Matsitama Weir	516	448	6.575	12.7	
L16	Shashe	Weir	2460	469	79.016	32.1	
L22	Tati	Weir	570	490	31.228	54.8	
L25	Inchwe	Weir	800	493	31.329	39.2	
L17	Shashe	Siding/Dam	3650	458	99.161	27.2	
L12	Shashe	below Tati	7810	450	206.545	26.4	below Shashe dam
L31	Motloutse	Tobane	5960	383	110.495	18.5	
L44	Lotsane	Palapye	3959	479	16.014	4.0	
L53	Mahalapshwe	Madiba	740	456	11.148	15.1	
	Notwane	Gaborone Resr.	4300	545	43.156	10.0	
	Nuane	Nuane Resr.	235	570	3.553	15.1	
	(Lobatse)	Hospital Weir	0.1457	(600)	0.008422	57.8	
Rhodesia							
A12	Tegwani	Weir	73	575	1.285	17.6	below dam
A47	Mananda		184	590			too short
A48	Manzamyama		150	590			" "
A55	Tegwani	Madhlambudzi	850	548			" "
B5	Mchabezi	Gwanda Weir	987	578	46.224	46.8	
B7	Mtsheleli	Freda Weir	1813	593	95.718	52.8	
B9	Tuli	Natalie Causeway	5789	566	262.288	45.3	
B12	Shashani	Antelope Mine	665	569	23.337	35.1	
B26	Sansukwe	Ingwesi	189	520	3.874	20.5	
B31	Tuli	Gorge	4144	582	183.534	44.3	
B35	Limpopo	Beit Bridge	195700		1970.651	10.1	
B64	Ingwezi	Dam	712	568	15.582	21.9	
B69	Insiza	Silalabuhwa Dam	2260	587	30.796	13.6	
B71	Ramaquabane	Madabe Dam	212	530	6.467	30.5	
B73	Ingwezi	Dam (d/s)	862	564	6.416	7.4	below dam
B77	Shashani	Antelope Dam	539	593	20.160	37.4	} Added to B12
B78	Zgalangamate	Antelope Dam	49	525	2.358	48.1	} Added to B12
B85	Tuli	Shashe	7674	539	292.470	38.1	
South Africa							
A2M19	Krokodil	Beestekraal	6175	699	26.290	4.3	below dam
A2M20	Elands	Bulhoek	4634	650	96.043	20.7	1962-70
A2M21	Pienaars	Buffelspoort	7453	660	76.434	10.3	1962-73
A2M25	Krokodil	Hardekoolbult	21411	664	200.476	9.4	" "

TABLE 3.5 COMPARISON OF MEAN ANNUAL RAINFALL AND RUNOFF AT GAUGED SITES

No	Station River	Site	Area km^2	Mean annual rainfall mm	Mean annual runoff $m^3 x 10^6$	runoff mm	Remarks
South Africa							
A3M07	Groot Marico	Erstepoort	8585	610	52.070	6.1	1962-73
A4M02	Mokolo	Vaalwater	1760	610	50.962	29.0	" "
A4M04	Matlabas	Haarlem Oost	1103	589	30.768	27.9	" "
A4M05	Mokolo	Dwaalhoek	3749	602	124.448	33.2	" "
A4M06	Poerseloop	Weltevreden	456	495			too short
A4M07	Tambotie	Blakeney	370	516	5.804	15.7	1962-68, 70-71
A4M08	Sterkstroom	Doornspruit	492	604	49.177	100.0	1964-73
A5M01&4	Palala	Doornkom/Muisvogelkraal	619	604	36.529	59.0	1962-73
A5M02&5	Palala	Vischgat/Hope Town	2340	556	79.739	34.1	" "
A5M03&6	Limpopo	Oxenham Ranch/Sterkloop	98123	558	538.469	5.5	1962-67, 68-73
A6M07	Mogalakwena	Steil Loop	9025	560	49.681	5.5	1962-72
A6M09	Mogalakwena	Aden	15011	504	71.224	4.7	" "
A7M04	Limpopo	Beit Bridge	200950		1332.011	6.6	1962-65, 66-73
	Limpopo (composite record)				1587.290	7.9	1962-73

separately by Midgley and Pitman. It seems sensible that the Karroo area above Palapye should be included in the Southern Region. There is a large area of Basement Complex rocks near Mahalapye where the relief is less marked than in the north, and it seems necessary to postulate a transitional Central Region; unfortunately there is only one gauge in this area, but the southern watershed of the Motloutse seems a reasonable boundary to this region. These three regions are outlined on Map 7548/2; it is scarcely necessary to stress the speculative nature of this division but it does not conflict with present evidence. (For the present the basalts east of Bobonong are provisionally included in the Northern Region, but this may be revised after the area is visited during Phase II).

The mean annual rainfall and run-off for the stations in the area are compared in Figure 3.1. On the basis of this diagram the Southern Region is equated with Zone 1 of Midgley and Pitman (1969), and the Central Region with their Zone 2. Curves for these zones are included in the diagram. For the Northern Region it was intended to use Midgley and Pitman's Zone 4 with the run-off increased by 50%, but as this corresponds with Zone 4 of Midgley (1952) the latter relationship was adopted and is also shown in Figure 3.1. These curves are based on a small number of short records, especially in South East Botswana, but there is no present alternative for estimation at ungauged sites.

3.7 Estimation of mean annual run-off at potential dam sites

The fundamental index of yield at potential dam sites is the mean annual run-off. Estimates of mean run-off have been made by estimating the mean annual rainfall, and estimating the mean annual run-off in millimetres for the appropriate region from Figure 3.1; this depth is multiplied by the catchment area (which excludes the catchments of existing upstream dams which are unlikely to contribute during critical droughts) to give the mean annual run-off for each site. Estimates are given in Table 3.6.

Where there are flow records at or near the dam site, it is possible to use these records to adjust the estimated mean annual run-off. These adjusted estimates are also given in Table 3.6. Where a gauging station coincides with a dam site, the mean run-off is substituted; where the gauging station is nearby but upstream or downstream, the measured run-off is multiplied by the simple ratio of catchment areas at the two sites. Where a dam site is below a confluence of two gauged rivers, the estimate should not be less than the sum of the two measured flows.

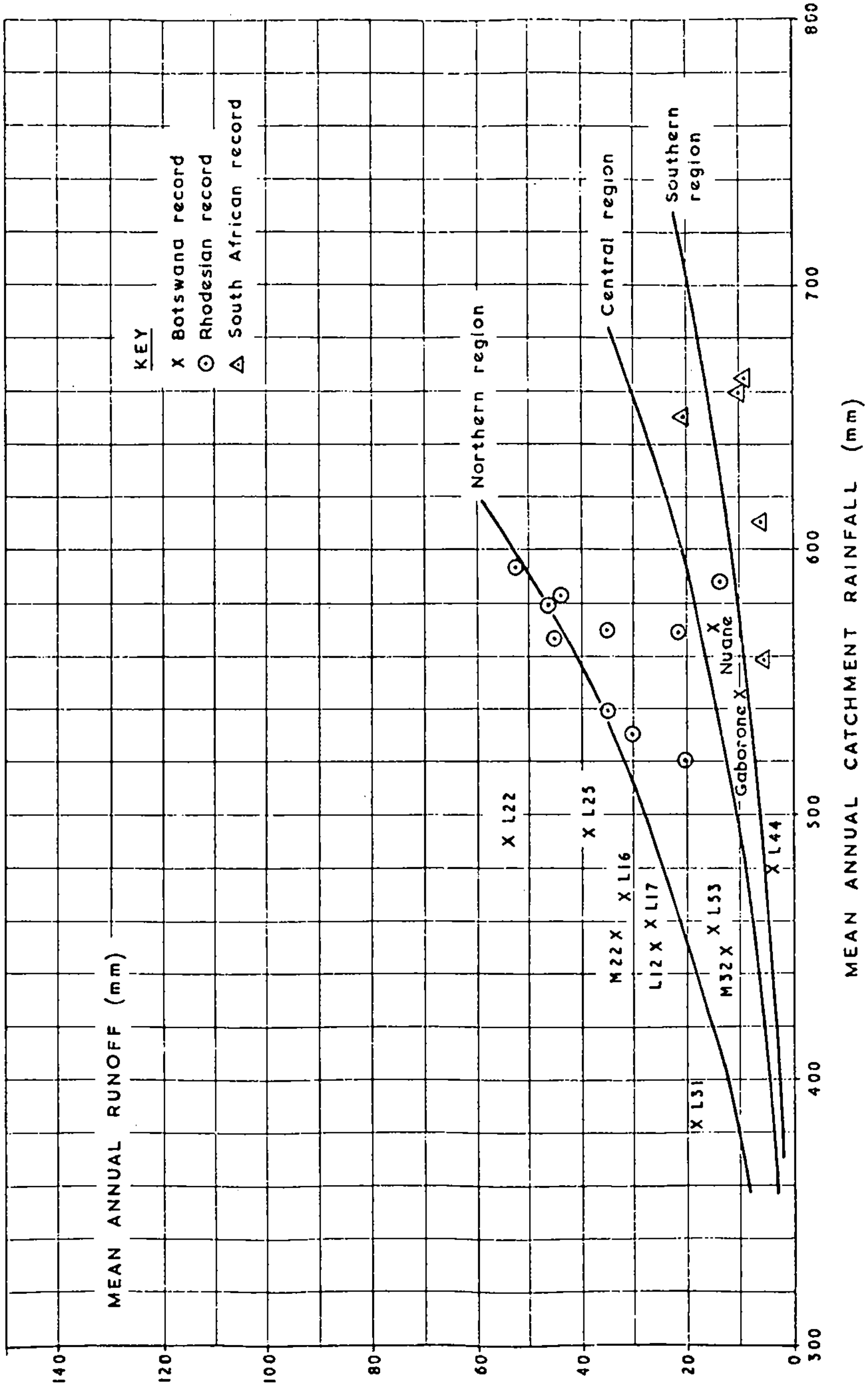

MEAN ANNUAL RUNOFF (mm)
MEAN ANNUAL CATCHMENT RAINFALL (mm)
KEY
X Botswana record
⊙ Rhodesian record
△ South African record
Northern region
Central region
Southern region
X L22
X L25
X L16
M22 X
L12 X
X L17
X L53
M32 X
X L31
X L44
Gaborone X
X Nuane
0
20
40
60
80
100
120
140
300
400
500
600
700
800

