RAINFALL AND STORMWATER HARVESTING FOR ADDITIONAL WATER SUPPLIES IN AFRICA

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INTRODUCTION

The paper examines storm and rainwater harvesting for additional water supplies in rural areas of Africa.

The first part of the paper discusses the physical and human characteristics of the continent thus giving a reader a firm background against which the various water harvesting methods can be assessed. These physical and human characteristics are not discussed on country basis although the methodologies for water harvesting discussed in the paper are practised in given countries.

The later section of the paper discuss storm water harvesting, harvesting of water from roof catchments and other techniques of water harvesting.

My special thanks go to Dr. L. Obeng for her encouragement and support. I also would like to thank Prof. Joseph Mungai, the Vice-Chancellor of the University of Nairobi for granting me permission to carry out research in connection with this paper. I would like to pay special tribute to Water Department and related Government Agencies in many African Nations who provided the necessary information enabling the compilation of this paper. X

I would like with gratitude to express my sincere thanks to Professor S.H. Ominde and Prof. F.F. Ojany, the Chairman of the Department of Geography for encouragement in research work. Last but not least I would like to thank the cartographic staff of the Department of Geography especially Mr. Wilson Okach for technical illustrations and Maria Nyawade for having ably typed the manuscript.

Dr. G.S. Ongweny
1979

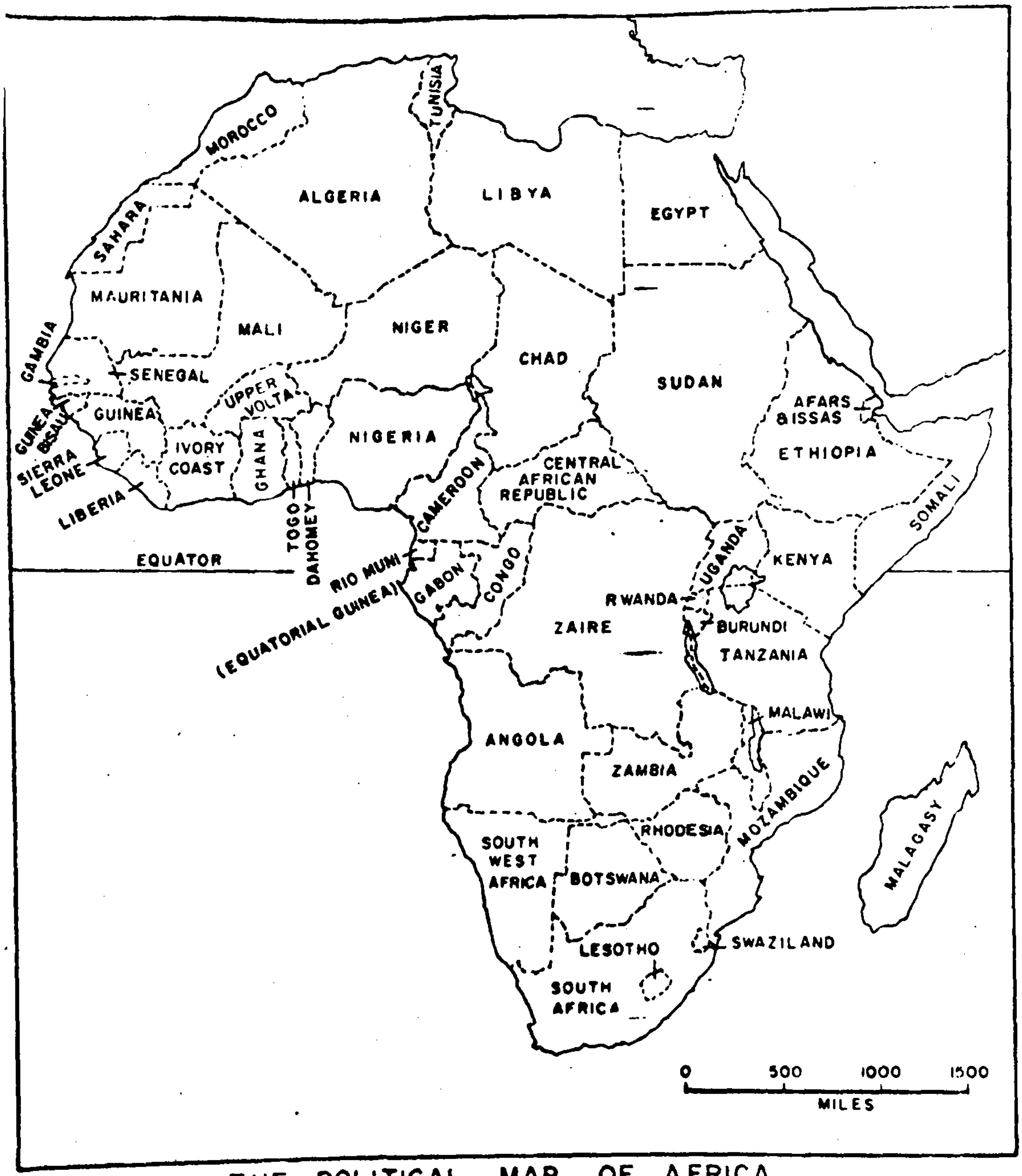
RAINFALL AND STORMWATER HARVESTING FOR ADDITIONAL RURAL WATER SUPPLIES IN AFRICA

PHYSICAL AND HUMAN BACKGROUND

GEOLOGY, TOPOGRAPHY AND DRAINAGE

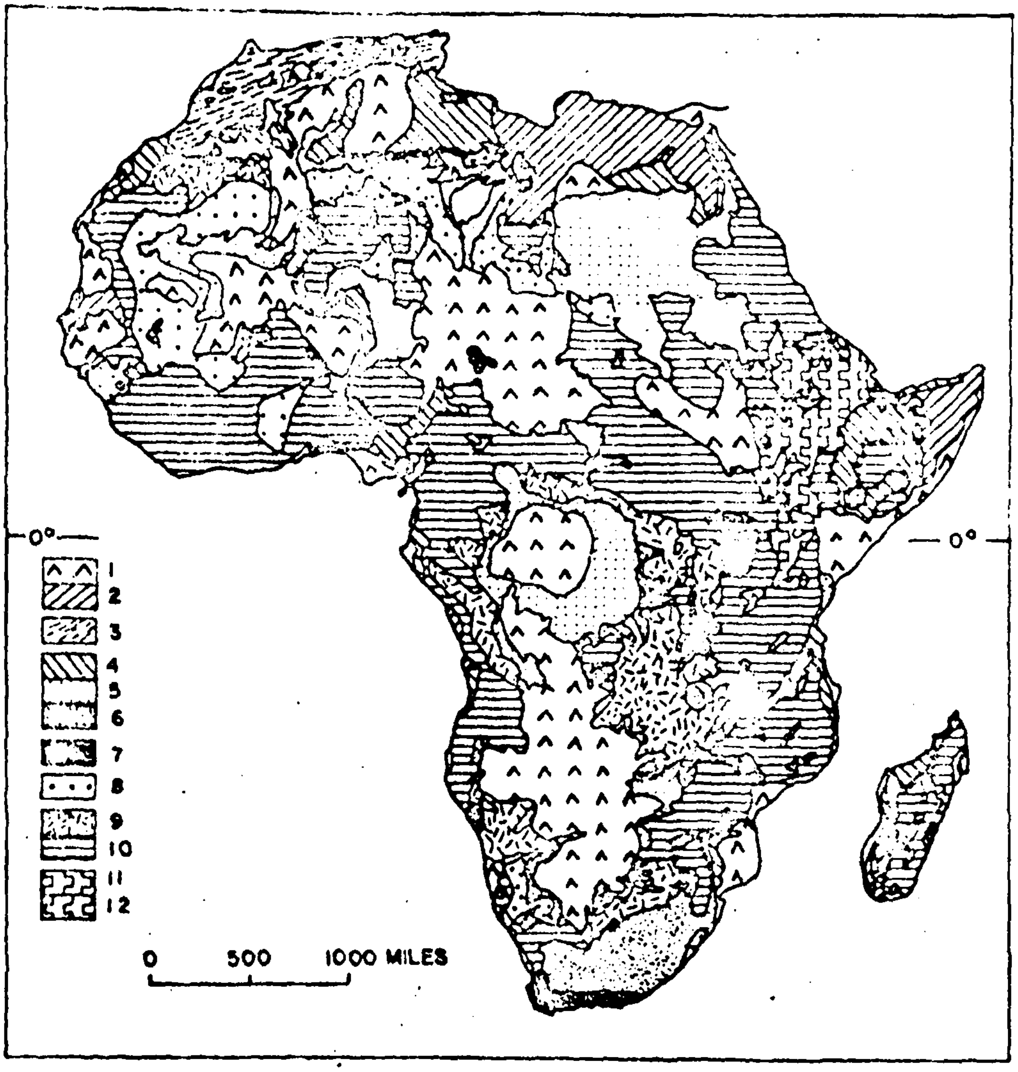
The continent of Africa including its islands which covers an area of about 30.1×10^6 km^2 lies almost symmetrically about the Equator extending from latitude 37°N. to latitude 35°S. It accounts for one-fifth (22.4%) of the dry land of the globe and is the second largest continent after Eurasia consisting of 48 nations (see Fig. 1). Because the continent narrows towards the south, its surface on the northern hemisphere is almost twice that in the southern hemisphere.

The simplicity of the coastline is matched by a simplicity of structure and of relief. Vast deposits of sedimentary rocks undisturbed by any folding alternate with basic outcrops of old crystalline rocks forming the Basement complex (see Fig. 2), the whole of which form a tableland bordered by broken terraces and escarpments as indicated in Figure 3. In the extreme north-west and the extreme south-west are regions of folded mountain system which form a separate structure. The large continental island of Madagascar as shown in Figure 3 remains a relic of a former land connecting with Africa. According to the Economic Commission for Africa (1977) the relief of Africa as shown in Figure 3 may be classified into three broad divisions which include the plateau country, the north-western (Atlas) Region, and south-western ridges and valleys. These are briefly reviewed below:-



THE POLITICAL MAP OF AFRICA

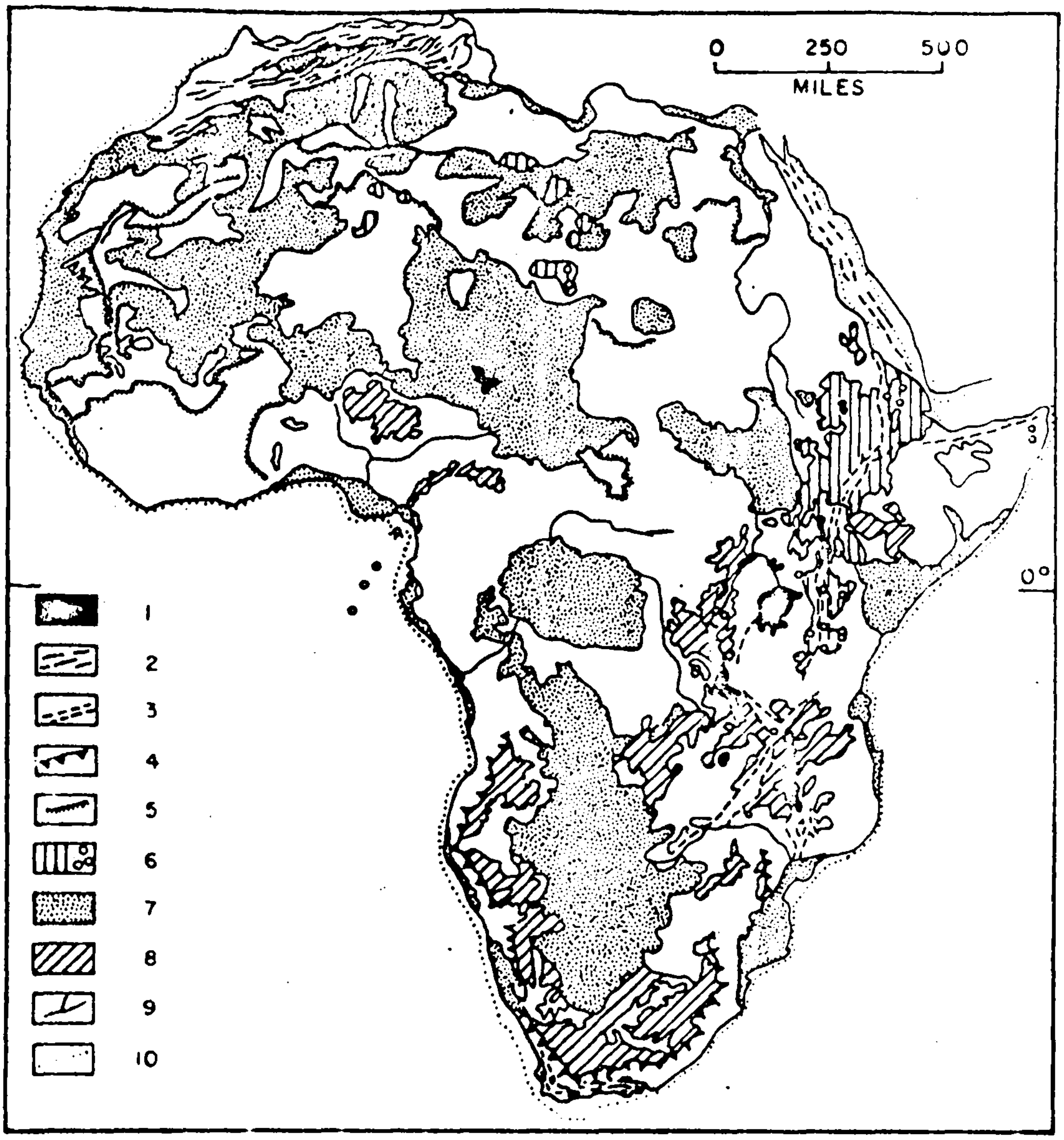
Fig. 1



1 QUATERNARY (undifferentiated) and continental Tertiary (unfolded) 2 MARINE TERTIARY (unfolded) 3. ATLAS FOLDED ZONE. 4. MARINE MESOZOIC (unfolded) 5 CONTINENTAL MESOZOIC other than Karroo 6. KARROO (unfolded). 7 CAPE FOLDED ZONE. 8. PALAEOZOIC (other than Karroo). 9. YOUNGER PRE-CAMBRIAN 10 Older and Undiffentiated PRE-CAMBRIAN. 11. POST-JURASSIC LAVAS. 12. OTHER IGNEOUS

THE GEOLOGY OF AFRICA

Fig. 2



THE GEOMORPHOLOGY OF AFRICA
1 Lakes 2 Fold Mountains. 3. Faults of the East African Rift Valley System. 4 The Great Escarpment of Southern Africa. 5. Erosion scarps in Northern Africa. 6. Post-Jurassic Volcanics, and associated volcanic cones. 7. Tertiary and Quaternary sediments 8 Erosion surface remnants ascribed to the Gondwana and African cycles by L C King 9 Major rivers (only part shown for reference) 10 100-fathom line of the sea floor

Fig. 3

The rim of the plateau country rises somewhat above the general level of the interior and falls abruptly to the sea. The highest point of the rim is in the south-east and is formed by Drakensberg mountains rising to well over 3400 metres. The comparatively low plateau of the northern and central Africa has an altitude ranging between 460-600 metres on the average and may be contrasted with the high plateaus of the east and south averaging between 900-1200 metres. The eastern Africa geomorphic and tectonic processes have affected the relief by giving rise to the African Rift System flanked by Africa's highest mountains including Kilimanjaro, Kenya and Ruwenzori. The Rift Valley contains several lakes and Lake Victoria (the largest lake in Africa) lies between the two branches of the Rift Valley.

The north-western (Atlas) region is composed of parallel mountain chains running roughly from south-west to north-east, enclosing high plateau area.

The southwestern ridges and valleys are formed by mountain folding and are cut by rivers flowing along the softer rock formations.

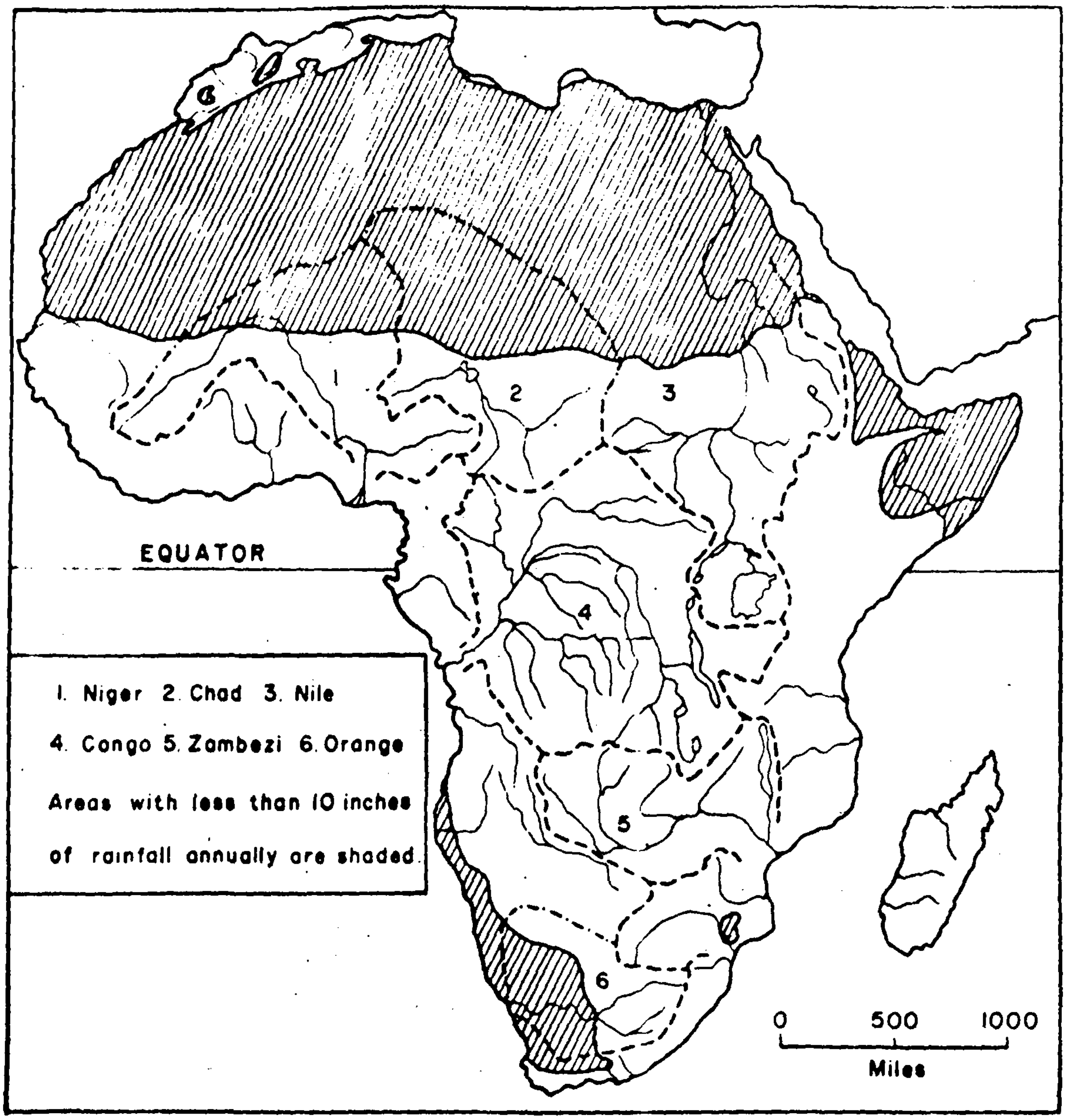
In summary then it may be said that in contrast to other continents, the surface of Africa is moderately rugged its mean altitude being 650 m. During its geologic development the continent was subject to epeirogenic movements that brought elevations into existence in the border region, the Atlas mountains (4165 m) the Fouta-Djalon (1537 m), Kilimanjaro (5895 m), the Drakensberg mountains (3482 m) the Ethiopian highlands (4630 m) and others. In the central part of the continent vast plains as well as tablelands and plateaux prevail at altitudes of 200 m to 500 m above sea level.

Deserts form important features of the African landscape. The greatest desert in the work i.e. the Sahara, covering an area of close to $7 \times 10^6 km^2$ extends from the Atlantic coast to the Red Sea. The second most arid area ($0.9 \times 10^6 km^2$), the Kalahari semi-desert is situated in the south of the continent.

DRAINAGE

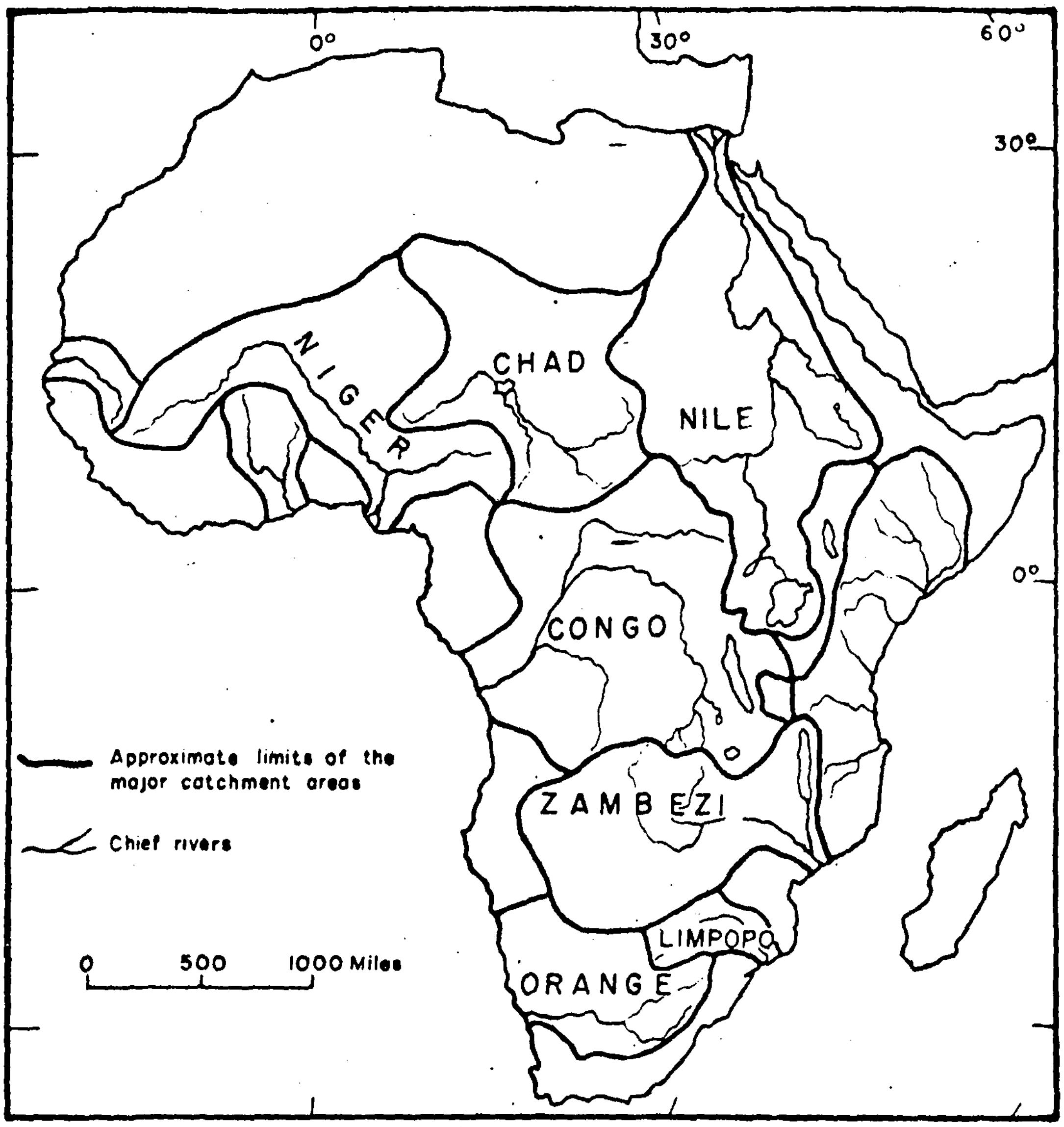
The general configuration of Africa i.e. that of a level plateau causes marked perculiarities in river drainage. While the divides between the head waters of rivers (see Fig. 4) are sometimes ill-defined in their middle courses the streams flow sluggishly and often spread out over wide flood plains or form swamps such as the Sudd on the Nile and the Inland delta on the Niger while in their lower courses they enter wild gorges and descend by falls and rapids to the sea. The drainage of the continent as illustrated by the main catchment areas shown in Figure 5 may be conveniently be grouped as follows:-

- the north flowing rivers mainly consisting of the basin of the Nile River and rivers in the north-west Africa;
- east flowing rivers including the Wabi Shebelli in the north, the Zambezi in middle and many short streams in the south;
- west flowing river systems including the Orange in the south, the Congo (Zaire) and the Senga in the north.
- In addition rivers such as the Gambia and the Senegal in West Africa form a separate group; south flowing river systems includin the Niger and the Volta and a number of other smaller streams and finally there are major inland drainage basins that include Lake Chad, Lake Rudolf (Turkana), the Okarango, the Gash, the Awash and Etosha pan. The drainage area and runoff contributions of main rivers of Africa is given in Table 1 while the characteristic of main lakes of Africa is given in Table 2.



THE RIVERS AND RIVER BASINS OF AFRICA

Fig. 4



MAP OF THE MAIN CATCHMENT AREAS IN AFRICA

Fig. 5

The drainage areas and runoff contributions of main rivers of Africa is given in Table 1 while the characteristics of main Lakes of Africa is given in Table 2.

TABLE 1

RIVERS OF AFRICA

Rivers	Drainage Area km^2 km^2	Mean Annual Runoff 10^6 $10^6 m^3$
North flowing rivers		
Nile (at Aswan)	2,800,000	84,000
Baraka	41,400	300
Medjerda (eastern Algeria)	34,800	5,500
Cheliff and Dahra Coast	48,600	1,720
Soummam	9,200	750
Sebaou and others	3,900	1,600
Others in northern Algeria	36,410	2,100
Moulouya	53,700	1,388
Rivers in Tunisia		
East flowing rivers		
Uadi Dhut (Somalia)		
Deb Nugaled (Somalia)		
Wabi Shabelle	205,400	2,500
Dawa-Juba	168,100	
Lok Bor		
Ewaso Nyero (Lok Dera)	15,022	739
Tana	42,217	4,700
Athi (Galana)		1,295
Umba		
Pangani (at Korogwe)	25,110	3,021
Wami (at Manderal)	36,450	2,592
Ruvu (at Morogoro Bridge)	15,190	2,261
Rufiji (at Pangani Rapids)	158,000	30,000
Matandu		
Mbemkuru		
Ruvuma	155,400	
Massalo (e.a. 2/ = 10,000 km^2)	24,000	1,030
Montepuez (e.a. = 2,415 km^2)	9,500	195
Rio Lurio (e.a. = 56,200 km^2)	60,800	7,330
Meouburi (e.a. = 4,000 km^2)	8,900	460
Monapo (e.a. = 8,000 km^2)	8,800	1,005
Meluli (e.a. = 9,007 km^2)	9,700	1,915
Ligonha (e.a. = 5,410 km^2)	16,299	820
Molocue (e.a. = 2,900 km^2)	6,500	865
Licungo (e.a. = 5,800 km^2)	27,726	1,210

East flowing rivers cont........

Zambezi (at D. Ana)	1,250,000	103,380
Rio Punge (e.a. = 15,000 km^2)	29,500	3,080
Rio Buzi (e.a. = 26,314 km^2)	28,800	1,450
Umbeluzi (e.a. = 3,100 km^2)	5,600	315
Sava	88,395	5,000
Limpopo (e.a. = 340,000 km^2)	412,000	5,330
Maputo (e.a. = 28,500 km^2)	29,800	2,800
Incomati (e.a.= 21,200 km^2)	46,246	2,300
Ngvuma		111
Tugala	29,085	4,699
Umgeni and others	18,260	3,472
Umzimkulu and others	46,610	7,714
Groot Kei	20,490	1,219
Amatola	7,910	535
Great Fish	30,280	580
Great Bushman	5,633	83
Sundays	21,110	293
Oteniqna, Gamtooa and Algoa	44,330	1,400
Gouritz	45,300	674
Breed	15,423	2,025

<u>West flowing rivers</u>

Grootberg and others	25,380	2,090
Olifants	48,600	1,020
Buffels and others	28,900	70
Orange	650,000	11,370
Kuiseb (Namibia)		
Ugab (Namibia)		
Cunene	83,000	6,774
Curoca		
Cobal		
Bentiaba		
Capoloro		
Catumbela		
Cuvo	17,231	5,838
Longa		
Cuanza	121,470	26,355
Bengo	7,370	1,194
Dande		
Loge		
MBridge		

West flowing rivers cont..........

Zaire	4,000,000	1,325,000
Loeme	1,640	
Kouilou (at Sounda)	55,340	31,000
Nyanga (at Ouyama)	20,800	20,500
Ogooue (e.a = 203,500 km^2)	203,500	148,850
Como-Mbei		
Temboni	5,000	
Benito	14,000	
Ntem (e.a. = 18,060 km^2)	26,350	9,050
Mungo	2,410	
Lobe and Lokoundje	3,120	4,380
Nyong (e.a. = 13,250 km^2)	26,200	4,540
Sanaga (at Edea)	131,500	65,280
Wouri	8,250	10,630
Chiloango	13,000	

Rivers in West Africa

Konkoure		
Fatala		
Kogon		
Corubal	20,000	
Kayanga		
Casamance	13,860	
Gambia (e.a. = 42,000 km^2)	77,850	5,050
Saloum		
Ferlo		
Senegal (e.a. = 268,000 km^2)	338,000	21,800
Khatt Atoui		
El Fuch		
Seguiet		
Oued Draa (at Zagora)	20,130	47
O.Sous (at Aft Melloul)	16,150	214
Oum or Rbia (at Im Fout)	34,400	4,100
O.Sebou (at A.E. Soltane)	39,000	6,302
Tensift	20,100	915
Other rivers in Morocco	35,700	7,679

South flowing rivers

Cross	48,000	
Ibo		
Imbo		
Niger-Benoue	1,215,000	2000,900
Sibuko		
Oshun		
Ogun		
Ose		
Oueme (at save and Okapara and Zou) e.a. = 40,150 km^2)	47,780	7,380

West flowing rivers cont......

Couffo		
Mono (c.a. = 20,500 km^2)	22,000	3,375
Zio (c.a. = 1,810 km^2)	2,806	300
Volta (at Senchi)	394,100	39,735
Todzie-Aka		86
Pra		7,400
Ankobra		2,220
Tano	15,000	1,600
Bia	— 9,320	1,234
Other coastal rivers in Ghana		1,234
Bia	9,650	
Boubo	3,070	
Komoe (e.a. = 66,500 km^2)	76,500	8,293
Agneby (c.a. = 4,600 km^2)	— 8,600	353
Bandama (e.a. = 60,300 km^2)	— 97,500	9,400
Mo	4,140	
So	1,880	
Sassandra	75,000	13,000
Cavalla	30,200	17,590
San Pedro		
Sangwin	4,662	
Cestos	12,560	1,968
St. John	17,220	15,130
Loffa	10,620	8,980
St. Paul	21,900	18,940
Mano	8,250	8,610
Other rivers in Liberia	17,230	
Moa	17,900	
Jong		
Scarcies	15,300	
Kolente	8,000	
Inland basins		
Chad-Basin:	2,400,000	
Chari-Logone (e.a. 600,000 Km^2)		43,250
Others		192
Lake Fitri:	——	
O. Batha (at Ati)	46,000	732
Lake Turkana:		
Tarkwell	—	
Omo	77,200	16,100
Kerio		

Inland basins cont..........

Other inland drainage in Kenya			
Lake Eyasi			
Mononga			
Lake Rukwa			
Aungwa			
Okavango Delta:			
Okavango (outflow from Delta)		53,000	600
Gash		23,500	600
Jebel Marra	—		300
Etosha			
Awash		113,700	
Hodna and Aurea		61,000	900
Madagascar			
Mahavavy (North		3,125	
Sambirano		2,980	3,564
Loza			
Sofia			
Mahajamba			
Ikopa	—	30,350	23,120
Mahavavy (South)		12,795	
Tsiribihina		38,000	
Mangoky		53,225	
Onilahy		28,175	
Itendro		18,550	
Mananjary		3,100	5,115
Mandrara		12,435	2,680
Rianila		5,875	
Vohitra		1,825	2,255
Ivondro		2,545	3,340
Mananara		14,162	
Reunion			
Mauritius			
Other Islands			

TABLE 2 LAKES OF AFRICA

Name	Surface Area km^2	Volume $10^9 m^3$	Mean depth m	Country
Victoria	68,800	2,750	40	Kenya, Uganda, United Republic of Tanzania.
Tanganika	32,900	18,940	700	Burundi, United Republic of Tanzania, Zaire, Zambia.
Malawi	30,800	8,400	426	Malawi, Mombambique, United Republic of Tanzania.
Chad	16,317	75	4	Cameroon, Chad, the Niger, Nigeria
Bangweulu	9,850	11	4	Zambia
Turkana (Rudolf)	7,200	555	73	Ethiopia, Kenya.
Mobutu S.S.	5,600	140	25	Uganda, Zaire.
Mweru	4,580	37	6.5	Zaire, Zambia
Tana	3,500	28	8	Ethiopia
Kyoga	2,700	20	6	Uganda
Kivu	2,699	650	240	Rwanda, Zaire.
Idi Amin Dada	2,300	78	34	Uganda, Zaire.
Maji Ndombe (Leopold II)	2,300	11	5	Zaire
Kitangiri	1,200	6	5	United Republic of Tanzania
Abaya	1,161	8.2	7	Ethiopia
Chilwa	750	1.5	2	Malawi, Mozambique
Tumba	720	2.9	4	Zaire
Shamo	551	5.5	13	Ethiopia
Upemba	530	0.9	0.3	Zaire
Ziway	434	1.1	2.5	Ethiopia
Shalu	409	37	86	Ethiopia
Malomba	390	1.6	4	Malawi
George	270	0.5	2.5	Uganda
Langano	230	3.8	17	Ethiopia
Abiyata	205	1.6	7.6	Ethiopia
Naivasha	189	-	-	Kenya
Guiers	170	0.2	2	Senegal
Awasa	130	1.3	10.7	Ethiopia
Baringo	130	0.7	5.6	Kenya
Rkiz	120	0.1	2.5	Mauritania
Runyoni	57	1.7	39	Uganda
Jipe	39			Kenya, United Republic of Tanzania.
Birket Quarun				Egypt
Asalo				Ethiopia
Abbe				Ethiopia, French territory of the Afar and Issas
Gamari				Ethiopia
Chew Bahir				Ethiopia, Kenya.
Assal				French Territory of the Afars and the Issas

Lakes of Africa cont..........

