INSTITUTE OF HYDROLOGY

KISHI WATER SUPPLY

HYDROLOGICAL STUDIES

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SUMMARY

This report presents our hydrological analysis of the catchments of the Soro river upstream of the proposed reservoir site. The reservoir is intended to supply the towns of Kishi, Igbetti and Igboho and is sited near a bridge on the Igbetti to Kishi road. The site is shown in Figure 1.

Our analysis has been based on the runoff data for the Ogun and Ofiki rivers; we have assumed that the headwater catchments of these rivers can be considered analagous to the ungauged Soro catchment.

We have used some results from previous work on the Ogun and Ofiki[1,2], but there are some important differences between the smaller headwater catchments considered here and the much larger, downstream catchments that were studied previously. A mathematical model to relate rainfall and runoff has been derived for the Ofiki catchment to Ofiki Town. This model is assumed to be applicable to the Soro catchment. A runoff record has been synthesised using the model and a representative record of long-term rainfall.

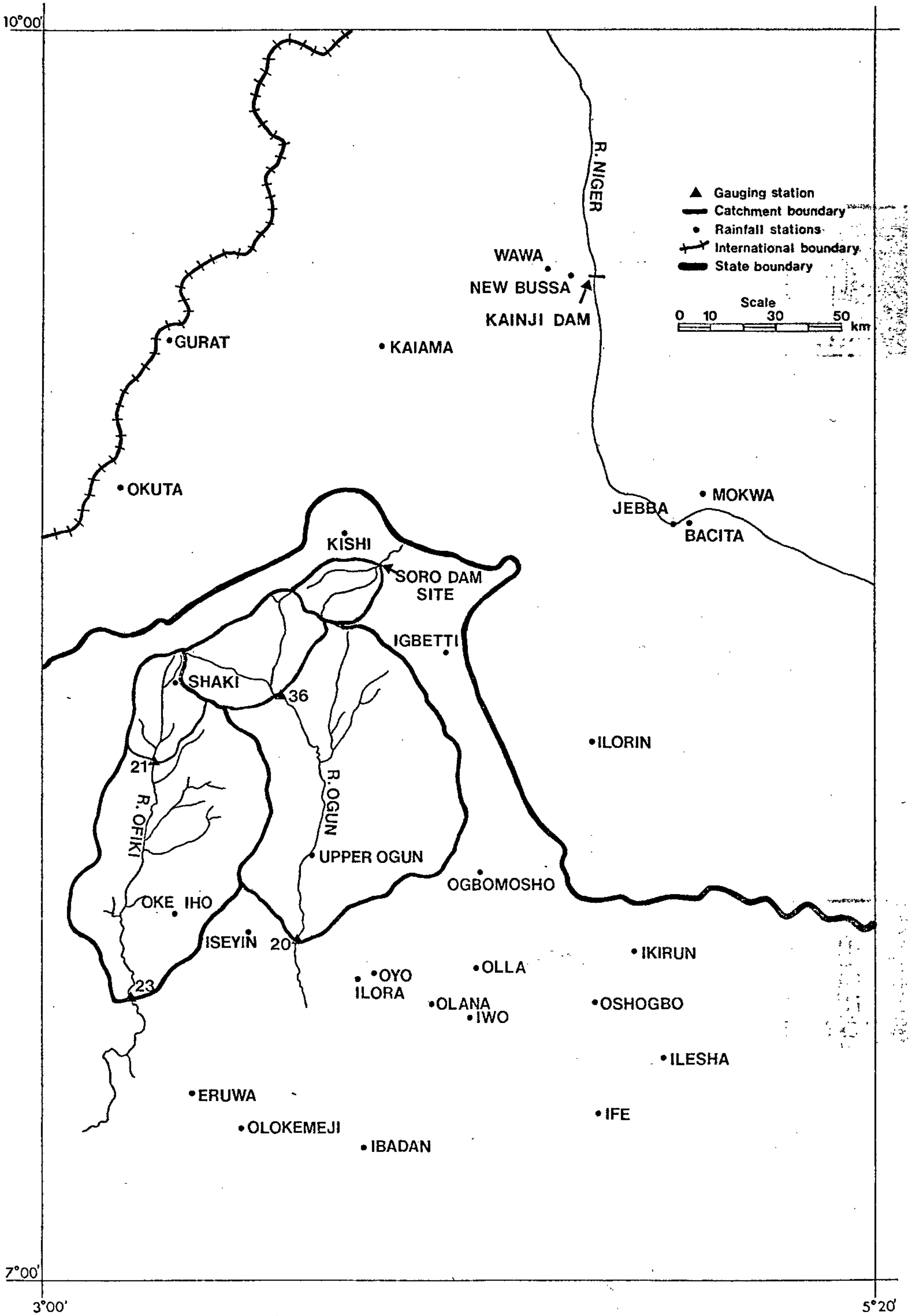
A reservoir operation program that takes account of demand, losses to evaporation, and spill was used to estimate the reliable yield of the proposed reservoir. For a number of reservoir sizes and demand rates, the proportion of time for which the demand could not be met was determined. The results are summarised in Table 10.

The analysis of floods has been based on an assumed synthetic unit hydrograph for the catchment and design storms. The size and duration of these have been deduced from the Meteorological Office report. The probable maximum flood at the dam site is estimated to be 1550 m^3/s.

[1] *Iseyin, Oke-Iho and Ejigbo Water Supplies: Hydrological Studies, Institute of Hydrology, February 1977*

[2] *Extreme rainfall in Western Nigeria. M C Jackson, Meteorological Office, 1977*

Figure 1



10°00'
7°00'
3°00'
5°20'
Gauging station
Catchment boundary
Rainfall stations
International boundary
State boundary
Scale
0 10 30 50
km
R. NIGER
WAWA
NEW BUSSA
KAINJI DAM
GURAT
KAIAMA
OKUTA
MOKWA
JEBBA
BACITA
KISHI
SORO DAM SITE
IGBETTI
SHAKI
36
ILORIN
21
R. OFIKI
R. OGUN
UPPER OGUN
OGBOMOSHO
OKE IHO
ISEYIN
20
IKIRUN
OYO
OLLA
ILORA
23
OLANA
IWO
OSHOGBO
ILESHA
ERUWA
IFE
OLOKEMEJI
IBADAN

Although the results presented here relate to the Soro, only minor amendments would be necessary to derive similar results from the other catchments that might also be used to contribute to the Kishi scheme.

INTRODUCTION

The study area

The study area includes the catchments of the Ogun and Ofiki rivers down to Olokemeji and Iganna respectively. There were no rivers north of the Oyo State boundary which were relevant to this study and for which runoff data were available. Figure 1 shows the catchment boundaries and the location of raingauges and river gauging stations. Because of the sparse distribution of raingauges, we have extended the study area southward as far as Ibadan and northwards to Wawa.

The whole area south of the State boundary lies on the PreCambrian basement which is exposed in small areas particularly subject to erosion. The distinctive inselberge stand out from the gently undulating topography but their small area suggests that their influence on the rainfall and runoff is not significant.

Drainage in the Ofiki and Ogun catchments is from north to south, whereas the Soro flows north-east into the Niger. The highest parts of the catchments are about 500 m above sea-level. Weathering of the basement rocks has produced fairly shallow soils which limit the range of soil moisture storage to perhaps 150-200 mm.

A detailed study of the soils of the Oyo State[3] shows that any differences between the soils of the Soro and the northern Ofiki and Ogun catchments would appear to be relatively unimportant as far as hydrology is concerned.

The vegetation of the three catchments has been classified as Guinea Savanna[3]. However, at certain times of the year, especially at the beginning or end of the wet season, quite marked differences

[3] *Soils of the Western State Savanna in Nigeria. ODM, Land Resources Division, 1976*

in the appearance of the vegetation can be observed within short distances. The rainfall data show no decrease in mean annual rainfall, and although evaporation might increase towards the north, there are no data for the area between New Bussa and Ibadan to support this. An alternative explanation is that the changes in vegetation are due to differences in the timing of the start and end of the wet season and not necessarily a result of variations in the depth of rain.

Climate

The dominant influence on the climate is the seasonal movement of the inter-tropical convergence zone (ITCZ) where the warmer, drier air from the north east meets the cooler more moist air flow from the Atlantic. Over Nigeria, the ITCZ is usually parallel to the lines of latitude throughout its north-south movements so that, apart from local effects due to altitude, the rainfall pattern is largely latitude dependent.

