Ministry of Agriculture and Agrarian Reform

People's Democratic Republic of Yemen

Feasibility Study for Wadi Bana and Abyan Delta Development Project

Volume II

Annexe A
Hydrology and Water Resources

WS Atkins & Partners

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CHAPTER 7

GLOSSARY

ECGC	-	Empire Cotton Growing Corporation
Kharif	-	term applied to flood season from July to mid-October
MAAR	-	Ministry of Agriculture and Agrarian Reform (PDRY)
MAR	-	mean annual runoff
Oqma	-	temporary diversion bund in wadi
PDRY	-	People's Democratic Repulic of Yemen
PWC	-	Public Water Corporation (PDRY)
Qbar	-	mean annual flood, ie mean of series of annual maxima
Q(T)	-	peak flow with return period T years
RBTA	-	Right bank traditional areas (former irrigated lands excluded from Phase I re-development)
Seif	-	term applied to flood season from mid-March to May
YAR	-	Yemen Arab Republic

Units

l	-	litre
meq	-	milliequivalent
$M.m^3$	-	million cubic metres
Mt	-	million tonnes
S	-	Siemen (= Ohm^{-1})

1. INTRODUCTION

1.1 PROJECT SETTING

1.1.1 Study area and catchment location

The Terms of Reference indicate that the study area is that part of the left bank of Wadi Bana downstream of Bateis which may be spate irrigated from Wadi Bana, plus the small right bank command of the Gharaib weir (also irrigable from Wadi Bana). The study area is part of the Abyan Delta, a segmented alluvial fan which lies approximately 55 km north-east of Aden, capital of the People's Democratic Republic of Yemen (PDRY). Its location is shown in Figure 2.1. The apex of the delta is at the point where Wadi Bana and Wadi Hassan, the two main sources of surface runoff, emerge from the mountainous hinterland. From the apex of the delta to the sea is approximately 30 km, while the base of the delta is about 20 km long. The small town of Giar is roughly at the centre of the delta and lies at 13°14'N and 45°18'E.

The delta rises gently from sea level to 180 m at Bateis, but is punctuated in the central and northern parts by a number of rock outcrops which typically rise 50-200 m above the surrounding land (see section 1.1.3 below).

The Wadi Bana catchment is also shown in Figure 2.1. Approximately 66% of its total area of 7 200 km^2 lies in the Yemen Arab Republic (YAR) and extends to 14°24'N. Maximum catchment altitude is 3 400 m.

1.1.2 Geomorphology

Formation of an alluvial fan at Abyan has been encourage by local topographical and climatic features:

(i) a high ratio of mountainous catchment area to depositional lowland area.

(ii) long dry periods in the catchment when weathered material can accumulate, to be evacuated in large amounts during storm rainfall.

Positions of drainage channels are probably less mobile than is usual in an arid alluvial fan, being to some extent constrained by the various rock outcrops and the establishment of small riparian bushes and trees.

Although Wadi Bana is by far the most important source of runoff and sediment, fan development has also been influenced by Wadi Hassan, the western wadis Maharia and Suhaybiyah, and occasional spates from the large number of tiny mountain-front catchments. There is no sign of any drainage pattern arising from storm rainfall on the alluvium itself.

Wadi Bana and Wadi Hassan currently flow within about 3 km of each other. From the shape of the delta and the width of Wadi Hassan it appears likely that Wadi Hassan at one time took some or all of the Bana discharge. Wadi Bana's sharp bend to the south-west at Bateis may result from deposition during an earlier stage of fan development, or may be a result of the underlying synclinal geology (see below).

An inherent feature of fan development is the continuously changing channel pattern: these shifts ensure that material is distributed over a wide area (a function now largely served by the irrigation system). It is therefore surprising that channel shifts during the major March 1982 flood (see chapter 4) were relatively minor. The main effects were generally to straighten the wadi channel and to make redundant the left hand branch of the wadi downstream of the Aden-Zingibar road bridge.

1.1.3 Geology

Geological conditions can be summarized very briefly as follows:

(i) the Wadi Bana catchment is dominated by Precambrian metamorphics and basaltic lavas of Miocene-Recent origin.

(ii) the study area is a delta of fluviatile sediments, interbedded with wind blown deposits and mainly silty soil deposited by the irrigation water.