FIGURE 3.1

TABLE 3.6 Estimated mean annual runoff and net yield at reservoir sites

Dam Site Ref. No	Region	Area km²	Mean Annual Rainfall mm	Mean Annual Runoff, mm	Mean Annual Runoff (MAR) m^3x10^6		Reserve Storage m^3x10^6	Probable Max m^3x10^6	Reserve ÷ MAR %		Net Yield Storage = MAR	Net Yield Storage = 2 x MAR m^3x10^6/year	Net Yield at Probable Max Storage
					Est.	Adj.			Est.	Adj.			
1	N	1310	450	20	26	37	10	500	38.5	27.0	6.47	9.99	
2	N	1030	442	19	19.6	9.1	10	300	51.0	110.0	1.59	2.46	
3	N	210	480	25	5.2		0.4	20	7.7		.91	1.40	
4	N	75	480	25	1.88		1	10	53.2		.33	.51	
5	N	34	490	27	0.92		1	8	108.7		.16	.25	
6	N	115	495	28	3.2		1.0	20	31.3		.56	.86	
7	N	240	520	32	7.7		0.7	50	9.1		1.35	2.08	
8	N	375	512	30	11.2		1	50	8.9		1.96	3.02	
9	N	380	500	28	10.6	21	0.5	25	4.7	2.4	3.68	5.67	4.16
10	N	440	505	29	12.8	17.2	1	50	7.8	5.8	3.01	4.64	
11	N	46	492	27	1.24		1	15	80.6		.22	.33	
12	N	1450	475	24	35	47	2	125	5.7	4.3	8.23	12.69	
13	N	86	487	26	2.2		0.7	20	31.8		.39	.59	
14	N	1740	483	25	44	63	2	80	4.5	3.2	11.03	17.01	12.92
15	N	1700	519	32	54		4	75	7.4		9.45	14.58	11.77
16	N	51	440	18	0.92		0.6	7.5	65.2		.16	.25	
17	N	2400	472	24	58	63	5	200	8.6	7.9	11.03	17.01	

Source of adjustment to MAR:-

(1) Mosetse mean = 36.799

(2) Matsitama mean = 6.575 x ratio $\frac{1030}{740}$ = 9.15

(9) Tati mean = 31.228 x ratio area = $\frac{380}{570}$ = 20.8

(10) Inchwe mean = 31.329 x ratio area = $\frac{440}{800}$ = 17.2

(12) Shashe mean = 79.016 x ratio area = $\frac{1450}{2460}$ = 46.6

(14) Tati and Inchwe mean = 62.557 = 62.6

(17) Tati and Inchwe = 62.6

Dam Site Ref. No	Region	Area km^2	Mean Annual Rainfall mm	Mean Annual Runoff, mm	Mean Annual Runoff (MAR) $m^3 x 10^6$		Reserve Storage $m^3 x 10^6$	Probable Max $m^3 x 10^6$	Reserve ÷ MAR %		Net Yield Storage = MAR	Net Yield Storage = 2 x MAR $m^3 x 10^6$/year	Net Yield at Probable Max Storage
					Est.	Adj.			Est.	Adj.			
18	N	4000	450	20	80	100	2	160	2.5	2.0	17.50	27.00	24.00
19	N	2600	466	3	60	63	3	150	5.0	4.8	11.03	17.01	
20	N	56	387	11	0.62		0.5	10	80.6		.11	.17	
21	N	24	380	10	0.24		0.5	7.5	208.3		.04	.06	
22	N	6100	466	23	140		3	300	2.1		24.5	37.80	
23	N	26	370	9	0.23		0.5	5	217.4		.04	.06	
24	N	290	410	14	4.1		1.5	25	36.6		.72	1.11	
25	N	69	370	9	0.62		1	10	161.3		.11	.17	
26	N	52	370	9	0.47		1	10	212.8		.08	.13	
27	N	13800	465	22	304		1	150	0.3		53.20	82.08	29.79
28	N	86	375	10	0.86		0.5	20	58.1		.15	.23	
29	N	14400	463	22	317		5	300	1.6		55.47	85.59	53.89
30	N	205	360	9	1.84		0.3	15	16.3		.32	.50	
31	N	3700	402	13	48		1	200	2.1		8.40	12.96	
32	N	6000	394	12	72	110	1	80	1.4	0.9	19.25	29.70	15.40
33	N	6700	390	11	74	110	5	150	6.8	4.5	19.25	29.70	23.65
34	N	150	357	8	1.20		0.5	15	41.7		.21	.32	
35	N	185	367	9	1.66		1	20	60.2		.29	.45	
36	N	175	370	9	1.58		0.5	15	31.6		.28	.43	

Source of adjustment to MAR:-

(18) Tati, Inchwe and Shashe below dam = 206 - 99, say 100

(19) Tati and Inchwe = 62.6

(22) (18 + 15 = 100 + 54 = 154, no amendment)

(32) Motloutse mean = 110

(33) Motloutse adj. mean = 110

Dam Site Ref. No	Region	Area km²	Mean Annual Rainfall mm	Mean Annual Runoff, mm	Mean Annual Runoff (MAR) $m^3 x 10^6$		Reserve Storage $m^3 x 10^6$	Probable Max $m^3 x 10^6$	Reserve ÷ MAR %		Net Yield Storage = MAR	Net Yield Storage = 2 x MAR $m^3 x 10^6$/year	Net Yield at Probable Max Storage
					Est.	Adj.			Est.	Adj.			
37	N	235	370	9	2.1		0.5	20	23.8		.37	.57	
38	N	93	360	9	0.84		0.2	10	23.8		.15	.23	
39	N	86	350	8	0.69		0.5	10	72.5		.12	.19	
40	N	9200	381	10	92	110	1	200	1.1	0.9	19.25	29.70	28.38
41	N	230	367	9	2.1		0.4	20	19.0		.37	.57	
42	N	475	370	9	4.3		0.2	20	4.7		.75	1.16	
42A	N	2400	370	9	22		0.5	40	2.3		3.85	5.94	5.65
43	S	117000	537	8	936	610	2	200	0.2	0.3	106.75	164.70	41.48
44	C	33	380	4	0.13		0.05	1	38.5		.02	.04	
45	S	2500	478	5	12.5	16	0.5	50	4.0	3.1	2.80	4.32	
46	S	5700	467	5	28		0.5	200	1.8		4.90	7.56	
47	S	170	425	3	0.51		2	30	392.2		.09	.14	
48	C	60	475	9	0.54		0.05	5	9.3		.09	.15	
49	C	69	475	9	0.62		0.1	5	16.1		.11	.17	
50	S	1000	430	4	4.0		0.5	100	12.5		.70	1.08	
51	C	440	460	8	3.5		0.5	50	14.3		.61	.95	
52	C	18	502	11	0.20		0.5	5	250		.04	.05	
53	C	26	500	11	0.29		0.1	5	34.5		.05	.08	
54	C	880	455	7	6.2		0.5	50	8.1		1.09	1.67	
55	C	660	450	7	4.6		0.5	50	10.9		.81	1.24	
56	C	1540	500	11	16.9		1	50	5.9		2.96	4.56	

Source of adjustment to MAR:- (43) A5M03 + A6M09 = 538.469 + 71.224 = 609.693 say 610

(45) Lotsane mean = 16.0

(40) Motloutse mean = 110; lower catchment runoff assumed equal to channel loss

Dam Site Ref. No	Region	Area km^2	Mean Annual Rainfall mm	Mean Annual Runoff, mm	Mean Annual Runoff (MAR) $m^3 x 10^6$		Reserve Storage $m^3 x 10^6$	Probable Max $m^3 x 10^6$	Reserve ÷ MAR %		Net Yield Storage = MAR	Net Yield Storage = 2 x MAR $m^3 x 10^6$/year	Net Yield at Probable Max Storage
					Est.	Adj.			Est.	Adj.			
57	S	59000	577	10	590	300	20	1000	3.4	6.7	52.50	81.00	
58	S	42000	618	13	546	250	2	1000	0.4	0.8	43.75	67.50	
59	S	89	510	7	0.62		0.02	2	3.2		.11	.17	
60	S	38	510	7	0.27		0.1	5	37.0		.05	.07	
61	S	165	490	6	0.99		0.3	20	30.3		.17	.27	
62	S	800	490	6	4.8		2.5	60	52.1		.84	1.30	
63	S	330	490	6	1.98		0.1	10	5.1		.35	.53	
64	S	870	500	6	5.2		0.25	20	4.8		.91	1.40	
65	S	255	500	6	1.53		0.3	15	19.6		.27	.41	
66	S	205	550	9	1.84		0.1	10	5.4		.32	.50	
67	S	2200	558	9	20		15	200	75.0		3.50	5.40	
68	S	9600	600	12	115	52	2	1000	1.7	3.8	9.10	14.04	
68A	S	8200	610	12	98	52	2	1000	2.0	3.8	9.10	14.04	
69	S	135000	521	8	1080	750	40	2000	3.7	5.3	131.25	202.50	
70	N	13100	377	10	131		1	500	0.8		22.93	35.37	
71	S	86000	558	9	774	540		500	0.1	0.2	94.50	145.80	90.72