The occurrence of rainfall can be related to the position of the ITCZ at ground level. The zone up to 200-300 km south of the ITCZ is one where the moist air is relatively shallow with dry air above and the occasional rainfall is usually in the form of isolated showers. The main rainfall zone is some 700-1000 km wide and to the south of the first zone. Cumulus cloud is developed and rainfall is substantial. Thunderstorms can give variable and sporadic rainfall over a large area, or they can be associated with disturbance lines moving from east to west. In the southern part of the zone, widespread heavy rain can develop. South of this main rainfall zone, stable conditions inhibit the upward movement of the moist air and there is little rain.

The effect of the seasonal movement of the ITCZ is illustrated by the distribution of rainfall throughout the year; there is a period of low rainfall from December to February when the ITCZ lies across the study area. From March to May, when the ITCZ is moving slowly north to about 15^{o}N (1500 km north of the study area) there is a period of heavier rainfall, before the 'little dry season' of August when the ITCZ is to the north of the study area. The heaviest rainfall occurs in September and October when the ITCZ moves rapidly southwards. Occasionally, this period extends into November, but more often there is a sharp end to the rains in late October, leaving November fairly dry.

This general pattern reported by Griffiths[4] and based on work by Garnier[5] provides a useful framework on which to base our understanding of the seasonal nature of rainfall and runoff. The localised nature of the storms does not lead to good correlation between raingauges, especially on a daily basis. The timing of the start and end of the wet season from year to year, which is a function of the position and speed of movement of the ITCZ, is particularly important in the smaller catchments relevant to this study.

None of the rivers of interest has perennial flow. Generally runoff occurs only during the months June to January; however, runoff can sometimes be produced as early as May or as late as July. This behaviour is consistent with the variability in the movement of the ITCZ and the onset of the wet season. The abrupt end of the rains in October or early November leads to a recession in streamflow which continues until late December or early January. In general, the larger the catchment area, the longer the recession continues.

The larger catchments, where individual, localised storms are not dominant in producing runoff, exhibit a distinct seasonal pattern of runoff. Rarely do storms cover the major part of the larger catchments; the runoff is then the effect of the integration of many storms. On the smaller catchments, such as the Soro, the Ofiki to Ofiki Town and the Ogun to Shepeteri, the effect of individual storms on the catchment runoff is far more important. This can lead to poor correlation between runoff events observed at the gauging stations and the corresponding measured rainfall due to the low density of raingauges in the study area.

[4] *Griffiths, J F. (Editor) Climates of Africa, World Survey of Climatology, Vol. 10, Elsevier, 1972*

[5] *Garnier, J B. Weather conditions in Nigeria, McGill University, Climatological Res. Ser. 2. 1967*

WATER RESOURCES

Rainfall

Annual rainfall data, of at least 5 years' duration, are available for 32 stations in the study area. Four of these, Ibadan, Ogbomosho, Oyo MOW and Ilorin, have over 50 years of data and are referred to here as long-term stations. The other data are mainly post 1950 and are not always complete records. A summary of all these data is shown in Table 1.

The mean annual rainfall appears to be fairly uniform over the study area as there is no obvious trend with respect to altitude or region. We have therefore made the hypothesis that the annual rainfall observations at each station are drawn from a single statistical distribution, the parameters of which can be best estimated from the long-term stations. Ibadan has the longest record and is therefore considered to be best represent the sequence of annual rainfalls at a single station. The data from each of the other stations were therefore compared with the Ibadan records using standard statistical tests. If the standard deviation and means are comparable, we can, by inference, confirm the hypothesis.

Results from 30 of the 32 stations give no evidence to suggest that the standard deviations are significantly different from Ibadan at the 5 percent level. The remaining two stations, Ife Moxuro Dam and Oke Iho N.A. School, both contain several unreasonably high values; these data have been discarded.

At the 5 percent level, 27 stations showed no indication that their means were significantly different from Ibadan. Of the remaining five, Ilorn and Ikirun conformed at the 2.5 percent level but Bacita Sugar, Ilesha MOW and Olana did not conform.

Generally, the results of these statistical tests suggest that the annual rainfall data at any point in the area may be assumed to be drawn from a normal distribution with a mean of 1218 mm and a

TABLE 1

RAINFALL STATIONS AND BASIC RAINFALL STATISTICS

Station	Altitude (m)	Altitude (ft)	Latitude °N	Longitude °E	Complete Yrs of Record	Mean Annual Rainfall (mm)	Mean Annual Rainfall (in)	Standard Deviation (mm)	Standard Deviation (in)
OLOKEMEJI, Forest Reserve	244	(800)	7 25	3 32	40	1240	(48.82)	243	(9.58)
IBADAN, Aero	227	(745)	7 26	3 54	70	1235	(48.63)	235	(9.25)
IFE MOXURO, Dam	305	(1000)	7 30	4 36	16	1532	(60.31)	344	(13.56)
ERUWA, Farm Scheme	213	(700)	7 32	3 25	13	1109	(43.67)	339	(13.36)
IWO, Waterworks	244	(800)	7 38	4 12	23	1146	(45.13)	245	(9.66)
ILESHA, MOW	366	(1200)	7 38	4 45	23	1364	(53.70)	296	(11.64)
OLANA, Agric Station	244	(800)	7 41	4 02	5	1339	(52.73)	582	(22.92)
OSHOGBO, PWD	305	(1000)	7 46	4 33	40	1248	(49.14)	257	(10.12)
ILORA, Farm Settlement	244	(800)	7 48	3 48	9	1253	(49.33)	335	(13.20)
ILORA, Crop Res Station	250	(820)	7 48	3 50	20	1244	(48.97)	256	(10.06)
OYO, MOW	260	(850)	7 50	3 57	61	1143	(45.01)	246	(9.68)
OYO, Fashola Stock Farm	229	(750)	7 54	3 47	20	1220	(48.05)	251	(9.88)
OLLA, Ejigbo	366	(1200)	7 57	4 18	14	1325	(52.15)	263	(10.36)
ISEYIN, D C School	335	(1100)	7 58	3 36	18	1292	(50 87)	248	(9.78)
OKE IHO, N A School	335	(1100)	8 02	3 19	10	1683	(66.25)	788	(31.04)
OGBOMBOSHO, Waterworks	351	(1150)	8 07	4 15	56	1210	(47.63)	270	(10.62)
UPPER OGUN, Estate	260	(850)	8 10	3 42	20	1260	(49.62)	289	(11.39)
SHAKI, L A School	457	(1500)	8 40	3 23	11	1251	(49.25)	167	(6.58)
IGBETTI	427	(1400)	8 45	4 07	19	1219	(47.99)	342	(13.46)
BACITA, spc	113	(370)	9 04	4 56	10	1119	(44.06)	293	(11.53)
BACITA, Sugar	107	(350)	9 04	4 56	15	1086	(42.74)	213	(8.38)
KISHI, D C School	350	(1150)	9 06	3 51	12	1233	(48.55)	302	(11.89)
JEBBA, U M S	122	(400)	9 08	4 49	7	997	(39.24)	291	(11.47)
GURAI	485	(1590)	9 37	3 21	7	1196	(47.09)	215	(8.48)
KAIAMA, Exp 30A	335	(1100)	9 37	4 03	12	1128	(44.43)	182	(7.18)
KAIAMA, 30	335	(1100)	9 37	4 03	6	1149	(45.25)	173	(6.83)
ILORIN	307	(1008)	8 29	4 35	59	1282	(50.47)	236	(9.30)
MOKWA	152	(500)	9 19	4 34	24	1052	(41.40)	130	(5.14)
WAWA	366	(1200)	9 55	4 26	8	1158	(45.58)	201	(7.90)
NEW BUSSA	199	(654)	9 54	4 30	6	1092	(42.98)	204	(8.03)
OKUTA					12	1194	(47.02)	334	(13.14)

standard deviation of 250 mm, estimated from the records of the 4 long-term stations.