Afrera	Ethiopia
Hannington	Kenya
Nakuru	Kenya
Pisso	Liberia
Natron	United Republic of Tanzania.
Eyasi	United Republic of Tanzania.
Manyara	United Republic of Tanzania.
Alaotra	Madagascar
Tshangalele	Zaire
Chott-el-Hodna	Algeria
Chott Melrhir	Algeria
Chott Djerid	Tunisia
Fitri	Chad
Mweru Wantipa	Zambia
Rukwa	United Republic of Tanzania.

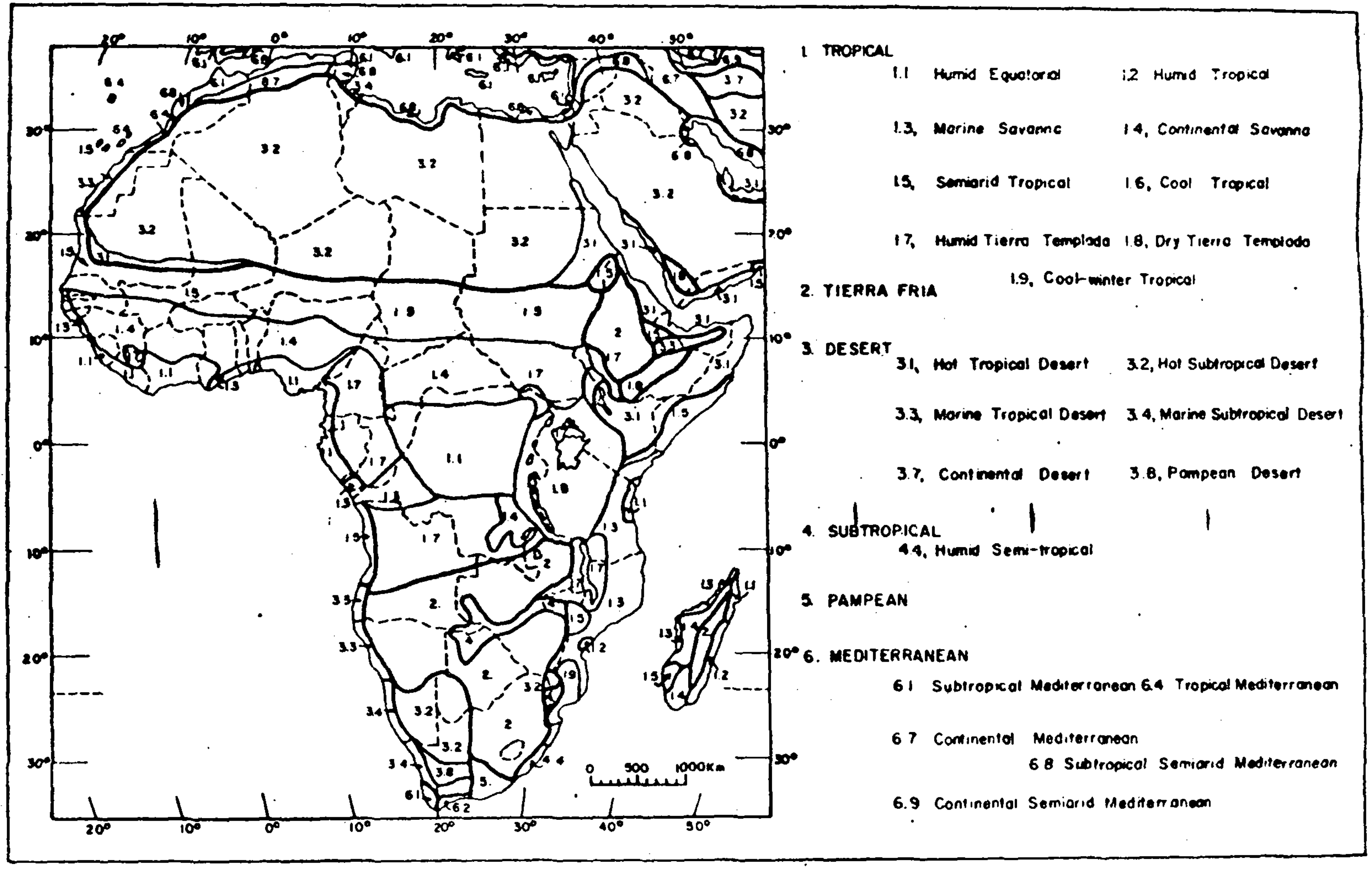
Source: FAO as reproduced in Water Resources of the World (Water Information Centre, N.Y. USA) (Ref. Footnote 1) indicating approximate volume based mean depth and surface area.

CLIMATE AND HYDROLOGY

Africa as shown in Figure 6 may be divided roughly into climatic belts following the parallels of latitude, this being particularly the case north of the Equator. The coastal areas of North Africa have a mediterranean climate, with a well defined period of drought in summer and a long period of somewhat irregular rainfall from September to May. The maximum precipitation in these areas is recorded in November and March. There is a great deal of erosion in these areas, the water is often salty and the underground waters are frequently abundant.

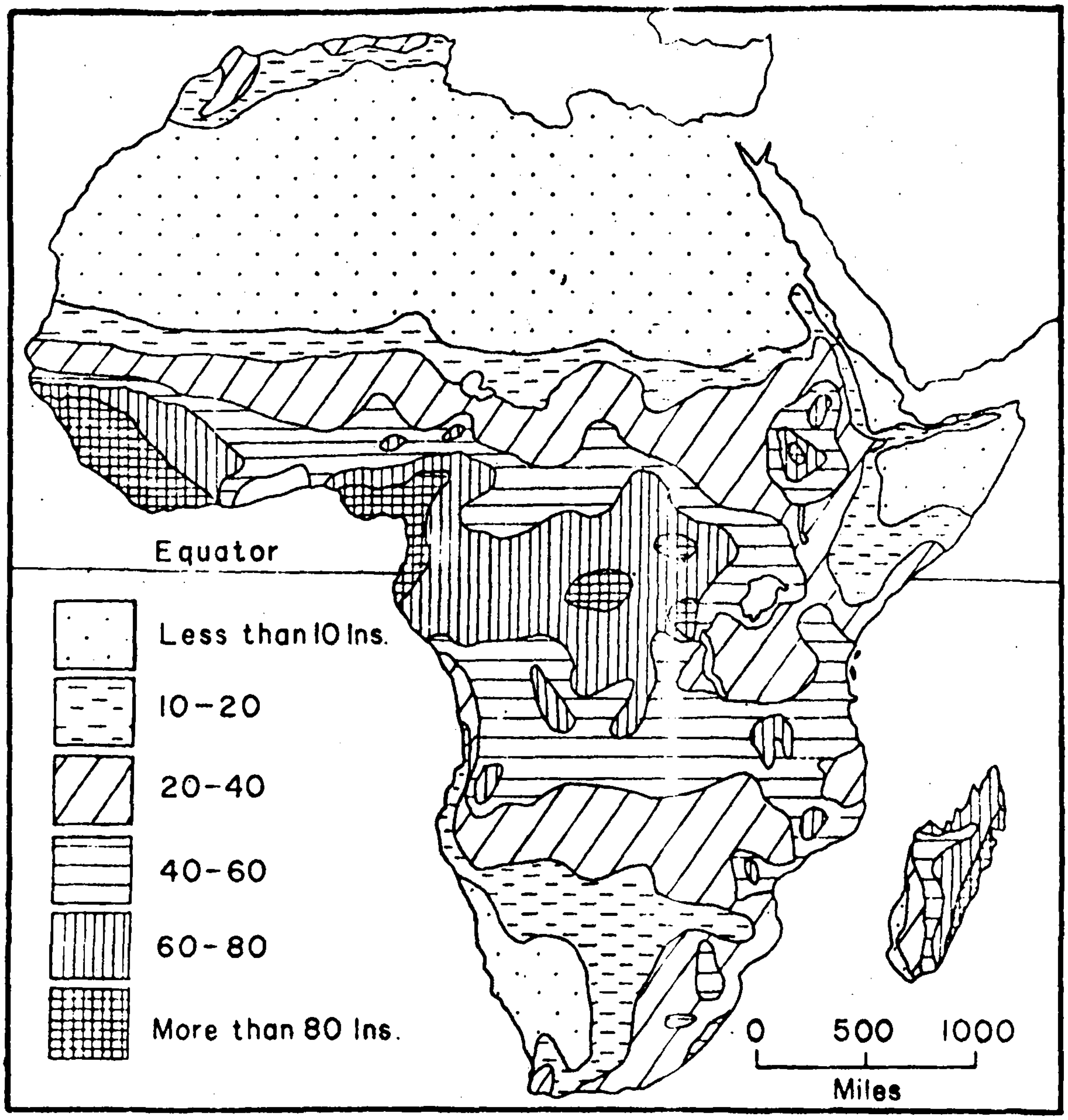
Towards the south the climate becomes more and more arid. The mediterranean regions give place to the Sahara desert as indicated in Figure 6 which extends to the Atlantic to the Red Sea, broken only by the Nile Valley, the lower part of which in Egypt is in many ways similar to the zone described above. Much of the Sahara is complete desert. Rain is very rare and scarse in most cases less than 254 mm (10 ins.) see Fig. 7. Rain may fall at any time of the year except in the extreme south where it occurs only during the northern summer. Surface runoff is of very short duration and occurs only in the more favoured zones. On the other hand, however, sedimentary rock formations may contain considerable reserves of underground water. Losses by evaporation are extremely high.

The region immediately south of the Sahara as shown in Figures 6 and 7 is the Sahelian Zone. It is a region of climatic contrasts, nine months of almost complete drought from October to June followed by a rainy season which transforms the greater part of the region where the relief is generally fairly low, into swamps. The runoff is torrential, unpredicable and frequently concentrated.



CLIMATES OF AFRICA

Fig. 6



AVERAGE ANNUAL PRECIPITATION, AFRICA

Fig. 7

The characteristically tropical regions, which as shown in Figure 6 lie south of a line ranging from Dakar to Cape Guardsfui have a typical hydrographic system. These regions as shown in Figure 4 are traversed by great rivers, the Senegal, Niger, Volta, Senaga, Shari and the principal tributaries of the Nile which have a clearly uniform regime (see Fig. 7), a rainy season from May or June to September or October, followed by distinct dry/. The annual rainfall is abundant exceeding /period 2000 mm in some parts. Further east it decreases fairly regularly to 900 mm in the Nile Basin (see Fig. 7). As shown in that figure it increases again on the slopes of the Ethiopian Highlands and then decreases very rapidly towards the eastern extremity of Africa where climate becomes semi-arid and even on the coast with annual precipitation of only 100 mm. Despite the vast extent of this zone there is very little variation in geologic conditions. One often finds especially in the west, the old gneissic shelf and the Precambrian metamorphic terrains or the cover of Ordorician Sandstone. In the first of these cases there is no possibility of finding deep undergroundwater reserves and in the second case very little possibility. Towards the east, on the contrary the terrains are much more varied and volcanic as well as sedimentary zones occur with some substantial underground water resources.

Typically, the equatorial regions have two rainy seasons. These regions are situated along the south coast of West Africa, south of the Cameroon Republic in the Ogowe Basin, the greater part of the Congo Basin, the extreme north of Angola, the principal branches of the Nile, the greater part of the Congo Basin, the extreme north of Angola, the principal branches of the Nile, the greater parts of the Greater Lakes and the coast of Kenya and Tanzania (except the extreme south). The rainfall pattern varies considerably. The coastlands of the Gulf of Guinea, many parts of which have an annual precipitation of more than 3000 mm a year have practically no dry season, whereas the annual figure for certain places in eastern Kenya is no more than 250 mm with a dry season which often lasts almost the whole year.

These variations are frequently observed within quite limited areas, especially around Lake Tanganyika where according to their orentation heavily forested mountains alternate with valleys covered with thorny vegetation. Permeable areas such as the sedimentary zones of the Congo (Zaire) Basin or the volcanic zones of the Rift Valleys are much more numerous than in the tropical regions.

The variations in the average discharge of the rivers as shown in Table 1 are much more pronounced than those in the annual amount of rainfall.

South of the equatorial regime towards the northern limits of the Congo (Zaire) Basin, Lake Nyasa and south of the Tanzania territory the tropical regime is found once again. In the most northerly districts there is a rainy season from November to April and a dry season of equal duration. Towards the south, the rainy season becomes shorter. In general the annual rainfall increases from the west coast which is semi-arid or arid towards the east where the pattern of isohytes is much less simple than in the northern hemisphere. In particular the east coast is fairly well watered as shown in Figure 7 down to the southern extremity of Africa even in the latitudes between 20°S. and 30°S, the northern component of which is around Rio de Oro the rainfall is more than 1000 mm a year. As against this, in the centre of the southern Africa the precipitation decreases from north to south and is as little as 100 mm in the Kalahari desert (see Fig. 7). One encounters the intermediary regimes similar to those in the northern tropical region, from Guinean regime in Katanga to the desert regime, including the zone of hydrographic degradation. In these regions as in the preceding zone the variations in land relief have a great effect on precipitation.

The southern extremity of Africa has a mediterranean climate (see Fig. 6) with a full winter season in the south east and rains distributed throughout the year in the south. In the eastern part of South Africa a gradial transition of the rainfall pattern is to be observed from a short regular rainy season—in the north to irregular distribution throughout the whole year with summer rains predominating in the south. Throughout the territory of South Africa the geologic structure favouring occurrence of groundwater bodies varies considerably and sedimentary formations are frequent.

In summary then it is necessary to point out that of the estimated total rainfall volume of 20700 x $10^9 M^3$ about 87 per cent occurs between 15°N. and 20°S of the Equator. More than three quarters of the total rainfall is lost through evaporation. Potential evaporation being only a function of temperature and wind, the variations in potential evaporation over Africa as a whole are not very marked while the rate of evaporation is relatively higher than in any part of the continent. This factor is extremely important especially in designing major water conservation projects. In one specific case for example, the evaporation from Lake Nasser in Egypt represents about a quarter of the flow of the Nile River at Aswan. For 1970-1971 evaporation was estimated to be about one tenth of the flow when the lake had not yet been completely filled.

About 90 per cent of the excess of rainfall over evaporation (i.e. runoff) is restricted within 10°N. and 20°S. This situation has important implication for development, especially in marginal rainfall deficient belt which have been subject to frequent devastating droughts resulting in acute water shortages and other human hazards. The problem extends to wetter summer rainfall areas where only one crop per year can be harvested because winters tend to be dry and hence water deficient. If winter water deficiency can be alleviated by irrigation development, more than one crop can be raised per year in the area.

The average annual water balances of Africa and the world are given in Table 3 while water supplies for some African countries are given in Table 4. This table contains information only of 20 countries out of 48 countries in Africa of the total surface water resources of Africa contained rivers and lakes. Available data on groundwater resources is not sufficient to enable quantitative appraisal of the groundwater resources of Africa.

VEGETATION

The striking fact regarding the vegetation of Africa from the standpoint of human use is the marginal utility of much of it. About 27 per cent of Africa is classified as in forest (see Fig. 8). But much of the total vegetation is savanna woodlands, whose trees, with few exceptions, are not suitable for lumbering but are important water catchment areas. The trees within the tropical rainforest are not comparable in utility to those of the middle latitude forests because they cannot be easily exploited because of the necessity to maintain some canopy and some pioneer or nurse communities. Most of the grass of the savannas and steppes are of relatively low nutritive value, Hance (1964).

TABLE 3 AVERAGE ANNUAL WATER BALANCE OF AFRICA AND THE WORLD ACCORDING TO PUBLICATIONS SINCE 1970

P = Precipitation
E = Evaporation
R = Run-off

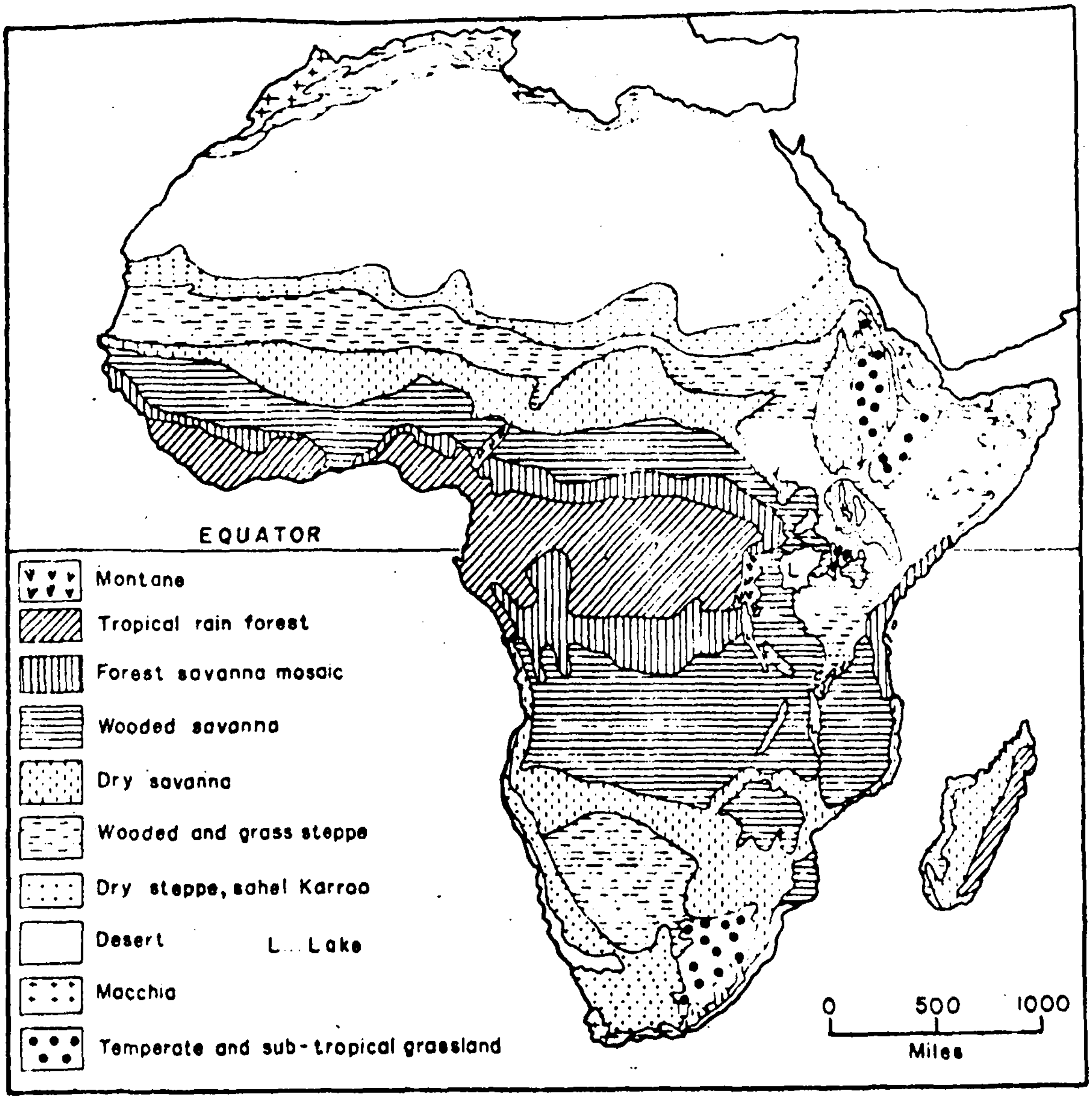
Region	Baumgartner, 1975			USSR Monograph, 1974			Lvovich, a/ 1974		
	Volume of Water (thousands of cubic kilometres)								
	P	E	R	P	E	R	P	E	R
Europe	6.6	3.8	2.8	8.3	5.3	3.0	7.2	4.1	3.1
Asia	30.7	18.5	12.2	32.2	18.1	14.1	32.7	19.5	13.2
Africa	20.7	17.3	3.4	22.3	17.7	4.6	20.8	16.6	4.2
Australia	7.1	4.7	2.4	7.1	4.6	2.5	6.4	4.4	2.0
North America	15.6	9.7	5.9	18.3	10.1	8.2	13.9	7.9	6.0
South America	28.0	16.9	11.1	28.4	16.2	12.2	29.4	19.0	10.4
Antarctica	2.4	0.4	2.0	2.3	0	2.3	...	...	...
Land areas a/	111	71	40	119	72	47	113	72	41
Oceans	385	425	-40	458	505	-47	412	453	-41
World	496	496	0	577	577	0	525	525	0
	Depth of water (millimetres)								
Europe	657	375	282	790	507	283	734	415	319
Asia	696	420	276	740	416	324	726	433	293
Africa	696	582	114	740	587	153	686	547	139
Australia	803	534	269	791	511	280	736	510	226
North America	645	403	242	756	418	338	670	383	287
South America	1,564	946	618	1,595	910	685	1,648	1,065	583
Antarctica	169	28	141	165	0	165	...	...	...
World	973	973	0	1,130	1,130	0	1,030	1,030	0

Sources: E/Conf.70ECBP/1/2.7.76, page 20; USSR, National Committee for IHD, World Water Balance and Water Resources of the Earth (Leningrad, 1974); Lvovich, Global Water Resources and the Future (Moscow, 1974); A. Baumgartner and E. Reichel, The World Water Balance (Munich, 1975).

a/ Values are adjusted upward to include Antarctica for comparison with corresponding volumes derived by the other two authors.

TABLE 4 SURFACE WATER SUPPLIES IN SELECTED AFRICAN COUNTRIES

Country	Mean annual runoff Million m^3
Algeria	11,475
Botswana (Excluding Chobe and other)	1,190
Burundi	6,850
Central African Republic	190,000
Chad (Total inflow into Lake Chad)	52,420
Egypt (Discharge of the Nile at Aswan)	84,000
Ethiopia	89,600
Ghana (Regulated river yield)	47,441
Kenya	14,836
Liberia	70,000
Malawi	9,000
Nigeria	259,000
South Africa	51,230
Sudan (Discharge of the Nile at Aswan)	84,000
Swaziland	451
Togo	15,000
Uganda (Exit from Lake Mobutu Sese Seko)	32,590
Upper Volta	10,000
Zambia	103,000



THE VEGETATION OF AFRICA

Fig. 8

POPULATION

Africa is the least populated continent excepting Oceania. During the last fifty years, the population of the continent has increased rapidly due to the rapid spread and adoption of modern medicine which has resulted in a marked drop in infant mortality and a significant increase in the life expectancy of the people.

In 1970 the population of Africa was estimated to be 344 million as compared with 327 million in 1967 and 270 million in 1960. The 1970 figure represented 9.5 per cent of the world population while that of 1960 represented 9.1 per cent. The relative size of the population of the continent is therefore increasing. The total land area of the continent as indicated earlier is 30.2 million km^2 which is about 22 per cent of the land surface of the earth. The average density of the population for the continent is therefore about 11 persons per km^2 which is much less than the world average of 25. There are, however, greater variations in the density of population between the major sub-regions, the various countries as well as within individual countries (see Table 5.) The table gives the size and density of the population of the various countries while Table 6 gives an indication of the community water supplies in African countries. The information contained in Tables 5 and 6 does not say much about the man-land or water in the various countries but do suggest that a greater population of Africa is not served by water both in urban and rural areas.

A cursory survey of the population density map shown in Figure 9 shows that by far the greater part of Africa south of the Sahara has a population density of less than 10 per square km., which is less

TABLE 5 AREA, POPULATION AND POPULATION DENSITIES OF AFRICAN COUNTRIES (1967)

Country	Area (thousand)	Population ('000)	Average Density	Persons per sq. km. of arabic land
Dahomey	113	2,456	21	153
Gambia	11	343	30	165
Ghana	239	8,143	33	304
Guinea	246	3,702	15	?
Guinea Bissau	36	531	15	200
Ivory Coast	322	4,014	12	186
Liberia	111	1,115	10	28
Mali	1,202	4,745	4	375
Mauritannia	1,031	1,085	1	399
Niger	1,267	3,546	3	22
Nigeria	924	59,764	63	264
Senegal	196	3,676	18	63
Sierra Leone	72	2,439	33	64
Togo	56	1,724	30	76
Upper Volta	274	5,054	18	99
Cape Verde Island	4	232	57	750
Total West Africa	6,104	102,574	16	146
Ethiopia	1,222	23,400	19	180
Kenya	583	9,948	17	552
Madagascar	587	6,346	12	221
Malawi	118	4,206	34	309
Mauritius	2	774	407	788
Reunion	3	419	163	639
Seychelles	0.4	49	130	276
Somalia	638	2,670	4	261
Uganda	236	7,933	33	199
Tanzania	938	12,178	12	97
Zambia	753	3,968	5	193
Total East Africa			15	183
Burundi	28	3,346	118	192
Cameroon	475	5,494	11	63
Central Africa Republic	623	1,459	2	23
Chad	1,284	3,403	3	47
Congo	342	869	2	133
Equitorial Guinea	28	277	10	121
Gabon	268	473	2	365
Rwanda	26	3,306	121	313
Sao Tome and Principe	1.0	59	63	187
Zaire	2,345	16,354	7	32
Total Central Africa	5,420	35,040	6	26

Angola	1,247	5,297	4	573
Botswana	570	593	1	339
Lesotho	30	887	29	237
Mozambique	783	7,127	9	263
South Africa	1,221	18,739	15	148
Namibia	824	594	22	89
Swaziland	17	386	22	149
Zimbabwe	389	4,530	11	232
Total Southern Africa	5,081	38,153	8	194
Total Africa South of the Sahara	21,709	247,673	?	?
TOTAL AFRICA	30,233	326,704	11	135

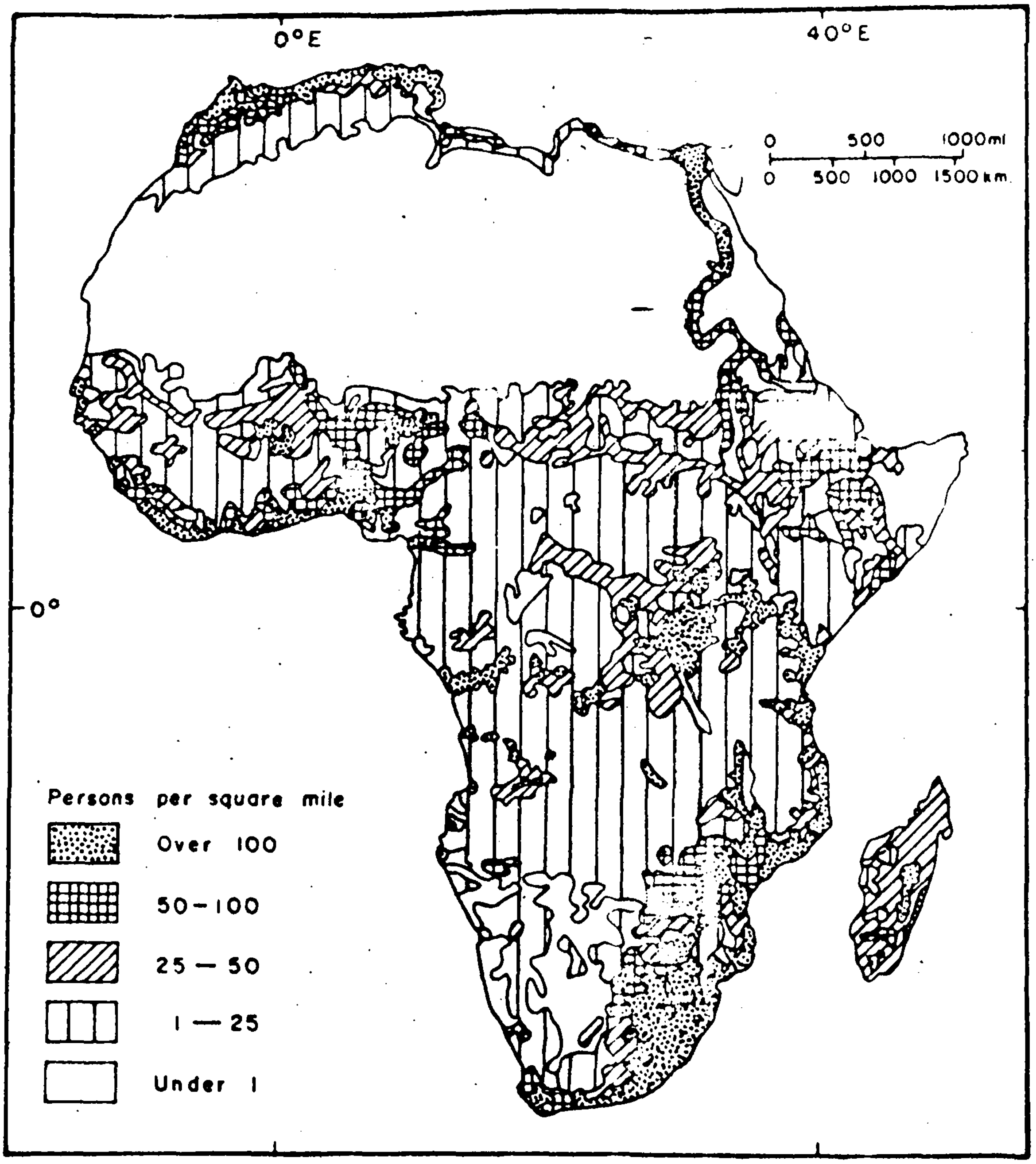
Source: UN/ECA (1975) **Demographic Handbook for Africa, Addis Ababa pp. 17-19 (Table 4).**

TABLE 6 COMMUNITY WATER SUPPLIES IN AFRICA

	Urban pop. ('000)	Pop. served ('000)	% of urban pop. served	Rural pop. ('000)	Pop. served ('000)	% of rural pop. served	Total pop. ('000)	Total pop. served ('000)	% of total pop. served
Algeria	6180	5500	89	(7923)			14103		39
Angola									
Benin	368	346	94	2395	455	19	2763	801	29
Botswana	35	35	100	596	149	25	631	184	29
Burundi	97	75	77	—	—	—	3750	75	2
Cape Verde									
Central African Republic	385	50	13	—	—	—	1667	50	3
Chad	263	200	76	3545	780	22	3808	980	26
Comoros									
Congo	284	278	98	657	46	7	941	324	34
Egypt	14894	14000	94	19355	18000	93	34409	32000	93
Equatorial Guinea									
Ethiopia	1900	1500	79	—	—	—	30000	1800	6
French Territory of the Afars and the Issas									
Gabon	100	6	6		1	n	700	7	1
Gambia	37	36	97	300	9	3	375	45	12
Ghana	2925	2135	73	6214	870	14	9100	3005	33
Guinea	451	437	97		—	—	3973	437	11
Ivory Coast	944	916	97	3448	1000	29	4355	1916	44
Kenya	1105	1072	97	12000	240	2	10933	1312	12
Lesotho	27	27	100		—	—	900	27	3
Liberia	140	140	100	1117	67	6	1218	207	17
Libyan Arab Republic	1197	850	71	714	300	42	1917	1150	60
Madagascar	954	830	87	4500	45	1	7292	875	12
Malawi									
Mali	621	180	29		—	—	6000	180	33
Mauritania	88	86	98	1140	114	10	1176	200	17
Mauritius									

Morocco	57	5200	91	10357	2900	28	1588	8100	51
Mozambique									
Namibia									
Niger	324	220	68	3562	570	16	3952	790	20
Nigeria	12862	7460	58	44825	3586	8	55230	11046	20
Reunion									
Rwanda									
St. Helena									
Sao Tome and Principe									
Senegal	1043	1022	98	2943	2178	74	3951	3200	81
Seychelles									
Sierra Leone	376	282	75	2100	21	1	2567	308	12
Somalia	571	120	21	2308	300	13	2800	420	15
Sudan	1597	1150	72	15000	1800	12	16389	2950	18
Swaziland									
Togo	256	248	97	1720	86	5	1856	334	18
Tunisia	2253	2050	91	2941	500	17	5204	2550	49
Uganda	692	616	89	8000	1600	20	8864	2216	25
United Republic of Cameroon	1169	900	77	4762	1000	21	5931	1900	32
United Republic of Tanzania	926	500	54	12000	1200	10	13077	1700	13
Upper Volta	206	140	68	5200	1300	25	5760	1440	25
Zaire	2918	1605	55	15000	750	5	18115	2355	13
Zambia	985	955	97	3395	645	19	4324	1600	37
Total for Africa	70030	51167	73	210571	40877	19	285048	91984	33
Total for the world (developing countries only)	481685	327546	68	1236307	173083	14	1726306	500629	29

Source: World Health Organization, World Health Statistics Report, Vol. 26, No. 11, 1973, table 3, pp. 726-730
– Not available n – nil or negligible



DISTRIBUTION OF POPULATION IN AFRICA.

Fig. 9

than the average density for the continent. Large areas in the northern parts of West Africa, the Central African Republic, Zaire, Tanzania, Botswana, Namibia and South Africa are uninhabited while pockets of very high densities, usually exceeding 60 persons per sq. km., occur in Nigeria, Burundi, Rwanda and the Shores of Lake Victoria in Kenya and Uganda. Other areas of high population densities occur in Southern Malawi, the highlands of Kenya and the Mossi area of Upper Volta. According to Udo (1979) the following population pattern can be considered:

1) Areas of Urban concentration
2) Very densely settleed rural areas, usually overfarmed
3) Heavily farmed medium density areas
4) Low density fertile agricultural districts and
5) Very sparsely settled and virtually uninhabited areas.

This proposal is considered to be reasonable since most of the people live in rural areas and since the availability or non-availability of farmland is an important factor in the continuing process of redistributing the population, a process which can be interpreted as on attempt to adjust the mal-distribution of population in relation to cultivable land.

Areas of Urban Concentration

The degree of urbanization in Africa is very low, although the situation has been changing since the early 1960's when most African countries became independent and pursued a vigorous policy of industrialization which has resulted in increasing concentration of people in towns. Indeed since the middle 1960's Africa has had the highest rate of urban growth of about 5.4 per cent per annum, which is almost twice the world average of 3.2 per cent. The percentage of people who line in towns with 20,000 or more inhabitants in Africa south of the Sahara is about 12 per cent. The most urbanized region is Southern Africa where 28 per cent of the people live in towns of 20,000 or more, followed by West Africa (14 per cent), Central Africa (10 per cent) and East Africa with only 6 per cent.