Source of adjustment to MAR:-

(57) A5M03-A5M02-A4M05, say 300

(58) A3M07+A2M25, say 250

(68) A3M07

(68A) A3M07

(69) 43+Motloutse

(71) A5M03=538.469

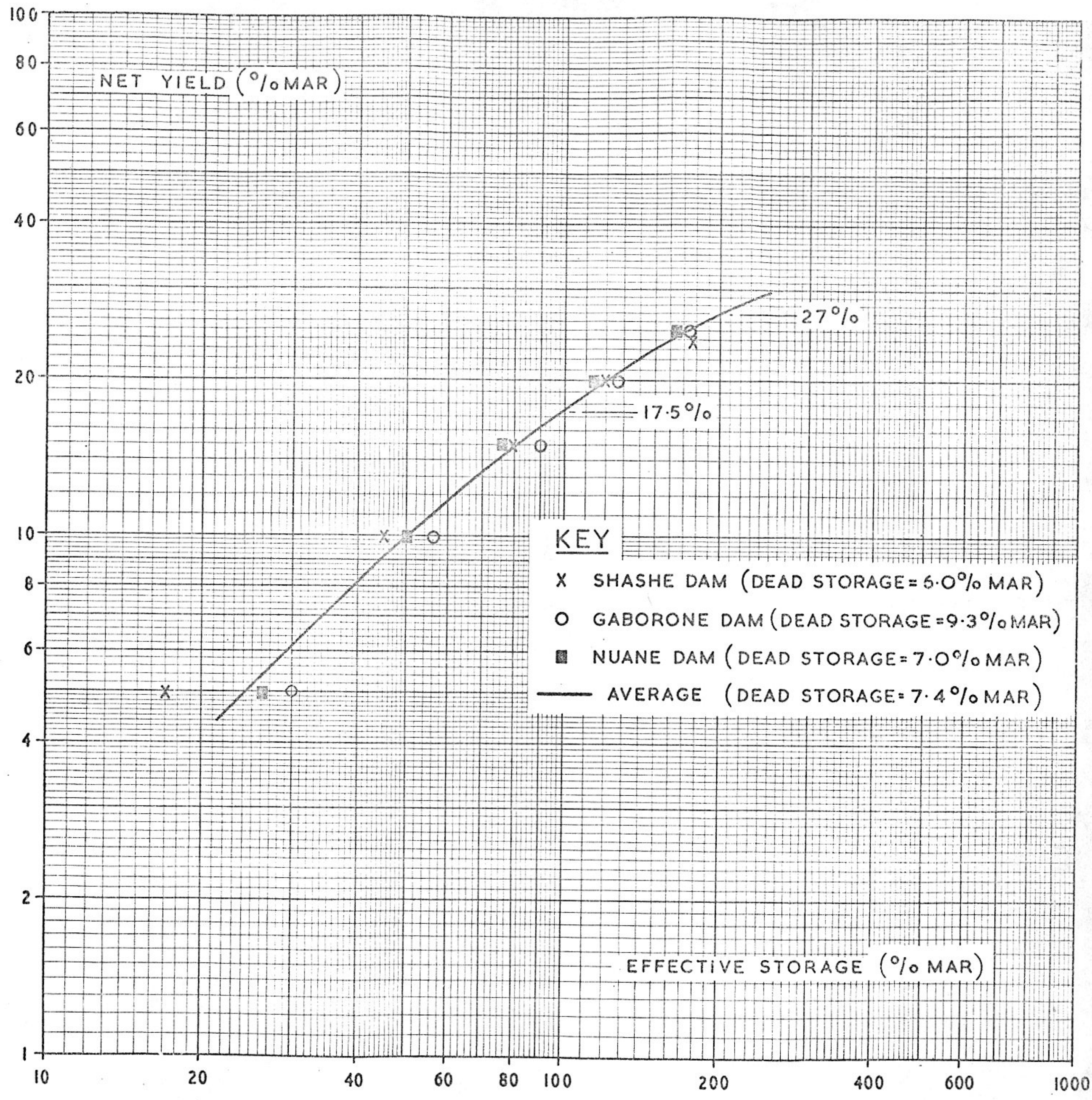
On the main Limpopo, the measured run-off at Oxenham Ranch can be used to correct estimates at sites upstream and downstream by subtracting or adding measured or estimated flows of tributaries. Indeed, the South African flows can be used as an indirect means of estimating run-off from the Botswana tributaries. For instance, the mean run-off of the Limpopo at A5 M03 (538 $m^3 \times 10^6$) compares with total measured flows of 487 $m^3 \times 10^6$ which includes flows measured on the Marico (A3 M07, 52 $m^3 \times 10^6$) the Krokodil (A2 M25, 200 $m^3 \times 10^6$), the Matlabas (A4 M04, 31 $m^3 \times 10^6$), the Mokolo (A4 M05, 124 $m^3 \times 10^6$) and the Palala (A5 M02, 80 $m^3 \times 10^6$). If one assumed that tributary run-off below these gauging stations was equal to attenuation by river bed storage, the contributions of the Notwani and the Mahalapshwe tributaries would be limited. Similarly, the measured flows of the Limpopo at Beit Bridge (1587 $m^3 \times 10^6$) provide an estimate of the total run-off contributed by the Rhodesian tributaries of the Shashe, the South African tributaries of the Limpopo, and the total surface water resources of Eastern Botswana.

3.8 Derivation of dimensionless reservoir yield curve

The methods used to relate reservoir yield to storage volume are those which have been developed by Midgley and Pitman (1969) following thorough analysis of a large number of flow records in South Africa. These methods depend on dimensionless curves or tables of cumulative deficient flows (as percentage of mean annual run-off) for different recurrence intervals in years. They find that these curves vary with climate (or in particular variability of rainfall) and have delineated regions with homogeneous conditions. In the absence of longer run-off records in Botwana, and pending correlation with rainfall, it seems reasonable to assume the run-off variability corresponds to their adjacent Drought Region No. 12, which is described as 'Lowveld areas of northern and north-eastern Transvaal. Summer rainfall,350-500 mm p.a. Arid bushveld and mopane veld'.

For this region the following cumulative flows,as % of mean annual run-off (MAR),correspond to a drought having a recurrence interval of 50 years which has been taken as the design drought.

Duration (years)	1	2	3	4	5	6	7	8
Cumulative flow (% MAR)	0	8.1	22.5	44.1	72.9	108.9	152.1	202.5



DIMENSION-LESS YIELD : STORAGE CURVE

FIGURE 3.2

It will be noted that the maximum storage considered does not exceed twice the mean annual run-off. More detailed study would be required to estimate the possible benefit of larger reservoirs, which did not seem justified at this stage. Indeed Midgley and Pitman (1967) have noted that 'increasing the storage provision beyond about 200 per cent MAR merely has the effect of transforming spillage losses to evaporation losses, with little improvement in utilization efficiency'.

The maximum net yield at the proposed reservoir sites usually depends on the mean annual run-off, though there are cases where the estimated available storage is less than twice the mean annual run-off and is therefore the limiting factor. In Table 3.6 the net yield at each site is given at storages of equal to and twice the estimated mean annual run-off or at the maximum storage, whichever is the limiting factor. The yield at a storage of 100% MAR is taken as 17.5% MAR, and at 200% MAR as 27.0% MAR. A number of sites are shown to provide less than the threshold yield of 1000 m^3/day, or 0.365 $m^3 \times 10^6$/year.

REFERENCES

BRIAN COLQUHOUN, HUGH O'DONNELL & PARTNERS (1970) Report on water supplies for Selkirk/Phoenix. Report to Anglo American Corporation, Botswana.

FIELD, D.I. (1975) A handbook of basic ecology for range management in Botswana, Land Utilisation Division, Ministry of Agriculture, Gaborone.

GEMMELL, B.A.P. (1972) Hydrological data for North Eastern Botswana UNDP/FAO Technical Note No. 28, Gaborone.

SIR ALEXANDER GIBB & PARTNERS (1968) Botswana - Shashe Feasibility Studies, Report to IBRD/UNDP (Special Fund).

JENNINGS, C.M.H. (1974) The hydrology of Botswana; Ph.D. thesis.

MIDGLEY, D.C. (1952) A preliminary survey of the surface water resources of the Union of South Africa; Ph.D. thesis, University of Natal.

MIDGLEY, D.C. and PITMAN, W.V. Aids to the appraisal of water resources: determination of storage requirements to meet variable drafts, Trans. S. Afr. Institution of Civil Engineers (December 1967).

MIDGLEY, D.C. and PITMAN, W.V. (1969) Surface water resources of South Africa, University of the Witwatersrand, Department of Civil Engineering, Hydrological Research Unit, Report No. 2/69.