The mean annual rainfall over a catchment will be the same as the mean annual rainfall at a point, but the variability of annual catchment rainfall will be less than the variability of annual rainfall at a point. To allow for this when deriving a long term record for the catchment, we have used the average rainfall from the 4 long-term stations to represent the historic sequence of annual catchment rainfalls. The standard deviation of this sequence is about 215 mm.

This annual sequence can be distributed by months using a long historic record whose seasonal rainfall pattern closely resembles that on the catchment of interest. We have discussed the factors governing the timing of the start and end of the rainy season and concluded that latitude is the most important factor. Thus we have used the Ilorin record as an index of the monthly rainfall, a choice supported by comparison with the relatively short period of record from Shaki. Use of the Ilorin record in this way constrains the length of the derived historic sequence of monthly catchment rainfalls to 64 years.

For recent years and specifically those for which runoff records are available, we are able to derive estimates of monthly catchment rainfall from the records from a number of stations in and around the headwaters of the Ogun and Ofiki. Using Theissen polygon methods and all the relevant data in each month, we have derived the monthly catchment rainfalls shown in Tables 2 and 3. These, in conjunction with the observed runoff records, are the basic data used to develop a rainfall/runoff model.

Runoff

River levels from the autumn of 1966 to date are available for the four gauging stations shown in Figure 1. There is also a gauge on the Soro near the dam site; this has been installed only recently and although the river levels confirm that the pattern

TABLE 2

OGUN ABOVE STATION 36

MONTHLY CATCHMENT RAINFALL

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
1966	0	0	47	198	58	263	136	145	143	138	0	0	1128
1967	0	28	79	69	73	216	115	263	232	186	12	20	1293
1968	10	63	93	197	124	338	336	265	291	141	16	0	1874
1969	0	25	89	80	122	156	104	168	153	209	66	0	1172
1970	24	8	47	62	187	160	247	256	362	70	0	0	1423
1971	0	32	58	72	190	151	158	204	254	112	0	0	1231
1972	0	56	31	71	236	121	98	48	146	91	0	0	898
1973	0	0	39	103	192	412	110	304	182	154	0	1	1497
1974	20	18	43	78	114	153	180	84	257	146	0	0	1093
1975	0	3	16	76	182	165	284	50	218	288	12	0	1294
1976	0	56	57	118	104	117	24	82	58	212	29	0	857
1977	16	51	64	154	290	388	22	63	151	247	0	0	1446
1978	0	8	114	184	174	75	488	8	115	96	10		

OFIKI ABOVE STATION 21

MONTHLY CATCHMENT RAINFALL

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
1966	0	0	31	167	139	241	124	188	156	167	1	0	1214
1967	0	16	89	73	77	256	122	315	144	250	12	24	1378
1968	10	63	93	197	124	338	336	265	291	141	16	0	1874
1969	0	25	89	80	122	156	104	168	153	209	66	0	1172
1970	60	0	18	86	182	220	116	94	247	174	0	0	1197
1971	0	28	51	76	245	152	161	206	260	106	0	0	1285
1972	0	59	42	73	236	122	92	45	148	89	0	0	906
1973	0	0	39	103	192	412	110	304	182	154	0	1	1497
1974	21	11	57	115	119	203	211	72	269	209	0	0	1287
1975	0	35	34	123	180	113	265	45	125	347	21	13	1301
1976	0	56	71	130	99	145	20	91	51	218	41	0	922
1977	23	71	71	213	361	500	30	66	50	139	0	0	1624
1978	0	10	116	212	217	94	640	0	112	102	0		

of runoff is similar to that on the Ofiki and the Ogun, the record is too short to be of further use in this study. A summary of the records available at each station for the period since 1966 is shown in Table 4. All these stations are at bridge crossings and have been rated intermittently by current meter. These gaugings invariably refer to the lower third of the range of river levels experienced, and thus the rating curves have to be extended to cover the range of medium and high flows.

The river level data for Ofiki 23 and Ogun 20 for the period up to 1975 were analysed in a previous study[1]. The rating curves were extended using a method based on Manning's equation that is described in the Appendix to that report. The rating tables developed previously have been used here to compute the flow data since 1975.

For the Ogun at Shepeteri and the Ofiki at Ofiki Town, the rating curves have again been extended and estimates of the monthly runoff derived from the daily water level records are shown in Tables 5-8. Incomplete months or those which contain doubtful records (usually very high water levels) have been neglected.

Evaporation

Estimates of open water evaporation have been derived by Penman's method using data from the meteorological station at the University of Ibadan. The mean monthly values from the 20 years of record are shown in Table 9. The variability from year to year is small and it is unlikely that there are significant differences across the southern part of the study area.

Evaporation has also been measured at Yelwa near the Kainji reservoir over 200 km to the north-east of Kishi; here the evaporation is higher than further south. On balance, we consider that it is more realistic to use the Ibadan data when estimating the open

TABLE 4

RIVER GAUGING STATIONS

River	Station name and number	Catchment area (km^2)	Highest river level gauged (ft)	Highest river level recorded (ft)
Ofiki	Ofiki Town, 21	715	7.15	12+[1]
	Iganna-Iwere Road, 23	2732	7.30	23.0
Ogun	Shepeteri, 36	1077	19.20	16.1
	Oyo-Iseyin Road, 20		10.40	20.0
Soro		303	4.38	5.1

Note: 1. At Ofiki 21 the highest flows overtop the gauge board whose maximum level is 12 ft.

MONTHLY RUNOFF FROM THE OGUN CATCHMENT ABOVE STATION 36

(SHEPETERI)

(mm)

	J	F	M	A	M	J	J	A	S	O	N	D	Total
1966							10	22	36	11			
1967	0	0	0	0	0	0	0	2	9	19	5	1	35
1968	0	0	0	0	0	3	12	84	110	55	6	1	271
1969	0	0	0	0	1	1	2	22	36	32	9	1	104
1970	0	0	0	0	0	0	11	8	22	26	1	0	69
1971	0	0	0	0	0	3	4	13	42	34	2	0	99
1972	0	0	0	0	0	0	1	1	1	3	0	0	6
1973	0	0	0	0	0	0	1	6	45	66	4	0	121
1974	0	0	0	0	0	0	2	6	81	40	3	0	132
1975	0	0	0	0	0	1	6	4	4	27	2	0	44
1976	0	0	0	0	0	4	2	0	1	38	33	1	80
1977	0	0	0	0	1	1	1	0	4	15	1	0	22

Notes: Slight inconsistencies may follow from rounding to the nearest millimetre

MONTHLY RUNOFF FROM THE OFIKI CATCHMENT ABOVE STATION 21
(OFIKI TOWN)

(mm)

	J	F	M	A	M	J	J	A	S	O	N	D	Total
1966	0	0	0	0	0	0	0	0	44	37	13	2	-
1967	0	0	0	0	0	0	2	16	30	54	12	5	120
1968	1	0	0	0	0	3	28	113	114	70	12	6	346
1969	1	0	0	0	2	1	4	19	33	33	34	6	132
1970	2	1	0	0	10	14	18	30	54	40	4	0	175
1971	0	0	0	0	4	3	6	58	78	49	4	0	203
1972	0	0	0	0	0	7	11	8	16	11	2	0	55
1973	0	0	0	0	0	2	2	24	27	44	4	0	103
1974	0	0	0	0	0	0	17	42	100	-	-	-	
1975	0	0	0	0	0	1	45	34	22	44	5	1	151
1976	0	0	0	0	1	11	4	1	3	39	28	2	88
1977	0	0	0	0	7	1	3	11	3	53	3	0	82

Note: Slight inconsistencies may follow from rounding to the nearest millimetre

MONTHLY RUNOFF FROM THE OFIKI CATCHMENT ABOVE STATION 23

(mm)

	J	F	M	A	M	J	J	A	S	O	N	D	Total
1966						24	11	38	33	44	17	2	169
1967	0	0	0	0	1	1	10	6	27	34	9	1	90
1968	0	0	1	2	3	2			51	44	12	1	
1969	0	0	0	0	1	6	5	39	38	42	13	3	149
1970	0	0	0	0	10	29	20	11	41	35	2	0	147
1971	0	0	0	0	0	3	6	15	29	24	2	0	79
1972	0	0	0	0	0	4	3	4	4	5	1	0	20
1973	0	0	0	0	0	4	2	35	55	95	11	1	202
1974	0	0	0	0	0	2	42	39	80	13	1	0	178
1975	0	0	0	1	3	4	29	24	16	30	6	4	116
1976	1	0	0	1	2	4	1	2	3	19	16	3	53
1977	2	0	0	3	4	3	8	6	18	38	8	1	91
1978	0	0	0	16	24	20	59	16	22				