The main areas of urban concentrations are southwestern Nigeria, the Nigerian Sudan, the Zambian-Katanga Copper belt and the Witwatersrand industrial belt of South Africa. The areas of urban concentrations in Nigeria are distinctively pre-colonial and are characterised by large pre-industrial cities, some of which like Lagos, Kano and Ibadan are now becoming industrialised. The Copper belt urban concentration, like that of the Rand, date from the colonial period and are essentially industrial towns based on mining and manufacturing. The capital cities of the various countries have become the main centres of attraction for migrants going to urban areas and most of them are growing so fast that the authorities are finding it difficult to provide adequate services like transport, pipe water, waste disposal, schools and hospitals.

In Nigeria, where the state capitals have become major administrative, educational and growing industrial centres, each state capital city has acted as an important growth centre attracting migrants from rural areas and smaller towns throughout the state. The Federal capital of Lagos however continues to grow at a faster rate and has become so crowded that new migrants now find it very difficult to obtain accommodation. The indication is that these urban centres will continue to grow largely through immigration, but since urban dwellers do not depend on farming, the problems posed by the influx of people to the towns are basically different from those of congested rural areas where farmland is inadequate to support the people.

The very densely settled and over-farmed rural areas

In a continent which is so sparsely settled, it is intriguing to find considerable pockets of very high rural population densities such as exist in parts of West Africa, East Africa and Southern Africa. In areas such as the Central Ibo districts of Awka, Onitsha, eastern Owerri and Annang-Ibibio districts of Ikot Ekpene, Abak and Uyo all in Nigeria, the population densities exceed 400 per sq. km. (1,000 per sq. mile). These districts therefore rank amongst the most densely settled rural areas of the world and are certainly over-populated as is evidenced from the extreme pressure of population on farmland. Other congested rural areas in West Africa include the Kano close-settled district, the Sokoto home districts, parts of the Katsina emierate, the Mossi district of Upper Volta and the Bolgatanga district in the extreme north-east of Ghana.

Unusually large concentrations of rural population of up to 400 persons per sq. km. also occur in East Africa, notably in the small hilly countries of Rwanda and Burundi, the Lake Victoria coastal districts of eastern Buganda, the southern part of eastern Province of Uganda, and the Nyanza, Rift Valley and Central Provinces of Kenya. Southern Malawi is also very densely populated and so are the rural areas of Zimbabwe and South Africa.

These areas of very high densities are characterised by acute shortage of farmland, reduced fallows and even permanent cultivation in extreme cases. Farm sizes are generally small, rarely exceeding two hectares, usually made up of two to five fragmented holdings scattered all over the village territory. Overcultivation has resulted in soil impoverishment and destructive soil erosion in some districts. The result is that although most of the people are farmers, these densely settled areas have become major food deficit areas. It is therefore not surprising that the congested rural districts have also become the main source regions for migrant labour in Africa South of the Sahara.

It may appear strange that these pockets of high densities occur in close proximity with areas which are very sparsely settled and therefore have abundant farmland. In South Africa and Zimbabwe, where rural Africans are largely restricted to rural areas, the situation is not difficult to explain. But although there are no such reserves in the other countries, we should remember that each ethnic group and indeed each village has a well-defined territorial area which it claims to be its own by right of occupation. It is therefore often not possible for those who live in these densely settled areas to expand and acquire more land except through migration to areas where the people are willing to lease farmland to them. There are of course other reasons which explain the high concentrations of people in these pockets of high densities. These reasons will be given later but at this point it is sufficient to observe that most areas of rural high densities have become settled for many centuries.

The heavily farmed medium density areas

Districts with population densities of about 160 persons per sq. km. (400 persons per sq. mile) are considered to be areas of medium density. In West Africa, such areas occur mainly along the coastal regions where there is considerable emphasis on tree crop production on peasant farms as well as in commercial plantations, and where mining is also important. Examples of such areas include the groundnut growing districts of western Senegal, southern Togo, the Yoruba cocoa belt and southern Tivland in Nigeria. In East Africa, heavily farmed medium density areas occur in the less congested districts of Rwanda and Burundi, western Buganda, the Kilimanjaro district and much of western and central Malawi. The densely populated areas of Lesotho and the Natal coastlands of South Africa are major areas of medium densities in Southern Africa.

Regular clearing and firing of bush for farming have resulted in large scale deforestation in areas of medium population density. Farmland is generally inadequate in some of these areas, and many of them constitute important source regions for migrant labour. Many of these medium density areas are relatively well served by all season roads and are therefore more accessible and have become rather attractive to migrant farmers who find it relatively easy to market their crops.

Low density fertile agricultural districts

About one-tenth of the sparsely settled areas of Africa South of the Sahara is blessed with fairly good soils, sufficient sunshine and adequate rainfall although some areas suffer from occasional severe droughts resulting in crop failures and disastrous famine. The population densities in such areas are generally below 80 persons per sq. km. (200 persons per sq. mile). Farmland is abundant and fallow periods are long, usually exceeding seven years. The coastal countries of Liberia and Ivory Coast in West Africa are low density areas with good farmland awaiting development. Other areas include the central provinces of Zaire, the well-watered areas of Mozambique and Zimbabwe, Gabon and Southern and Central Cameroon.

Extensive areas of high forest still survive in those sparsely settled areas which receive more than 1,250 mm of rainfall per annum. In the drier savanna areas of West Africa and the East African plateau, the sparsely settled areas are usually infested by tsetse flies. But although the people who live in these areas have more farmland than they require, they are hardly better off materially than those in the congested rural areas, largely because of the isolation of such areas from major centres of population and manufacturing. The money circulation in such areas is extremely small and peasant farming activities have hardly advanced beyond the pre-colonial period stage. Thus while some of these areas have attracted an increasing number of migrant tenant farmers, the local educated young people tend to migrate to work in the towns.

Other sparsely settled and virtually uninhabited areas.

The areas considered in this section fall into two categories, namely: forest and game reserves and areas with adverse environmental conditions which are at best marginal areas for human settlement. Together, the areas in these two categories cover more than two-thirds of the land area of sub-Saharan Africa but support less than five per cent of the population.

Sparsely settled areas with adverse natural conditions include the water deficit areas of the Sahel and semi-arid regions of the western and eastern Sudan, the dry Gonja district of northern Ghana, the extensive swamps of the Niger delta, the seasonally flooded and tsetse infested Great Muri plains of the Benue Valley and the extensive hill country of the Cameroon - Adamawa highlands. In East Africa, the arid lands of Somalia, eastern Ethiopia and northern Kenya as well as the semi-arid areas of the Karamoja District of Uganda and the Maasai country of Tanzania support less than two persons per sq. km. The Namib desert along the coast of Namibia as well as the Kalahari desert extending from Botswana to northern Cape Province in South Africa are understandably uninhabited, while the rest of Namibia, Botswana and that half of South Africa lying west of longitude 25° are very sparsely populated.

Forest and game reserves cover a much smaller area than the sparsely inhabited and uninhabited marginal lands. As a rule, settlement and farming are prohibited in the reserves which are all located in areas which were either uninhabited or very sparsely populated.

RAIN AND STORM WATER HARVESTING SCHEME IN AFRICA WITH SPECIAL REFERENCE TO MANDA ISLAND, KENYA

PHYSICAL BACKGROUND

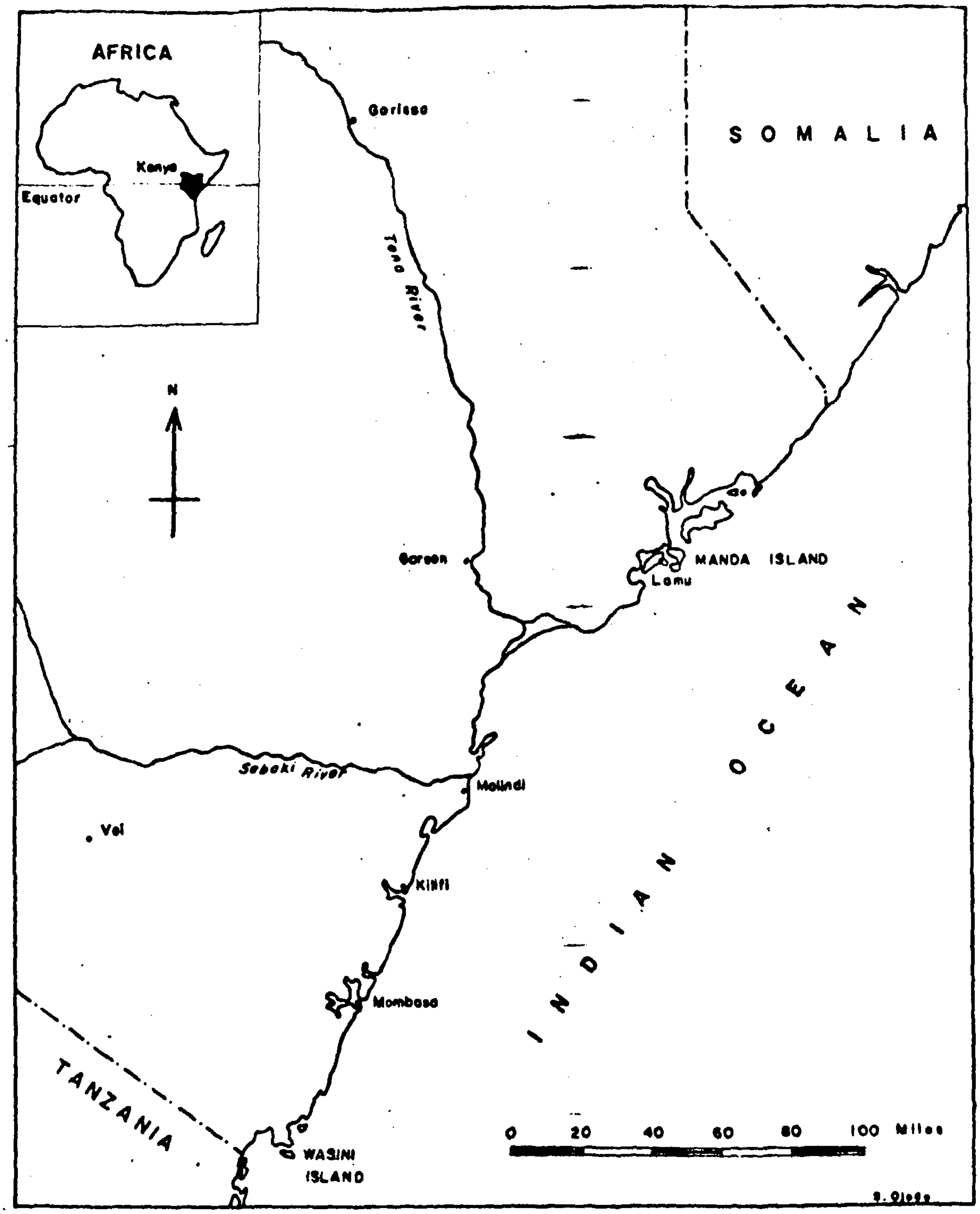
A precipitation and storm water harvesting scheme can be defined as a scheme for the collecting, conveying and storing of water from a catchment area which has been treated to increase the runoff resulting from precipitation. Although the concept of such schemes is not new, considerable scope exists for their further utilization. Technological advances in the past decade, resulting in the availability of new and relatively inexpensive materials for use in constructing such simple schemes, makes this type of water supply potentially attractive for many African countries.

It is extremely difficult to obtain information on how to use precipitation harvesting schemes to supply water to people. The concepts are simple and have been in use for centuries. But try to find a handbook or design manual on the subject is difficult.

Manda Island is a small island, about five miles long and eight square miles in area, lying adjacent to the coast of northeast Kenya, in the Indian Ocean some 160 miles south of the Equator (see Fig. 10). A coral island with limited soil cover mostly covered with scrub bush and birtually uninhabited in the mid-1960's.

In contrast to this scruffy, bush-covered, empty island there is the Lamu Island, directly opposite Manda Island, with approximately the same area as Manda but with a population of about 5,000. Coconut palms, goats and cattle are a main source of livelihood for farmers over most of Lamu Island. The town of Lamu has been an important port on Indian Ocean trading routes for centuries, and in recent times Lamu has been the administrative headquarters for Lamu District in the Coast Province of Kenya.

Lamu Island was different from Manda Island in one significant respect. On Lamu, particularly near the sand dunes on the seaward southern side of the island, there are plenty of shallow wells with a plentiful supply of sweet water. A public water supply is mainly composed of 20 developed wells and distributing chlorinated water to



KENYA COAST

Fig. 10

323 consumers in Lamu, whose supplies were on the average of the order of 29,000 gallons daily in 1967/68. Manda Island had no supply of potable water by 1968. In the past there had been attempts to settle Manda Island but today there is almost no trace of Manda, Takwa and Kitau, three small towns said to have been conquered in the 13th century by Sultan Omar of Pate. The towns are believed to have been abandoned because wells yielded only brackish water, Kirkman (1964). In spite of Manda Island's water supply problems, settlers began arriving there in 1964.

On Manda Island, about 40 miles south of the Somalia border, the Kenya government allocated ten acres of land to each displaced family and provided limited agricultural assistance, through a local instructor, to help the new settlers get established. Realizing that there was a water problem the government built two precipitation harvesting schemes, called 'jabias' locally, on the island. Each of these consisted of a rainwater catchment of 1,600 sq. ft. of corrugated asbestos cement sheets, supported on a timber frame, and a concrete-lined excavated storage tank of 20,000 gallons below the catchment.

By August 1968 some 114 families had settled on Manda Island. The land was proving to be fertile after the bush was cleared but the water supply problem was acute. The two 'jabias' were inadequate to provide as much water as the people required. One leaked, had not been repaired. In an attempt to obtain water locally the people dug eight wells through the farming area. The water from these shallow wells was so saline, except immediately after the rainy season. A thin lens of fresh water apparently floated on the saline groundwater before being dispersed or abstracted. This region lies within groundwater Quality Zone No. IV of Hove and Ongweny (1974) characterized by high concentrations of total dissolved solids.

Some farming families moved to Lamu Island, about a mile away, to live in a community having a reasonable water supply. They crossed the channel between Lamu and Manda twice daily, but in so doing were forced to somewhat neglect their farms. Others stayed on Manda but existed on water taken there in tins in small boats from Lamu. The Manda settlement was a limited success because of lack of an adequate water supply. Nevertheless the Government decided to use the remaining undeveloped land on Manda Island to settle hundred more families. The existing water supply problem would be intensified. Some solution had to be found.

This then meant that there was a water supply problem in Manda Island. An apparent solution was the construction of precipitation harvesting schemes.

The Manda Islands situation gives an excellent opportunity for an assessment of the issues involved in a precipitation harvesting scheme for a community water supply in Africa. The parameters of the Manda Island situation are used in this paper as the basis for design of a water supply system which would be relevant in many parts of Africa. As in any design problem many assumptions were to be made. The assumptions made were realistic with respect to Manda Island and may be representative of similar situations elsewhere in Africa. But even if the parameters for Manda are unique the method used in this solution could be applied elsewhere.

The most economical means to provide an adequate water supply to an agricultural settlement assumed to be developed on Manda Island was to be determined. Although previous settlement planning was rather haphazard, the new settlement was to have its water supply designed and available before the farmers take possession of the new land. For the purposes of this problem the proposed settlements consisted of 200 families, each owning a plot of about 10 acres (1,000 ft. x 435 ft.) (see Fig. 11).

Water Consumption

The estimated population and the projected water demand of Manda were as follows:

Agricultural Settlement:

200 families, average family population = 5.0

On-farm per capita water consumption = 5 gallons per day (g.p.d.)

Domestic animal water consumption per farm (approx. 1 cow or 3 goats for every two farms) = 5 g.p.d.

Total daily farm consumption = 6,000 g.p.d.

Community Centre:

(shops, school, dispensary)

Daily demand = 500 g.p.d.

Total = 6,500 g.p.d.

The total demand for water for the settlement was assumed to be constant throughout the year. As Manda Island is within 160 miles of the equator the temperature varies little (constantly hot) and seasonal variations at this relatively low level of water consumption would not be significant.

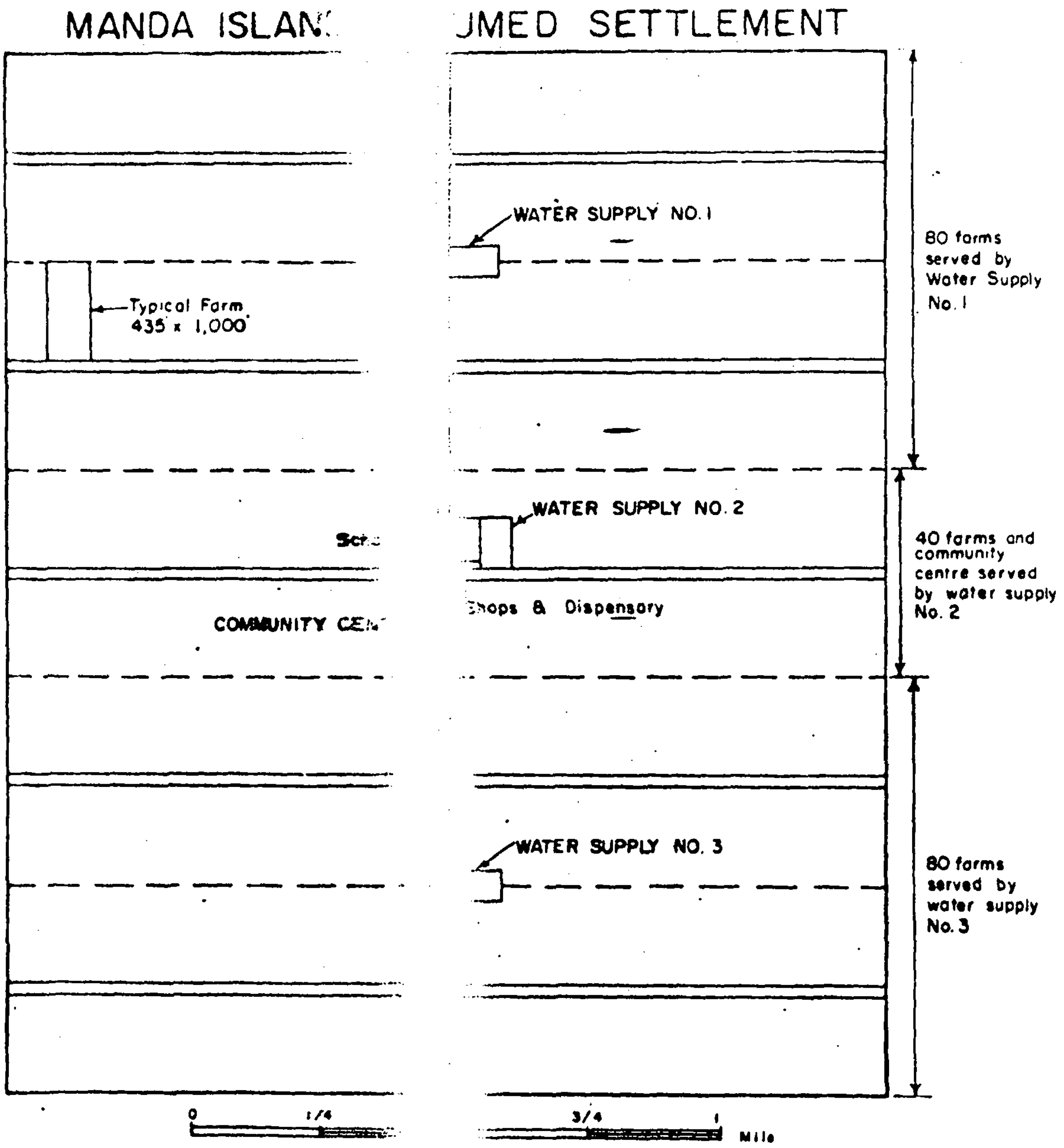
MANDA ISLAN
UMED SETTLEMENT
WATER SUPPLY NO. 1
Typical Farm 435 x 1,000
80 farms served by Water Supply No. 1
WATER SUPPLY NO. 2
Sch
40 farms and community centre served by water supply No. 2
Shops & Dispensary
COMMUNITY CEN
WATER SUPPLY NO. 3
80 farms served by water supply No. 3
0
1/4
3/4
1
Mile

Fig.

Alternative Sources of Supply

No surface water sources exist and it is assumed that no groundwater is available as a water supply source on Manda Island. The island is generally low, with most of its surface not more than 50 feet above the surrounding sea. Due both to the topography and geology of the island rainwater is not collected in any developed drainage patterns: that which does not sink into the coral formation as soon as it falls tends to collect in small pools to either evaporate or infiltrate slowly into the coral.

The adjacent Lamu Island has no surface water but does have a good source of groundwater. Much of this island is sandy and large sand dunes on the seaward side of the island are the location of the 20 wells from which water is pumped to provide the public water supply in the town of Lamu. The capacity of this aquifer was unknown but was not believed to be much greater than the withdrawal rate in 1969 (approximately 30,000 g.p.d.).

The water supply for Manda Island would not be provided by water from Lamu Island. No other sources of surface water or groundwater on the mainland or nearby islands are assumed to be available to supply Manda. As desalination of seawater on such a small scale in such a place would be uneconomic, there are two possible means of providing the required water supply:

a) importation of fresh water by ship; or

b) precipitation harvesting scheme built on Mands Island to supply the local requirements.

Costs for the first alternative can be estimated. The nearest place to Manda Island where a ship could obtain supplies of fresh water is Malindi, 80 miles south. The water would have to be purchased from the government-operated Malindi water supply. The source of Malindi's water is the Sabaki River (see Fig. 1). Water pumped from this river is treated by coagulation, sedimentation, rapid sand filtration and chlorinatian before being pumped to the town of Malindi. The retail price of this water to consumers was Shs. 6.00 ($0.90) per 1,000 gallons.

To provide 6,500 gallons or 3¼ tons of water daily on a 160 mile round trip would necessitate leasing one small ship or barge continuously. The transportation costs would be the largest element in the total cost but initial purchase of the water and storage and distribution of the water at Manda Island would contribute to the costs. A preliminary estimate of the costs involved in this alternative is about $200 per day ($73,000 per year).

The water supply for Manda Island could be provided more economically by a precipitation harvesting scheme than by any other means.

The per capita consumption of 5 g.p.d. used as the basis for design of the water system is quite low. Habbil and Doland (1975) have suggested that the minimum human requirement for biological purposes has been estimated at one-quarter of a gallon per day, but the normal estimates of minimum water requirements in developed countries are usually higher.

On Manda Island no water would be used for water-borne sanitation. Most of the water requirements then would be for washing, cooking and drinking.

To determine the level of water demand in these circumstances a survey which took place on Manda Island over a six day period in August 1968 was carried out. At that time, many of the 114 families on the island obtained water from one small precipitation harvesting scheme there. This water was removed from the 20,000 gallon reservoir by a hand pump and carried in pails to the farmers' buildings. Most people carried the pails on their heads (4 gallons or 40 lbs.) but several used a donkey for this task. The per capita consumption measured during the survey period was 3.1 g.p.d. This figure is probably less than the actual average consumption since auxilliary supplies of water were believed to have been imported during the same period from Lamu Island.

As indicated on Figure 11 farms were assumed to be laid out on a grid system, with each farm facing on a 100 foot road reserve. Farmers would live on their plot, presumably near the road. The community centre was located at the crossroads in the middle of the farming area.

One water source was located in the community centre to serve the daily demand there of 500 g.p.d. At least two more sources were required in the area.

The three sites of water sources are shown on Figure 11. This arrangement minimized the total distance between all consumers and their nearest water source, with no plot on the settlement more than one mile from water. Water supplies No. 1 and No. 3 each serve 80 farms, so each of these schemes has a demand of 2,500 g.p.d. Water supply No. 2, serving 40 farms and the community centre, has a demand of 1,700 g.p.d.

The rest of this section will concentrate on the design of a precipitation harvesting scheme for an average demand of 2,400 g.p.d. A different scheme for the smaller demand of water supply No. 2 was designed using the principles developed, but three similar schemes were assumed to be constructed, having a total capacity of 7,200 g.p.d. This was to give the settlement an excess supply capacity of 700 g.p.d., or just over 10% of the total estimated demand of 6,500 g.p.d.

Hydrometeorological Data

The settlement on Manda Island is within two miles of the Lamu meteorological station which has been collecting data since 1906. Of particular interest in connection with a precipitation harvesting scheme are the records of precipitation. To have monthly records available over such a long period is fortunate but the data cannot be used indiscriminately if they are not reliable. The East African Meteorological Department when questioned about the accuracy and reliability of the precipitation data, advised that those for the initial period, 1906-1910, were not considered to be reliable.

Characteristics of the climate at Lamu are indicated by the following parameters provided by the East African Meteorological Department.

Minimum monthly mean air temperature : 77.2°F (25.1°C)
Maximum monthly mean air temperature : 82.6°F (28.1°C)
Average total sunshine per year : 3,242 hours
Average relative humidity at 3:00 p.m. : 75%
Mean annual precipitation : 35.6 in. (905 mm)

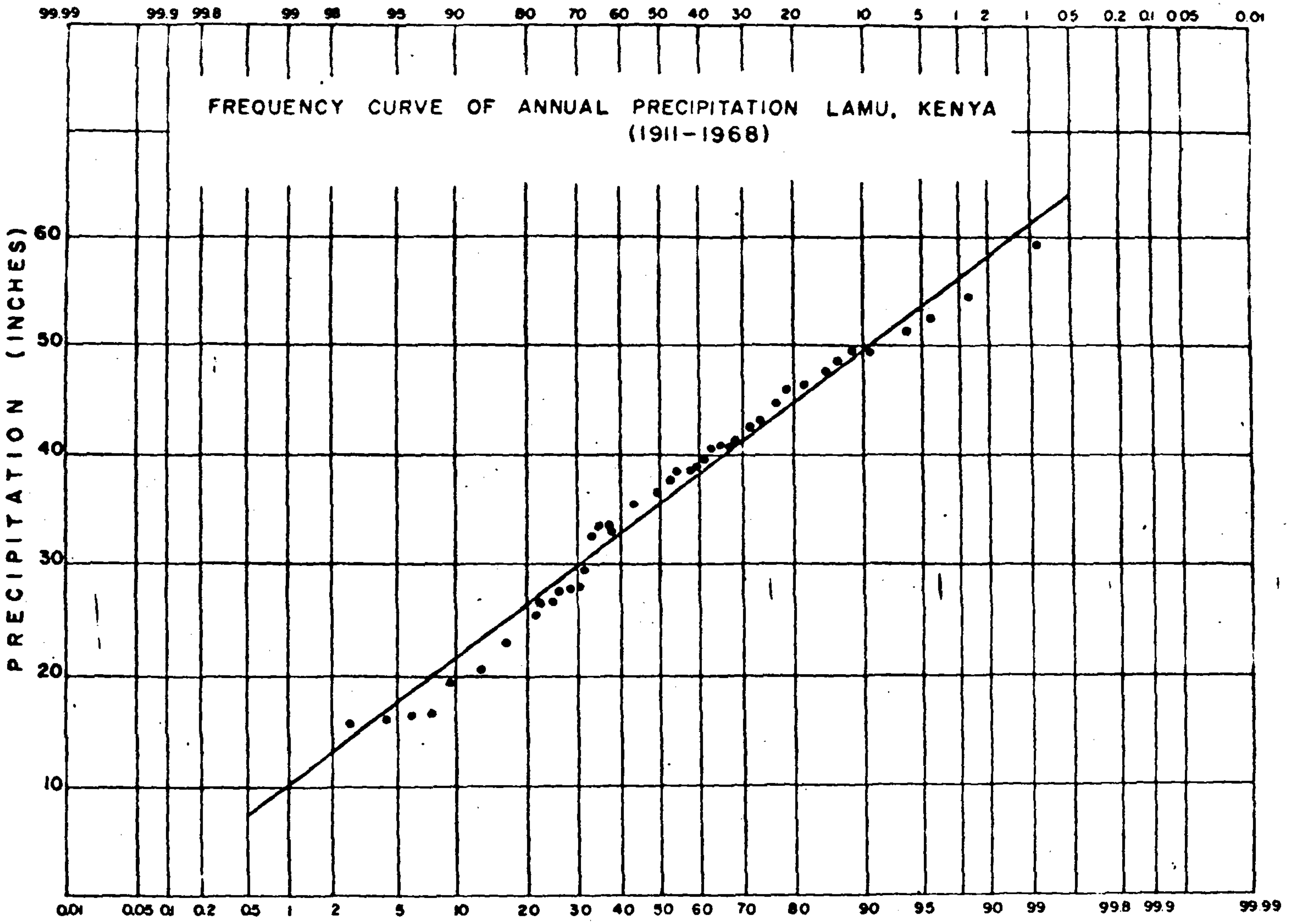
Average number of days of precipitation per year:	85
Mean annual potential evaporation	91.5 in. (2,327 mm)

The coefficient of variation for the precipitation data, calculated as outlined by Chow (1964) is 0.3F. Arid regions have coefficients as high as 0.5: for well-watered regions the value is as loo as 0.1. Using this criterion, Manda Island and Lamu are semiarid. This concurs with Meighs (1968) classification for the region, which is based on water requirements for plants and the deficit of precipitation in relation to the potential evapotranspiration of the area.

The annual rainfall over the 58 year period was plotted on probability paper using the Hazan plotting position (see Fig.12). As discussed subsequently, however, the design of the scheme was based on an analysis of historic monthly precipitation rather than on annual data.

There is a distinctly seasonal pattern of precipitation at Lamu, as indicated by the following monthly averages

Month	Precipitation (inches)
January	0.2
February	0.1
March	0.8
April	5.0
May	12.7
June	6.2
July	2.9
August	1.6



FREQUENCY CURVE OF ANNUAL PRECIPITATION LAMU, KENYA
(1911-1968)

Fig. 12

Month	Precipitation (inches)
September	1.7
October	1.7
November	1.6
December	1.1
TOTAL	35.6

Nil precipitation was reported in almost 20% of the months but never in the period from April through July.

To test whether or not the precipitation data are statistically reliable is desirable but difficult for records from a single station. Fortunately rain gauges tend to under-register the amount of precipitation (due to surface wetting of the instrument, leakage, evaporation, etc.) at a point of view of runoff for water supply.

As there was no practical way of testing or improving the precipitation data from the single station at Lamu, the design of the precipitation harvesting scheme proceeded on the assumption that the available records provide an accurate indication of historic conditions at the Manda site.

Construction Methods

For a precipitation harvesting scheme the basic design problem was to find the minimum cost solution capable of producing a sufficiently reliable supply of potable water. It was necessary to consider the methods used to construct the components of a precipitation harvesting scheme and to determine the level of costs associated with alternative methods of constructing these components. The principal components are the catchment area used to collect the rainwater and the reservoir used to store it.

The rain which falls on the catchment flows by gravity into the reservoir. Site topography determines whether or not water can be withdrawn from storage by gravity. For relatively level terrain the reservoir can supply water by gravity only by being above ground level: this requires the catchment area to also be above ground, such as the roof of a building. If the catchment is at ground level on level terrain the reservoir has to be excavated and water can only be withdrawn by pumping.

Site Conditions at Manda Island

Manda Island is accessible by sea and by air. The nearest point on the mainland, Mokowe (which has a large jetty at which ships of about two hundred tons can berth) is within two miles. Transportation constraints made it almost impossible to consider using heavy construction equipment for the construction of water supply facilities on the island.

The area for the agricultural settlement on Manda Island is generally flat, with slopes of about 1½%. A shallow layer of topsoil (averaging three feet in depth) overlies the previous coral of which the island is composed. The coral can be excavated slowly by hand or more efficiently with pneumatic hammers. Gravel and sand for use in structural concrete are not available on the island. Large quantities of fine coral sand are available on ocean beaches within one mile of the sites of the precipitation harvesting facilities but the salt content in this sand makes it unsuitable for good concrete.

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Land on which the water supply is to be built was assumed to cost $450 per acre or approximately $0.01 per square foot.

The difficulties of transporting and operating construction equipment and the availability of large numbers of unskilled labourers (earning approximately $1.50/day) made it desirable to use unsophisticated construction techniques. Skilled labour was obtained from Mombasa, at a cost (including accommodation) of approximately $5.00/day.

Prototype Scheme at Wasini Island

In Kenya Grover (1969) had the opportunity to construct a prototype precipitation harvesting scheme on Wasini Island, approximately fifty miles south of Mombasa (near the Tanzania border) at a site very similar to Manda Island (see Fig. 10).

Prior to the construction of this prototype scheme, drinking water was being taken to the village in dugout canoes from wells on the mainland, about one mile away. Water imported in this manner augmented the limited amount of fresh water collected in several small precipitation harvesting schemes constructed in earlier times. These consisted of excavated and plastered tanks (approximately 5,000 gallons each) with the excavated material piled alongside and plastered to form a small catchment area (approximately one hundred square feet). These individual schemes were in poor repair, leaked badly and could not probide the water requirements of the population in the dry season.

A large catchment area and reservoir were proposed as a central water supply for the village. Using principles similar to those already in use there, an excavated reservoir was planned with a catchment at approximately ground level to supply the reservoir. Spoil from the excavation were used to eliminate depressions and improve the slope over the catchment area.

Preliminary designs and cost estimates indicated that the most economical means of increasing the runoff from the previous material on the catchment was to seal the surface with sprayed asphalt. The excavated coral had to be covered first with enough sand from the nearby beach to provide a reasonably smooth surface for runoff.

Simple tests were arranged at the Water Development Department headquarters in Mombasa to determine the best means to seal the sand surface. A membrane formed by spraying various asphaltic materials directly on the sand was impervious but was unsatisfactory as a surface because it was too easily damaged. It could be pealed off the sand and would crumble when walked upon.

The sand which was the base for the impervious surface had to be strengthened. Tests indicated that this could be achieved by mixing modest quantities of cement in the top few inches of the sand and moistening the mixture to form a type of soil cement. When the cement set the sand was sufficiently firm and conesive to support the pedestrian traffic which would be used to apply the waterproof surface.

Various asphaltic materials were considered for making the surface impervious. Tests indicated that a combination of two locally available products which could be applied without heating worked best. The first spray applied, the seal coat, consisted of a medium curing cutback asphalt (MCO) which is asphalt cement in solution with kerosene (about 9.4 lbs. asphalt per gallon). This solution penetrated the top layer of the stabilized sand before the solvent evaporated, leaving behind a light deposit of asphalt.

The second and final application was a spray consisting of emulsified asphalt ("Colas" trade name) which is asphalt cement in an emulsion with water (about 10.0 lbs. asphalt per gallon). The second spray bonded well to the seal cost and when the water evaporated, after a period of several days, a good waterproof surface resulted.

For the reservoir it was decided to excavate a volume of about 11,000 cubic feet (to store 70,000 gallons of water) in the coral and line the reservoir with a single butyl sheet. Selection of the reservoir volume was arbitrary.