PIKE, J.G. (1970) An interim report on the hydrology of the Mahalapshwe River in relation to the Mahalapye Township water supply; UNDP/FAO Technical Note. No. 6, Gaborone.

PIKE, J.G. (1971) Rainfall and evaporation in Botswana, UNDP/FAO Technical Document No. 1, Gaborone.

RHODESIAN DEPARTMENT OF METEOROLOGICAL SERVICES (1969) Mean monthly and annual rainfall in Rhodesia: commentary on the Mean Monthly and Annual Rainfall Maps.

ROBINS, N.S. (1973) The Lobatse Hospital gauging weir: Report Geol. Surv. Botswana.

SOUTH AFRICAN WEATHER BUREAU (1957) Climate of South Africa: Part 4, Rainfall Maps.

UNITED NATIONS DEVELOPMENT PROGRAMME (1972) Surveys and training for the development of water resources and agricultural production: Botswana: Review of Resources and the Water Resources of Eastern and Northern Botswana and their Development. FAO Rome, 1972.

CHAPTER 4

SELECTION OF MOST FAVOURABLE DAM SITES

Chapter 2 described the identification of a total of 73 possible dam sites. We now discuss the criteria which could be used to select the most favourable sites for subsequent more detailed investigation.

4.1 Hydrology

The terms of reference set minimum net yield limits of 1000 m^3/day (0.365 x 10^6 m^3/year) for small rivers and 5000 m^3/day (1.825 x 10^6 m^3/year) for large rivers. In practice it is difficult to decide whether a river is small or large, and we therefore suggest that only the lower limit should be used at this stage to eliminate possible sites on hydrological grounds. Using this criterion the following sites, 21 in number, could be eliminated at a reservoir capacity of twice the mean annual run-off: 5, 11, 16, 20, 21, 23, 25, 26, 28, 34, 38, 39, 44, 47, 48, 49, 52, 52, 59, 60, and 61.

An additional hydrological factor is the possibility of reservoirs being built in the future in the catchment area of a dam site, thus reducing the yield. This is of particular importance in the case of border rivers where such development (including farm dams) will be difficult to control. However, it is not possible to take this factor into account at the present time, but it must be borne in mind that the present estimates of yield are based on the existing situation and assume that no further reservoirs (apart from the existing reservoirs) have been constructed in the catchment areas.

4.2 Previous Studies

As mentioned in Chapter 2 a number of sites have already been studied and reports are available giving details of the dam sites and reservoir areas. Using this criterion the following additional sites, 9 in number, need not be further investigated at this stage: 1, 9, 14, 18, 22, 32, 45, 54 and 63.

4.3 Effect on existing dams

A number of sites are within the catchment areas of the existing Shashe or Gaborone Dams. We consider that the construction of dams at the following additional sites, 5 in number, would be largely at the expense of the present or future yield of Shashe or Gaborone, and on this criterion could be eliminated: 12, 64, 65, 66, and 67.

We have not eliminated Dam Site No. 6 on this basis, because although it is within the Shashe Dam catchment, its catchment area is too small to have more than a marginal effect on the yield of Shashe.

4.4 Effect of Adjacent Sites

Some of the possible sites are close together and further investigation of both sites is unlikely to be beneficial. Using this criterion we consider that the following sites, 12 in number, could be eliminated for the reasons stated:

Dam Site No.	Reason for Elimination
4	3 superior
7,8	10 superior
15	14 superior (1)
19	17 superior
27	29 superior
31	32 superior
36	37 superior
42	42A superior (2)
43	69 superior
51	54 superior (3)
68	68A superior (4)

(1) Preferred by Colquhoun following site inspection of 15.

(2) Although not on same river the best spillway arrangement for 42A would involve discharging into the reservoir of 42; this would increase the necessary spillway capacity of 42 to an uneconomic extent.

(3) Provided that development of Mahalapye still allows full exploitation of this site.

(4) Provided that agreement can be reached with South Africa for the joint exploitation of this site. It could be argued that 68 has the advantage of the dam being on the border(although all the reservoir would be in South Africa) but some development of 68A by South Africa is likely in any event and this would rule out 68.

4.5 Geology

(a) General

Approximately 70% of the study area is underlain by rocks of the Basement Complex, and about 20% by sedimentary rocks of the Waterburg and Karroo Systems. Intrusive rocks, mostly of granitic or basaltic origin, occur within both these major rock groups, occupying the remaining 10% of the area.

The Basement Complex rocks can be divided into two groups:

(i) Gneisses with subordinate areas of intrusive granite and metamorphosed sedimentary and volcanic rocks.
(ii) Schists and associated sedimentary rocks of varying metamorphic grades including marbles and quartzites.

The former group is the more extensive.

The Waterburg System is a pre-Karroo sedimentary succession of folded quartzitic sandstones and shaly/silty rocks resting unconformably on rocks of the Basement Complex. They occur around Palapye and in the Notwani catchment area.

The Karroo system occurs in two main areas:

(i) The approximate limits of the western boundary of the study area is underlain by sedimentary rocks which form part of the Karroo System in central Botswana. The Karroo Beds which outcrop in the study area are shale, sandstone, grit, mudstone, limestone, tillite and coal of the Ecca and Dwyka series.
(ii) Between the Limpopo and Shashe Rivers in the extreme east of the study area, comprising sandstones and shales overlain by basalts.

A number of prominent dykes extending for many kilometres are intruded into the above mentioned successions which generally extend in a WNW/ESE direction; they are post-Karroo and mainly doleritic.

The principal structural features of the area are the faults and shear zones of post-Karroo age.

(b) Dam Site Locations

Many of the possible dam sites are underlain by the gneisses and granites of the basement complex and are likely to be geologically favourable sites both from the point of view of foundation conditions and of the availability of construction materials.

With regard to those sites located on sedimentary or layered rocks it is not possible to say at this stage whether any serious foundation problems are likely to be found, but there may be a greater degree of difficulty in obtaining local supplies of suitable construction materials such as concrete aggregates and rip-rap.

Assuming that the sites mentioned in Sections 4.1 to 4.4 inclusive are eliminated, of the remaining sites the following are probably located on layered type rocks and may for this reason be less favourable: 2, 17, 35, 37, 40, 41, 42A, 46, 57, 69, 70.

However, we do not consider that there are sufficient grounds for eliminating any of these sites at this stage of the study.

4.6 Most Favourable Sites

Table 4.1 gives details of the remaining sites, 26 in number, listed in descending order of net yield, which could be considered to be the most favourable sites for further investigation.

It will be noted that the maximum water depth for a number of sites is rather low and a more rigorous investigation into reservoir yield could well show that evaporation losses have been under-estimated by the method adopted for the present study which essentially assumes a uniform reservoir geometry and ratio of reserve storage to MAR. This applies in particular to the following sites: 2, 35, 37, 50 and 62.

However, the estimation of maximum water depth is based on small scale surveys, and unless this consideration lends weight to other factors we do not think that the elimination of these sites would be justified at this stage of the study.

For completeness Table 4.2 gives details of the sites mentioned in Section 4.2 which qualify on hydrological grounds, but have been the subject of previous reports.

These drought curves determine the storage required to maintain a given draft, where both are expressed in terms of mean annual run-off, if evaporation from the reservoir is neglected. Evaporation is a significant proportion of the gross yield in reservoirs in Botswana, because of the climate and the topography; therefore the estimation of net evaporation loss is important and it is recommended that estimates should be made at individual sites for design purposes.

The method of estimation of reservoir yield is as follows. The relationship between surface area (A) and reservoir volume (V) is expressed in the form $A = CV^N$ and the reserve or dead storage and maximum storage volumes are determined; the ratio between reserve and total storage for a given yield and the exponent in the area/volume equation determine the evaporating area and thus the loss. It is assumed that the reserve storage level is reached at the end of the design drought and the storage volumes, and therefore areas during the drought are determined by the balance between inflow and net draft. The evaporation from the reservoir during the design drought is estimated as the product of reservoir area and the net evaporation, or the difference between average monthly open water evaporation (Table 3.2) and monthly 'dry year' rainfall (Table 3.1). The station used for reservoir trial was Francistown for the Northern Region, Mahalapye for the Central Region, and Gaborone for the Southern Region. This calculation determines the total storage required to maintain the net yield, and a curve can be drawn relating net yield to effective storage.

Thirty-one dimensionless yield storage curves were plotted for reservoirs having a range of ratios between dead storage and mean annual run-off and differing exponents in the area volume equation, for each of the three run-off regions. It was found that the main variation between sites depends on the ratio of reserve or dead storage to MAR. If this ratio was greater than 15% even for a net yield of only 10% MAR a storage in excess of twice the mean annual run-off was required. For ratios less than 15% the characteristics of the area volume equation become increasingly significant. Because the dead storage cannot be estimated reliably without site survey, it was decided to use a dimensionless curve based on the average curve for the storage at the three existing reservoir sites (see Figure 3.2).