Note: Slight inconsistencies may follow from rounding to the nearest millimetre

TABLE 8

MONTHLY RUNOFF FROM THE OGUN CATCHMENT ABOVE STATION 20

(mm)

	J	F	M	A	M	J	J	A	S	O	N	D	Total
1966	0	0	0	0	0	21	20	16	57	73	60	6	253
1967	0	0	0	0	0	1	4	1	13	30	7	1	57
1968	0	0	0	0	1	10	30	140	182	75	12	2	452
1969	0	0	0	0	0	2	8	22	77	70	20	2	201
1970	0	0	0	0	1	6	10	6	25	23	4	0	75
1971	0	0	0	0	0	0	7	9	22	31	2	0	71
1972													
1973	0	0	0	0	0	0	0	8	39	50	8	0	105
1974	0	0	0	0	0	0	7	9	33	46	6	0	101
1975	0	0	0	0	0	1	23	16	7	28	3	0	78
1976	0	0	0	0	1	13	4	1	1	36	23	2	81
1977	0	0	0	0	0	0	0	0	3	22	1	0	26
1978	0	0	0	1	13	19	25	14	7				

Note: Slight inconsistencies may follow from rounding to the nearest millimetre

ESTIMATES OF OPEN WATER EVAPORATION AND POTENTIAL TRANSPIRATION AT IBADAN

(mm)

	J	F	M	A	M	J	J	A	S	O	N	D	Total
Open water evaporation	129	150	159	150	147	126	110	104	112	130	138	131	1585
Potential transpiration	103	120	126	120	118	101	88	83	90	104	110	105	1268

water and potential transpiration for the area around Kishi. Potential transpiration is taken to be 80 percent of open water evaporation.

The relationship between rainfall and runoff

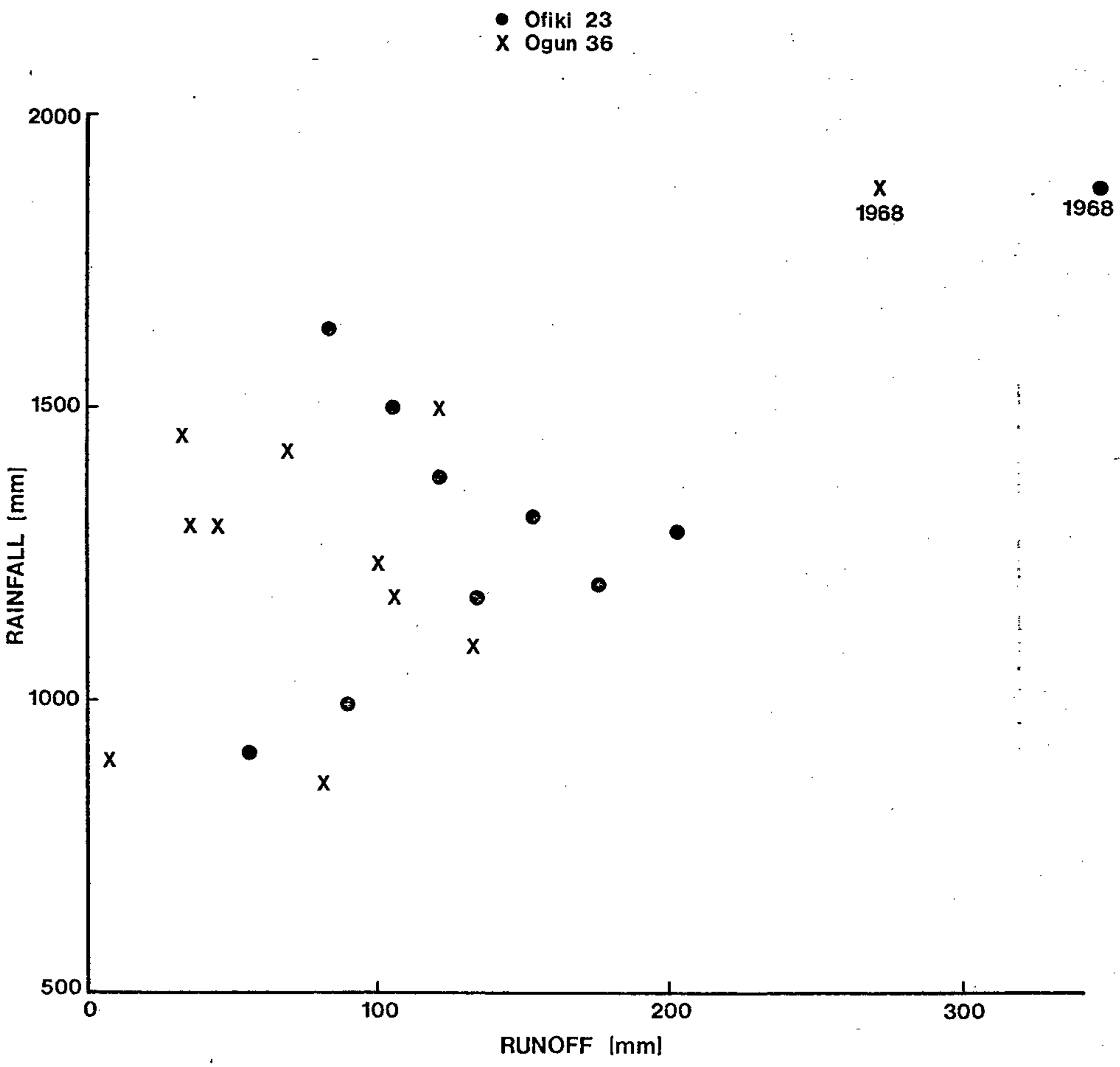
The estimated annual rainfall and runoff values for the Upper Ofiki and Ogun catchments are shown in Figure 2. The year 1968 stands out as exception in the period of record; other years, with much lower rainfall and runoff, show a good deal of scatter.

As mentioned in our previous report[1], there is a slight tendency for the runoff from the Ofiki catchment to be higher than the runoff from the Ogun. This feature is particularly noticeable in the data for the stations at Ofiki Town and Shepeteri. It is difficult to account for this difference, if it is real. It could be due to a number of factors such as differences in the rainfall that are not shown up by the sparse network of raingauges, errors in the estimates of runoff or differences in vegetation and hence the losses due to interception and transpiration.

The first two of these possibilities cannot be easily checked without further extensive field investigations, and particularly without an increase in the density of the raingauge network. To examine the effect of differences in evaporation, we have postulated a conceptual model linking rainfall, runoff, evaporation and the state of the soil moisture store.

Groundwater is effectively absent, and the amount of water held in the soil at the end of the wet season should be fairly constant from year to year. Thus the difference between rainfall and runoff in each year will represent the sum of transpiration and the evaporation of rainfall intercepted by the vegetation. The pattern of rainfall and runoff suggests that the soil moisture deficit (SMD) should be approximately zero at the end of December, when runoff ceases. The SMD will also be zero in late May or early June before significant runoff begins. Hence there is no carry over in the water balance from year to year. For the model, we have

RELATIONSHIP BETWEEN RAINFALL AND RUNOFF



assumed that during the dry season, January to May, when the potential transpiration exceeds rainfall, we can expect the actual transpiration to equal rainfall or to be suppressed if the soil moisture deficit is greater than the root constant. Once sufficient rain has fallen to reduce the SMD below the root constant, we have assumed that transpiration will proceed at the potential rate. This implies that during the wet season (June to December) there is always sufficient water available either as rainfall or excess soil moisture to allow transpiration at the potential rate. Interception losses will be additional to transpiration losses.

A model with up to six parameters was formulated to carry out a water balance from month to month taking account of all the factors mentioned above. Realistic estimates of the parameters were chosen, but it became clear that although the model worked reasonably well in one or two years, it was unable to model the whole period of data for either catchment realistically, even with a wide range of parameter values. This is a rather surprising result in view of the success of similar models on catchments elsewhere in the world. We must therefore suspect that the quality of the data is a major constraint in the development of a good runoff model.