Excavation of the reservoir had already been started by the local people before the preliminary design was complete. Sides of the reservoir were sloped at about 60° to the horizontal. The coral stood in a vertical excavation but the supplier of the reservoir liner recommended the 60° slope to prevent the rubber liner from stretching when all edges were anchored at ground level. The reservoir was square in plan, with dimensions of 40 feet on each side at ground level and 30 feet at the bottom of the 10 feet deep hole. Because the surface of the excavation was jagged in many places and might have punctured the butyl linear, the bottom and sides were smoothed by filling holes in the surface with rough plaster (using beach sand with cement). The reservoir was lined with a single sheet of butyl measuring 60 feet x 60 feet x 0.030 inches thick. All edges of the linear sheet were anchored in trenches, which were backfilled with sand, near the reservoir edge.

Spoil from the excavation was sufficient to smooth an adjacent area of about 15,000square feet. This determined the extent of the catchment. Beach sand was used to cover the coral spoil and eliminate minor depressions in the surface. The catchment area was first dampened with sea water and compacted with a small vibratory roller (used normally for highway surface repairs) before being covered with a three inch layer of soil cement, consisting of beach sand mixed with 6% cement by weight. This proportion of cement is in accordance with the 3% - 10% range recommended for road construction using granular soils, Yoder (1959).

The seal coat of MCO was sprayed on the stabilized sand at an application rate of about 60 square feet per gallon. The asphalt solution was pumped from 45 gallon drum using a hand sprayer on a four wheel carrieage. Several days later the second application, consisting of "Colas", was sprayed at an application rate of about 30 square feet per gallon.

A hand pump was installed to withdraw water from the reservoir. It was planned to install a simple roof over the reservoir by suspending a second sheet of butyl on ropes anchored at the reservoir edges to provide a grid pattern of support for the butyl sheet. Small holes, centred in each grid of the roof cover, were to be used to allow rainwater to enter the reservoir. Unfortunately this part of the prototype structure failed. The ropes sagged and the holes intended to pass rainwater were offset from the centre of each grid section. When heavy rains fell the water which could not enter the reservoir through the offset holes remained on the cover. This caused the ropes to stretch further and eventually the sagging butyl sheet ripped in several places.

It is interesting to note the simplicity of the construction methods which had to be used at Wasini Island. All material had to be taken to the island in small boats: the 750 lb. vibratory roller was very difficult to transport.

Experience gained in the construction at Wasini Island indicated that this prototype was a practical solution to community water supply problems in similar situations along the African coastline.

Reservoir for Manda Island Scheme

As the site at Manda Island is similar to that at Wasini Island, a community water supply similar to the Wasini prototype was proposed, with a catchment at ground level supplying runoff to an excavated reservoir. Because the coral in which the reservoir was to be excavated was pervious the reservoir would have to be lined.

Reservoir linings of plastered masonry or concrete were considered but rejected on the basis of cost. Flexible membranes of various types would be cheaper. On the bais of experience elsewhere vinyl and polythene were rejected because of their relatively short service life: they are not tough enough. Butyl rubber, however, has been tested as a water barrier in many applications and has been found to have excellent characteristics, waterproof and durable over long periods of time, even when exposed to sunlight, Lauritzen (1967).

A single prefabricated sheet of butyl rubber was proposed as the liner for the reservoir. The excavated surface of the reservoir was smoothened as required to eliminate jagged edges which might cause holes. Patches were welded to the sheet to make it watertight in the event of a puncture.

To minimize land requirements and potential surface evaporation the reservoir was as deep as possible. The cost of excavation increases with the depth, however, and simple hand pumps which would be used to withdraw water from the reservoir are limited in practice to a sunction head of about fifteen feet. The reservoir depth selected in these circumstances was fifteen feet.

A novel method of covering the reservoir was proposed. To avoid the costs of a rigid structure supporting a roof the reservoir consisted of a single sheet of butyl attached to flat pieces of polystyrene which would float on the reservoir surface. (With a specific gravity of 1.25 the butyl would sink unless buoyed up). The floating cover would be impermeable and would rise and fall with the level of the reservoir.

There were no holes in this top cover. This would reduce the risks of pollution but would waste all rainwater falling on the reservoir surface: it would eventually evaporate, since potential evaporation is roughly three times annual average rainfall in the area.

The cost of providing a cover for the reservoir cannot be justified on the basis of evaporation prevention alone, as sufficient extra catchment area to produce the runoff lost annually through evaporation could be constructed more cheaply than the reservoir cover. The floating cover, however, has several other advantages:

(a) prevention of algae formation in the reservoir by elimination of sunlight on water surfaces, X

(b) prevention of airborne pollution (e.g. seabirds, etc.), and

(c) visual indication of water level (psychological assistance for water conservation in drought periods).

On the basis of the costs of labour and materials expected at Manda Island, the approximate cost of excavating, lining and covering the reservoir in the manner proposed is $0.20 per cubic foot. This cost includes an allowance for placing the excavated material on the catchment. In the range of storage volumes required for the 2,400 g.p.d. supply at Manda Island this unit cost would be reasonably constant.

With butyl rubber sheets proposed for lining and covering the reservoir it is assumed that water losses from the reservoir due to evaporation and seapage will be nil.

The Catchment for Manda Island Scheme

The catchment was at ground level, sloping towards the excavated reservoirs. For Manda Island the following methods were considered for preliminary cost estimates:

	Catchment Surface	Cost/sq.yd.
(a)	Corrugated asbestos cement sheets	$4.50
(b)	Precast concrete paving stones	$4.00
(c)	Concrete slab (east in place, 3 in. thick)	$3.50
(d)	Butyl sheet (0.030 in. thick)	$2.60
(e)	Sprayed asphalt on stabilized base	$1.35

These preliminary estimates and the experience on the Wasini Island prototype indicate that the last alternative, sprayed asphalt on a stabilized base, was practicable and the most economical. The same means of preparing the area that was used at Wasini Island was proposed for Manda Island. Excavated material from the reservoir was placed is deprssions in the area of the catchment and used to increase its slope. The area was compacted by a vibratory roller before the top three inch layer was mixed with cement (approximately 6% by weight) to stabilize the base. At Wasini Island this mixing was done accurately, batch-mixed like plaster. This method produced excellent results but was time consuming and labour intensive. It should be possible to achieve satisfactory results by spreading measured quantities of dry cement on the sand surface and mixing it with rakes and hand tools. The high cost of using machinery and the low cost of labour would preclude the use of any mechanical plant except for the roller.

A drawback to using an asphalt-covered catchment was that the runoff was frequently coloured as a result of deterioration of the asphalt. The coloured water was usually odourless and tasteless and has been consumed by people (e.g. at Kilifi on the Kenya coast) with no known ill effects but not enough is known to state categorically that it causes no problems. At least in Kenya, however, the attitude has been that an imperfect water supply is better than no water supply. It seems acceptable to continue to utilize asphalt-covered catchments since there is no suspicion that they are not harmites. Asphalt is classified as a non-toxic material, Gleason et.al (1957).

The breakdown of asphalt into the water-soluble degredation products which discolour runoff is caused by a comination of light, heat oxygen. This degradation can be reduced by protecting the surface of the asphalt from sunlight: a layer of stone chippings frequently performs this function on roofs waterproofed by asphalt. Recent research indicates that sprayed asphalt catchments can be protected by a spray incorporating flaked aluminum, Frasier et.al (1968). For Manda Island it was proposed to spray a cover of this material on the final asphalt surface to prevent degradation of the asphalt.

Using the construction methods tested at Wasini Island and improved by spraying a protective layer on the asphalt, the estimated cost of constructing the impermeable catchment area was $0.15 per square foot.

The quantity of runoff from a catchment depends on how much precipitation is lost on the catchment through depression storage, infiltration and evaporation. The total runoff from a given area can be assumed equal to the total volume of precipitation falling on the catchment, reduced by a runoff coefficient. This can be expressed mathematically as:

$$R = KPA \qquad (1)$$

where R = total runoff in period (volume)

K = runoff coefficient

P = total precipitation on catchment in period

A = area of catchment

Equation (1) can be obtained by integrating over time the standard expression for rate of runoff (the rational method).

$$Q = cIA \qquad (2)$$

where Q = rate of runoff (volume/time)

c = runoff coefficient

I = intensity of rainfall (depth/time)

A = area of catchment

There is plenty of discussion in the literature of urban hydrology concerning values for the runoff coefficient "c" for use in determining peak flow rates. It is obvious, however, that its value will vary for a given catchment depending on the intensity of precipitation. (Runoff for a light drizzle can approach zero). What is required for a precipitation harvesting scheme is a constant "R" which can be applied to all precipitation occurring within a period. While obtaining such a coefficient may be desirable it is also extremely difficult. It will depend on a number of factors which apply to a specific site, including:

(a) precipitation patterns (variations in intensity),

(b) slope of catchment,

(c) smoothness of catchment, and

(d) permeability of catchment.

Since a precipitation harvesting scheme is constructed to maximize the runoff from the catchment the runoff coefficient should be relatively high. Researchers in Arizona have measured runoff from asphalt pavements similar to those proposed for Manda Island and have found runoff ranging from 96% to 101% of measured precipitation over one year, Meyers et.al (1967). These experimental catchments were in areas with annual rainfall averaging only eight inches. The catchments were 2,500 square feet in area and had slopes of 5%. The explanation for runoff being more than 100% of measured precipitation is that the rain gauges under-registered the actual precipiation at the site.

No measurements of runoff were made at the prototype catchment built at Wasini Island. In the absence of better information, it has been assumed that the catchments proposed for Manda Island (with annual precipitation averaging about 36 inches and catchment slopes of 1½% to 2%) would have a runoff coefficient "K" of 0.90. It is felt that this is a conservative estimate of the coefficient.

Design of Scheme

In a conventional water supply using a surface water source the catchment area is defined by the regional topography. The design problem in such a case is basically to determine the necessary reservoir volume to meet the estimated water demand for expected runoff conditions. Reservoir volume is the only design variable.

In a precipitation harvesting scheme there are two design variables: catchment area and storage volume. Many combinations of sizes of catchments and reservoirs can supply the estimated demand. Since multiple solutions are technically possible, selection of the optimum solution requires determination of the least cost solution. A complication arises, however, since not all of the appropriate combinations of catchment area and reservoir volume would provide a water supply having the same reliability.

Reliability of Water Supply

The future rainfall on which a precipitation harvesting scheme depends can only be estimated. Normally this is done by referring to records of historic precipitation. Frequency curves of historic precipitation indicate that it is virtually impossible to ensure the provision of 100% of the demand for water over 100% of the time from a water supply based on runoff unless an infinite amount of storage is provided. The designer of a precipitation harvesting scheme needs to be aware of the reliability of the supply which can be provided by the various alternative combinations of catchment area and reservoir volume.

It is apparent that a precipitation harvesting scheme can be made more reliable by increasing its catchment and/or storage. These improvements cost money. To select the appropriate degree of reliability the designer should be able somehow to evaluate this reliability in money terms. The scheme would then be increased in size until the incremental cost of increasing the size of the scheme exceeds the incremental benefit of increased reliability of supply.

Unfortunately it is seldom easy to measure the benefits of increased reliability of supply. In the case of Manda Island, however, there was a means of evaluating this aspect of the problem.

The per capita water consumption of five gallons per day estimated for the Manda Island settlement was relatively low. Any reduction in this supply would create major difficulties for the population. Nevertheless the people could survive periods of reduced supply, by one or more of the following means:

(a) restricting their use of water,

(b) using alternative sources for water, such as importing water, or

(c) leaving the area temporarily and moving to an area with an adequate water supply (e.g. Lamu).

If the proposed precipitation harvesting schemes on Manda Island ran dry the people would probably restrict their consumption somewhat and import water by boat. It has been assumed that imported supplies would have to ensure that at least 60% of the estimated requirements would be provided. For total failure of the Manda Island supply this would mean importing a total of about 4,000 g.p.d. Emergency supply could be provided from Lamu in drought periods. Alternatively the water could be imported from Malindi.

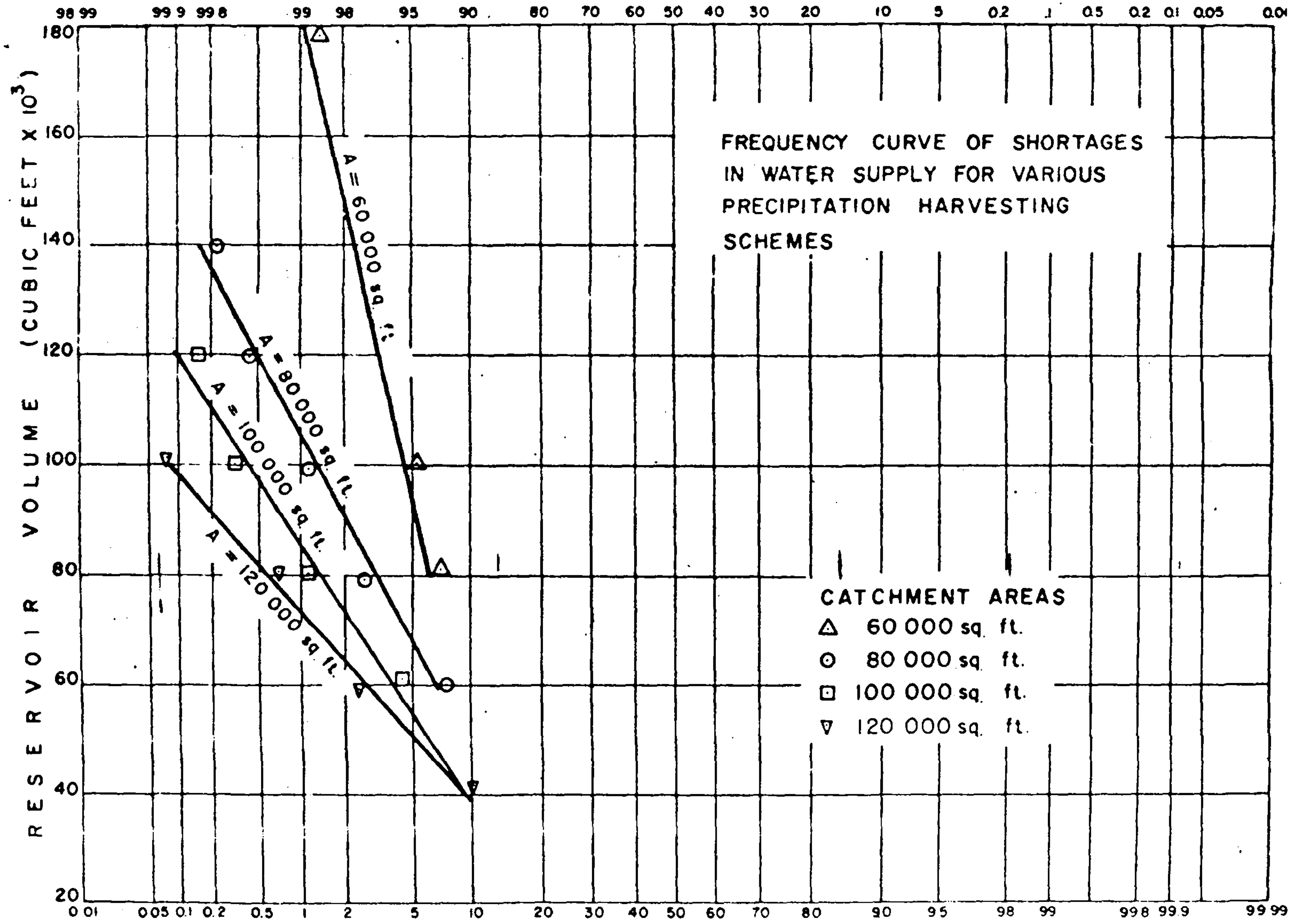
Rather than select an arbitrary degree of reliability which each water supply must provide (e.g. at least 70% of the supply 100% of the time) the reliability has been treated as a cost function. For each day when the full supply cannot be provided by the precipitation harvesting scheme it was assumed that supplementary supplies to provide at least 60% of the demand are obtained at a daily cost of $70. (This assumption over-simplifies the actual situation slightly, since a partial supply of water from the precipitation harvesting scheme reduces the amount of water which has to be imported. Setting up the temporary measures to augment the water supply for Manda Island would probably involve constant daily costs, however, even if smaller quantities of water were delivered. (The refinement of varying costs for degrees of shortages were not considered to be warranted.)

Selection of Uptimum Catchment Area and Reservoir Volume

The precipitation harvesting scheme for Manda Island was designed on the assumption that precipitation records for Lamu over fifty-eight consecutive years (1911-1968) are indicative of the precipitation which can be expected in the future on Manda Island.

Since both catchment area and reservoir volume are design variables, iterative calculations were required to determine the dimensions of the optimum scheme. The method of calculation for each trial was straightforward. First a catchment area was selected. For that area several trial calculations were made with reservoirs of differen capacity. For each reservoir capacity the reliability of the supply was estimated by determining the shortages which would have occurred with the precipitation of the period of record. Costs associated with constructing the schemes and providing alternative supplies of water during periods of shortage were considered to determine the optimum scheme.

For each of the four catchment areas investigated (from 60,000 square feet to 100,000 square feet) at least four reservoir volumes were checked to determine what shortages occurred over the fifty-eight years or 696 months of record. Naturally the largest reserviors were able to provide the more reliable supplies of water, but in none of the twenty trials was water supplied 100% of the time. A frequency curve was plotted to relate the shortages to the reservoir volume for each catchment area. The results, on Figure 13 show a family of curves which fit the data quite well.


FREQUENCY CURVE OF SHORTAGES IN WATER SUPPLY FOR VARIOUS PRECIPITATION HARVESTING SCHEMES
RESERVOIR VOLUME (CUBIC FEET X 10^3)
180
160
140
120
100
80
60
40
20
98 99
99 9
99 8
99
98
95
90
80
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95
98
99
99.8
99.9
99 99
A = 60 000 sq. ft.
A = 80 000 sq. ft.
A = 100 000 sq. ft.
A = 120 000 sq. ft.
CATCHMENT AREAS
△ 60 000 sq. ft.
○ 80 000 sq. ft.
□ 100 000 sq. ft.
▽ 120 000 sq. ft.

Fig. 13

Following compilation of the frequency curves of shortages associated with various combinations of catchment area and reservior volume, it was fairly easy to determine the least cost solution for the precipitation harvesting scheme. The three principle costs which varied for each combination were:

(a) construction costs for the catchment area,

(b) construction costs for the reservoir, and

(c) costs of importing water during shortages caused by drought.

For each of the trial values of catchment area the minimum total annual cost is underlined. Larger reservoirs cause higher total costs because of greater construction costs and smaller reservoirs cause higher total costs because of increasing shortages in supply.

The data indicate that the minimum total annual cost results with a catchment area of 100,000 square feet, and a reservior volume of 80,000 cubic feet. A precipitation harvesting scheme of these dimensions could have supplied 2,400 g.p.d. with shortages occurring only 1.03% of the time (about seven months in total over the period 1911-1968). All other combinations of catchment and reservior resulted in higher annual costs.

The relative ease of determining the optimum size of the principal components of the precipitation harvesting scheme by using the variable scale mass curve technique should be emphasized. All calculations, including plotting of data and repetitive graphical analyses, could be carried out for the Manda Island situation in approximately one week of work by a single person (once cost data were available on the basis of preliminary designs). The results clearly indicate the optimum solution for the given parameters, but basic assumptions could be varied and new solutions obtained without much extra work. For example, sensitivity analyses could easily be carried out to determine how various interest rates affect the determination of the optimum project size.

It would be possible to define the size of the catchment area and/or reservoir volume for Manda Island more precisely by repeating the analysis for smaller increments of size and by plotting the curve of total annual costs to determine the minimum value. For the meteorological data and preliminary cost estimates available, however, further refinements to the calculations are not warranted.

Construction Details

The principal elements of the precipitation harvesting scheme are the catchment and reservoir. Once the size of these elements had been decided, as above, the final design was completed and attention paid to minor elements in the scheme. The details of the typical scheme for Manda Island, having a capacity of 2,400 g.p.d., are discussed below. The design is illustrated on Figure 14.

The required reservoir volume of 80,000 cubic feet was obtained with an excavation 16 feet deep, 80 feet square at the surface and 65 feet square at the bottom (giving the side slopes of about 30° to the vertical). The catchment area was arranged to drain runoff into one edge of this reservoir. The specific configuration of the catchment area depended on site conditions. A regular shape was not essential. The optimum catchment avoided major depressions and take advantage

PRECIPITATION HARVESTING SCHEME

mainly for domestic purposes

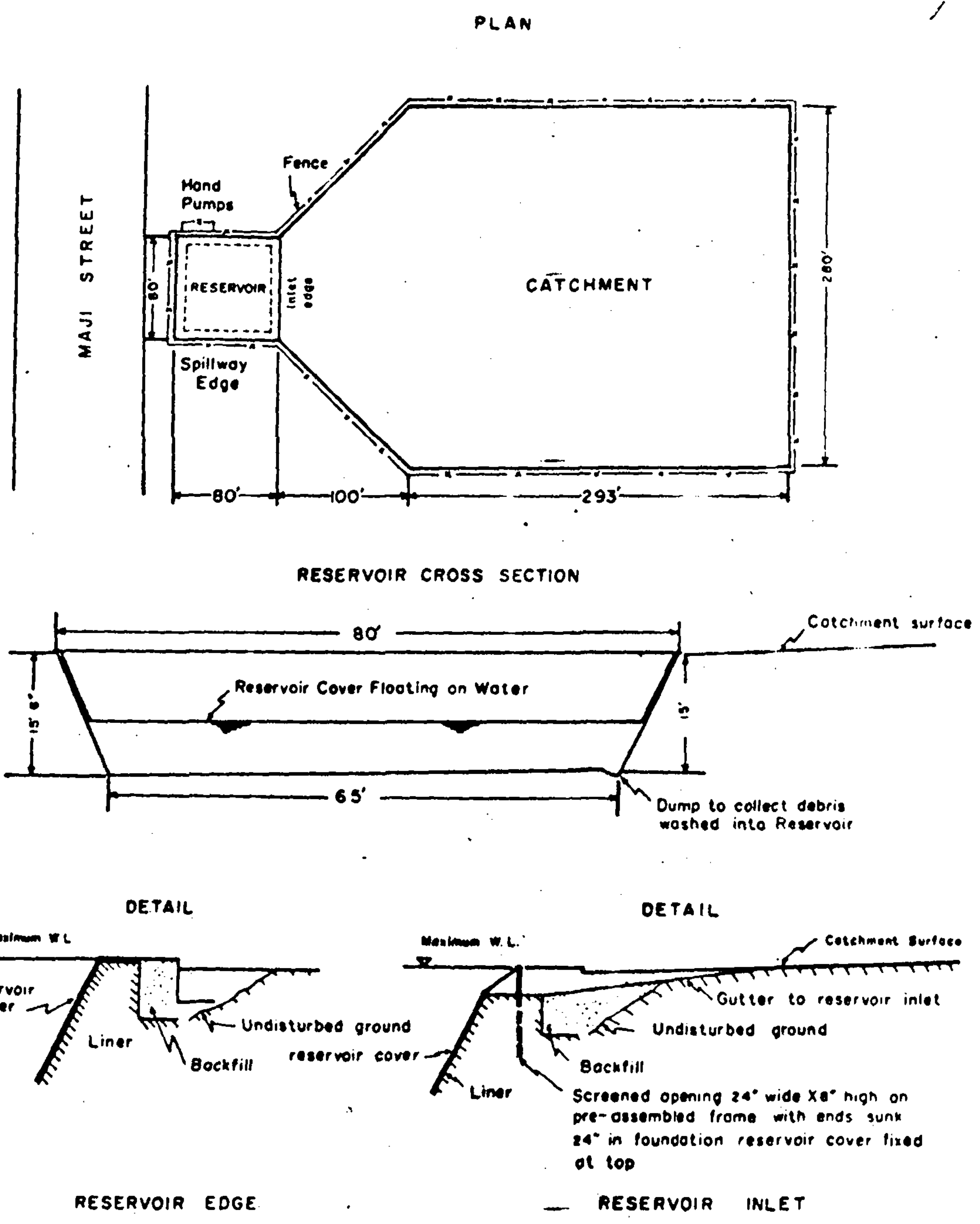


Fig. 14

of favourable slopes adjacent to the reservoir. Runoff losses were minimized by keeping the time taken for runoff to enter the reservoir to a minimum. The best theoretical layout for the catchment would therefore be a circular area with the reservoir in the middle. Since the roof arrangement favours collection of water on only the edge of the reservoir, the layout on Figure 14 was a compromise with this optimum, using straight edges for ease of construction.

The volume of material removed from the reservoir site (80,000 cubic feet) covered the catchment area (100,000 square feet) to an average depth of about ten inches. This excavated spoil was used mainly to eliminate depressions in the catchment area. The excess material was available after smoothing the catchment it was used to increase its slope. The natural slope at the site, which was assumed to be 1½%, could not be increased to as much as 2% even if all the excavated material were used for this purpose. The material from the reservoir thus improved the runoff coefficient mainly by eliminating depression storage: its effect on reservoir slope are velocity of runoff, which influence evaporation losses from the catchment, which would be negligible.

As in any surface water supply scheme the reservoir required an inlet, outlet and spillway. The innovative floating roof for this scheme makes the design of these components a bit different than in other reservoirs.

The roof consisted of a sheet of 0.030 inches thick butyl attached to floats of plystyrene or any suitable, buoyant material. As the edges of the reservoir were vertical the cover was made fairly rigid so that it would float on the surface with no need to be attached at the top. With a butyl liner for the reservoir, however, the

the reservoir sides were sloped to avoid excessive tension in the butyl sheet on the sides of the reservoir, which was anchored at the top edge. A flasting cover would run into difficulties with the varying surface area of the reservoir (80 feet by 80 feet when full and 65 feet by 65 feet when empty.)

The design illustrated in Figure 14 was to anchor the reservoir cover sheet at the top on all sides. When the reservoir is empty (as when it is constructed) this floating sheet, attached at all top edges, lying along the sloping sides and bottom of the reservoir. From one edge to the opposite one the length of the sheet would be 98 feet with the reservoir empty. As the reservoir fills the floating cover would rise until the distance between opposite edges because only 80 feet, the width of the reservoir. The slack in the floating cover with a full reservoir resulted in a crinkled sheet, possibly not too pleasing aesthetically, but functionally adequate. If a good reason were found for smoothing this top sheet the slack could be taken in as the water level rises (and conversely released when the level drops) but it seems difficult to justify such a chore.

All edges of the reservoir liner, and two of the top sheet, would be anchored by placing the edge in a trench and backfilling to weight the sheet in place. Arrangements on the two other edges of the reservoir cover were somewhat different.

The inlet edge of the reservoir, adjoining the catchment, requires openings to allow runoff to enter storage. Specially constructed inlets were mounted equally spaced on the edge of the reservoir adjoining the catchment. East inlet had a pre-assembled rustproof frame, with screening to prevent trash from entering the reservoir. A sheet of butyl hanging on the inside of this screen acted as a flap valve, preventing any evaporation loss and also preventing the entry of insects into the reservoir. The catchment was contoured to direct runoff to each inlet. Ten such inlets (24 inches long by 8 inches high) would allow some 17 c.f.s. to enter the reservoir, assuming that each inlet acts as a broadcrested weir with a depth of flow of 6 inches and a discharge coefficient of 2.5. This runoff was expected for the catchment area of 100,000 square feet with a rainfall intensity of some 7.5 inches/hour, a torrential downpour which would be expected only infrequently. The reservoir cover was 8 inches above the inlet level and 2 inches above the general catchment level, giving additional freeboard to prevent storm runoff overflowing onto the top of the reservoir. As the reservoir cover was floating on the water surface, however, no structural damage would result in such a case. The only loss would be the volume of water which overflowed.

If the reservoir had no spillway, the runoff from the catchment would back up, flood the spillway and overflow onto adjacent areas (and possibly the reservoir cover) when the reservoir is full. Since erosion damage would be possible in the vicinity and water lying on the catchment might be subject to pollution prior to slowly entering the reservoir, a spillway was therefore considered essential. For simplicity the same arrangements used at the inlet portals was used on another reservoir edge for spillways. Screened and preassembled frames prevented rodents or debris from entering the reservoir. On each spillway portal the butyl sheet acting as a flap valve was placed on the outside of the screen. A small overflow channel was located parallel to the spillway edge to lead the overflow away from the site and to prevent erosion.

The average annual rainfall of 35.6 inches produced an average daily inflow of 4,600 g.p.d. (for 100,000 square feet of catchment with a runoff coefficient of 0.9). Since the design capacity of each scheme was only 2,400 g.p.d., almost half of the runoff would be wasted over the spillway. This waste of water was reduced by increased consumption (extra water for laundry, etc.) at times when the reservoir is full, but strenuous efforts was required to remind the settlers that this excess water could not be provided regularly.

The function of the entire scheme was to provide water for people. As the reservoir was below ground level, water would have to be removed by pumping. Settlers on Manda Island would generally went collect their water twice daily, morning and evening, based on experience with existing schemes in the area. Assuming that total daily water requirements of 2,400 g.p.d. are to be withdrawn in two periods of two hours each, the pumping rate was about 600 gallons per hour or 10 gallons per minute. Two pumps were installed, both to reduce queueing and to provide for occasional maintenance to either pump. Simple and robust hand pumps were be mounted sturdily near the corner of the reservoir, with plastic suction pipes laid along the sloping reservoir wall to the reservoir bottom.

The bottom of the reservoir sloped gradually from the inlet edge so that its depth at the pumps was some six inches greater than on the inlet edge, ensuring that all water could be removed from the deep end of the reservoir in times of drought. To facilitate the settling of larger particles liable to be washed into the reservoirs, a sump several inches was arranged on the inlet edge as indicated in Figure 14. This facilitated reservoir cleaning by concentrating larger particles for removal.

pre-cautions

The entire catchment and reservoir area was fenced for at least three reasons:

(a) to prevent damage to facilities by domestic animals or children,

(b) to minimize pollution on the catchment, and

(c) to conserve the water supply by preventing unauthorized withdrawals from the reservoir.

The methods used to construct the facilities were similar to those in the prototype built at Wasini Island.

Operation and Maintenance

Compared to other types of water supply, a precipitation harvesting scheme requires only minimal operation or maintenance. Its simplicity is one of its principal advantages. Nevertheless this aspect deserves mention.

Water Quality

The purest water found in nature, rainwater, is stored in a precipitation harvesting scheme within minutes of its arrival on the surface of the earth. The catchment surface was constructed to produce maximum runoff with minimum change in water quality, the aluminum spray mentioned earlier was successful in eliminating degradation of the asphalt, thus making the water in storage to be free of discolouration from this source. When such discolouration existed on previous asphalt catchments the water was nevertheless odourless and tasteless. Discolouration was caused by materials comprising less than 10 mg/l Meyers (1967). As colour removal was difficult, requring ionic exchange resin columns, there was no justification for attempting to remove this discolouration as it did not occur at Manda Island.

Two potential sources of pollution were considered to be:

(a) wind-blown particles (sand, etc.) which could be washed into the reservoir from the catchment, and

(b) depositions from birds (mainly seabirds).

The constructed fence around the catchment prevented the catchment from being made dirty in any other manner. Screens on the inlet portals kept out most matter but some sediment could be expected to enter storage. The reservoir, however, acted as a very quiescent settling basin and any material washed into it soon settled to the bottom. With the pump suction located several inches above the reservoir floor the water withdrawn from storage contained little suspended solids.

The reservoir liner and cover made of butyl was unaffected by the water stored. It appears true also that the water would not be affected by this butyl.

Algae, which can cause aesthetic and odour problems in reservoirs, require sunlight for their photosynthesis process, Palmer (1962). The reservoir cover could not allow water in storate to be exposed to light, and runoff moved quickly across the catchment in rainy periods so algae were not likely to exist in the precipitation harvesting scheme.

To maintain water of high quality in the precipitation harvesting scheme required simple attention to prevention of pollution. All people and animals were to be kept completely away from the catchment and reservoir, by fencing and by administrative enforcement. Regular maintenance activities were supposed to be performed by trained personnel so that the water supplied by the scheme remains wholesome and palatable.

There was no treatment required due to mineral or organic matter in the water collected by the scheme. Since there was no reason to expect any poisonous substances or disease-producing organisms to enter the water of this simple scheme, it was assumed to be hygenically safe. In these circumstances no provision was proposed for any kind of water treatment at Manda Island.

If there were any reason to suspect bacteriological contamination of the water supply (by known entry of fecal pollution into the reservoir, for example), the immediate solution to avert a public health problem would be simply to stop using the particular scheme which was affected. Two of the three schemes should be unaffected since the pollution would likely be only local.

A possible disadvantage of the arrangement proposed for covering the reservoir is that the black butyl sheet, in direct contact with the water except where the polystyrene floats are attached, would absorb and transmit heat from the sunlight. The thermal conductivity of butyl has not been investigated but it is reasonable to expect that the water stored in the reservoir would generally be somewhat warmer than the air temperatures in the area. Effective prevention of evaporation from the reservoirs by the floating cover would prevent cooling of the body of water by evaporation from the surface. If the warm temperature of the water were sufficiently objectionable the consumers might cool it through controlled evaporation, possibly by using canvas water bags for water transport or storage.

Maintenance Procedures

There was minimal maintenance of the scheme. The catchment area required occasional sealing of cracks and a resealing of the entire surface would probably be desirable, perhaps on an annual basis This was done by spraying with emulsified asphalt or, if the final spray incorporating flaked aluminum succeeded in preventing degradation of the asphalt, this top layer of aluminum was resprayed. In either case the work involved was done by one man in one day using the spraying equipment which were obtained during construction.

The fence would have to be ke t mended and the hand pumps could require occasional repairs. Such simple jobs could be completed as and when required.

The reservoir requires inspection and removal of sediment periodically. Most of this sediment accumulates in the small sump at the intake edge of the reservoir. (See Figure 14). This material is removed most simply with the reservoir empty. This involves removing the floating cover temporarily. At that time a visual inspection could be made of the reservoir linear, pump installation, reservoir cover and floats, etc. The reservoir is designed, however, to be seldom empty. As the settlement would have three similar schemes, and as each would use about half the normal available runoff, it would be possible to empty one by pumping before the rainy season so that it could be cleaned.

The butyl liner and cover of the reservoir should remain perfectly watertight after installation. The cover is the more vulnerable element. If the cover or the liner should tear or develop a hole, the necessary repair could be made fairly simply by patching. A supply of patches, tape and adhesive for repairing the butyl sheets were left on the site following construction.

GENERAL OBSERVATIONS CONCERNING PRECIPITATION HARVESTING SCHEMES

The preceding section described in some detail a precipitation harvesting scheme supplying water for a specific situation in Kenya. The discussion focussed on many of the problems which must be dealt with in any such scheme. Each situation where a precipitation harvesting scheme could be useful, however, is different from all others.