TABLE 4.1

DETAILS OF MOST FAVOURABLE SITES

Dam Site Number	River	Catchment Area (km^2)	Mean Annual run-off ($m^3 \times 10^6$)	Reservoir capacity ($m^3 \times 10^6$)	Approximate maximum water depth (m)	Approximate net yield (m^3/day)
69	Limpopo	135 000	750	1 500	27	550 000
71	Limpopo	86 000	540	500	33	250 000
57	Limpopo	59 000	300	600	15	220 000
58	Limpopo	42 000	250	500	24	185 000
29	Shashe	14 400	317	300	28	148 000
70	Motloutse	13 100	131	262	27	97 000
40	Motloutse	9 200	110	200	31	78 000
33	Motloutse	6 700	110	150	15	65 000
17	Tati	2 400	63	126	16	46 600
68A	Marico	8 200	52	104	15	38 500
46	Lotsane	5 700	28	56	18	20 700
42A	Thune	2 400	22	40	23	15 500
10	Ntshe	440	17.2	34.4	24	12 700
56	Bonwapitse	1 540	16.9	33.8	19	12 500
2	Mosupe	1 030	9.1	18.2	5	6 700
3	Tutume	210	5.2	10.4	20	3 800
62	Metsemotlhaba	800	4.8	9.6	7	3 600
55	Taupye	660	4.6	9.2	11	3 400
24	Seswe	290	4.1	8.2	12	3 000
50	Semakwakwe	1 000	4.0	8.0	9	3 000
6	Shashe	115	3.2	6.4	12	2 400
13	Tiaye	86	2.2	4.4	17	1 600
37	Bojale	235	2.1	4.2	9	1 600
41	Selepswe	230	2.1	4.2	11	1 600
30	Sekgopye	205	1.84	3.68	13	1 400
35	Metsemaswaane	185	1.66	3.32	7	1 200

TABLE 4.2

DETAILS OF SITES PREVIOUSLY STUDIED

Dam Site Number.	River	Catchment area (km^2)	Mean Annual run-off ($m^3 \times 10^6$)	Reservoir capacity ($m^3 \times 10^6$)	Approximate maximum water depth (m)	Approximate net yield (m^3/day)
1	Mosetse	1 310	37	74	9	27 400
9	Tati	380	21	25	34	11 400
14	Tati	1 740	63	80	24	35 400
18	Shashe	4 000	100	160	23	65 800
22	Shashe	6 100	140	280	30	104 000
32	Motloutse	6 000	110	80	18	42 200
45	Lotsane	2 500	16	32	13	11 800
54	Mhalapshwe	880	6.2	12.4	13	4 600
63	Tsube	330	1.98	3.96	13	1 500

APPENDIX A

TERMS OF REFERENCE FOR A RECONNAISSANCE STUDY FOR MAJOR SURFACE WATER SCHEMES

1. BACKGROUND

1.1 Rapid growth in Botswana necessitates extensive construction of water supplies; and in order to place its construction programme on a sound footing, it is essential that the Government mount a substantial water research programme at the present time. Four possible sources of water can be used in the development of a water supply of any size:-

- boreholes
- sand river beds
- Okavango Delta water
- river surface dams

1.2 The Government is presently planning a large project to evaluate ground-water resources in parts of the country scheduled for development in the short and medium term future. The sand beds of 11 major rivers in Eastern Botswana will be prospected from early 1975. Considerably more than a million rand will be invested over the next three years in studies of the Okavango Delta as primary water resouces.

1.3 It is presently anticipated that if water is transferred from the Okavango Delta it will serve development in the Okavango Corridor region only (stretching roughly from 20° to 21° 30' and 22° to 26° 30'); transfer of this water east of the Makgadikgadi Pans is not likely to take place for many years. Throughout the country, borehole and sand river extraction schemes will, in general, be used as sources for water supplies up to the major village level wherever this is physically possible.

1.4 The demand for river surface dams, therefore, arises principally in connection with mining and urban development in Eastern Botswana. At present three urban centres- Gaborone, Lobatse and Selibe-Pikwe - depend on dams for their water and the fourth, Francistown, is likely to have to do so in the near future, and another dam on the Mosetse river is to be built to serve the new township being built under the Sua project. It is anticipated that there will be a number of further large dams required within the next 20 years.

1.5 Accordingly, the objectives of this research study will be to compile an inventory of dam sites suitable for the development of major surface water supplies. Dams capable of being developed on these sites must have a safe yield of at least 1,000 cubic metres per day for small rivers and 5,000 cubic metres per day for large rivers, at the 1 in 50 years level of failure risk.

2. SCOPE OF THE STUDY

2.1 The study will be divided into two parts : Phase I and Phase II.

2.2 Under Phase I the consultant will:-

(a) Examine air photographs of all the rivers of the Limpopo and Makgadikgadi drainage systems, with the exception of the Boteti river. The international boundary rivers - the Ramogwebana, Shashe, Limpopo and Marico - are to be included.

(b) Every dam site conforming with the specifications of paragraph 1.5 on these rivers must be picked out, its catchment area identified and the likely size of dam rendering the largest safe yield possible that can be erected on it should be estimated. In cases where the development of two or more dam sites are mutually exclusive options, the most promising possibility should be selected in conjunction with the reference group (see below). In the absence of other compelling considerations, the site on which the dam with the largest safe yield can be erected will be taken as the most promising.

(c) Every site remaining after this process should be marked on a 1:1,000,000 map of Botswana, together with the catchment area and an indication (in terms of roughly estimated yield) of the size of the dam that could be constructed there.

(d) A brief accompanying report should specify, for each site marked on the map:-
  (i) the size of the catchment area;
  (ii) the roughly estimated mean annual run-off over the catchment;
  (iii) the roughly estimated capacity of the largest possible dam that could be constructed, with the largest possible safe yield;
  (iv) the roughly estimated safe yield of such a dam;
  (v)*cost estimates of Phase II work in accordance with the specification below.

2.3 Material available which may be of assistance is as follows:-

(a) The Lund report on surface water resources in Bechuanaland and accompanying maps. This was published in 1962.

(b) Lund Reports on specific dams sites at: Tobane, Mahalapye, Timbale, Kanye, Palapye, Molepolole and Mosetse.

(c) Report prepared by Brian Colquhoun, Hugh O'Donnel and Partners on Francistown.

(d) A report commissioned by the Anglo-American Corporation. on dam sites to serve Selkirk-Phoenix.

(e) Alexander Gibb and World Bank reports: Gaborone, Lobatse and the Shashe river.

* Our agreement covers the cost of Phase II and this requirement is considered to be in abeyance.

(f) Air photographs held by the Departments of Surveys and Lands and Water Affairs to the scales of 1 : 40,000, 1:30,000 and (for certain rivers) 1 : 15,000.

(g) Print laydowns of air photographs to reduced scale.

(h) Maps to the scale of 1 : 125,000 and (in some areas) 1 : 30,000.

(i) The hydrological records of the Department of Water Affairs.

(j) Such material on dam sites along the boundary rivers as can be obtained from the governments of Southern Rhodesia and South Africa.

(k) Rainfall maps and data kept in the Department of Meteorological Services.

2.4 Within two months of receiving the map and report specified in paragraph 2.2 sections (c) and (d), the Government will draw up a list (most likely on the order of 10 to 20) of sites to be further investigated by the consultant.

PHASE II

2.5 For each site contained in the above list, the consultant will make a field reconnaissance which will involve:

(a) Surveying a cross-section of the proposed line of the embankment and one longitudinal section of the area to be flooded, related to an arbitrary datum and benchmarks described below.

(b) Constructing two permanent benchmarks at positions to be identified on air photographs.

(c) Conducting a reconnaissance study of visible geology and other site features.

(d) Estimating the storage capacity, volume of earthworks and safe yields (at the 1 in 50 years and 1 in 20 years failure risk levels) of the dam. The size of the dam should be such as to maximise the yield within reasonable cost limits.

If permission cannot be obtained from Southern Rhodesia and South Africa to survey international sites, the consultant will be required to make estimates of the levels of the far banks of the boundary rivers.

2.6 In addition to the above field-work, the consultant shall, for each site:

(a) Advise on restrictions to be imposed on other water development work in the catchment, if the safe yield of the dam is not be decreased by more than 10% as a result of upstream works.

(b) Recommend general localities for hydrological gauging stations capable of collecting river flow data essential to detailed decisions about development of the site.

(c) Estimate, in 1975 prices, the cost of developing the largest possible dam on the site, up to and including the outlet facilities.

TIMING AND REPORTS

2.7 Phase I shall be completed, and the map and report specified shall be submitted to the Government within two months of the signature of the project agreement. The map shall be submitted in 100 copies and the report in 50 copies, in English. The map and report shall contain printed warnings of the preliminary nature of the figures and an indication of their accuracy.

2.8 Phase II will be completed and report submitted within four months of the notification by Government of the list of sites to be investigaged in detail. The report shall be submitted in 50 copies in English.

2.9 METRIC UNITS WILL BE USED THROUGHOUT.

3. LIASON

3.1 The reference group referred to in paragraph 2.2 section (b) shall be composed of:

(a) The Senior Hydrological Engineer, Department of Water Affairs and/or other offices nominated by the Director of Water Affairs.

(b) A representative from the planning unit, Ministry of Mineral Resources and Water Affairs.

3.2 In addition, the consultant should liaise with the Department of Surveys and Lands on cartographic matters and the Department of Meteorological Services on rainfall and evaporation data.