To investigate the effect of possible data errors, we have reverted to a simpler model and examined the differences (residuals) between the observed and predicted monthly flows as a time series. Using various statistical tests, we can then see whether there is any pattern in the residuals, such as a serial correlation structure or a relationship with any other hydrological variables, which would suggest that there was further information in the data that we could model. On the other hand, if the residuals were effectively random, their variance would give a measure of the errors in the rainfall or flow data and this error level would indicate the reliability of any flow sequences generated using the model.

Our simpler version of the model assumed zero runoff during the months January to June (a slightly conservative assumption) and runoff linearly related to rainfall in the other months as follows:

$$Q = kR$$

where Q is the runoff in mm

R is the rainfall in mm

and k is a constant to be estimated.

These 'lumped' monthly runoffs were routed through a linear reservoir with a decay constant of 1.5 months to allow for the dynamic behaviour of the catchment and particularly the seasonal variation in the soil moisture storage.

For the Ofiki catchment above Ofiki Town, the model gave reasonable results, Figures 3 and 4, in all but 3 years when the observed runoff was much higher than that predicted. Over the period of record the model explained only 70 percent of the variance of the observed runoff data, a relatively poor result. However, the residuals appeared to be randomly distributed suggesting that the model could not usefully be improved.

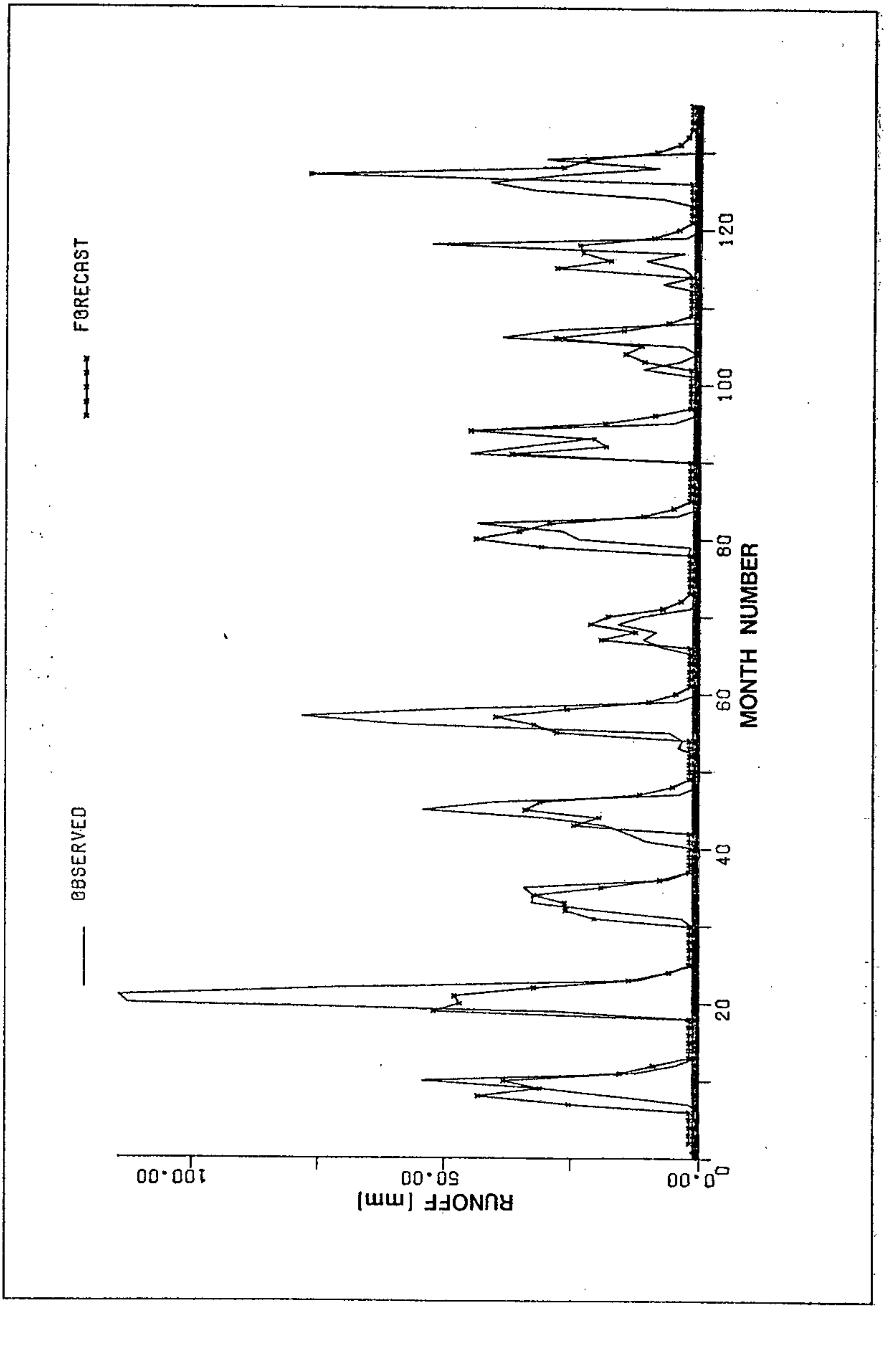
This result indicates fairly conclusively that errors in the data are much higher than one would normally expect. Further support for this conclusion can be found in a comparison of the records for the two stations on the Ofiki. The records for the 3 years, 1968, 1970 and 1971, the years of serious apparent under-prediction by the model, are grossly inconsistent.

The results from fitting the model to the Ogun data were not at all encouraging. It is difficult to see why this should be so, but one possible explanation could be the poorer distribution of raingauges within this catchment. The rainfall in the area is very localised and only a proportion of the runoff-producing storms will be monitored by the gauging network. This proportion is likely to be greater in the Ofiki catchment than the Ogun. As a result, the derived rainfall-runoff model will be closer to the real physical relationship than the Ogun model and hence will be more appropriate to the Soro catchment.

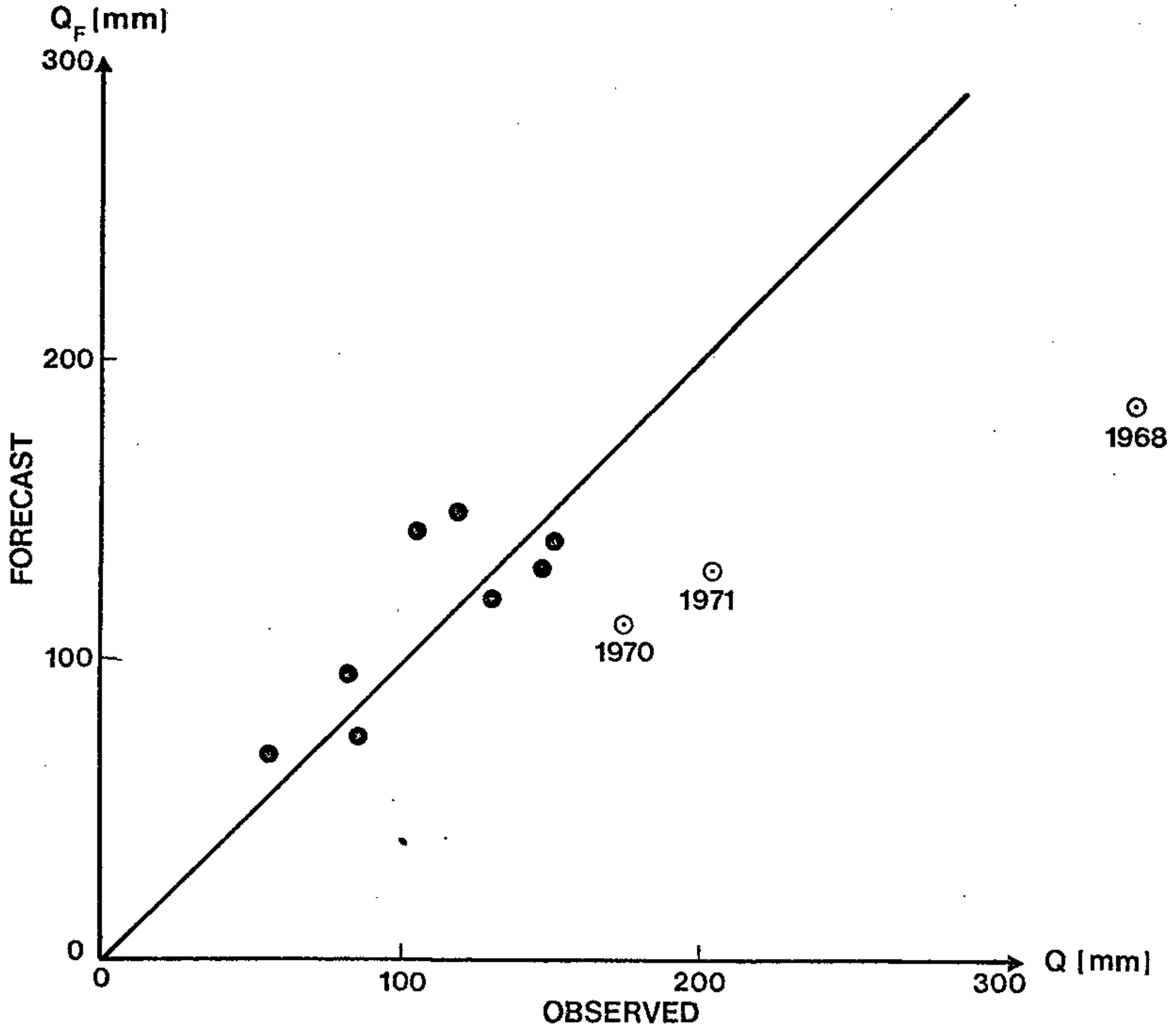
The final stage of the modelling exercise was to use the 64 years of monthly rainfall data to forecast runoff in the Soro catchment. To reflect the uncertainty associated with the runoff