This section is concerned with this particular type of water supply in a more general sense, attempting to provide guidance on how, where and when precipitation harvesting schemes might be utilized for community water supplies. Following discussion on construction techniques and design considerations, an attempt is made to outline the type of situation in which a precipitation harvesting scheme could be relevant and this is considered to be applicable to many parts of Africa.

A. CONSTRUCTION TECHNIQES

Precipitation harvesting has been defined as the collecting, conveying and storing of water from an area which has been treated to increase its runoff. Such schemes can be used to supply water for crops, wildlife and livestock as well as for domestic use. The principles involved in constructing them do not greatly depend on the use which is eventually made of the water.

Because of the simplicity of such schemes they have been used in one form or another from ancient times. In the Negev desert some 4,000 years ago, for example, irrigation water was supplied in an area with an average annual rainfall of about four inches. Hillsides were cleared of rock and gravel to increase runoff and ditches were constructed to carry the water to fields below, Evanari et.al (1961). This example illustrates that there is nothing new about the concept of precipitation harvesting.

There are many examples available of various techniques which have been used in the construction of precipitation harvesting schemes. A literature survey on the subject is not too productive, however, for at least two reasons:

(a) The schemes are so simple that few authors have bothered to record or analyze them, and

(b) Precipitation harvesting schemes have been discussed in conjuction with water supplies for animals and crops as well as for people, so that the available literature is spread thinly in the publications of several disciplines.

Nevertheless a fair number of precipitation harvesting schemes have been discussed and a summary of the experience gained in previous projects can be useful when considering how to proceed on future ones. It is worth emphasizing, however, that advances in technology, particularly in the production of low-cost waterproofing materials, make the experience of past construction methods of only limited relevance to the future.

Various methods of construction which have been used in the past or are available at present are discussed subsequently. Construction methods for catchments and reservoirs are treated separately.

1. Catchments

The various means of increasing the runoff from on area can be classified as follows:

(a) Clearing sloping surfaces of vegetation and loose material,
(b) Improving vegetation management by changing ground cover,
(c) Mechanical treatments, such as smoothing and compacting the surface,
(d) Reducing soil permeability by the application of chemicals,
(e) Surface-binding treatments to permeat and seal the surface,
(f) Covering the catchment with a rigid surface, and
(g) Coverning the catchment with a flexible surface.

The suitability of these various methods for use in conjunction with community water supply schemes depends on the quality of water which results, the runoff coefficient, and, of course, the associated costs.

(a) Surface Clearing

This is perhaps the simplest means of improving the runoff from an area. In ideal situations, very little effort is required. Where the area is fairly impermeable, such as a rock catchment, virtually all of the runoff can be utilized if the material which interferes with the runoff is removed.

Removing obstructions to runoff can be expected to increase the velocity of the runoff. Unless the natural surface is quite hard, erosion can be expected to increase after the surface is cleared. This simple method may not be appropriate for domestic water supplies if the effect of such erosion will be to greatly affect water quality.

(b) Improved Vegetation Management

Runoff from grass-covered areas tends to be greater than that from forest and brush covered lands, Meyers (1969), and it appears that this approach can increase runoff without appreciably increasing erosion. Empirical data which indicate what improvement in runoff can be obtained by changing the vegetation in a watershed are difficult to obtain. Research in Utah and Colorado indicated that runoff could be increased from four to nine inches by converting the vegetation from aspen to grass, Beattie (1969).

The uncertainties associated with this method of increasing runoff tend to make it of limited use when planning water supplies for communities. Catchment areas used exclusively for water supply purposes are naturally preferred. Increasing competition for limited land resources, however, may make this concept more important in the future.

(c) Mechanical Treatment

Smoothing and compacting a surface will eliminate losses due to infiltration and depression storage of rainwater and hence will increase runoff. Conventional construction equipment (graders, rollers, etc.) can provide such treatment quickly and fairly cheaply. Sealing fissures on a rock surface can also be a simple way of increasing the effectiveness of the rock catchment.

Erosion remains a possible problem if the material of the catchment, even when compacted, is not water resistant.

(d) Chemical Application to Reduce Soil Permeability

Hillel differentiates colloidal dispersion treatments and hydrophobic treatments, Hillel (1967). In the former, self-crusting of soils containing clay is caused by the addition of sodium salts which disperse the colloids. The treatment is cheap but recent research has found that erosion of the soil is a severe problem with such treatment and that the salt tends to be washed away in a short period, Meyers (1967). The salt washed away by the runoff would obviously have an adverse effect on the water quality.

Hydrophobic soils are created by the addition of water-repellant materials to reduce the wettability of the soil surface. Many materials can be used, of which the most successful in research in Arizona, Meyers et.al (1967), was a sodium methyl silanclate compound. It penetrates into soil to form an inert, hydrophobic resin which is not biodegradable. Erosion remains a problem with this relatively low-cost soil stabilizers currently under investigation. This could mean that advances in this method of increasing runoff can be expected.

(e) Surface Binding Treatments

Petroleum products which penetrate the surface, bind soil particules together and provide an impermeable surface have been used in many situations. Extensive research and investigation has been undertaken in the United States on the use of asphaltic materials in irrigation canal linings. Many types of construction have been completed using pavements, prefabricated mats, etc. The projects discussed in a good summary, Brusdi (1963), were usually large enough to employ special equipment and frequently used hot-mixed asphalts. Where asphalt membranes were sprayed onto the ground they were generally given a protective cover (earth, gravel, etc.) to prevent damage to the membrane seal.

Meyers and others have described five catchments, from 10,000 square feet to 22,500 square feet, constructed with sprayed asphalt pavements and used to supply water to livestock, Meyers et.al (1967). Experience gained with various types of asphalt materials allows the authors to conclude that properly constructed and maintained asphalt pavements can be built at relatively low cost and provide essentially 100% runoff of precipitation.

A significant problem with asphalt catchments is their degradation when exposed to the atmosphere. In South Australia a five acre catchment, constructed by spraying two coats of asphalt on a graded and compacted gravel surface, supplies water to the Koonibba Aboriginal Reserve. The water from this scheme is reported to be discoloured, no doubt due to the breakdown of the top layer of asphalt, Martin (1968). Research now underway to discover satisfactory protective coverings may eliminate this drawback, Frasier and Meyers.

Conventional asphalt pavements in use for airports, highways, parking lots, etc. are built to higher standards than required for precipitation harvesting schemes. The structural requirements for catchments are minimal since only very light and infrequent traffic would normally be expected. The appropriate approach in designing a catchment should be to see how little pavement is required other than a waterproof seal. In many cases sprayed asphalt itself will suffice.

At the Wasini Island prototype in Kenya the fine sand on the base required strengthening by adding cement. On sites with larger granular material the necessary base preparation could be only compaction. Each site warrants individual analysis for determination of the minimum pavement required for the catchment area.

(f) Rigid Surface Coverings

Conventional techniques used for the construction of roofs for buildings provide a large variety of rigid coverings which can be utilized as rainwater catchments. These include concrete, asbestos cement sheets and metal sheets such as corrugated iron and aluminum.

The roofs of buildings are an obvious source of rainwater and in many places are the principal source of water for people. On the Indian Ocean coast in Kenya, for example, many beach houses and hotels have to rely on roof catchments to supply water for cooking and drinking. Brackish water from local wells is used for the larger volume requirements where quality is less important (showers, laundry, toilets).

Bermuda, an island with an average annual rainfall of fifty-seven inches, depends almost entirely on precipitation harvesting schemes for its water. Government regulations ensure that all buildings have properly constructed roofs, gutters and storage tanks. Each house uses water collected from its own roof and stored in a cistern beneath the house. The systems are said to be able to supply a per capita demand of twenty gallons daily. These private schemes are augmented by government schemes with concrete catchments, from which water is trucked in dry spells. But this water supply system requires augmentation from outside the island occasionally.

One of the best known precipitation harvesting schemes exists at Gibraltar. One catchment, occupying ten acres on the east side of the rock, consists of corrugated galvanized iron sheets bolted to a timber framework which rests on piles, Sheppard (1962). Runoff from the catchment is stored in reservoirs excavated in the rock.

In Australia rainwater catchments have been built, not as building roofs, but independently to provide water for people and livestock. Over forty years age Kenyon (1929) prepared a paper on "ironclad catchments" in which he analyzed demand patterns and precipitation records. He proposed a scheme with a 26,000 square feet catchment made of flat sheets of galvanized iron on a timber framework at ground level. Similar schemes had already been constructed in the

State of Victoria, feeding into concrete storage tanks, Kenyon (1929).

Along stock routes in South Australia roof catchments of iron or timber sub-structures were constructed as early as 1885. They continue to be a practical and necessary solution to water supply problems in this arid area. Three schemes built in 1960 consisted of "rainsheds", 7,200 square feet in area, of galvanized steel supported on a steeel frame about 6 feet above ground. Two 10,000 gallon steel tanks stored water under each shed, Martin (1910).

Rigid surface coverings are generally much more expensive than flexible ones and cannot usually be justified as a means of construction unless their primary function is that of a roof.

(g) Flexible Surface Coverings

In about the last decade a variety of prefabricated products have become available which make it possible to quickly and effectively waterproof virtually any area. Earlier coverings were materials similar to those used for building roofing. One type used in canal linings was a prefabricated fiberglass mat saturated with asphalt and produced in rolls.

As various plastics became available they were tested extensively by the U.S. Bureau of Reclamation for use as canal linings, USBR (1968). Results of these tests indicated that no plastic was suitable as an exposed lining, but if covered by at least one foot of material (to prevent exposure of the membrane to air and sunlight) the newer plastics, particularly polyvinyl chloride and polyethylene, worked very well in reducing water losses.

Limited experience with expected plastic films as water catchments indicates two principal problems:

(i) deterioration of the plastic, and

(ii) wind damage to the lightweight membrane.

One way of reducing these problems is to cover the sheets with a layer of material such as gravel. This is an unsatisfactory solution for a catchment surface, however, since:

(i) possible damage to the sheet cannot be detected, and

(ii) the material used to cover the sheet retards runoff and decreases the effectiveness of the catchment.

Plastic materials appear therefore to be of limited use in waterproofing catchments.

Another interesting possibility is aluminum foil, rolls of which were laid on a hot-sprayed asphalt emulsion in Arizona. One particular catchment gave trouble when individuals walking on the sheet caused pebbles on the unsmoothed base to protrude and rip the aluminum, Meyers (1967). The asphalt bond eliminated problems due to wind. Aluminum is stable in air so it may be that this construction method would be satisfactory on a very smooth base.

The most robust of the flexible coverings currently available is butyl rubber. It does not deteriorate when exposed to sunshine. Being tough and elastic it can be laid on a base with limited preparation. Extremely large sheets can be preassembled and transported to a site: field joints are simple. Patching can be done easily if necessary.

Meyers reports that nylon-reinforced butyl sheeting has been successfully installed over sharp cinders and on slopes of up to 40% in Hawaii. About thirty catchments there, from about two to seventeen acres in area, were covered with butyl sheeting from 1963 to 1967, Meyers (1967).

2. Reservoirs

There are many ways to store water. The storage requirements for precipitation harvesting schemes used to supply water to communities present no new technical problems. The conventional methods of construction, using steel or concrete, can accommodate a great range of storage capacities. In general, however, these conventional techniques tend to be relatively expensive.

Newer storage techniques involve the use of flexible surface coverings, as discussed in the preceding section dealing with catchments. Polyvinyl chloride or polyethylene sheets are less vulnerable to wind or sunlight when used as reservoir liners but they are still not as satisfactory as butyl rubber.

In Hawaii recently a liner consisting of top and bottom layers of butyl, laminated to nylon, was used to line a reservoir with 4,500 acre-feet capacity. A basic question associated with the design of a reservoir is whether or not it should be covered. One possible justification for covering a reservoir is to prevent the loss of water through evaporation. To justify the covering of a reservoir on these grounds requires estimates of the potential evaporation losses and the cost of compensating for such losses by building a slightly larger catchment area and storage volume.

As mentioned in connection with the Manda Island scheme discussed earlier, the covering of a reservoir containing water for domestic use is desirable on other grounds than the reduction of losses. Control of the quality of the water is probably the principal concern.

Algae can be encountered in surface water supplies exposed to sunlight. Their accumulation in a reservoir can cause taste and odour nuisances as well as being aesthetically objectionable. Algae require nutrients and sunlight to survive. An open reservoir of a precipitation harvesting shceme provides the latter requirement, but the quantity of nutrients in the water would generally be much less than in a conventional scheme (depending on the catchment area). Pure rainwater would wash little organic matter into a reservoir from an impervious and protected catchment designed specifically for a water supply scheme. The question of possible algae problems and the justification for eliminating them warrants consideration in each particular situation.

Pollution of the water in an open reservoir could result from wind-blown particles or from bird life. Near oceans seabirds often seek quiet inland waters in times of storms. If scavengers are possible visitors to the reservoir the danger of contamination of the water exists. To justify covering a reservoir may be difficult in quantifiable terms but the prevention of pollution can nevertheless provide strong reasons for such construction.

In many areas (for example, Singapore) local ordinances prohibit any open water surfaces because they provide breeding places for vectors, such as mosquitoes, which can be carriers of malaria and yellow fever. Where such situations exist the covering of the reservoir is not a subject for discussion: the reservoir must be covered. Where such public health considerations do not apply it may be advisable to cover the reservoir simply to eliminate a breeding area for nuisance insects.

Covering of reservoirs by traditional methods of rigid construction is generally quite expensive, particularly for large reservoirs. Recent developments, however, allow consideration of more economical means of performing the functions of normal reservoir covers.

Suppression of reservoir evaporation by spreading of a surface film of chemicals, such as hexadeconol and octadeconol, has been investigated. Recent research in Australia suggests that monolayers are feasible economically only for large reservoirs in arid or semi-arid regions which are used mainly for domestic purposes or for industry, Mansfeed (1968). Similar research in the United States resulted in similar conclusions:

> "At the present time evaporation suppression using monolayers on ponds less than one acre in size does not appear to be economically competitive with other methods of evaporation control such as using a floating cover or physically reducing the surface area to volume ratio by deepening the reservoir or diking of shallow areas." Cliff (1966)

A drawback to the use of monolayers is that they do nothing to solve the problems of pollution and vector control associated with open reservoirs. More substantial covers are needed for such purposes.

It might be possible to overcome the drawbacks associated with monolayers on reservoir surfaces, without incurring the expense of traditional roof structures, by covering the water surface with a floating cover. Hardly any experience with such a method of covering reservoirs has been discovered in the literature.

When reservoirs are constructed with sloping sides the problem of covering them with any type of floating cover is complicated by the changing surface area of the reservoir. The polystyrene-supported butyl cover used for the Manda Island scheme is a possible answer. Another would be to use many small pieces of polystyrene (or a similar floating material) to eliminate evaporation, providing the material is resistant to sunlight, air and water. Each of these possible solutions presents problems with precipitation falling on the reservoir cover: either the water is lost through evaporation, or pollution is possible if the rain can flow off the cover into the reservoir. Further trials using various types of floating covers are required to determine their merits.

The versatility of butyl in reservoir construction permits novel types of reservoirs to be considered. Lauritzen and Thayer have proposed a "rain trap" installation for supplying water to livestock. This consists of a sheet of butyl spread on the ground as a catchment. It supplies rainwater to a butyl storage bag lying slightly downhill. Water for livestock is supplied from the storage bag to a trough through an automatic float valve. Apparently prefabricated bags for this application are available, made of nylon-reinforced butyl sheeting. The bags may also be incorporated. These authors have designed a 50,000 gallon reservoir consisting of an excavation some seven feet deep and forty-three feet square, with sloping sides, having a bottom linear and a top which expands as the bag fills with water, Lauritzen et.al (1968). Where cleared land is available the construction of these "raintraps" appears to be so simple that they could be completed within a day. Storage costs would no doubt be less expensive than for concrete or steel reservoirs of similar capacity.

In Kenya the supplier of butyl constructed a prototype of a substitute for the steel or concrete cistern normally used with roof catchments of buildings. A cylindrical cage made of galvanized steel wire, such as that used for fencing or for reinforcing steel for concrete slabs, contained a butyl bag supported at the top of the cylinder. The light steel frame provided the structural support for the reservoir while the butyl bag provided the watertight storage.

Investigations and prototype construction of low cost water reservoirs in the Sudan produced several novel possibilities, Anon. (1967). The emphasis was on "intermediate technology" - or cheap and easy construction - using large amounts of relatively cheap labour and minimum amounts of imported and expensive materials. Excavated tanks were supplied with rainwater in an area having about sixteen inches of annual precipitation. One model reservoir had a lining consisting of four layers of polythene sheeting, with layers of mud between the sheets, so that any hole in the sandwich liner would tend to plug itself with mud carried down by escaping water.

The "pillared roof tank" proposed for large volumes would be about 100 feet square and have a thatched roof supported by tree poles (or black polythene supported by wire netting). Columns in the reservoir were made with "sausages", ory mixtures of sand and cement (ratio about 15:1) in tubes of polythene sheet. The columns were built of layers of these "sausages", which were then made rigid by puncturing the polythene sheet to allow water to set the cement in the mixture.

These examples of innovative construction techniques illustrate that the components of precipitation harvesting schemes can be built effectively and economically if common sense and available materials are used appropriately. The principal ingredient required for the successful application of currently available technology is simple: it is imagination. Designers and builders willing to use their heads should be able to come up with satisfactory precipitation harvesting schemes at only a portion of the cost for schemes providing the same output but constructed by conventional methods.

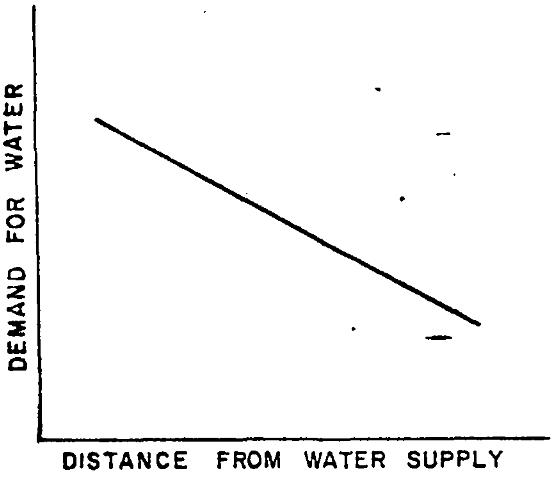
Location of Water Supply Facilities

For precipitation harvesting schemes based on catchments which are building roofs or which depend on rocks or other topographic features there is little choice concerning the location of the facilities. The catchment area is defined independently from the requirements for water supply. The design problem is to determine the dependable capacity of a supply based on the available catchment and to selecte the reservoir size needed to develop as much of the capacity as is required. The reservoir location, between the outlet of the catchment area and the demand center, is selected to minimize pumping and transmission costs. Under favourable circumstances water can flow to all points of use entirely by gravity.

Where a natural catchment such as a roof or rock surface does not exist, the site of all components of the precipitation harvesting scheme can be rationally selected principally on the basis of the distribution of the demand for water. The cost of land is the other major criterion in site selection. The opportunity to locate all components of such water supplies close to their point of use distinguishes them from conventional schemes, whose location is generally controlled by topography (surface water schemes) or geology (ground water schemes).

In unsophisticated communities, where water is carried from a central supply to the point of use by the consumers, the matter of site determination becomes a simple transportation problem. There will be an economic limit to the distance between the location of the water storage and the point of use. As water weighs ten pounds per gallon, and as people carrying water cannot walk more quickly than two or three miles per hour, the effective radius of the area which such a water supply can serve is quite small. If two separate precipitation harvesting schemes can be used to serve an area at little cost above that for one large scheme, the water supply can be made more amenable to the consumers by the construction of two supplies.

The proximity of consumers to the water source naturally affects demand. A single scheme to serve a community would probably require less capacity than two or more schemes sited to reduce the average distance between source and consumer. The situation can be depicted thus:



In some areas the quantity of average precipitation varies considerably within fairly short distances. Hilly or mountainous regions generally have greater precipitation than lower adjacent areas. This is caused by orographic precipitation, occurring when moisture-laden air is forced to rise, expand and cool as it meets a topographic barrier, Wisler et.al (1963). The rainy slopes of volcanic formations in the Hawaiian Islands, on which are situated the precipitation harvesting schemes used to irrigate the high value sugar and pineapple crops in the fields below, area a good example of areas whose predominant precipitation type is orographic.

Local anomalies in precipitation patterns may indicate that the precipitation harvesting scheme could be built more cheaply if situated to receive higher precipitation away from the demand center. In these circumstances the costs associated with the transmission of water from the source to the consumers would have to be added to the construction costs of the precipitation harvesting scheme to determine the optimum location of the supply.

Demand Projections

The demand for water has been shown to be related to the location of the water supply facilities. Several other factors which affect the demand for water, and which are common to all water supplies, can be listed as follows:

(a) selling price of water,
(b) income and standards of living of consumers,
(c) dependability of water supply,
(d) water quality,
(e) availability of alternative or supplementary water supplies.

The standard of living, determined by the income level of the consumer, obviously affects his deamdn for water. If a swelling is supplied with piped water considerable amounts of water will be used for washing and toilet flushing. But these uses of water require the substance only as a medium for carrying away wastes. Non-potable water can be used for these functions where fresh water is scarce, allowing high value rainwater to be used only for drinking and cooking. Where a source of low quality water is available, only a small portion of the total demand needs to be supplied from a precipitation harvesting scheme.

When attempting to determine per capita water demand for an area it is generally more profitable to investigate water consumption patterns in nearby regions than to resort to any literature survey. A survey to measure the water demand of consumers similar to those who would be served by a precipitation harvesting scheme will probably provide the best indication of future demands.

Water Quality

Precipitation harvesting schemes should produce water of higher quality than any other form of surface water supply since the catchment is deliberately constructed, or at least utilized, to provide water for domestic use. The catchment area is relatively small and possible pollution can be reduced by controlling or eliminating the use of the area for any other purpose but water supply. Wind-blown particles will be deposited on the catchment, however, and birds and other creatures may have difficulty in reading man-made warnings of "keep Out". Complete elimination of pollution over the catchment area is impractical.

Pollution, however, does not necessarily mean contamination of the water, or rendering it unfit for human consumption. Pathogenic (disease-producing) organisms or toxic substances must be introduced into the water before it is unsafe to drink. For most precipitation harvesting schemes the control over the entry of toxic substances into the water should not be difficult. Chances of contaminating a well operated scheme with pathogenic organisms should also be remote, since

> "Water, to act as a vehicle for the spread of a specific disease, must be contaminated with the disease organisms from infected persons", Calvato (1958).

A fenced catchment (or elevated roof) is unlikely to be contaminated by an infected person. The reservoir should be above ground or, if in an excavation, made watertight to eliminate the possible entry of polluted ground water. If the reservoir is covered the possibility of any transmission of disease organisms by insects or birds would also be eliminated while at the same time the growth of algae would be prevented.

Water quality can be positively influenced by the sensible design of a precipitation harvesting scheme. The surface of the catchment determines whether or not the runoff will contain suspended or dissolved solids. Since some debris is liable to accumulate on the catchment or in conduits leading to the reservoir some elementary precautions can reduce pollution of the water in storage. Fine mesh screens of flap valves on all inlets, ducts and spillways will prevent the entry into the reservoirs of animals, birds and large insects as well as debris.

Simple maintenance, including rhe removal of such debris when it accumulates, would prevent blockages in water conduits and the possible waste of water which could result from overflows.

Where the roof of a building serves as the catchment, it is possible to prevent the dirt which might accumulate on the roof or in the gutters from reaching storage. A simple device, which can be constructed at the end of the gutter leading into the cistern, consists basically of a tipping bucket. The first volume of runoff, the dirtiest, would fill the bucket on one side of the device and be tipped to waste. This tipping action would cause all subsequent runoff, presumably much cleaner, to flow directly to storage. The device could be reset after a rain to again function automatically when runoff next flowed off the roof.

If the catchment area produces runoff containing suspended matter, and if the quiessence of the reservoir does not clarify the water sufficiently through sedimentation, some sort of filtration might be advisable. Cloudy water is not particularly attractive, and water which is hygenically safe may nevertheless be unpalatable.

Runoff from an elevated catchment could be forced to flow through sand or charcoal to filter it. If water from a ground level catchment is stored in an excavated reservoir, it can be filtered before it is withdrawn. In the Sudan water is removed from "hafirs", or excavated tanks, by pumping it from a well shaft in the corner of the tank. This shaft is surrounded by sand through which the water must flow before it is pumped out, Anon (1967).

If precautionary disinfection of the community water supply is required the preferable system for a small precipitation harvesting scheme would probably be an unsophisticated type of chlorination. Good discussions on appropriate techniques are available in manuals by W.H.O., Wagner and Lanoix (1959), and the U.S. Public Health Service, U.S.D.H.E.W. (1965).

Treatment of water by individual consumers is also possible. Suspended matter can be removed in diatomaceous earth filters, which are available for home use in the shape of cylindrical jars. A simple charcoal filter could be devised if required to improve the tast of the water.

Home disinfection can be accomplished by boiling the water. Chemical disinfection of small quantities of water is also possible.

Military requirements have assisted in the development of two types of tablet which are currently used for water disinfection in the United States. "Globaline", containing an iodine-based disinfectant, and "Halazone", employing a chlorine compound, require several minutes for disolution and effective treatment in water, Connord Kapoor (1970). They are not perfect disinfectants, as they impart a taste to the water, but if used effectively they can provide the water consumer with reliable protection against pathogenic organisms.

Any decision concerning treatment of a water supply of this type should be based on both the water quality expected from the scheme and the consequences of not providing treatment. A designer must also be aware of the sophistication of the consumers. Not all users of water in a primitive society could be relied on, for example, to utilize disinfectant tables even if they were freely available.

CONCLUSIONS

1. General

Since precipitation harvesting schemes are a legitimate form of water supply, can general guidelines be indicated to characterize situations in which such schemes ought to be used? This is a proper but very difficult question. Unfortunately there is no easy answer, just as there is no easy answer to a question such as "Where should wells be used as a source of water supply?" The short answer is that a specific type of water supply should be used when it is the least cost solution to meeting a specified demand for water.

The rationale for this conclusion warrants some elaboration, but before briefly discussing the economics of water supply it may be helpful to reconsider a few basic generalities concerning precipitation harvesting schemes.

Rainfall cannot be harvested in an area where no rain falls. True desert areas, where annual rainfall is frequently if not always nil, cannot be sites for precipitation harvesting schemes, such as a large portion of the Sahel.

Areas of nil rainfall, however, are rare. The average annual rainfall over the driest continent, Australia, is 16.5 inches, whereas that for the entire surface of the earth averages about 26 inches annually, Chow (1964). Using the average annual rainfall for Australia, and assuming a precipitation harvesting scheme with a runoff coefficient of 0.9 and sufficient storage to allow utilization of 80% of all runoff, the catchment area required for an individual with a daily water consumption of 25 g.p.d. is 1,400 square feet or 0.034 acre. Expressed differently, an acre of catchment could provide a water supply of 25 g.p.d. to about 30 people in an area with such limited precipitation. (The amount of storage required to allow utilization of 80% of the runoff would obviously depend on the anticipated precipitation pattern.)

As per capita consumption rises and as precipitation drops the catchment area requirements for such schemes inevitably rise. In urban areas, with high density settlements, there is simply not enough area available within the settlement to allow consideration of precipitation harvesting schemes there. These

X

schemes are best suited for low density settlements with relatively low per capita consumption of water.

Regions having severe winter climates can present problems for this type of water supply. If the reservoirs are not insulated or heated they could freeze solid, or at least freeze partially and reduce the effective storage volume. The calculation of storage requirements in such climates must discount precipitation falling as snow since it can only be used to meet the demand for water after melting and running into storage.

hm !

By using local construction techniques and making minimum use of imported materials the construction costs of a precipitation harvesting scheme can be kept small. Where local labour can be provided on a self-help basis (as at Wasini Island) the costs can be further reduced. Such schemes are easy to design, construct and operate. These features tend to make this type of water supply appropriate in underdeveloped countries.

Modular construction is possible with precipitation harvesting schemes. Because additional catchment area or storage volume can usually be provided to increase the capacity of existing schemes, or independent new modules built more easily than with conventional water supplies, there is no need to "over design" schemes of this type. They can be built for reasonably estimated immediate demands and extended as and when demand increases.

2. Economic Considerations

The construction of a precipitation harvesting scheme for a community water supply can be justified, as can any other investment, when all the benefits from such a scheme exceed all the costs. We know how to measure costs fairly well, although we are still learning now to measure costs which are external to water supply projects, such as the economic costs of changes in ecology brought about in the construction and operation of such projects. As precipitation harvesting schemes are quite simple, we shall assume that all costs associated with them, both initial and recurrent, can be measured.

The measurement of benefits from a water supply, however, is more difficult.

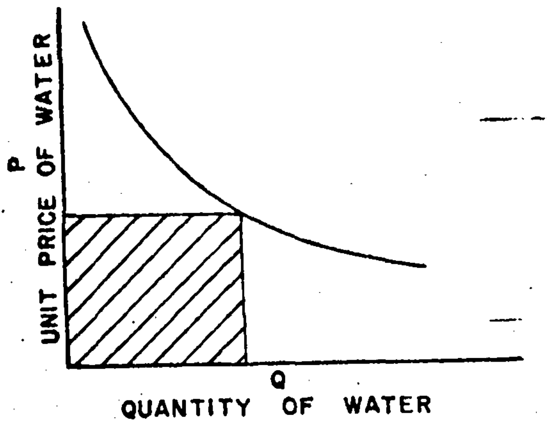
The economic benefit accruing to a consumer of any particular product is conventionally assumed to be represented by the maximum amount that he would be prepared to pay for it. Thus an indidivual consumer expresses his own estimate of the value of water by his personal demand curve, which has been explained clearly by one wall known economist as follows:

> "When water is very dear, I demand only enough of it to drink. Then when its price drops, I buy some to wash with. At still lower prices, I resort to still other uses; finally, when it is really very cheap, I water flowers and use it lavishly for any possible purpose."
> Samuelson (1967).

Consequently, if the water supplied by a scheme is charged for on the basis of the amount consumed the benefit of the scheme can be conservatively estimated as the total revenue from the sale of water. Such a scheme would certainly be economically justified if the present value of the stream of revenues exceeds the present value of the stream of costs associated with it, where the present value of both streams is determined using the appropriate discount rate.

However, even where benefits indicated by the consumers' willingness to pay do not exceed project costs, a scheme might be justifiable. This might, for example, be on the grounds that the government is unwilling to allow its poorer citizens to die from thirst simply because they can't afford the price of water, or because there are additional benefits which are not revealed by the potential revenues from the sale of the water. These additional benefits could be due to several factors:

(a) A consumer's willingness to pay does not measure all benefits which he expects to receive from the purchase of water. This is illustrated by his demand curve:



At a unit price P he will purchase a quantity Q and the revenue, in the shaded rectangle, is a partial measure of the value he places on the water. The entire area under the demand curve at the quantity Q, however, is the full measure of the value of the water, since he would be willing to pay higher unit prices for the first Q units of water. No account is taken of the "consumers' surplus", the triangular area under the demand curve and above price P, if the benefit is measured simply by his willingness to pay price P.

(b) People may not be as rational or well-informed as suggested by their personal demand curve. For example, they may not be in possession of all the relevant facts concerning the health benefits likely to accrue from using clean water. Their revealed willingness to pay may therefore be an under-estimate of the total value of water to them.

(c) There may be public health benefits which are external to those measured by an individual consumer's willingness to pay. In other words, the consumption of water by X may be of benefit to the health of his neighbour Y, but X may not take this into account in his own private market decision.

Because of these complications it is frequently not possible to measure all benefits which can be expected to result from a community water supply. The decision whether or not to invest in a water supply scheme can therefore seldom be made by the usual method of comparing costs and benefits. Instead the conventional approach is to assume that the provision of a supply of water can somehow be justified and that the problem is reduced to finding the least cost solution to supplying the estimated demand for water.

In the absence of the test of comparing benefits and costs of the scheme, the determination of the quantity of water to be supplied is crucial. Scarce resources will be wasted if a project is constructed to supply large quantities of fresh water for low value utilization by the consumers (e.g. garden watering). The selling of water at a price at least approaching the true economic costs of providing the commodity has the advantage of restricting the demands of consumers and therefore of minimizing over-investment in water supply facilities.

When determining the least cost solution to supply the estimated demand for water the costs to be considered for each scheme include:

(a) initial costs of construction,
(b) recurrent operating costs, and
(c) costs of augmenting the water supply during periods of shortages.

It would perhaps be convenient to provide a set of guidelines which would simply indicate the situations where precipitation harvesting schemes are the least cost solutions to supply water. Unfortunately no such simplistic guidelines are possible. Every situation requires individual analysis.

It is possible, however, to indicate factors which result in relatively low total costs for precipitation harvesting schemes in any specific area. These include:

(a) high average precipitation (reduced catchment area),
(b) little seasonal or annual variability in precipitation (reduced storage volumes),
(c) available roof areas to serve as catchment areas at no cost to water supply schemes, and
(d) low land costs.

Situations where many of these factors exist are liable to be wet rural areas where all buildings have impermeable roofs (simply to waterproof them) which can be used to catch rainwater. But in such conditions the alternative forms of water supply are also likely to be inexpensive: puddles, rivers and lakes will be common and the development of surface water and/or groundwater sources should also be relatively cheap.

Precipitation harvesting schemes will also be attractive where the costs of alternative water supplies are relatively high, in areas where no fresh surface water or groundwater exists. Such circumstances exist on many islands, such as Bermuda, although saline water conversion may be competitive for large scale water demands in maritime areas.

Determining the alternative costs of supplying water in any situation presents no new problems. Production costs for fresh water depend on pumping requirements and on the degree of treatment needed. These production costs can range from nil (fresh water springs requiring no pumping or treatment) to many dollars per thousand gallons for expensive treatment of small quantities of water, as in desalination plants. Added to the production costs are the transmission costs, which on a unit basis vary directly with the distance and inversely with the quantity delivered.

The exercise then becomes the usual one of comparing all costs of the two alternatives. The present value of the alternatives can be determined for any specific discount rate, or alternatively, the discount rate at which the present value of the two alternatives is equal can be determined. If the present value of the cost stream for the precipitation harvesting scheme is lower than that for all other alternatives at discount rates up to the opportunity costs of capital, the decision is simple: the preferable type of water supply in the particular situation is the precipitation harvesting scheme.