APPENDIX B

MONTHLY FLOWS AT BOTSWANA SITES

M3 NATA AT NATA BRIDGE (Area 22900 km^2)

Monthly flows, million m^3

	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	TOTAL	RUNOFF mm	SOURCE
69-70	*	*	51.628	.548	0	0	0	0	0	0	0	0	52.176	2.3	Tech
70-71	0	0	0	62.310	1.832	0	0	0	0	0	0	0	64.142	2.8	Note
71-72	0	4.659	5.940	607.8	143.3	22.8	20.8*	0	0	0	0	0	805.299*	35.2	28
72-73	0	0	0	0	2.466	6.882	0	0	0	0	0	0	9.348	0.4	Records
73-74	0	0	39.347	529.589	157.162	47.152	.708	0	0	0	0	0	773.958	33.8	with
74-75	0	0	.510	7.264	44.534	19.920	7.516	.129	0	0	0	0	79.873	3.5	letter
												Mean	297.466	13.0	
												Adjusted mean	278.735	12.2	

* Incomplete record

M22 MOSETSE AT MOSETSE (Area 1090 km^2)

Monthly flows, million m^3

	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	TOTAL	RUNOFF mm	SOURCE
70-71	*	.316	8.184	29.116	.185	0	0	0	0	0	0	0	37.801	34.7	Tech Note 28
71-72	0	.351	.341	95.909	.104	1.081	0	0	0	0	0	0	97.786	89.7	
72-73	0	0	0	1.392	.548	.876	0	0	0	0	0	0	2.816	2.6	Records with letter
73-74	0	2.907	29.402	31.609	6.958	1.103	0	0	0	0	0	0	71.979	66.0	
74-75	0	.283	.611	.860	6.030	1.209	0	0	0	0	0	0	8.993	8.3	
												Average	43.875	40.3	
												Adjusted mean	36.799	33.8	

* Incomplete record

M32 MOSUPE AT MATSITAMA WEIR (Area 516 km^2)

Monthly flows, million m^3

	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	TOTAL	RUNOFF mm	SOURCE
70-71	.243	.897	1.577	6.100	0	0	.134	0	0	0	0	0	8.951	17.3	Tech Note 28
71-72	0	.954	.591	13.113	.333	0	0	0	0	0	0	0	14.991	29.1	
72-73	0	0	0	0	0	0	0	0	0	0	0	0	0	0	Letter
73-74	0	0	.780	9.023(1)	2.472	.003	0	0	0	0	0	0	12.278+	23.8	Letter superseded by sheet collected by JVS
74-75		.137	1.051	1.220	.172		.397						2.977	5.8	Sheet collected by JVS
												Mean	7.839	15.2	
												Adjusted mean	6.575	12.7	

(1) Flow 10-31/1/74 estimated by comparison with Mosetse

L16 SHASHE AT MOOKE WEIR (Area 2460 km^2)

Monthly flows, million m^3

	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEPT	TOTAL	RUNOFF mm	SOURCE
62-63	0(1)	37.540 (1)	5.707(1)	21.587	1.341	0	19.077	0	0	0	0	0	85.252	34.7	Lund
63-64	0	.08	11.925	2.054	0	0	0	0	0	0	0	0	14.059	5.7	Lund
64-65	0	1.525(1)	6.765(2)	9.619	1.833	0	0	0	0	0	0	0	19.742	8.0	Lund
65-66	0	13.604	1.181	18.857	57.485(3)	17.823	0	0	0	0	0	0	108.950	44.3	Lund
66-67	0	4.121	36.150	53.493(1)	44.612(1)	0	2.891	0	0	0	0	0	141.267	57.4	Lund
67-68	0	0	0	5.053	38.952	1.034	4.518	0	0	0	0	0	49.557	20.1	Lund
68-69	0	2.548	8.025	6.928	7.032	61.903	14.910	0	0	0	0	1.080	102.426	41.6	Tech
69-70	2.333	5.632	9.301	0	17.62	0.02	0	0	0	0	0	0	34.906	14.2	Note
70-71	0	0	16.35	28.98	3.43	0	8.90	0	0	0	0	0	57.66	23.4	28
71-72	0.88	5.42	13.99	164.6	5.8	5.4	0.1	0	0	0	0	0	196.19	79.8	
72-73	0	0	0	2.845	5.591	1.773	0	0	0	0	0	0	10.209	4.2	Records with
73-74	0	24.0(4)	21.6(4)	79.6(4)	6.5(4)	2.8(4)	0	0	0	0	0	.8(4)	135.3(4)	55.0(4)	letter
74-75	0	2.246	7.694	31.664	22.350	3.263	4.473	0	0	0	0	0	71.690	29.1	Sheet handed to JVS
												Mean	79.016	32.1	

(1) Gap estimated by comparison with Tati and Inchwe
(2) Gap estimated by comparison with Francistown rainfall
(3) Provisional estimate using Francistown rainfall and regression from Gibb (1968)
(4) Recorder pipes blocked for whole season; flows estimated from Shashe reservoir inflow x 0.80 (after comparison of other years)

L22 TATI AT TATI WEIR (Area 570 km^2)

Monthly flows, million m^3

	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	TOTAL	RUNOFF mm	SOURCE
62-63	0	8.954	5.584	7.749	2.731	0	2.915	0	0	0	0	0	27.933	49.0	Lund
63-64	0	0	5.496	0	.070	0	0	0	0	0	0	0	5.566	9.8	Lund
64-65	0	0	3.413(1)	1.771	1.378	0	0	0	0	0	0	0	6.562	11.5	Lund
65-66	0	4.684	.344(1)	5.585	15.463(1)	3.112	0	0	0	0	0	0	29.188	51.2	Lund
66-67	.738	.295	5.941	7.159(1)	11.611	.320	0	0	0	0	0	0	26.064	45.7	Lund
67-68	0	0	0	.303	17.512	0	.232	0	0	0	0	0	18.047	31.7	Lund
68-69	0	0	0	1.518	11.698	.310	1.357	0	0	0	0	0	14.883	26.1	Colquhoun (2)
69-70	*	.248*	3.883	0	3.446	0	0	0	0	0	0	0	7.577*	13.3*	Tech
70-71	0	.035	8.657	12.853	1.439	.279	1.535	0	0	0	0	0	24.798	43.5	Note
71-72	0	1.732	7.956	113.1	4.8	8.0	0.9*	0	0	0	0	0	136.488*	239.5*	28
72-73	0	0	0	.198	.209	.333	0	0	0	0	0	0	.740	1.3	From letter
73-74	0	4.820(3)	7.294	40.810	11.355	6.786	0	0	0	0	0	0	71.065	124.7	From sheets
74-75	0	2.173	3.487	6.187	16.217(3)	7.170(3)	1.814	0	0	0	0	0	37.048	65.0	handed to JVS
												Mean	31.228	54.8	

(1) Gap estimated by comparison with Shashe

(2) Annual total (from Colquhoun report) distributed in proportion to Shashe monthly flows

(3) Gap estimated from Inchwe

* Incomplete record

L25 INCHWE AT INCHWE WEIR (Area 800 km^2)

Monthly flows, million m^3

	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	TOTAL	RUNOFF mm	SOURCE
62-63	0	5.806(1)	2.804	6.704	1.415	.006	2.177	0	0	0	0	0	18.912	23.6	Lund
63-64	.640	0	2.829(1)	0	.160(1)	0	0	0	0	0	0	0	3.629	4.5	Lund
64-65	0	0	4.951(1)	1.476(2)	.554	0	0	0	0	0	0	0	6.981	8.7	Lund
65-66	0	3.063	.062	4.686	13.279(1)	4.403	0	0	0	0	0	0	25.493	31.9	Lund
66-67	0	0	4.576(1)	16.679(1)	19.409(2)	.744(2)	.148(2)	0	0	0	0	0	41.556	51.9	Lund
67-68	0	0	0	0	5.688	.455	.661	0	0	0	0	0	6.804	8.5	Lund
68-69	0	0	0	2.007	15.469	.410	1.794	0	0	0	0	0	19.680	24.6	(3)
69-70	*	.445	5.047	0	1.853	0	0	0	0	0	0	0	7.345*	9.2*	Tech
70-71	0	.178	4.238	12.981	.153	.872	1.290	0	0	0	0	0	19.712	24.6	Note
71-72	0	2.660	3.869	104.5	5.2	8.8	2.9*	0	0	0	0	0	127.93*	159.9*	28
72-73	0	0	0	1.414	3.527	.772	0	0	0	0	0	0	5.713	7.1	Recorder
73-74	0	9.066(2)	12.684(2)	40.205(2)	13.154(2)	7.314	0(2)	0	0	0	0	0	82.423	103.0	levels with
74-75	0	1.748	5.465	10.831	15.764	7.170	.128	0	0	0	0	0	41.106	51.4	letter
												Mean	31.329	39.2	

(1) Gap estimated by comparison with Shashe
(2) Gap estimated by comparison with Shashe and Tati
(3) Annual total (from Colquhoun report) distributed in proportion to Shashe monthly flows

* Incomplete record

L17 SHASHE SIDING AND SHASHE DAM (Area 3650 km^2)

Monthly flows, million m^3

	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	TOTAL	RUNOFF mm	SOURCE
70-71	0	0	14.134	45.577	4.049	0	11.964	0	0	0	0	0	75.724	20.7	Tech Note 28
71-72	0	3.059	20.161	216.8	5.1	4.5	0	0 (1)	0 (1)	0 (1)	0 (1)	0 (1)	249.62	68.4	
SHASHE RESERVOIR															
72-73	0 (1)	0 (1)	0 (1)	5.5	7.0	1.5	0	0	0	0	0	0	14.0	3.8	
73-74	0	30.0	27.0	99.5	8.1	3.5	0	0	0	0	0	1.0	169.1	46.3	
74-75	0	5.0	15.0	31.0	27.4	2.0	2.3	0	0	0	0	0	82.7	22.7	
75-76	0	0.5	7.0												
													Mean 118.229	32.4	

(1) Estimated by comparison with Shashe Weir (obtained in graphical form from Francistown)

(2) Reservoir inflow estimated from level changes and spillage estimated from levels above spillway using formula $Q = 3/\sqrt{3.281}\ l\ h^{1.5}$ cumecs, where h is level above spillway in metres, and l is length of spillway crest (305m). The spillage was approximately estimated as 85.1 million m^3 in 1973-74, and 53.3 in 1974-75.