Figure 3

MONTHLY FORECAST AND OBSERVED RUNOFF FOR OFIKI AT 21



FORECAST AND OBSERVED MEAN ANNUAL RUNOFF AT OFIKI 21



forecasts, a random noise series was added to the forecast flow series. This process was repeated 10 times to obtain 10 sets of 64 years of forecast monthly runoffs for use in the reservoir yield simulation exercise.

This precaution ensures that the reservoir simulation cannot be unduly biassed by a single runoff series which might, by chance, be unrepresentative of the expected reservoir inflow especially as the noise term is unusually large.

The mean annual runoff predicted for the Soro catchment is 130 mm which is 11 percent of the mean annual rainfall. This compares well with previous estimates for other catchments in the region. The standard deviation of annual runoff is 38 mm and it is more difficult to be sure that this figure is representative of the real historic flows. However, the use of a number of simulated sequences in the reservoir operation should ensure that some sequences are more variable than the average and it is these that will tend to ensure that the size of reservoir is not significantly underestimated.

Estimates of reservoir yield

A computer-based model to represent the operation of the proposed reservoir on the Soro using mass balance techniques was used to assess reservoir reliability. The balance equation forming the basis of the model equates the change in storage to the inflow, less the spillage (when full), evaporation and releases, on a monthly time base. Four different reservoir sizes were examined. The yield of each was estimated by examining the reliability of the reservoir when used to supply a fixed, predesignated demand. The maximum yield for a given reliability of supply could then be inferred.

For each reservoir size and demand, the simulation was repeated using ten different inflow sequences of 64 years of monthly data and recording the number of months when the demand could not be met within each sequence. The results are summarised in Table 10. It was found that the standard deviation of the number of failures recorded within each sequence was about 10 failures, thus underlining the problems of estimating reservoir reliability on a single inflow sequence.

RESERVOIR RELIABILITY

Reservoir max. storage level (m)	Max. storage volume (million m^3)	Demand (million m^3/year)	Av. no. months of failure	%	Av. no. years of failure
353.0	81.0	45	154	20.1	43
353.0	81.0	40	70	9.1	23
353.0	81.0	35	5	.7	2
353.0	81.0	30	0	0	0
352.0	73.5	40	71	9.2	23
352.0	73.5	35	7	.9	3
352.0	73.5	30	0	0	0
351.0	65.0	40	73	9.5	23
351.0	65.0	35	9	1.2	4
351.0	65.0	30	0	0	0
350.0	58.4	40	75	9.8	24
350.0	58.4	35	12	1.6	5
350.0	58.4	30	1	.1	1
350.0	58.4	25	0	0	0

Note: minimum water level assumed to be 338.0 m giving a dead storage volume of 5.2 million m^3

In order to investigate the sensitivity of reservoir yield to the uncertainty associated with the estimation of the parameter k in the model, alternative series of 10 sets of runoff data were calculated using a constant k' given by

$$k' = k(1 \pm \varepsilon)$$

where ε is the standard error of estimate associated with k. In this case ε is 0.15.

The effect of using the value of $k' = k(1-\varepsilon)$ is to produce a series of forecast monthly flows whose mean is reduced by 15 per cent. This series has been used in the reservoir simulation program and gives the results shown in Table 11. This shows that the ability of the reservoir to meet a given demand is particularly sensitive to the value of the constant used in the model, and hence the mean annual runoff from the catchment.

RESERVOIR RELIABILITY
(LOWER ESTIMATE OF RUNOFF)

Reservoir max. storage level (m)	Max. storage volume (million m³)	Demand (million m³/year)	Av. no. months of failure	%	Av. no. years of failure
353.0	81.0	45	263	34.3	60
353.0	81.0	40	187	24.4	50
353.0	81.0	35	93	12.1	29
353.0	81.0	30	6	.8	2
353.0	81.0	25	0	0	0
352.0	73.5	40	187	24.4	50
352.0	73.5	35	93	12.1	29
352.0	73.5	30	7	.9	3
352.0	73.5	25	0	0	0
351.0	65.0	40	187	24.4	50
351.0	65.0	35	93	12.1	29
351.0	65.0	30	9	1.1	3
351.0	65.0	25	0	0	0
350.0	58.4	35	93	12.1	29
350.0	58.4	30	11	1.4	4
350.0	58.4	25	0	0	0

Note: maximum storage assumed to be 338.0 m giving a dead storage volume of 5.2 million m³

SPILLWAY DESIGN FLOOD ESTIMATION

Introduction

We believe that the most reliable estimate of the spillway design flood follows from the conversion of the probable maximum precipitation (PMP) to the probable maximum flood (PMF) using the unit hydrograph technique. The absence of good quality long term discharge data precludes the use of statistical methods of flood estimation and it is felt that empirical methods derived from flood data from other parts of the world are also inferior. The unit hydrograph approach allows all available local data to be incorporated into the design.

We have estimated the spillway design flood (PMF) for the proposed dam site. Data from a recording raingauge at Ibadan University were made available for the period 1960 to 1970 and for 1973 to 1975. The available rainfall data were analysed as described in the Met. Office Report[2]. The short duration rainfall data from Ibadan were used to complement the earlier data as a means of estimating the PMP for durations of 1 hour to 1 day.

Extensive use has been made of the techniques used in the Flood Studies Report[6] with substitution of local Nigerian data where possible. A number of inputs are required to calculate a flood hydrograph by the unit hydrograph method. In this case, the return period of the flood is fixed as the probable maximum flood (nominally about 1 million years). The duration of the design storm must be chosen and this determines the total storm depth from the unique depth versus duration curve for the catchment shown later. The duration was taken as approximately two to three times the catchment lag based on Flood Studies Report findings. This rainfall must then be distributed in time according to some design profile and converted from a point rainfall to an areal value. The profile used is again based on Flood Studies Report recommendations

[6] *Flood Studies Report in 5 Vols. Natural Environment Research Council 1975*

and appropriate areal reduction factors are obtained from the Met. Office Report. This design rainfall hyetograph must then be multiplied by a runoff coefficient or percentage runoff to determine the net or effective rainfall. Because no suitable detailed rainfall-runoff relationship could be developed for the study catchment, percentage runoff data from Cameroon and Togo were used. Finally, this net rainfall must be combined with a unit hydrograph and a baseflow component added to yield the total flood hydrograph.