The Ethiopian Water Resources Authority (1979) have shown that this process of water harvesting is practised within the central highlands and some parts of the Rift Valley in Ethiopia (see Figs. 1-7 and 9 and 15).and The Ministry of Mineral Resources and Water Affairs of Botswana (1979) have indicated that this storm water harvesting (Fig. 16) is practised by the rural people where people are used in digging hafiirs in a few places east of Botswana which has a characteristic summer rainfall (see Figs. 6-7 and 9). In Lesotho the Phuthiatsana Irrigation Project (1979) have shown that storm water is collected from cisterns and ponds as illustrated in Figure 17 while the Sudanese Water Resources Cooperation have shown that stormwater is collected from hafiirs as illustrated in Figures 18 and 19 such wells are quite common in parts of Nigeria, Ghana and

STORMWATER COLLECTED ON THE SURFACE OF THE GROUND IS LET TO THE RECEIVING RESERVOIRS IN PARTS OF THE CENTRAL HIGHLANDS OF ETHIOPIA

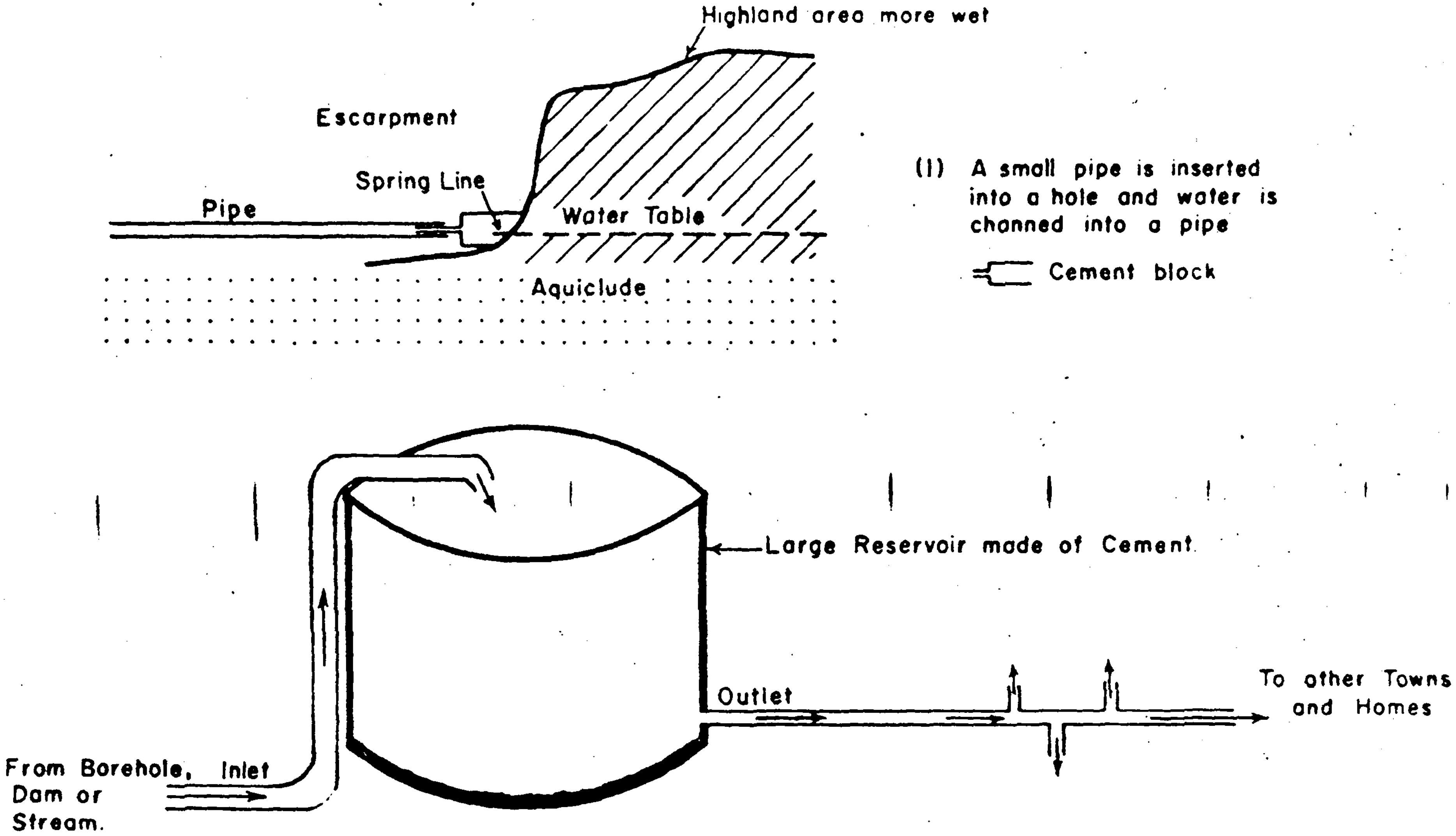


Fig. 15

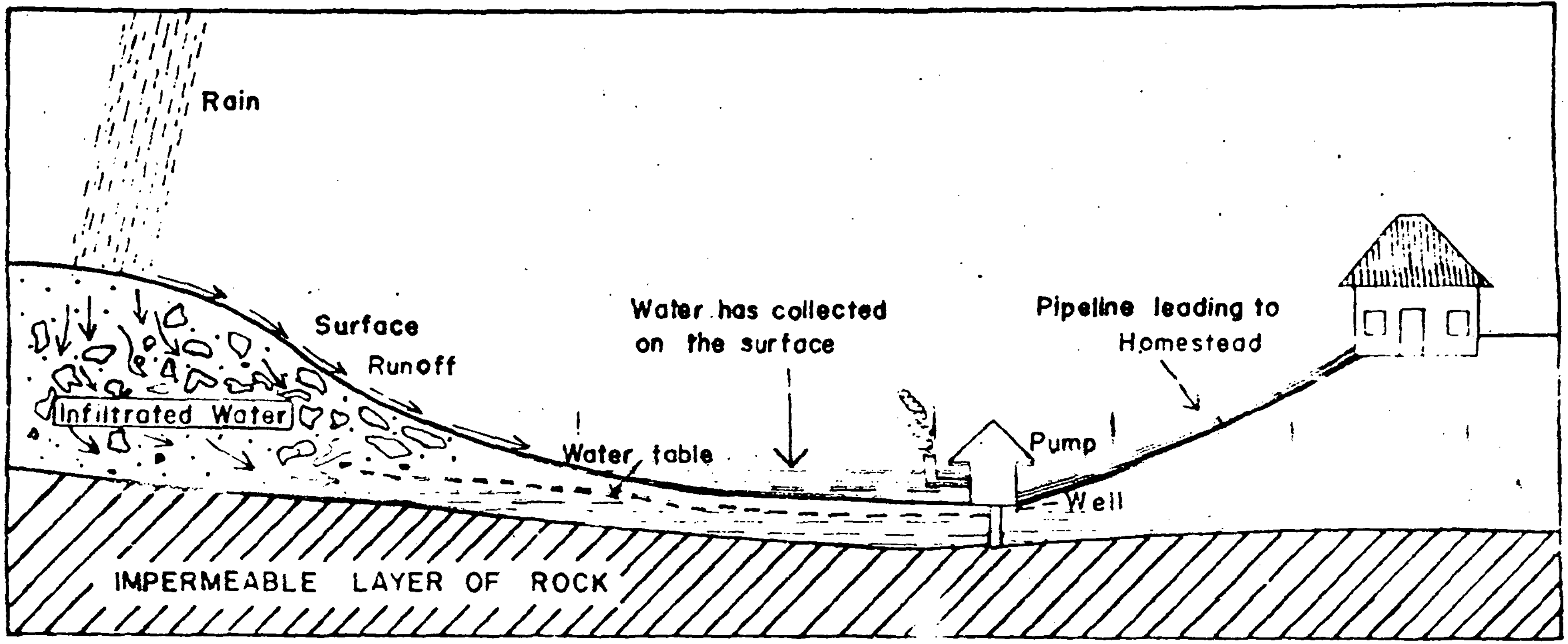
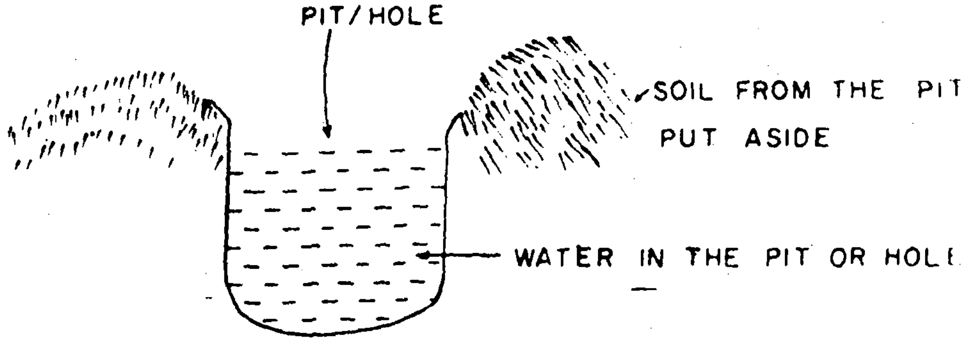
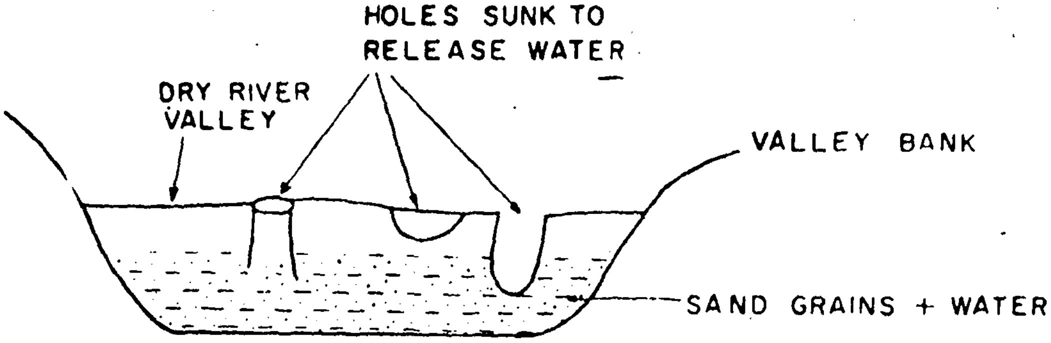


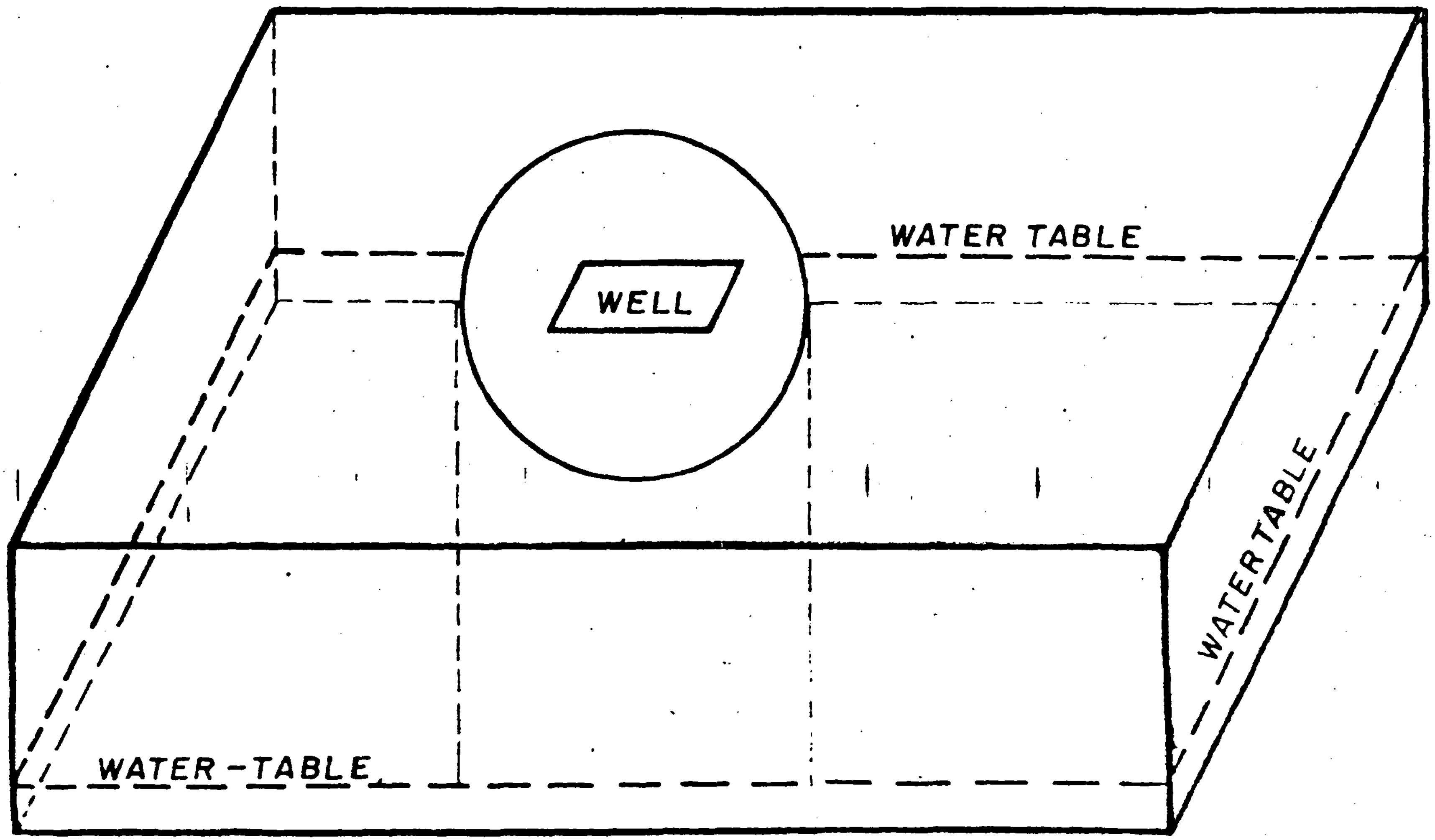
Fig. 16 Cross-section of water surface dam and its hydrogeologic components in parts of Botswana.

WATER COLLECTING PONDS IN PARTS OF LESOTHO





STORMWATER WHICH HAD FORMED A WELL IN PARTS OF THE SOUTHERN SUDAN



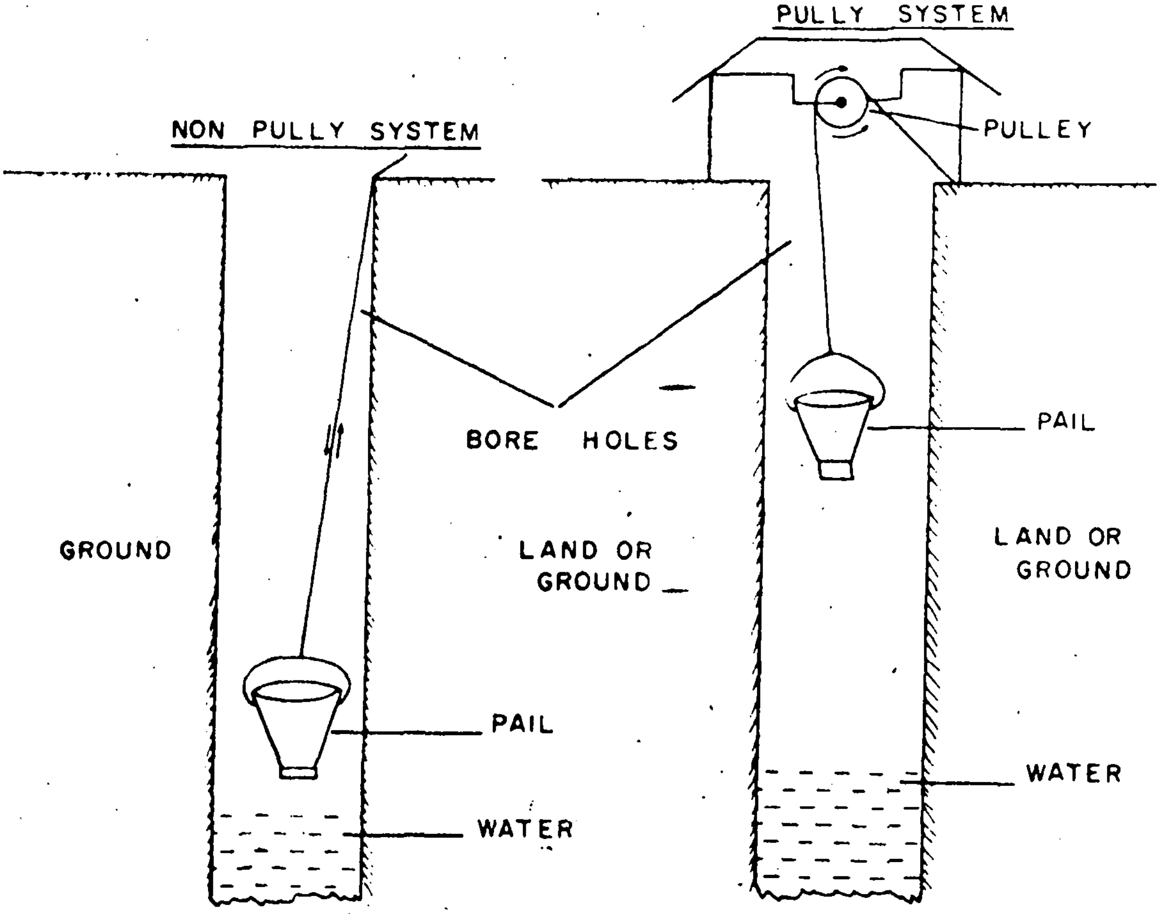


Fig. 19 Stormwater being collected from wells in parts of the Southern Sudan.

Kenya as shown in Figure 20. In Nigeria Lewis (1966) has shown how stormwater can be conserved for groundnut growing.

Modification of these is what has been achieved through the development of technology into multipurpose man-made lakes whose one function is to provide water for the rural areas in some African countries. These dams and their characteristics are listed in Table 7. A sample of Small scale dams such is illustrated in Figures 21 and 22 and Table 8.

These type of rainfall climate, population and other characteristics prevailing in these areas have all been very well documented earlier on in this paper and need not be repeated here. It is however, necessary to point out that these systems are not any different from those discussed by Dedrick (1976) being practised in parts of Israel, Southeastern Arizona, Hawaii and Jamaica. They are also not different from those assessed by Deshmukh (1979) for parts of India and Australia.

In the preceding discussion storm water harvesting has been discussed with particular reference to Manda Island in Kenya with examples drawn from other parts of Africa. The discussion shows that a considerable amount of water could be made available to millions of people in humid, sub-humid and semi-arid parts of Africa by application of this simple technology. Attention will now be focussed on water harvesting from roof-catchments.

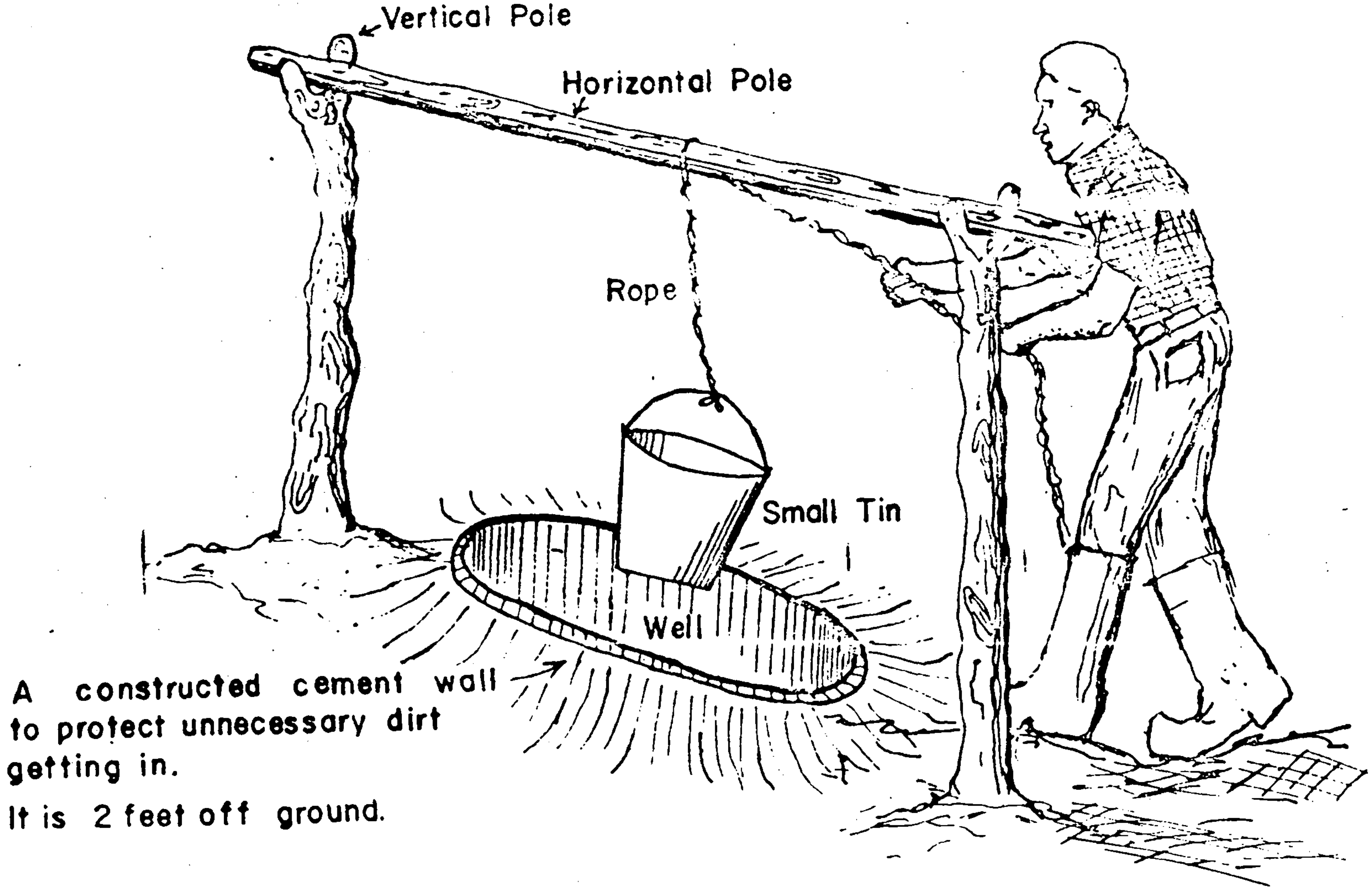


Fig. 20 Stormwater which has formed a well in collected from the groun in parts of Kwale, Kenya.

TABLE 7 MAJOR DAMS AND RESERVOIRS IN AFRICA AND WORLD

	Name	River	Country	Year completed	Dam height	Gross reservoir capacity $10^6 m^3$	Use
1	Agrioun	Irhil-Emda	Algeria	-	85	127	H
2	Ait Ouard	El Abid	Morocco	1954	-	3.8	I - H
3	Akosombo	Volta	Ghana	1965	141	148000	
4	Ali Thelat	Yaou	Morocco	1934	-	25	I - H
5	Aswan	Nile	Egypt	1925	38	5000	
6	Bamendjin	Noun	United Republic of Cameroon	1975	21	1800	M
7	Bangala	Kyle	Southern Rhodesia	1963	50	130	
8	B. Namoussa	La Cheffia	Algeria	-	51	170	I - W
9	Bezirk		Tunisia	-	22	6	I
10	Bin-el-Ouidane	El Abid	Morocco	1953	-	1500	I - H
11	Bou Djabroun	Merad	Algeria	-	23	1	I
12	Bou-Regreg	Bou-Regreg	Morocco	1974	-	570	W
13	Cabora-Bassa	Zambezi	Mozambique	1975	160	159600	H
14	Cheliff	Ghrib	Algeria	-	65	280	I
15	Chila	-	Tunisia	-	26	7	I
16	Daourat	Aum-er-Rbia	Morocco	1950	-	24	H
17	Delcommune	Lualaba	Zaire	1952	-		
18	Djendjen	Erraguene	Algeria	-	76	200	H
19	Eau Bleue	-	Mauritius	-		6.1	M
20	Edea	Sanaga	United Republic of Cameroon	1953	-		
21	El Abiod	Foumel Gherza	Algeria	-	65	43	I
22	El Hammam	Bou Hamidia	Algeria	-	50	52	I
23	El Hamman	Fergong	Algeria	-	50	18	I
24	El Kansere	Beht	Morocco	1935	-	297	I - H
25	Fincha	Blue Nile (Trib)	Ethiopia	1973	-		
26	Fodda	Fodda	Algeria	-	85	228	I
27	Gambambe	Rio Quenza	Angola	-	-		
28	Grou	Grou	Morocco	1968	-	18	W
29	Gueiss	Foum el Gueiss	Algeria	-	23	3	I

30	Hamiz	Hamiz	Algeria	–	45	15	I
31	Hassan Addakhil	Ziz	Morocco	1971	–	380	I
32	Heinrik Verwoerd	Orange	South Africa	1971	–		
33	Idriss ler	Inaouene	Morocco	1973	–	1270	I – H
34	Imfout	Oum er Rbia	Morocco	1974	–	83	I – H
35	Inga	Zaire	Zaire	1973	–	–	
36	Jebel Aulia	Nile	Sudan	–	–	3575	
37	Kafui Falls	Kafue	Zambia	1972	–	–	
38	Kainji	Niger	Nigeria	1968	–	1270	
39	Kariba	Zambezi	Zambia, Southern Rhodesia	1959	128	160368	H
40	Kasseb		Tunisia	–	58	80	W
41	Khashm el Girba	Atbara	Sudan	–	–	11	
42	Kidatu	–	United Republic of Tanzania	–	–	–	
43	Kossu	Bandama	Ivory Coast	1972	–	28750	
44	Ksob	Ksob	Algeria	–	32	8	I
45	Kyle	–	Southern Rhodesia	1961	63	1330	
46	La Ferme	–	Mauritius	–	–	11.8	M
47	Lakhness	–	Tunisia	–	37	8	I
48	La Nicoliere	–	Mauritius	–	–	5.8	M
49	Lala Takerkoust	N'Fis	Morocco	1935	–	52	I – H
50	Le Marinnel	Loulaba	Zaire	1956	–	–	
51	Manjirenji	Chiredzi	Southern Rhodesia	1966	52	284	
52	Mansour Eddahbi	Draa	Morocco	1972	–	560	I – H
53	Mansouriah	Djen Djen	Algeria	1965	–	–	
54	Mare aux Vacoas	–	Mauritius	–	–	45	M
55	Mare Longue	–	Mauritius	–	–	6.3	M
56	Masri	–	Tunisia	–	38	7	
57	Massingir	Elefantes	Mozambique	–	48	2844	I – H
58	Mavuzi	Revue	Mozambique	–	17	1.5	H
59	Mbakou	Djerm	United Republic of Cameroon	1969	25	2.2	M

92	Vaal Dam	Vaal	South Africa	-	-	2337	
93	Vila Pery	Mezingaze	Mozambique	-	15	0.3	W
94	Youssef Ben Tachfine	Massa	Morocco	1973	-	310	I
95	Zemrane	Mellah	Morocco	1950	-	0.6	W
96	Bratsk	Angara	U.S.S.R.	1967	120	169400	
97	Glen Canyon	Colorado	U.S.A.	1964	216	33304	
98	Daniel Johnson	St. Laurence	Canada	1968	214	141975	
99	Krasnoyarsk	Yenisei	U.S.S.R.		124	73300	

Source: Various, as reproduced in 'Water Resources of the World' Van der Leeden (1975); and Electric Energy in Africa, (E/CN.14/NRSTD/8/3) 9 February 1976

I = Irrigation H = Hydropower

M = Multipurpose W = Water supply

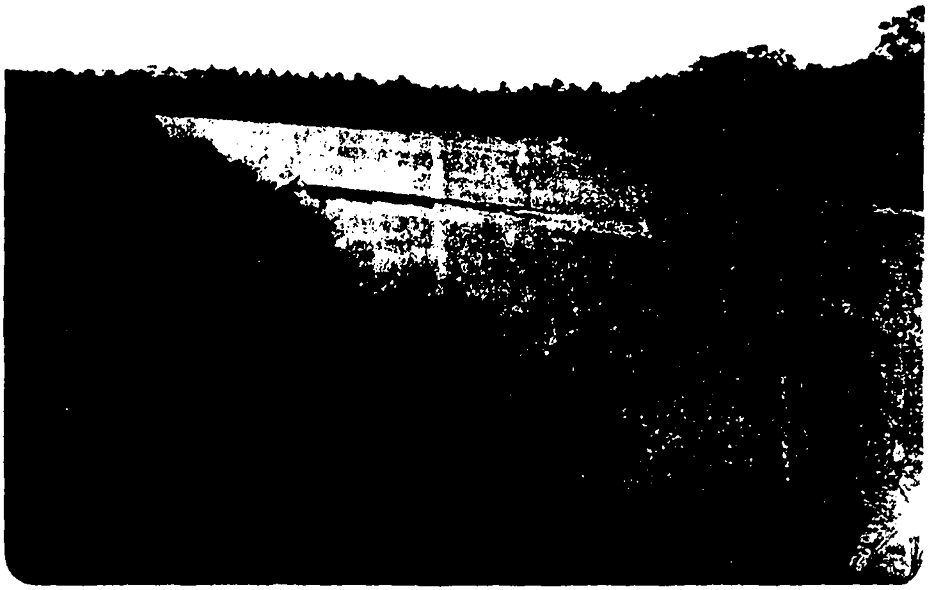


Fig. 21 Stormwater harvesting dam in parts of Kilifi, Kenya.

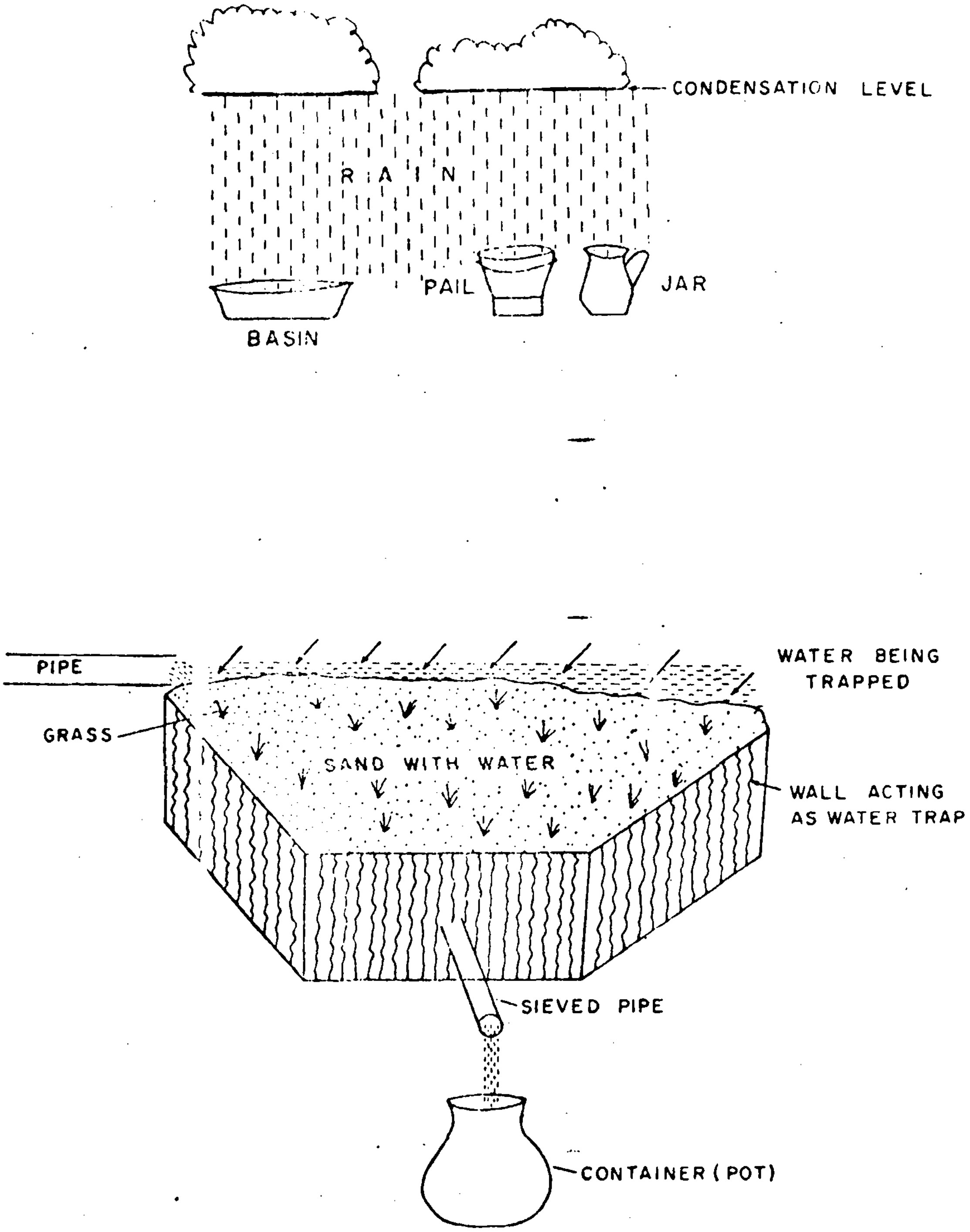


Fig. 22 Stormwater harvesting in parts of Embu District, Kenya.