L12 SHASHE BELOW TATI CONFLUENCE (Lower Shashe) (Area 7810 km^2)

Monthly flows, million m^3

	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	TOTAL	RUNOFF mm	SOURCE
70-71	*	0*	25.138	99.9	2.8	0	16.3	0	0	0	0	0	144.138*	18.5	Tech
71-72	0	11.6	36.7	556.2	21.8	20.0	3.8	0	0	0	0	0	650.1	83.2	Note 28
72-73	Still being computed														
73-74	0	7.377	39.330	108.171	15.368	45.906	0	0	0	0	0	0	216.152	27.7	Telex of
74-75	0	4.417	15.703	61.125	100.960	2.555	9.471	0	0	0	0	0	194.231	24.9	23 March 1976
										Mean			301.155	38.6	
										Adjusted Mean			206.545	26.4	

* Incomplete record

L31 MOTLOUTSE AT TOBANE (Area 5960 km^2)

Monthly flows, million m^3

	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	TOTAL	RUNOFF mm	SOURCE
69-70	*	.071	6.716	0	2.890	.412	.808	0	0	0	0	0	10.897	1.8	Tech Note 28
70-71	0	0	11.663	66.853	2.595	0	2.442	0	0	0	0	0	83.553	14.0	
71-72	0	3.671	16.209	207.5	6.1	8.6	.128	0	0	0	0	0	242.208	40.6	
72-73	0	.566	.924	14.550	7.798	5.167	0	0	0	0	0	0	29.005	4.9	From letter
73-74	0	10.711	89.333	11.548	4.025	13.363	0	0	0	0	0	0	128.980	21.6	Sheet handed to JVS
74-75	0	26.622	10.487	98.953	71.674	0.544	4.476	0.124	0	0	0	0	212.880	35.7	
												Mean	117.921	19.8	
												Adjusted mean	110.495	18.5	

* Incomplete record

L44 LOTSANE AT PALAPYE (Area 3959 km^2)

Monthly flows, million m^3

	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	TOTAL	RUNOFF mm	SOURCE
69-70	0	0.010	0.293	0	0.008	0	0	0	0	0	0	0	0.311	0.08	(1)
70-71	0	0.640	27.161	17.516	1.301	0.099	0	0	0	0	0	0	46.717	11.8	(2)
71-72	0	0.442	.605 (3)	11.070 (3)	.018	1.143	0	0	0	0	0	0	13.278	3.4	(2)
72-73	Nil recorded flow												0.0	0.0	Letter
73-74	2.709	0.322	11.532	2.976	1.044	0	0	0	0	0	0	0	18.583	4.7	Sheet collected by JVS from Francistown
74-75	0	0	2.011 (3)	3.557	11.237	.258	.132	0	0	0	0	0	17.195	4.3	Sheet collected by JVS from Francistown
												Mean	16.014	4.0	

(1) Sheet collected by JVS from Gaborone

(2) Sheet posted to JVS from Gaborone

(3) Flow in gap neglected after comparison

L53 MAHALAPSHWE AT MADIBA (Area 740 km^2)

Monthly flows, million m^3

	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	TOTAL	RUNOFF mm	SOURCE
67-68													0	0	Pike, Tech
68-69													3.19	4.3	Note 6
69-70	0	0	.106	0	1.462	.043	0	0	0	0	0	0	1.611	2.2	Letter
70-71	0	0	41.117	7.661	0.208	0	0	0	0	0	0	0	48.986	66.2	Letter
71-72	0	4.693	1.459	0.643	0.101	0.005	0	0	0	0	0	0	6.901	9.3	(1)
72-73	0	0	0	0	0.189	0	0	0	0	0	0	0	0.189	0.3	(2)
73-74	0	0	1.998	4.285	6.197	0.044	0.024	0	0	0	0	0	12.548	17.0	(3)
74-75	0	0	1.087	8.554	3.631	1.013	1.461	0.011	0	0	0	0	15.757	21.3	(3)
													Mean 11.148	15.1	

(1) Telex received 17/3/76

(2) Sheet handed to JVS

(3) Telephoned records from Francistown

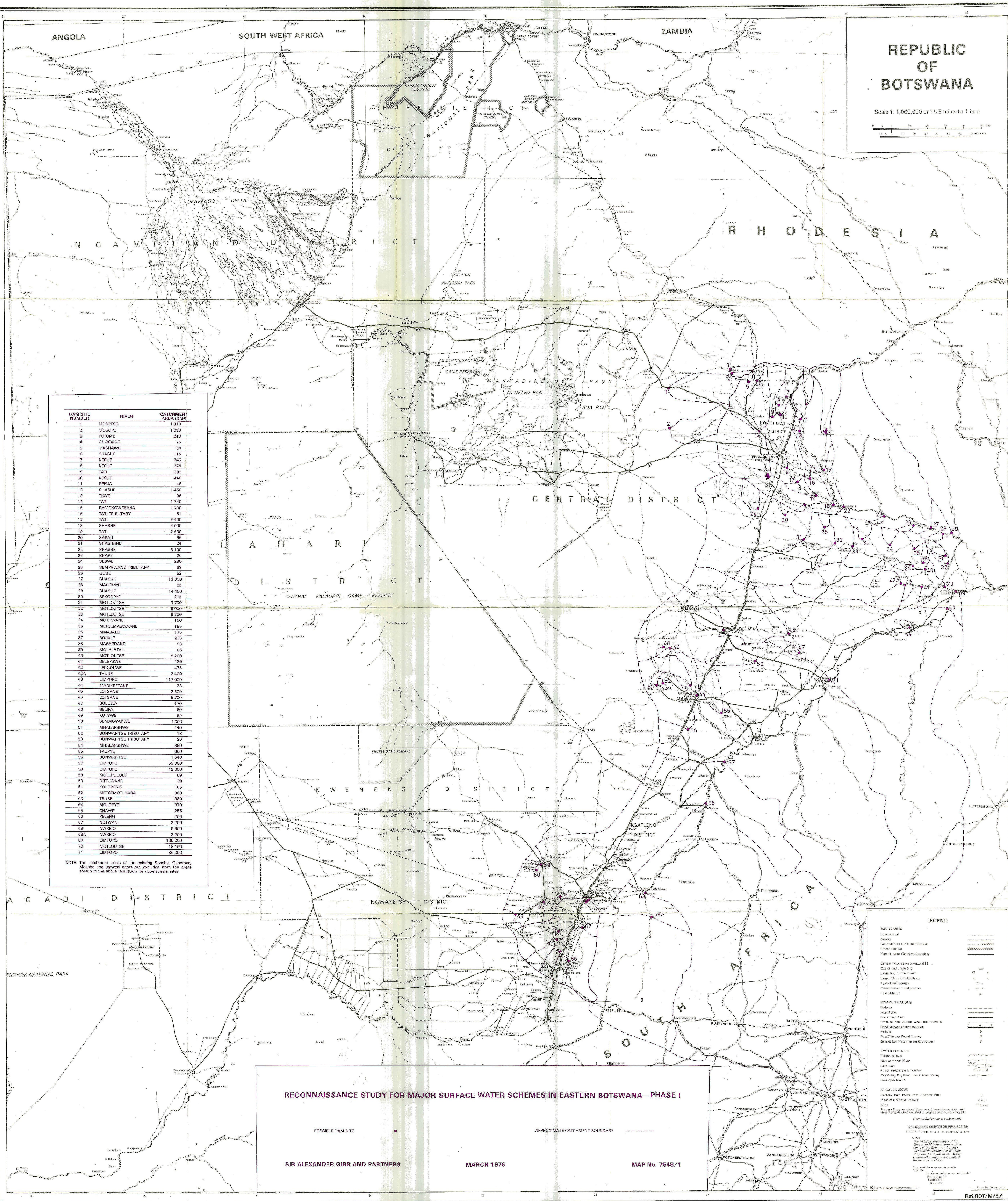
GABORONE RESERVOIR (Area 4300 km^2)

Monthly flow,(2) million m^3

	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	TOTAL	RUNOFF mm
65-66	0	0	.738	10.209	73.257(1)	0	0	1.722	0	0	0	1.722	87.648	20.4
66-67	.369	2.030	9.325	41.792	35.160	11.487	71.790	4.620	.160	0	.492	.246	177.471	41.3
67-68	0	1.599	0	1.599	0	6.396	1.230	.123	1.599	0	0	1.353	13.899	3.2
68-69	.984	.615	.492	.123	.369	0	.123	0	0	0	0	0	2.706	0.6
69-70	0	.062	.061	0	0	.123	0	0	0	0	0	0	.246	0.1
70-71	0	.615	1.230	1.722	4.920	.738	.123	0	0	0	0	0	9.348	2.2
71-72	0	11.931	.738	31.029	0	0	0	0	0	0	0	0	43.698	10.2
72-73	0	0	0	0	.861	0	10.578	0	0	0	0	0	11.439	2.7
73-74	5.781	3.444	10.726	14.530	19.610	13.330	1.240	.240	0	0	0	0	68.901	16.0
74-75	0	1.107	.369	.369	0	4.305	7.153	2.900	0	0	0	0	16.203	3.8
(75-76	0	0	1.968)											
												Average	43.156	10.0

(1) Recession estimated from maximum level on 9/2/66; later rise estimated by comparison with Notwani levels

(2) Inflow estimated from level changes, and spillage estimated from levels above spillway, using formula $Q = 3 \times 888.6 \times h^{1.5}$ cusecs, where 888.6ft is spillway length and h is height in feet above spillway. Spillage is approximately estimated as 48.042 million m^3 in 1965-66, 167.63 in 1966-67, 15.90 in 1971-72, 56.85 in 1973-74, and 7.47 in 1974-75.