Derivation of unit hydrograph

The unit hydrograph for the dam site could not be derived in the conventional way by analysing short duration rainfall and discharge data simultaneously because of the very limited discharge data available. In addition, the rainfall is spatially and temporally very variable and it is difficult to identify a particular storm associated with any flood. It is possible to estimate the time to peak of a unit hydrograph, T_p, from mainstream length (L), slope (SL1085) and a short duration rainfall index (RSMD) which is the 1-day rainfall of 5-year return period minus average soil moisture deficit (SMD), using a number of regression equations developed for the Flood Studies Report:

$$T_p = 46.6L^{0.14}\ SL1085^{-0.38}\ RSMD^{-0.4} \qquad (1)$$

$$T_p = 20.46\ SL1085^{-0.598} \qquad (2)$$

$$T_p = 2.8(L/\sqrt{(SL1085)})^{0.3} \qquad (3)$$

A fourth empirical relationship, due to Snyder, relates T_p to L, the length from the catchment centroid to the stream (L_c) and a coefficient, usually between 1.8 and 2.2, (C_t):

$$T_p = C_t(L.L_c)^{0.3} \qquad (4)$$

For the dam site, the average of these methods (range 7.5-9.3 hrs) is 9 hours for a 1-hour, 10 mm unit hydrograph. Whilst using a regression equation developed from United Kingdom data in Nigeria is questionable, the equations are physically based in the sense that they rely largely on length and slope to determine T_p. Thus we expect the estimates of

T_p to be reasonably valid.

From the Flood Studies Report, we find that accurate resolution of hydrograph peaks is obtained using a time unit of the order of one fifth of the time to peak; in this case, a time interval of two hours was selected. The time to peak of a two-hour unit hydrograph can be adjusted using the relationship from the Flood Studies Report:

$$T_{p2hours} = T_{p1hour} + \left(\frac{2-1}{2}\right) \text{ hours}$$

$$= 9.5 \text{ hours}$$

A simple triangular unit hydrograph was derived from this single parameter, T_p, where the peak discharge (Q_p) is given by

$$Q_p = \frac{220}{T_p} \text{ cumecs/100 km}^2$$

The time base (TB) is given as

$$TB = 2.52\, T_p \text{ hours}$$

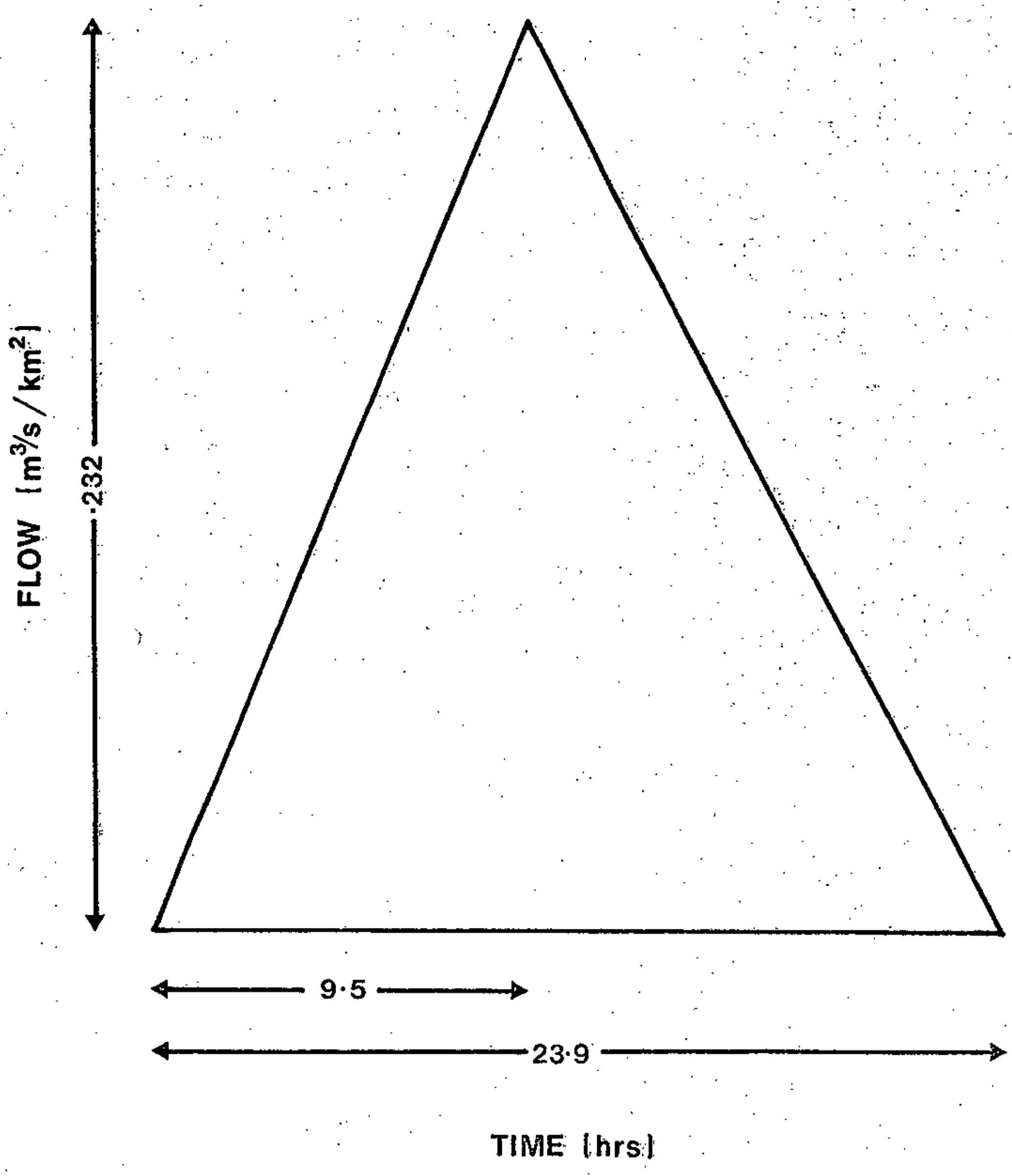
It was found in the Flood Studies Report that a single parameter was sufficient to define the unit hydrograph, whose total area is of course defined as being 10 mm over the catchment. The deduced unit hydrograph is shown in Figure 5.

Percentage runoff

It was next necessary to decide how much of the gross rainfall would be effective in producing rapid response runoff, (surface or near surface flow) rather than subsurface baseflow. Little published data were available but data from Cameroon to the east and Togo to the west were available from ORSTOM[7]. On small representative basins of similar geology (PreCambrian basement complex) and soils (tropical soils with ferruginous concretions of sands and gravels) a percentage runoff of 35 to 45 percent is common for Togo; for Cameroon 20-50 percent is observed. These areas of Togo and Cameroon are obviously rather

[7] *Office de la Recherche Scientifique et Technique Outre-Mer (ORSTOM) Recueil des donneés de base de Bassins Representatifs et Experimentaux Paris 1971. Vols 1 and 2*

SYNTHETIC UNIT HYDROGRAPH FOR SORO CATCHMENT



different to Western Nigeria but since they have similar climates (as shown by mean annual rainfalls, rainfall distributions and temperature data from ORSTOM), the percentage runoffs quoted for these annual floods will be a good first approximation to the standard percentage runoff (SPR) component of the Flood Studies Report prediction technique:

$$PR = SPR + 0.22\ (CWI-125) + 0.1\ (P-10)$$

where SPR = standard percentage runoff (produced by 10 mm of rain on the catchment under standard antecedent conditions of zero soil moisture deficit and zero antecedent precipitation during previous days)

CWI = catchment wetness idex, an index of the antecedent state of the catchments

P = total storm rainfall.

This standard percentage runoff is increased by the contributions from CWI and storm rainfall so that greater percentage runoffs are experienced for large storms on wet catchments. Based on the ORSTOM data an SPR of 45 percent was chosen for the small Soro catchment, in line with our previous estimates for the Ejigbo scheme. In the case studied here the conservative percentage runoff of 82.2 percent was obtained using values for CWI and storm rainfall described below.

Design rainfall

A choice of duration and time distribution of the rainfall or rain profile must be made to specify the design storm. The return period is the PMP (nominally 1 million years) and once the duration is determined, the depth follows from the curve (Figure 11 in the Met. Office Report) which gives the rainfall depth for any duration at any point in the catchment. An areal reduction factor from Figure 9 of the Met. Office Report must be applied to get the measure of areal rainfall which is given in Table 21 of that report.