TABLE 8 DISTRIBUTION OF WATER DAMS IN KILIFI DISTRICT IN COASTAL KENYA

Division	Location	No. of Dams	Total Population	Remarks
NORTHERN	GANZE	15	11,953	It is difficult to estimate the number of people served per each dam. The entire Location has no other source of water apart from the dams indicated.
	VITENGENI	7	10,311	As above.
	BAMBA	15	34,120	As above.
	KAUMA	16	10,450	Part of the population is served by a pipe line.
	SOKOKE	3	5,690	As above.
CENTRAL	JUNJU	5	12,331	Most of the population is served by a pipe line.
	TAKAUNGU	2	13,189	Part of the population is served by a pipe line.
MALINDI	GARASHI	1	7,132	The dam is the only source of water available in the Location.
	ADU	4	3,776	The Location has no other source of water apart from the indicated dams.
	JILORE/ MADUNGUNI	4	7,398	Part of the Location is served by a pipe line.
	GEDE	2	17,128	Most of the population is served by a pipe line.
	CHAKAMA	1	2,228	The Location has no other source of water apart from the dam.
	MARAFA	9	5,371	Part of the population is served by a pipe line.
	MAGARINI	4	24,915	Part of the population is served by a pipe line.
TOTAL		88	165,992	

WATER HARVESTING FROM ROOF CATCHMENTS

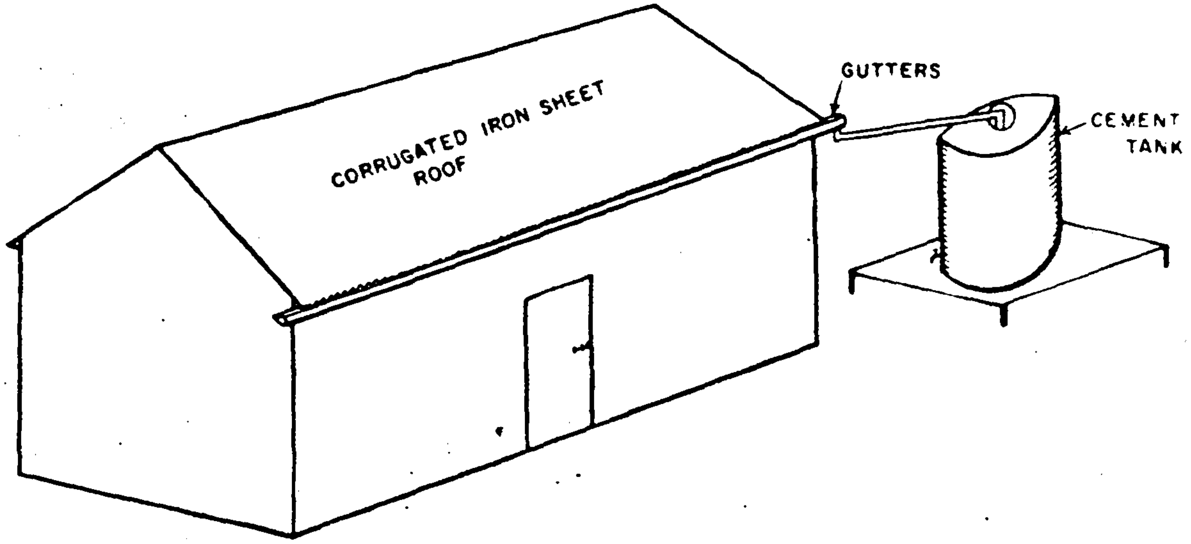
Water harvesting process is a fairly simple processes that involves collection of water from permanent or semi-permanent houses with thatched roofs, or roofs made of tyres or corrugated iron sheets as shown in Figures 23,24, 25 and 26. The process includes collecting water on the roof catchment before it gets into the ground by laying a gutter to the caves of the roof.

The type of roof catchments can vary very widely and their sizes will depend on the size of the houses such as illustrated in Figures 27-34 The collecting tanks range from the brick built ones illustrated in Figures 35-41, the ribbed galvanized iron sheets tanks shown in Figures 42-45 and the stone built such as shown in Figure 46.

It has been shown in parts of Gusii Highlands in Kenya where the storage tanks have a capacity of 5000 litres with an average roof catchment area of 120 m^2 with an annual rainfall of over 1800 mm such as prevailing in the humid and sub-humid parts of African continent with rainfall intensities of about 0.2 mm/minute it will take about 12 hours to fill up such that additional storage tanks as shown in Figure 47 become a necessity.

Such amount of water i.e. 5,000 litres can serve an average family of 6 people in the district (assuming a daily consumption rate of 100-120 litres). for a period of 45 days. Realizing that rainy days are over 150 in such humid areas with such

CORRUGATED IRONSHEET HOUSE PLUS A CEMENTED TANK USED TO HARVEST RAIN WATER



THATCHED HOUSES

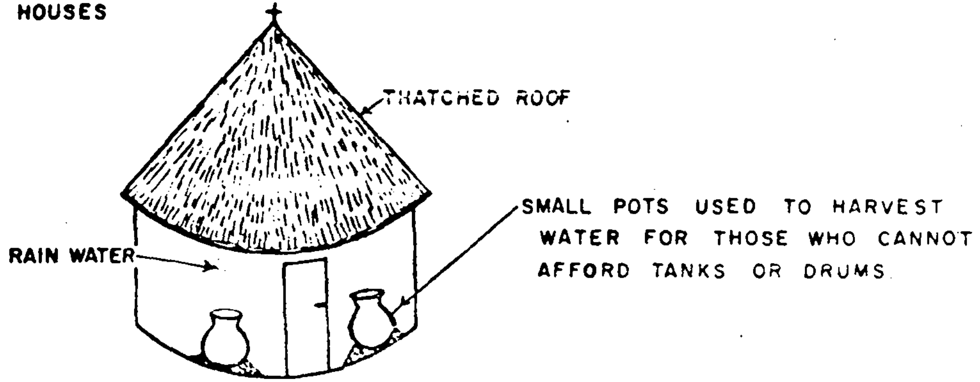


Fig. 23 Rain harvesting from thatched roof with containers (below) and rain harvesting from corrugated iron sheets roof with receiving tank in parts of Buganda, in Uganda.

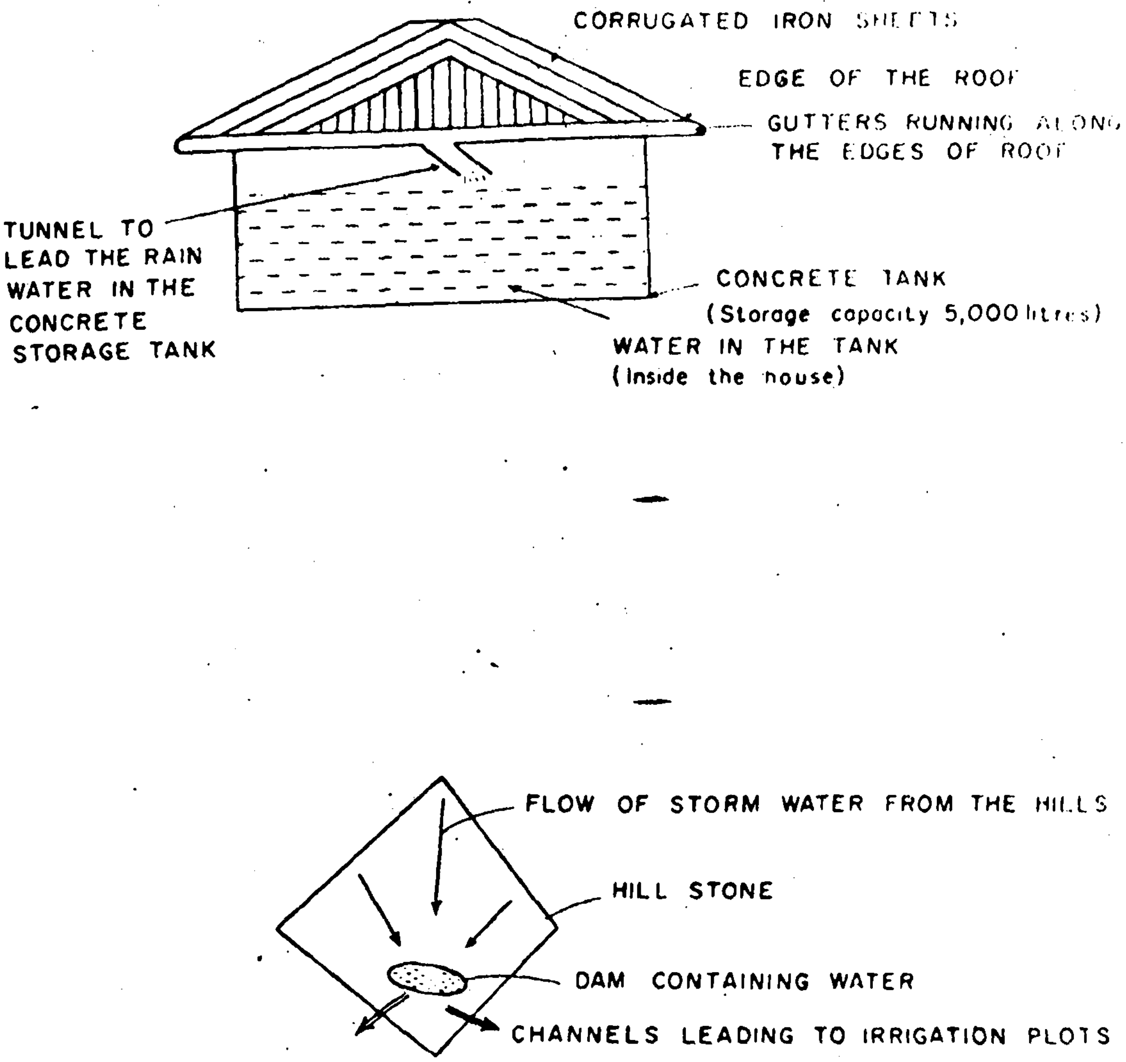


Fig. 24 Rain harvesting from corrugated iron sheet roof (above) and stormwater harvesting in parts of Uluguru, Tanzania.

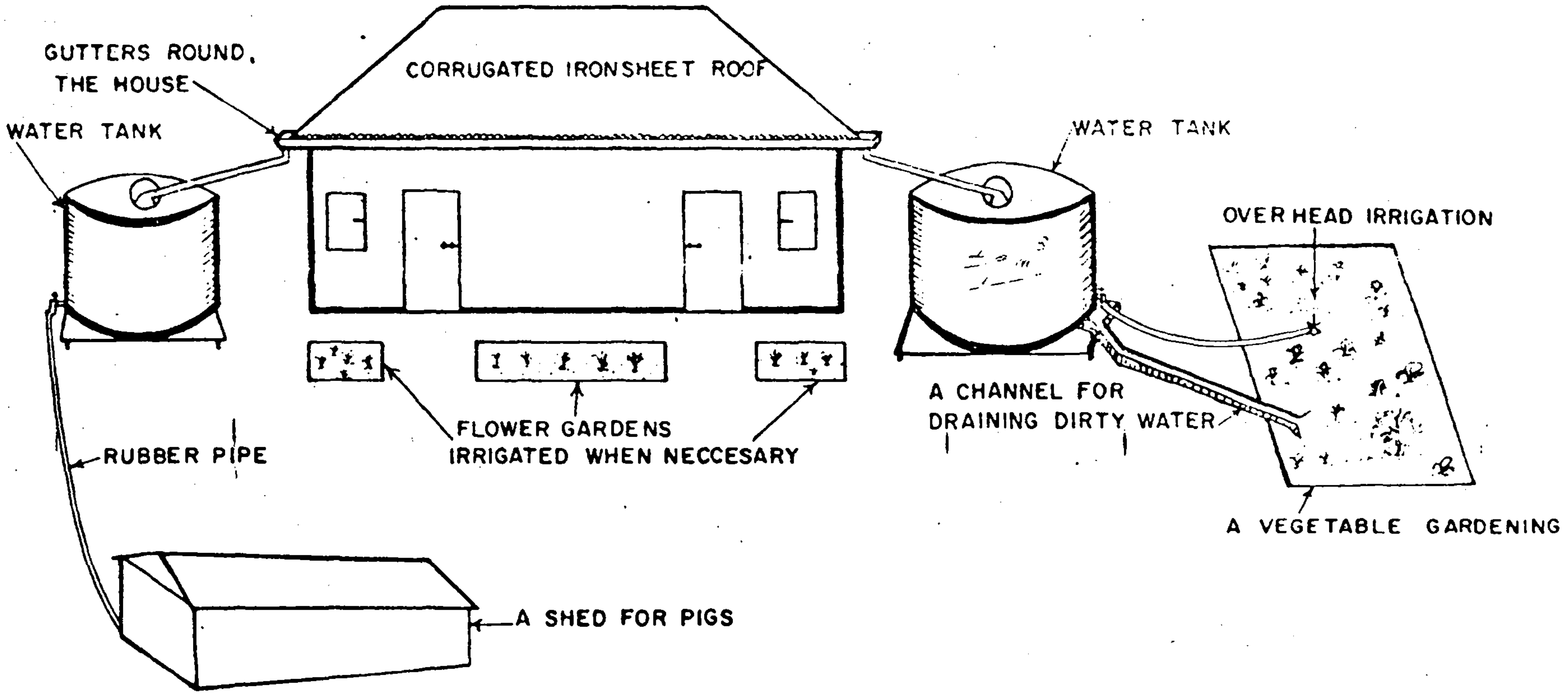


Fig. 25 Rain harvesting for various uses in parts of the Central Highlands of Kenya.

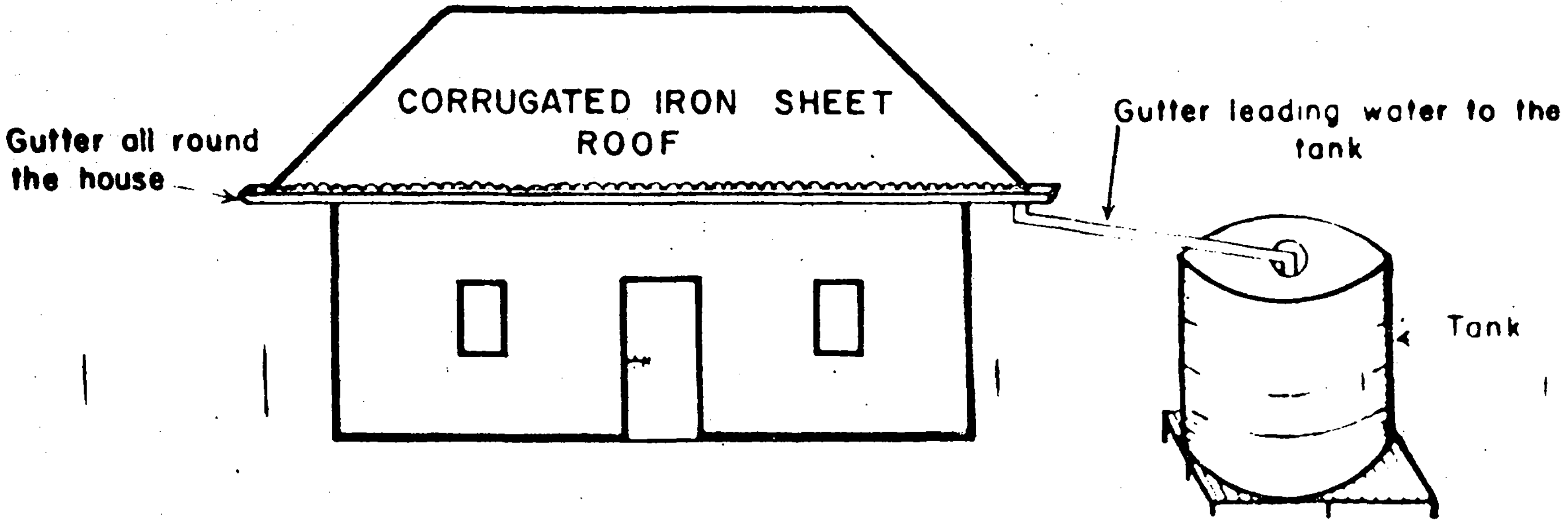


Fig. 26 Rainharvesting from corrugated iron sheet roof in parts of Zambia.

Fig. 27 A permanent house with ptched roof without gable with a gutter for collecting water into a permanent house in Buganda (note that the head of the water in the tank has been sufficiently raised in order to enable water to flow by gravity from the permanet tank into the house).

Fig. 28 A permanent house built of bricks with a tyre roof without gable used for collecting water from the roof into a permanent brick built water tank in Buganda.

Fig. 29 A semi-permanent house with corrugated sheet iron roof without gable is connected to a gutter which collected water into a permanent tank in parts of Gusii District, Kenya.

Fig. 30 A permanent house with corrugated iron roof without gable has a gutter on one side of the roof such that not all the water is collected to the ribbed galvanized iron-sheets tank in Gusii District, Kenya.

Fig. 31 The corrugated iron sheet pitched roof without gable has started rusting such that the water being collected into the tank may be polluted in parts of Zambia.

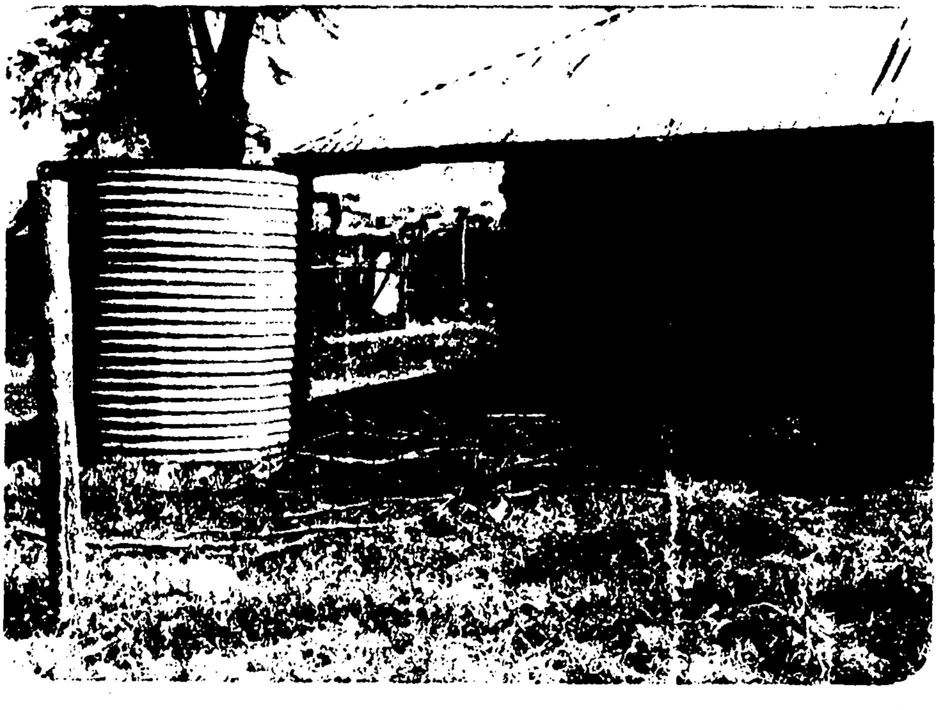


Fig. 32 Semi-permanent house with a corrugated iron sheet pitched roof with a ribbed galvanized iron sheet water tank for collecting water in Lesotho.

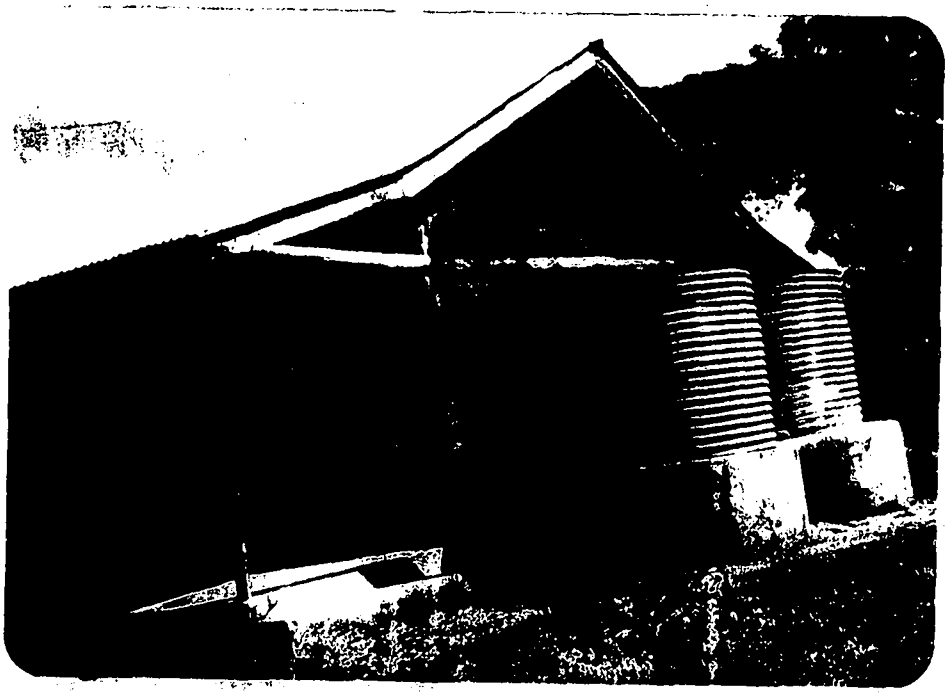


Fig. 33 A permanent house with a corrugated iron sheet pitched roof with gable with two collecting tanks in parts of Central Province of Kenya.

Fig. 34 A permanent primary school house in Gusii District, Kenya with a corrugated iron sheet pitched roof with gable with gutters collecting water from both sides of the roof into a brick tank.

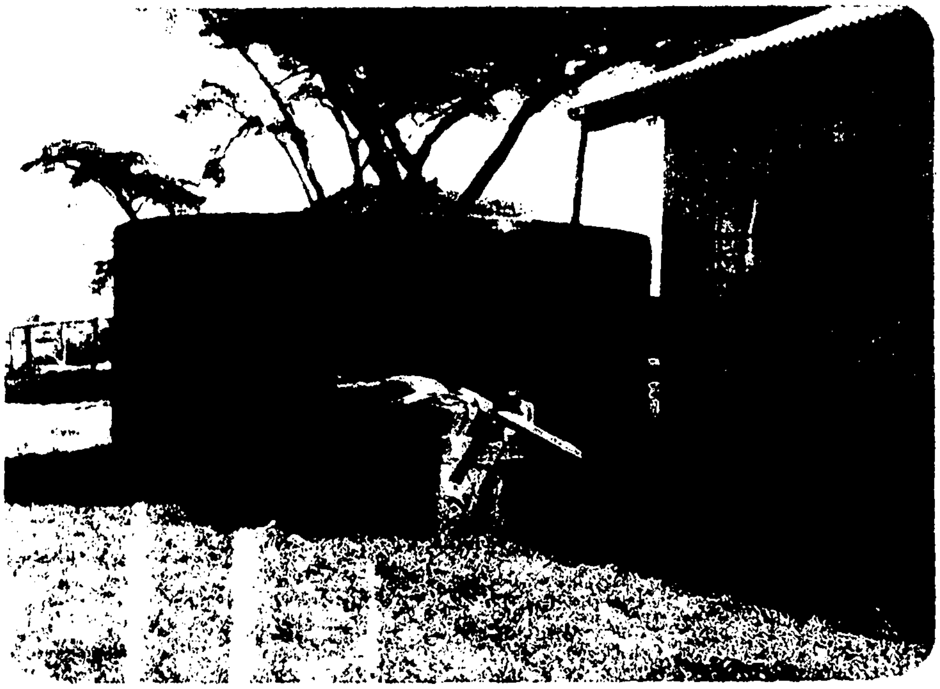


Fig. 35 A brick built tank with one pipe leading water from the gutter connected to the roof in parts of Nyeri, Kenya.

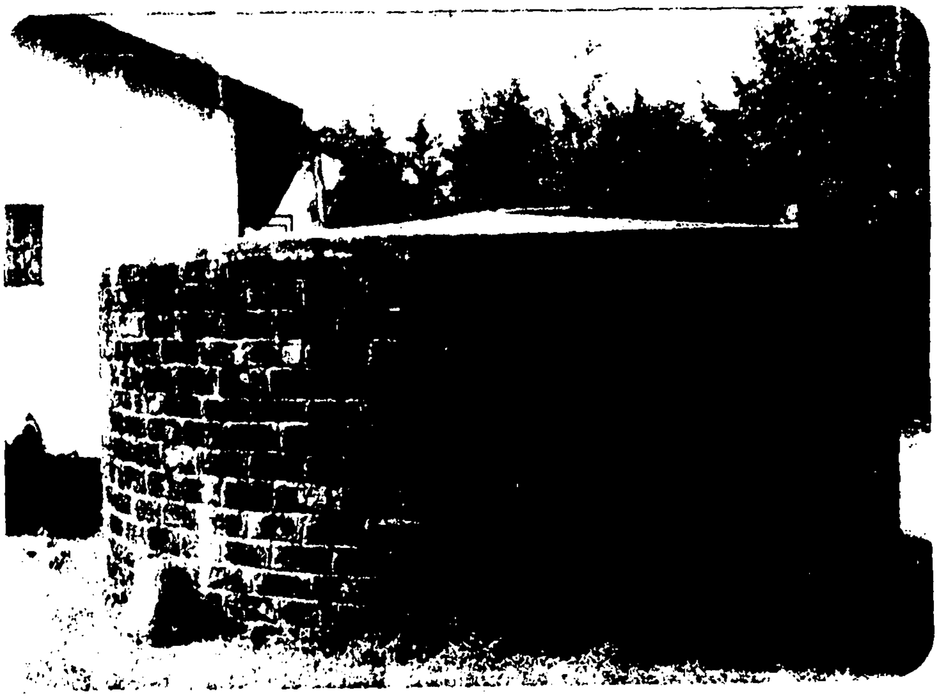


Fig. 36 A brick built tank is well sealed at the top in order not to let in any dust or pollutants in Nyeri, Kenya.

Fig. 37 A brick built tank is used for storing water collected from a tyre roofed house in parts of Uganda.

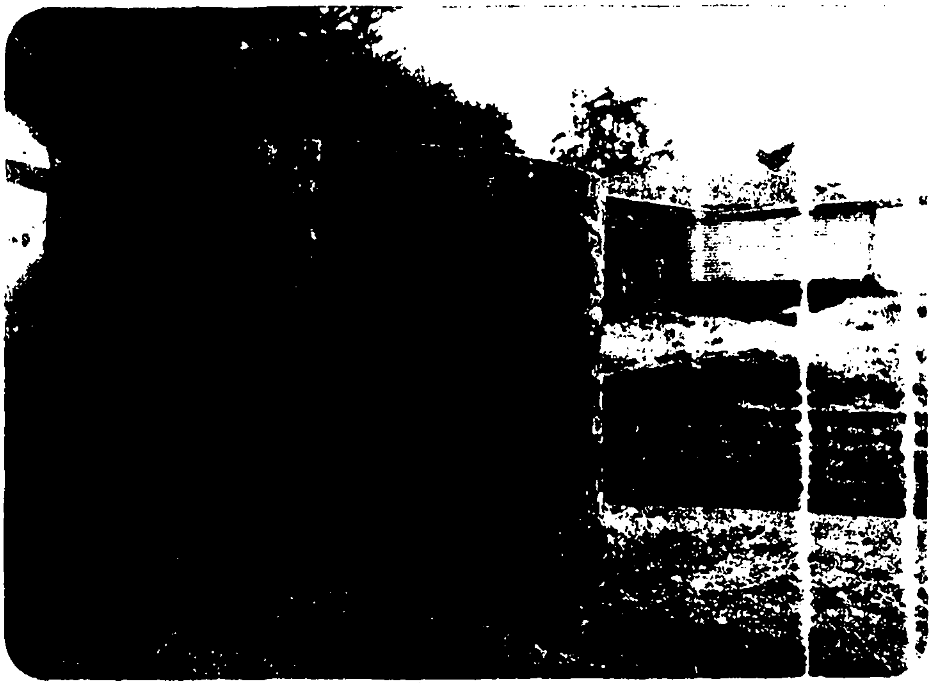


Fig. 38 A brick built large tank is used in collecting water from two nearby houses in Uganda.

Fig. 39 The pipes leading water to the brick built tank are not protected against possible dust in the school in Gusii District in Kenya.

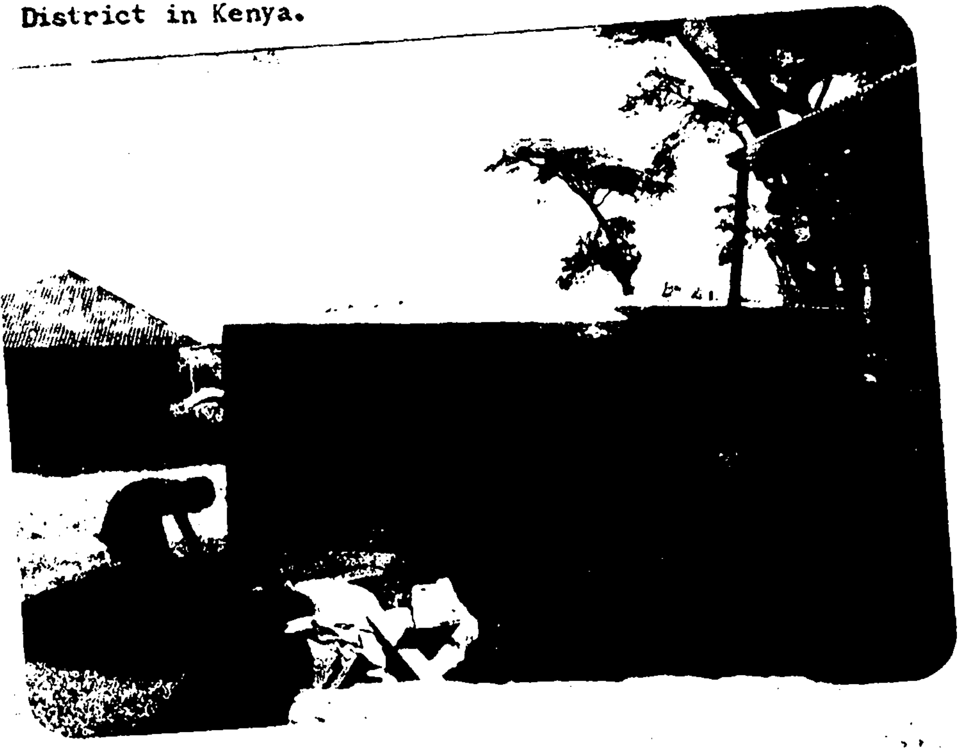


Fig. 40 Water is collected from a water tap connected to the brick storage tank in parts of Nyeri, Kenya.

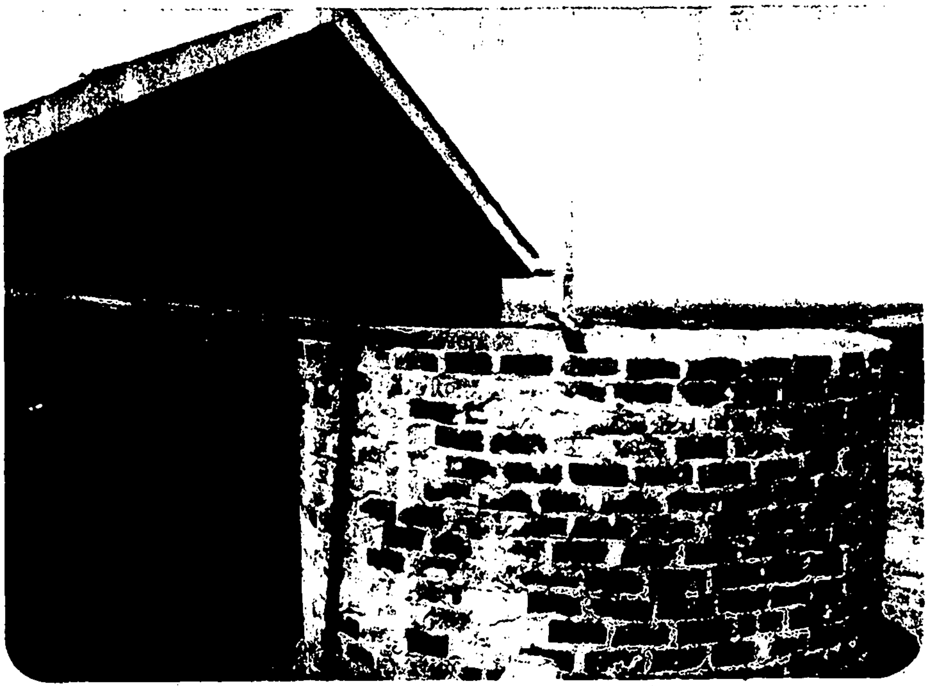


Fig. 41 The brick built tank is not sealed at the top such that dust and other impurities could easily get into the stored water in this primary school in Gusii District, Kenya.

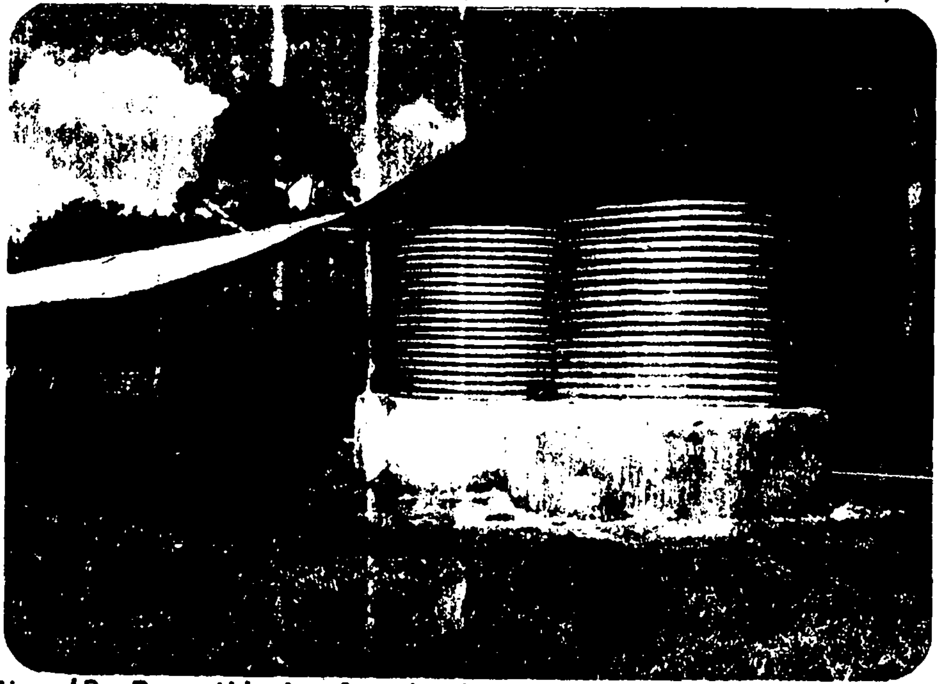


Fig. 42 Two ribbed galvanized iron sheets tanks used for collecting water from two different houses in parts of Zambia. This enables a greater quantity of water to be stored during heavy rains.