DAM SITE NUMBER	RIVER	CATCHMENT AREA (KM^2)
1	MOSETSE	1 310
2	MOSOPE	1 030
3	TUTUME	210
4	GHOSAWE	75
5	MASHAWE	34
6	SHASHE	115
7	NTSHE	240
8	NTSHE	375
9	TATI	380
10	NTSHE	440
11	SENJA	46
12	SHASHE	1 450
13	TIAYE	86
14	TATI	1 740
15	RAMOKGWEBANA	1 700
16	TATI TRIBUTARY	51
17	TATI	2 400
18	SHASHE	4 000
19	TATI	2 600
20	SASAU	56
21	SHASHANE	24
22	SHASHE	6 100
23	SHAPE	26
24	SESWE	290
25	SEMPAWANE TRIBUTARY	69
26	GOBE	52
27	SHASHE	13 800
28	MABOLWE	86
29	SHASHE	14 400
30	SEKGOPYE	205
31	MOTLOUTSE	3 700
32	MOTLOUTSE	6 000
33	MOTLOUTSE	6 700
34	MOTHWANE	150
35	METSEMASWAANE	185
36	MMAJALE	175
37	BOJALE	235
38	MASHEDANE	93
39	MOLALATAU	86
40	MOTLOUTSE	9 200
41	SELEPSWE	230
42	LEKGOLWE	475
42A	THUNE	2 400
43	LIMPOPO	117 000
44	MADIKEETANE	33
45	LOTSANE	2 500
46	LOTSANE	5 700
47	BOLOWA	170
48	SELIPA	60
49	KUTSWE	69
50	SEMAKWAKWE	1 000
51	MHALAPSHWE	440
52	BONWAPITSE TRIBUTARY	18
53	BONWAPITSE TRIBUTARY	26
54	MHALAPSHWE	880
55	TAUPYE	660
56	BONWAPITSE	1 540
57	LIMPOPO	59 000
58	LIMPOPO	42 000
59	MOLEPOLOLE	89
60	DITEJWANE	38
61	KOLOBENG	165
62	METSEMOTLHABA	800
63	TSUBE	330
64	MOLOPYE	870
65	CHAWE	255
66	PELENG	205
67	NOTWANI	2 200
68	MARICO	9 600
68A	MARICO	8 200
69	LIMPOPO	135 000
70	MOTLOUTSE	13 100
71	LIMPOPO	86 000

NOTE: The catchment areas of the existing Shashe, Gaborone, Madabe and Ingwezi dams are excluded from the areas shown in the above tabulation for downstream sites.

RECONNAISSANCE STUDY FOR MAJOR SURFACE WATER SCHEMES IN EASTERN BOTSWANA—PHASE I

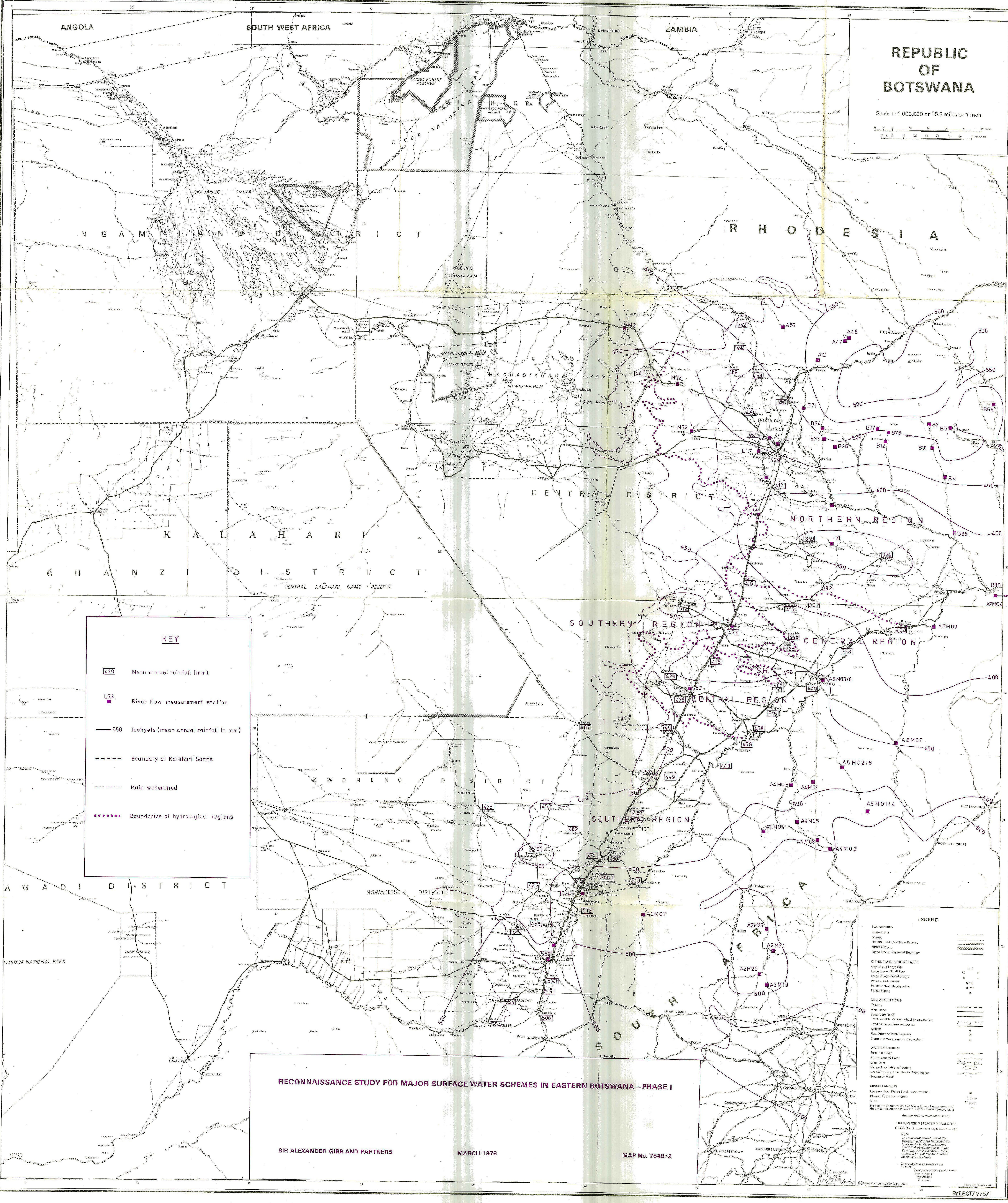
POSSIBLE DAM SITE •

APPROXIMATE CATCHMENT BOUNDARY - - - - -

SIR ALEXANDER GIBB AND PARTNERS

MARCH 1976

MAP No. 7548/1



REPUBLIC OF BOTSWANA
Scale 1: 1,000,000 or 15.8 miles to 1 inch
ANGOLA
SOUTH WEST AFRICA
ZAMBIA
RHODESIA
SOUTH AFRICA
CHOBE DISTRICT
CHOBE NATIONAL PARK
CHOBE FOREST RESERVE
OKAVANGO DELTA
NGAMILAND DISTRICT
NXAI PAN NATIONAL PARK
MAKGADIKGADI PANS GAME RESERVE
MAKGADIKGADI PANS
NTWETWE PAN
SOA PAN
CENTRAL DISTRICT
NORTH EAST DISTRICT
FRANCISTOWN
BULAWAYO
LIVINGSTONE
NORTHERN REGION
CENTRAL REGION
SOUTHERN REGION
KALAHARI
GHANZI DISTRICT
CENTRAL KALAHARI GAME RESERVE
KWENENG DISTRICT
SOUTHERN DISTRICT
NGWAKETSE DISTRICT
AGADI DISTRICT
EMSBOK NATIONAL PARK
KHUTSE GAME RESERVE
MAFEKING
PIETERSBURG
POTGIETERSRUS
RUSTENBURG
PRETORIA
JOHANNESBURG
POTCHEFSTROOM
VANDERBIJLPARK
KEY
439 Mean annual rainfall (mm)
L53 River flow measurement station
550 Isohyets (mean annual rainfall in mm)
Boundary of Kalahari Sands
Main watershed
Boundaries of hydrological regions
LEGEND
RECONNAISSANCE STUDY FOR MAJOR SURFACE WATER SCHEMES IN EASTERN BOTSWANA—PHASE I
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MARCH 1976
MAP No. 7548/2
Ref.BOT/M/5/I