An areal rainfall depth duration curve for the catchment was plotted from Figures 9 and 11 and Table 21 of the Met. Office Report and is shown here as our Figure 6.

We considered that a duration of approximately 2 to 3 times the unit hydrograph time to peak would be appropriate and we used a duration of 26 hours. Whilst some comments on the distribution of the rainfall in time (the rainfall profile) were given by the Met. Office, we considered that a more extreme, peakier profile should be used for the PMP case. We chose a nested profile whereby the PMP for all durations should occur in the same storm; that is, the PMP 2-hour fall should occur at the centre of the PMP 6-hour fall within within the PMP 10-hour fall and so on. In this way a symmetrical rain profile was built up from the depth duration diagram of Figure 6 for the duration chosen. This produces a very severe profile that maximises the flood peak. This technique is recommended for use in the United Kingdom.

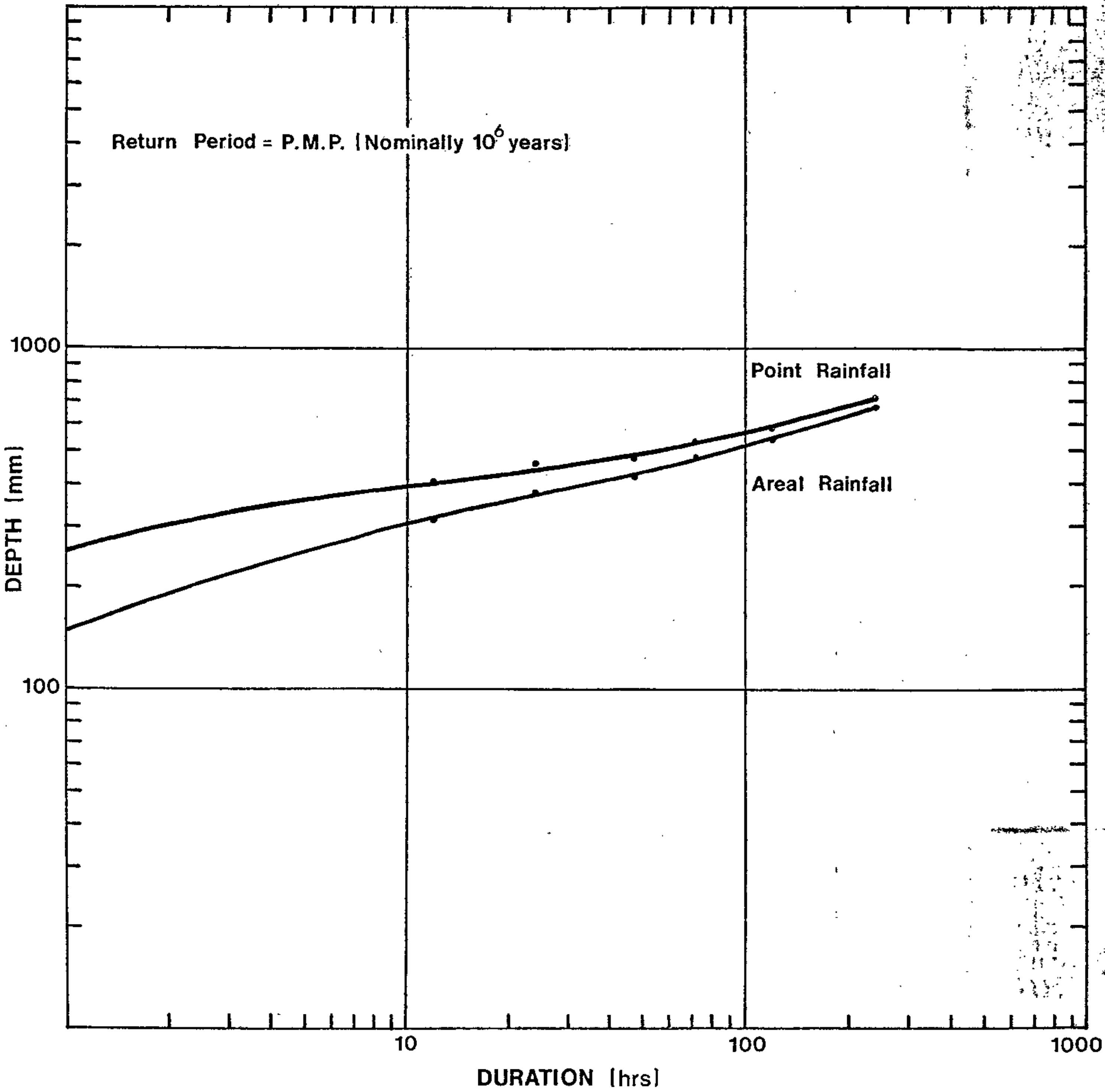
Catchment wetness index

Because the percentage runoff varies with catchment moisture state, some index of the state of the catchment prior to the design storm was required. In the absence of local rainfall-runoff relationships we used the Catchment Wetness Index (CWI) from the Flood Studies Report. This combines soil moisture deficit (assumed zero in the wet season) and a short-term precipitation index. A rainfall profile for the PMP was used to estimate the CWI appropriate for a heavy storm, and this value of 144 was used to estimate the percentage runoff.

Baseflow

The convolution of the unit hydrograph with net rainfall gives the rapid response component of the total hydrograph. To this must be added a slow response baseflow component of the hydrograph. This was estimated at 2.4 m^3/s which is a very small proportion of the design flood.

RAINFALL DEPTH DURATION CURVE FOR SORO CATCHMENT



Results of rainfall runoff convolution

The design storm discussed above was multiplied by an appropriate percentage runoff and convoluted with the unit hydrograph. It should be noted that the chosen 'standard' percentage runoff of 45 percent was increased by the contribution from CWI and the storm rainfall, P. The results are given in Table 12.

Conclusions and recommendations

We believe that the recommended design flood with a peak of about 1550 cumecs is the best estimate that can be made at present. A number of assumptions have had to be made about antecedent conditions, storm duration and percentage runoff. However, such assumptions have been made following examination of all presently available local data.

We recommend that during the period from the presentation of this report to dam construction, additional rainfall data and flow data should be collected. In particular a recording river level gauge should be installed upstream of the proposed reservoir site to enable better estimates of catchment lag to be made. If the section could be rated to give reliable discharge estimates this would also provide a check on the assumptions that led to the estimates of reservoir yield. In addition, the installation of some raingauges in the Soro catchment should give results that would enable unit hydrographs to be derived in the conventional way.

We believe that such a programme of data collection is vitally important and that the costs incurred would be very small in comparison to the total scheme costs.

LPT ACCOUNT: IP27

FLOODS AT SORO,NIGERIA-----PMF 2 HOUR DATA

PMF T=2 HOURS

AREA (SQ.KM.)	3[illegible]3.0
DATA INTERVAL (HR)	2.0
DESIGN DURATION (HR)	25.0
TOTAL RAIN (MM)	344.0
PERCENTAGE RUNOFF	82.6
ANSF (CUMECS PER SQ.KM.)	.0080
CWI AT START OF STORM	144.0

TRIANGULAR UNIT HYDROGRAPH COMPUTED FROM TP= 9.5

CONVOLUTION OF UNIT HYDROGRAPH AND NET RAIN PROFILE

TIME	TOTAL RAIN MM	NET RAIN MM	UNIT HYDROGRAPH ORDINATE	TOTAL HYDROGRAPH
.00	4.50	3.72	.00	2.41
2.00	8.00	6.61	4.88	7.90
4.00	9.50	7.85	9.75	23.15
6.00	12.50	10.32	14.63	49.99
8.00	18.50	15.24	19.50	92.08
10.00	39.00	32.21	22.36	154.45
12.00	160.00	132.13	19.17	253.58
14.00	39.00	32.21	15.99	530.99
16.00	18.50	15.23	12.80	835.30
18.00	12.50	10.32	9.62	1133.93
20.00	9.50	7.85	6.43	1400.16
22.00	8.00	6.61	3.24	1538.25
24.00	4.50	3.72	.06	1424.43
26.00				1251.26
28.00				1050.13
30.00				832.85
32.00				607.08
34.00				381.61
36.00				180.15
38.00				104.56
40.00				61.76
42.00				33.99
44.00				16.22
46.00				6.19
48.00				2.48

URVATURE AROUND PEAK = -62.994