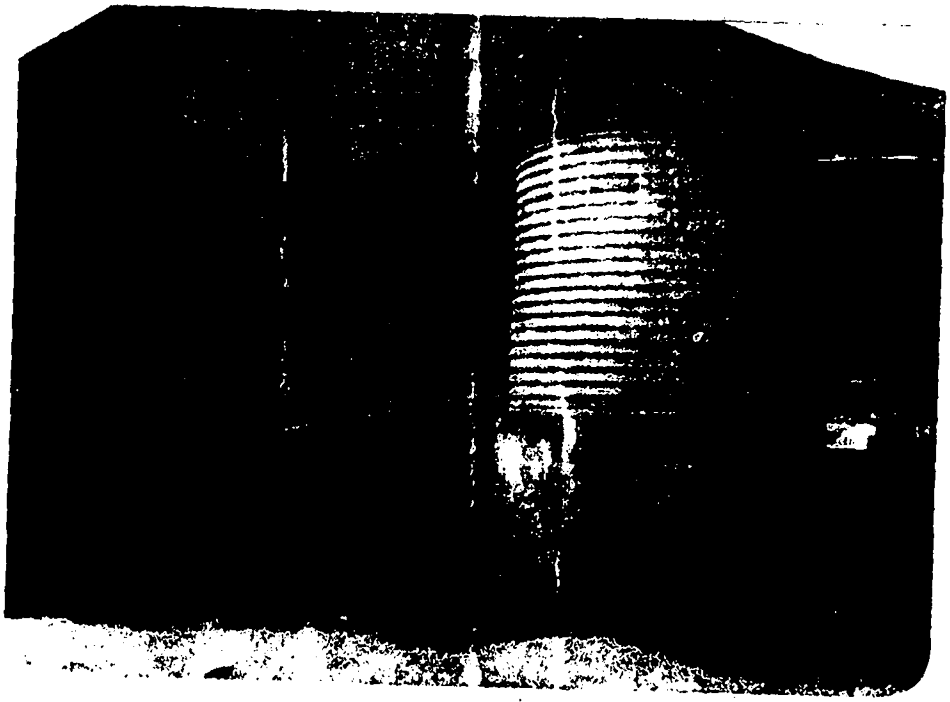


Fig. 43 A concrete base has been built in order to raise the head of the water in parts of Gusii Highlands in Kenya.

Fig. 44 Water tank is placed on a concrete base in order to protect the tank against possible rusting in Gusii Highlands in Kenya.

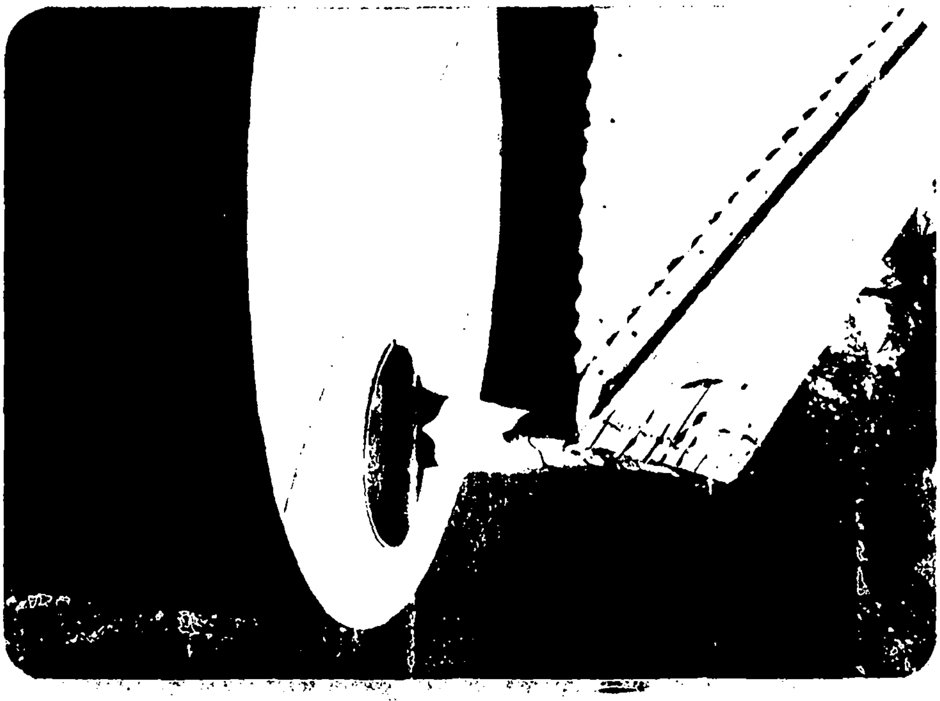


Fig. 45 A galvanized mesh of wire gauze.acts as a seive which does not allow certain sizes of physical impurities to get into the tank in parts of Gusii Highlands, Kenya.

Fig. 46 A stone built tank is used for storing water and the water pumped by a hand pump for household uses in parts of Uganda.

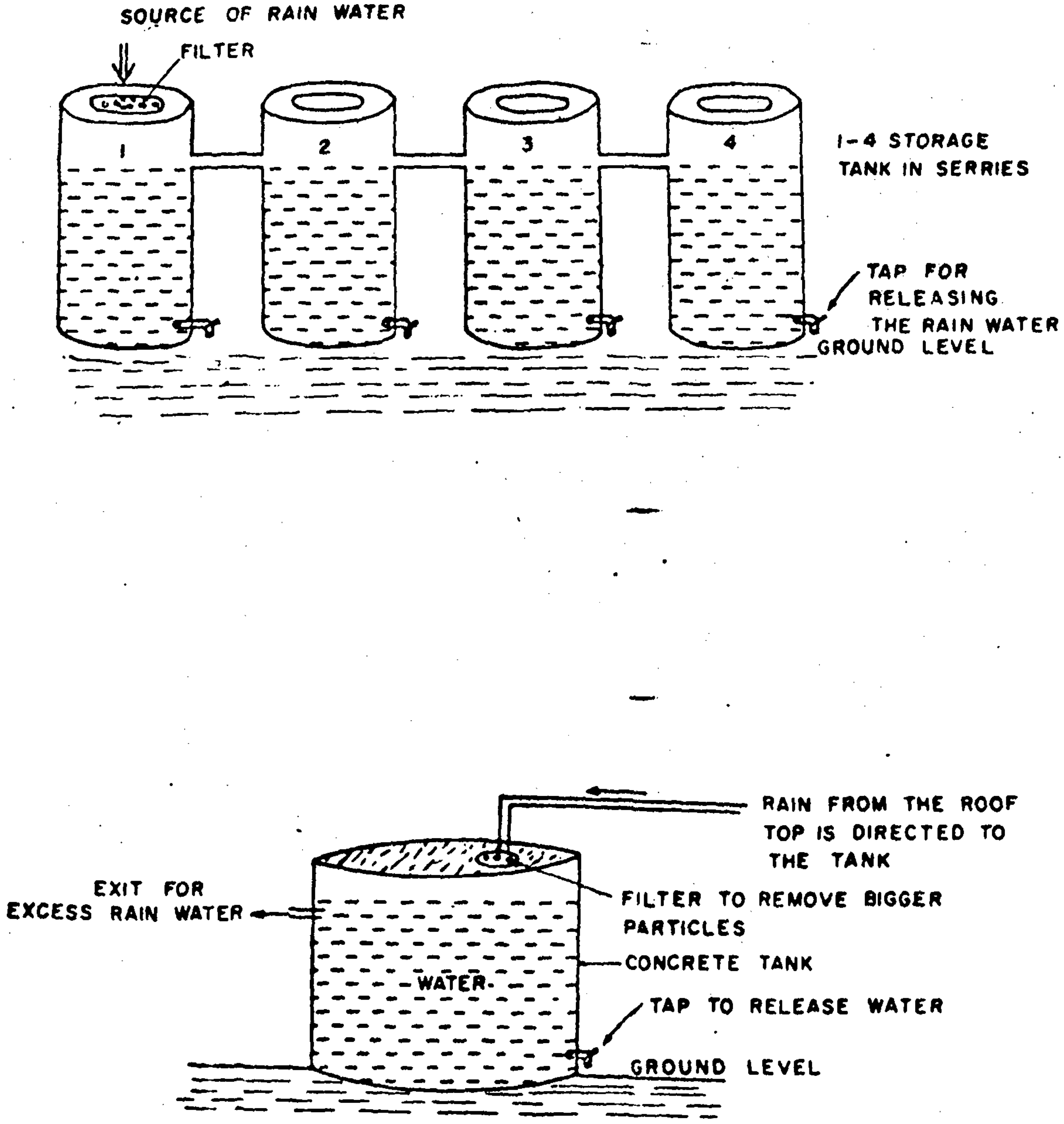


Fig. 47 Additional water storage tanks for storing water during heavy rainfall periods in parts of Gusii Highlands, Kenya.

a consumption/ there is bound to be surplus water throughout the year /rate round. At present for example there are close to 10,000 people in Gusii District benefiting from rain harvesting from roof catchment. Close figures of population have been reported in various parts of Tanzania, Uganda, Zambia, Lesotho, Ethiopia, Nigeria, Ghana and Botswana.

By application of small scale technology and proper layout of storage tanks as illustrated in Figure 48 a lot of water can be harvested and can be used for domestic and sanitary uses within a household. This water can also be collected on a small scale using containers shown in Figure 49 .

This will therefore provide readily available water thus saving the rural people who often have to fetch untreated water from streams valuable time of drawing water from long distances. This will also make people concentrate on other economic activities and will uplift the general health of the people by giving them clean water. This will mean a better healthy environment and will minimize water related diseases within the population including their livestock.

This particular system will also lessen the amount of surface runoff with consequent reduction in accelerated soil erosion which will ensure clear and clean water within stream systems with low turbidity. The system is particularly appropriate and necessary as the water catchment areas continue to diminish due to human interference.

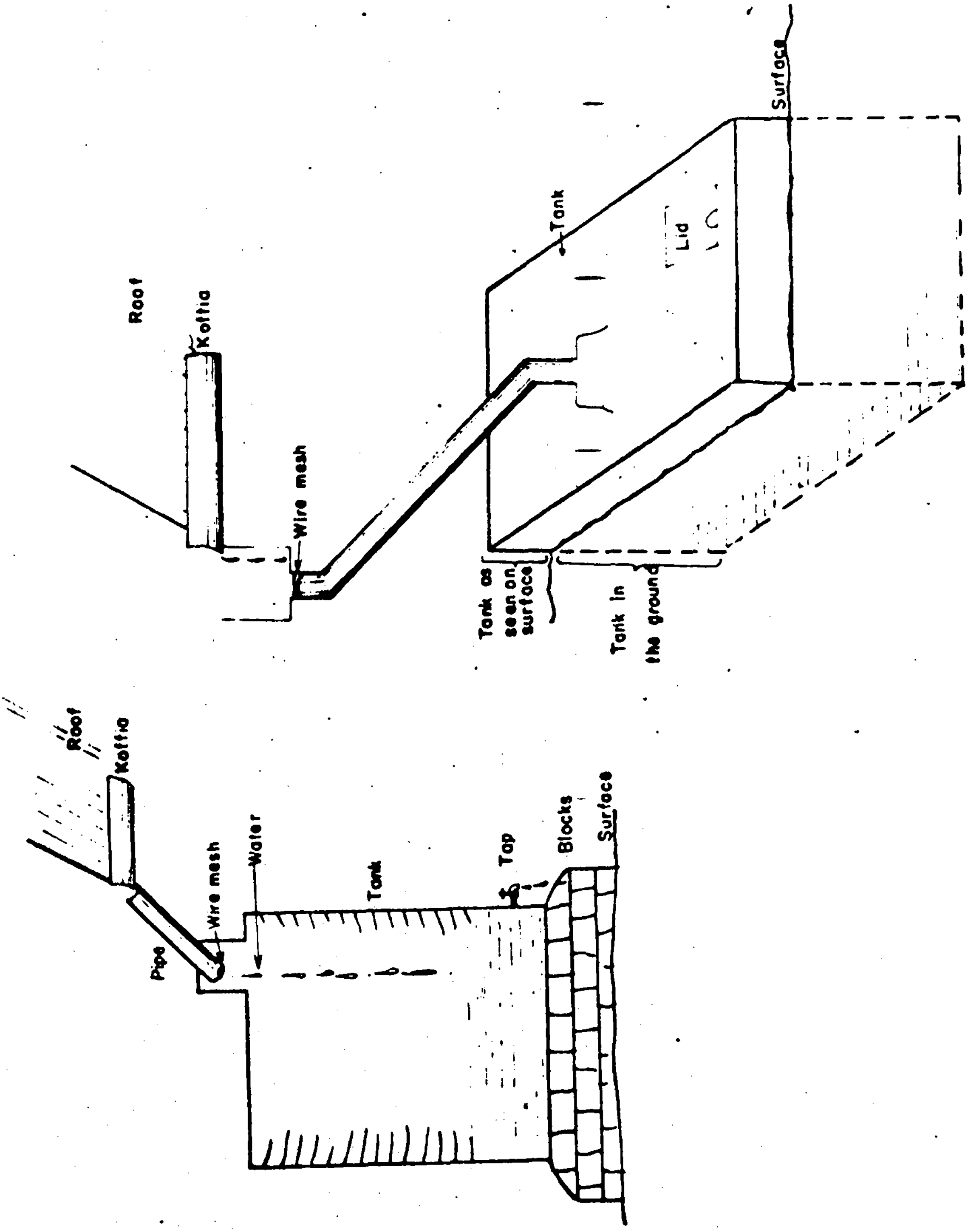


Fig. 48 Layout of storage tanks for water harvesting in parts of Botswana

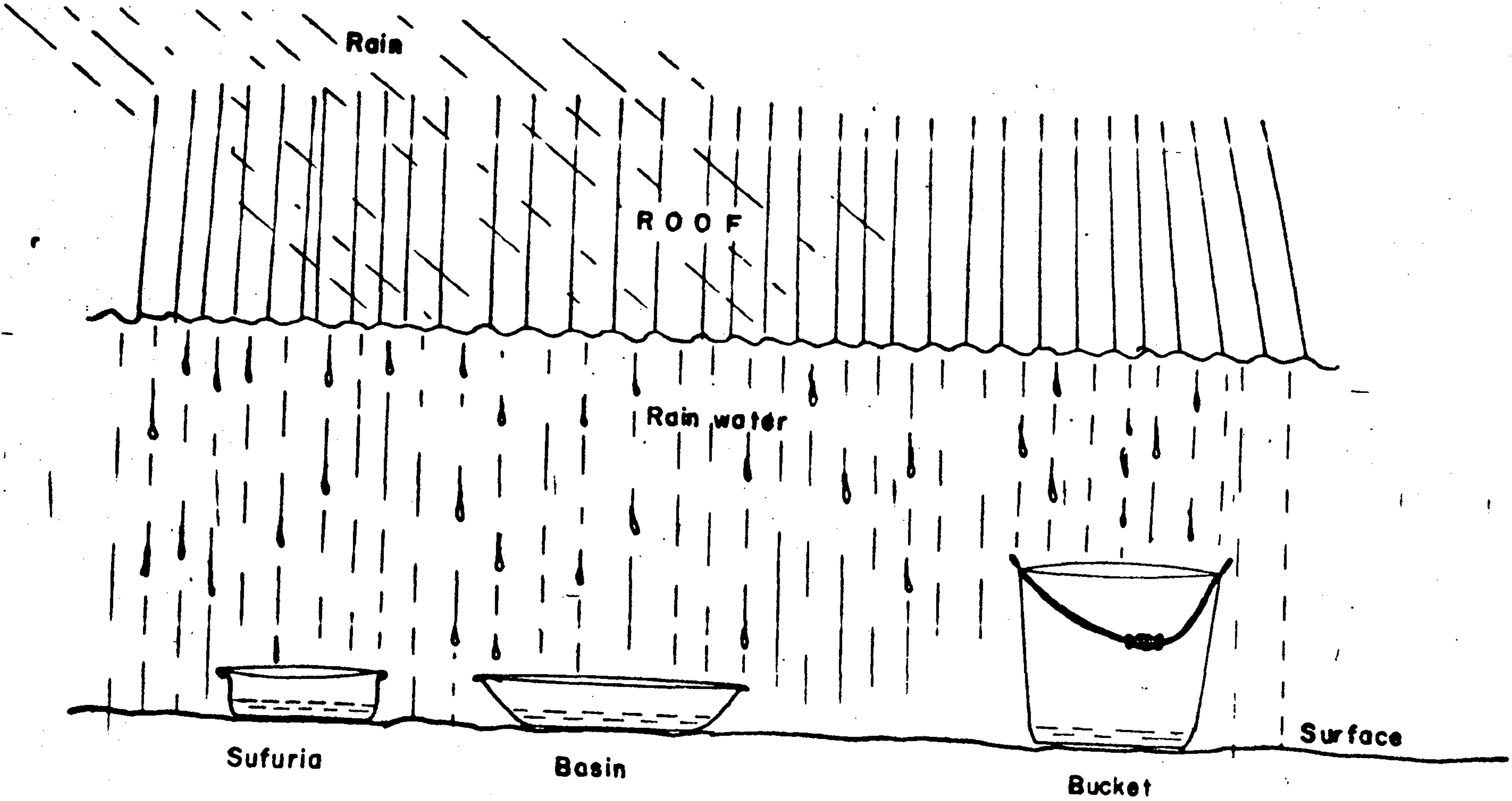


Fig. 49 Some of the containers for collecting water in parts of East Africa

OTHER SOURCES FOR WATER HARVESTING

When one considers the water resources of Africa, the mind turns initially to thoughts of rivers, lakes and boreholes, and then perhaps to rock or artificial catchments for rain such as pans, and to desalination, cloud seeding and suchlike, some of which have been discussed earlier in this paper.

It is perhaps because most people in well-watered and hospitable climates are used to having water available in terms of tens of gallons rather than single pints, that one does not realise how much the reliable provision of just a few cupfulls of water a day can contribute to the life of an inhabitant of a dry area. For man in arid and semi-arid areas, rivers and lakes are few and far between, and the other sources require a combination of technical knowledge, money and incentive to make them work. It is the intention of this section to look at less well known sources of water and the methods which could be used by those living in arid areas to exploit them.

It is rarely considered that there is a large reservoir of water in the form of water vapour. As an example, taking recorded meteorological data, typical relative humidity at Wajir in north-eastern Kenya at 9.00 East African Time is 75% and the average dry bulb temperature at the same time is 25°C. Then at an atmospheric pressure of 990 millibars, the air over Wajir contains about 15 grams of water per Kg of air, or nearly 18 grams per m^3. Assuming that the kilometre of air near the ground is well mixed and contains the same proportion of water throughout, it can be concluded that in one cubic kilometre of air over Wajir there is about 16 million litres of water. The assumptions involved are generous, but it gives an idea of the potential of such a source, and the figures are typical of Kenya's arid area.

The problem is how to realise this potential. One could not expect to remove anything more than a fraction of one percent of this water, but even that would yield something like a thousand litres per square kilometre a day.

It should not be forgotten that the soil, though by outward appearance dry, contains large amounts of water within the soil pores. Monteith (1956) gives a diagram showing that a dry sand, no longer able to support vegetation, nevertheless contains 2½% by weight of water, equivalent to about 50 litres in a cubic metre of 'dry' soil. The hygroscopic properties of some soils are well known, and as an example he reports that Ramdas and Katti found the moisture content in the surface layer of an Indian 'black cotton soil' increased from 2.6% to 7.7% of dry weight by absorption overnight. Unfortunately, a soil dry enough to absorb moisture from the atmosphere is rarely wet enough to yield it to plant roots. However, Halacy (1966) describes experiments conducted in Japan and frequently repeated elsewhere, in which plastic sheets or miniature glass houses have been used to distill this water out of the ground and condense it in a container. About a litre of water a day can be collected from a square metre of ground in this way. The principle of operation is similar to the solar still, but one does not need even a brackish supply of water as a raw material. The soil moisture is replenished constantly by diffusion from deeper layers of soil and by absorption of atmospheric moisture.

A great deal has been written about dew as a source of water. Review papers by Milthorpe (1960) and Stone (1957) show the degree of controversy that exists between experts, many of whom express diametrically opposed views.

Entusiastic, and rather subjective investigations by Hubbard and Hubbard (1905) asserted that "There is still in England at least one wandering gang of men...who will construct for the modern farmer a (dew) pond which, in any situation will always contain water, more in the heat of summer than during the winter rains". However, Martin (1910) three year investigation into dew-ponds gave almost conclusive proof that the ponds were replenished more by mist and fog than by dew. Many writers have since indicated that the maximum theoretical deposit of dew in a single 10 hour night, computed from energy considerations, is of the order of 0.8 mm, certainly not enough to replenish a 'dew-pond'.

More recent investigations into dew have verified this maximum figure experimentally. The measurement of dew is difficult, and artificial dew gauges so far devised cannot properly imitate the physical characteristics of natural collectors such as plants and rock. Also, it is difficult to distinguish between dew formed from truly atmospheric moisture, dew formed by distillation of soil moisture, and guttation, the moisture exuded by plants into their leaves.

There are many cited examples, though few are backed up by quantitative measurements, of plants being grown by reliance on dew. Went (1955) suggests that in California, tomatoes are grown in an area where no rain falls during the growing season. On

Lanzarote in the Canary Isles, the writer has seen small depressions a metre or so across, lined with black volcanic pebbles said to condense dew which then trickles to a solitary onion plant in the middle. Grape vines are said to suffer less from drought than normal when grown on rocky slopes; near Amman, tomatoes are said to be grown almost entirely on dew, and it has been claimed that the spreading thorn tree, by its shade, derives from the atmosphere enough moisture to survive. Gilbert White (1906) mentions that some dew-ponds are overhung with 'two moderate beeches that doubtless afford it much supply', Milne and Milne (1964) describe how, on a clear starry night, they stood under a tropical raintree in Trinidad and became soaked by the drips from the leaves. Whether this last experience was the result of condensation dew or guttation they were unable to tell, but at least it gave rise to a thick carpet of grass under the tree, whereas that exposed away from the tree was thin and dry.

Arvidsson and Hellstrom (1955) working in Sweden and Egypt have indicated that dew could provide water in useable amounts. They constructed large funnels of various materials, supported about 1 m above the ground. Dew was collected on them on about a third of the nights on which the apparatus was exposed, cloud cover preventing radiation and the subsequent cooling necessary for dew formation on the other nights. Dew collected on the inside and outside of a wooden funnel with a plan area of one square metre gave a maximum collection on one night of 0.4 litre.

Meteorological data for many parts of Africa is sparse and gives little indication as to when and where dew can be expected to form. However, observant persons will have noticed the row of drips frequently found under the eaves of buildings in many parts of the country in the early morning, even in warm dry weather. A medium grade house with a plan roof area of 29 m^2, would, applying the above average figures, collect 320 litres of dew-water a year. This may seem a small amount compared with the amount of rainwater normally collected, but might be a significant amount at the end of a long dry period. It is surprising to note how many buildings in humid and sub-humid Africa, and even in dry areas, do not have gutters and a storage tank.

Monteith (1957) conducted a series on careful experiments on dew on a playing field in England. Though the environment in which his experiments were conducted was very different from that of many parts of Africa he did verify one fact that is often mentioned, that is the necessity of a light wind. In order to condense the moisture present in the atmosphere as dew, it must be brought into contact with the condensing surface; a light wind speed, i.e., 2-3 m/sec. will stir up the 100 metres or more of air nearest the gr ground and bring most of it into contact with the condensing surface. A stronger wind, over 5 m/sec. always resulted in net evaporation. Anon (1961) and Deacon et.al (1958) have reviewed the possibility of choosing areas with significant amounts of dew for planting crops which can use it effectively and to enhance its formation in places where there is none at present. Went (1955) has suggested that rows of trees be planted in suitable locations to reduce wind speed to that required for dew formation. Though we know that the maximum dew precipitation is small, various writers have referred to the capability of plants to 'attract' dew. It is suggested by Slatyer and McIlroy (1961) that plants might concentrate the precipitation of dew, but only at the expense of surrounding areas. Certainly, if an artificial dew collector could do this as effectively as the tropical rain trees in Africa appears to have done, then there may well be scope for developing this source. A vast amount of data collection and investigation on dew has been done by Duvdenani et.al (1957) in Israel with particular emphasis on the part it plays in arid land agriculture. They are convinced that dew absorbed through the leaves of plants plays an important part in maintaining plants through periods of drought.

Gindell (1973) descrives how pine, tamarisk and eucalyptus seedlings were planted in the Judean Hills. Near each plant was arranged a plastic sheet, 1.3 m^2 in area. The dew collected on the sheet was led to the plant pit.

Saplings planted in heat and drought conditions unsatisfactory for survival nevertheless survived until the rains four months later, while those without the dew supply dried up and died within a month. The plastic sheet may also have had a significant effect in preserving soil moisture from evaporation.

Dew has often been credited with providing large quantities of water which have actually been the result of interception of mist and fog. In this case, the moisture is already condensed, but is in the form of small droplets floating about in the air, too small to fall to the ground. Martin (1910) acknowledges the role of mist interception as a source for his dew-ponds, and it is likely that some of the instances of plant survival mentioned above owe more to this than to direct condensation of dew.

The significance of mist and fog interception was noted by Hursh and Pereira (1970) when considering the water economy of the Shimba Hills, in Kenya and in Japan, have noted the significance of mist and fog interception and have related this special fog to prevention forests or belts of trees which have been planted for the specific purpose of straining moisture out of the fog. Similar work has been carried out by Hori (1953) and Kashiyama (1956).

This process has been used for many years by the people inhabiting the escarpment facing the moist south-easterly winds near Kitui, and in other parts of Kenya. A tree is chosen, such as a gum tree, which has its branches pointing upwards away from the stem (see Fig. 50). A rope coiled around the stem with its loose lower end resting in a bucket, can collect a bucketful of water which originates from mist and fog interception in the upper branches. Some work on this subject was done at the EAAFRO station at Muguga, Anon. (1961). Fog catching guages there showed in preliminary trials up to three times as much water was caught in them as in a standard rain guage.

Nagel (1956, 1962) investigated mist and fog interception on Table Mountain and along the coast of South West Africa. Table Mountain has an almost permanent covering of cloud, nick-named the Tablecloth. Nagel set up rain guages, some of which had fog catchers mounted above them. The fot catcher consisted of a gauze cylinder with its axis set vertically above the axis of the rain guage. His results showed fog interception over a year to be

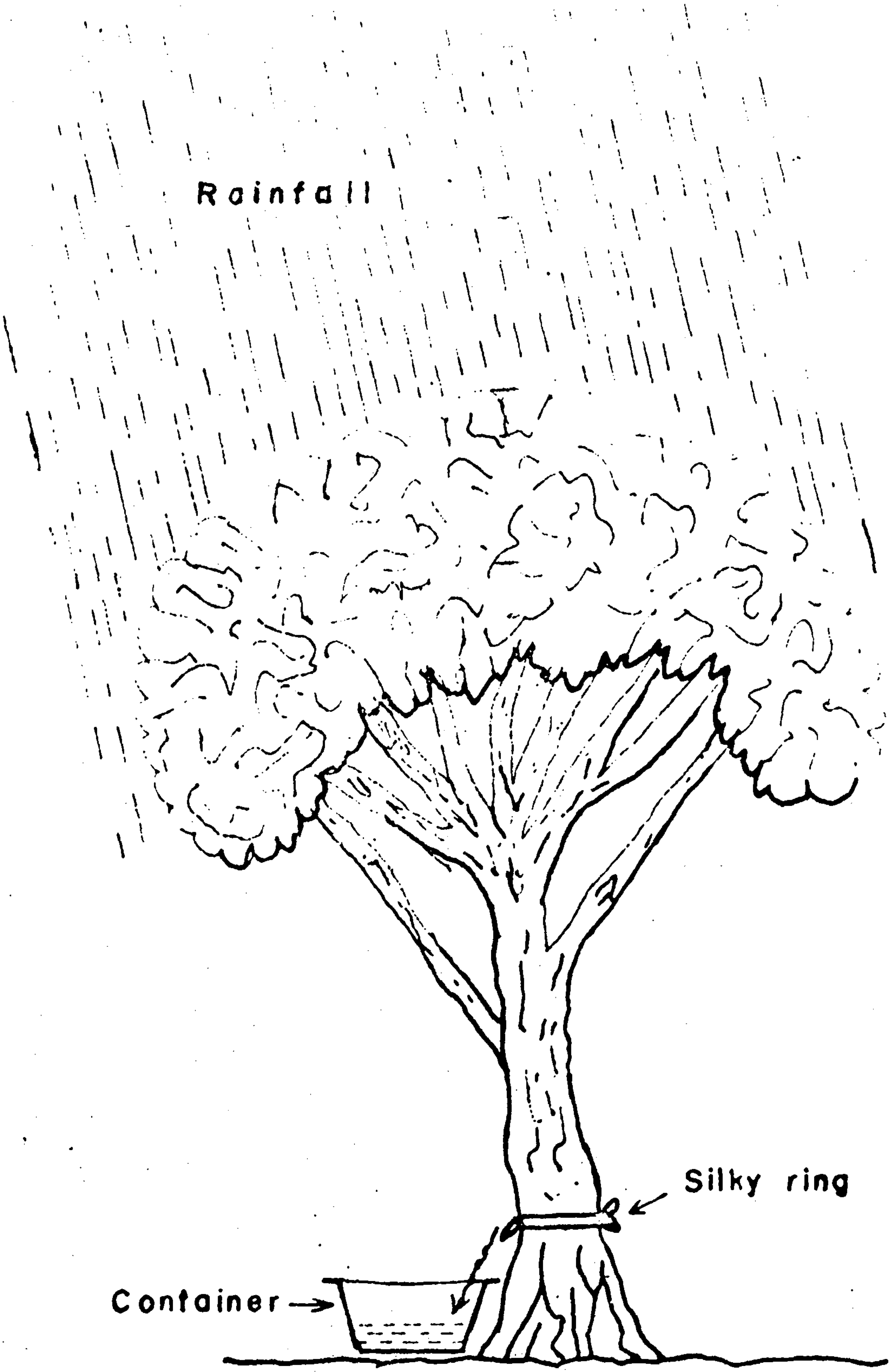


Fig. 50 Water Harvesting from trees in parts of East Africa.

equivalent to 3,294 mm of rain, compared to actual rainfall over the same period of 1940 mm. On theoretical grounds, he concluded that the amount of water available in the fog was about 12 times that actually intercepted. Further experiments gave similar results in other locations. One surprising result was that the amount collected by a flat gauze screen mounted on a lorry and driven through the fog at different speeds did not vary very much with the speed. The results of such experiments are often complicated by the fog catcher's ability to intercept rain, drizzle and dew as well.

Twomey (1957) in similar experiments in Tasmania, found that a section of flat mesh 36 inches high and set vertically above an eight inch rain guage yielded about ten times more water than a rain guage without mesh. Taking the water content of cloud to be 1 gm/m^3, he points out that with a light wind of only 4 m/sec. this represents a potential catch of 14 litres of water per hour passing horizontally through a square metre. Nagel quotes a measured wind speed of 13 km/sec. for Table Mountain, which could theoretically yield nearly 47 litres per hour. Twomey's mesh was of steel wire with 3.2 mm per apperture. Nagel's mesh was finer, with 1.6 mm per apperture and was similar to mosquito wire, a cheap and readily available material throughout the tropics. Some work to test different types of fog catcher was done in Hawaii, and is described by Ekern (1964).

A simple method of catching mist to promote the germination of seeds is to put a stake in the ground next to the seed. The stake will intercept mist and other precipitation, and guide it down to the seed. Kerfoot (1968) gives an extensive review of work on this topic which leaves little doubt as to its potential.

It seems that the ancients had similar ideas. Jumikis (1965) reports extensively on the discovery of rock mounds on hilltops in Theodosia (Crimea). These mounds, over two thousand years old, were 30 m in length, 25 m wide and 10 m high, and were connected with tile pipes to the coastal town. Appropriately known as aerial wells, they have counterparts in many places. Jumikis mentions the fogaras of Tunisia, and the rotaras of Morocco, and references in his and many other writers' work to the teleilat of Israel are common. Unfortunately, information on how they may have worked is hard to come by. Evenari, Shana and Tadmor (1971), after extensive investigations, concluded that the teleilat or stonemounds found on hillsides in the Negev desert had nothing to do with dew at all. Their observations failed to show any significant deposition of dew on the mounds, certainly not enough to cause the water to drip off and wet the ground underneath. Apparently the name 'toleilat el einab' (translated from the Arabic as 'the hillocks for grape vines') is a mis-nomer based on wishful thinking, similar to the English dew-ponds which don't catch dew. They advance the theory that the mounds are the result of stone clearing from the rocky slopes, for the purpose of increasing run-off into the valleys where most of the fertile soil is to be found. Their rather surprising conclusion was that shallow slopes of about 10%, split into small plots of about 10 ha. and cleared of stones gave the best yield of run-off water which was then stored in cisterns for irrigation in the valleys. Steeper slopes gave less run-off; doubling the area less than doubled the run-off, and the clearing of stones did not cause significant problems of soil erosion. The idea therefore was to prevent rain water from infiltrating and to encourage it to flow quickly to collecting channels.

been discussed by Obeng et.al (1969) and these should be monitored before, during and after construction of these man-made lakes.

Water harvesting from roof catchments has been practised for many years in various African countries, however, on a very small scale. The construction of houses with permanent and suitable roof catchments has an added advantage in that one draws good quality water ready for use. In these respect no water maintenance costs are involved nor are the rural people supposed to pay for the water which they have collected from their own houses. It would be much easier and cheaper to organize people in the rural area in self help groups for purposes of building the appropriate structures and the storage tanks. These would work on the line of the successful Harambee Water Projects quite common in parts of Kenya. This method would provide more than adequate water for people in the humid and sub-humid parts of Africa with little economic constraints. It will also raise the standard of living of the people by providing good housing facilities. It will also minimize surface runoff and other related environmental hazards such as erosion, sedimentation and flooding.

Other water harvesting methods such as dew, fog and mist although favoured in certain countries are very tidious and time consuming and can only collect very limited amount of water.

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As for the Theodosian aerial wells, whether it was fog interception, dew formation, direct run-off or some hygroscopic quality of the rock resulting in what Jumikis and Tropical Agriculture Anon (1935) call 'Dehydration of air', that was primarily responsible for the water that flowed down the tile pipes is a question yet to be satisfactorily answered.

CONCLUSIONS AND RECOMMENDATIONS

In this paper three major methods of storm and rainwater harvesting have been discussed. The methods discussed are simple to apply. It is apparent that stormwater harvesting from dams, reservoirs, haffirs or man-made lakes are appropriate in areas of great surface runoff with little vegetation cover which would be quite appropriate in sub-humid and semi-arid parts of Africa (see Figs. 6,7, and 8). The major constraints here would be turbidity of the water and water related diseases and evaporation from open (surface) water bodies. In such situations it may be advisable to construct underground water storage structures such as discussed earlier in this paper. In these areas water as shown by Economic Commission of Africa (1977) alternative sources of water are scarce or absent such that this water harvesting scheme should be expoited further in order to meet the challenge of providing water to the rural people by the year 2000. This scheme is inexpensive in terms of maintenance and construction when thinking in terms of piped water from streams or large reservoirs. In this respect a number of multipurpose dams have been constructed in Africa. These should be fully utilized as they are one means of harvesting and storing water in the continent. These environmental problems have

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