The Precambrian metamorphics in the Bana catchment are thought to be mainly gneisses and schists, and are of low permeability. These basement complex rocks are strikingly dissected by pinkish-red pegmatite dykes and sills. Basaltic lavas are significant only in the upper catchment. They belong to the Aden volcanic series.

At the southern edge of the catchment Jurassic formations are encountered, lying unconformably on the basement complex. They have been dated as Upper Jurassic and at Bateis are composed of limestone interbedded with marls. Much faulting and folding has occurred in the southern part of the catchment.

The study area alluvium is broken by rock outcrops, chiefly in the Al Husn and Giar area. The outcrops appear either to be of limestone (eg Jebel Khanfar at Giar and Jebel Ar Rawwa) or of metamorphics (eg at Al Husn). It is possible that they are evidence of a synclinal valley, in effect a continuation of the Wadi Hassan valley line stretching from east-north-east to west-south-west.

1.2 STUDY OBJECTIVES

The scope of the hydrological studies is contained in paragraph 1(a) of the Terms of Reference, which states that the consultants are required to "study, analyse and evaluate all *existing hydrological data, reports and studies of Wadi Bana*".

In addition, paragraphs 1(f) and 1(g), which are principally of concern to the engineering and agricultural studies, have implications for the hydrological work:

1(f) "study the behaviour of wadi flows under peak floods and normal floods between Bateis and Gharaib and to recommend on the necessary training works required to keep the wadi in a steady course commanding the weirs at all times and protecting the area of the project from future scour or damage by floods".

1(g) "study the existing traditional irrigation system of phase II consisting of the lands now commanded by the Bateis, Makhzan and Gharaib system and recommend reasonable rehabilitation and improvements aiming at efficiency of irrigation, water economy and increased yields".

In order to meet these project tasks the following main hydrological objectives were set:

(i) derive study area climatic means and estimate potential reference crop evapotranspiration rates.

(ii) obtain flood frequency curves at all potential weir sites on Wadi Bana below Bateis.

(iii) estimate the areas of land which may be irrigated from flood flows in Wadi Bana, and quantify the reliability of such irrigation. For these studies it was of course necessary to include all land commanded by Wadi Bana (ie right bank land as well as study area land which is chiefly on the left bank).

1.3 STUDY TIMING AND INPUTS

The Binnie & Partners team hydrologist, Mr T. Yates, was in PDRY for three months from 20 May to 18 August 1983. This was followed by a period of approximately two months in London. A Hewlett-Packard 9825A desktop computer was taken to PDRY and was used extensively to rework basic flow data. There were no counterpart hydrology staff.

The period in PDRY spanned the gap between the Seif and Kharif flood seasons. Wadi flows are low during this period and little irrigation takes place. The Kharif flood season in 1983 began later than is usual: the first spate of any size did not arrive until 17 August (whereas a majority of years enjoy high wadi flows from the beginning of August - see Figure 3.6). The timing of this part of the study was less than ideal, therefore, as flows were not especially low nor were there sufficient floods to observe the progress of Kharif irrigation down the wadi or to collect sediment samples at high flows.

A full bibliography appears in chapter 8. The most important reports seen were:

(i) Dar Al-Handasah (1973): Abyan Delta Project definite plan report, annex III, climate and hydrology.

(iii) Sogreah (1981): Greater Aden Water Supply Project, Wadi Bana hydrogeological survey and study.

(iii) Groundwater Development Consultants (1980-1): Wadi Tuban Water Management Study.

The following mapping was available:

(a) ONC series sheet K-6, edition 5, scale 1:1 000 000 (1975)

(b) TPC series sheet K-6AG, edition 2-GSGS, scale 1:500 000 (1975)

(c) South Arabia series K669, sheet 1345C, edition 1-GSGS, scale 1:100 000 (1967)

(d) South Arabia series K667, Sheets 1344B-D, 1345A, 1345C and 1445C, edition 4-DOS (1964)

Aerial photography of the delta (but not the catchment north of Ligma) at 1:10 000 scale was available, flown in May 1971 by Aero-Precisa, Beirut and November 1982 by Middle East Aerial Photogrammetric Surveys Ltd (MAPS). Limited coverage of the northern part of the delta, flown by Hunting Aerial Surveys in the late 1950s, was also available.

2. CLIMATE

2.1 GENERAL DESCRIPTION

The study area climate is hot and arid, becoming semi-arid further inland over the Bana catchment. Rainfall amounts are low and are highly variable, both areally and temporally. Both study area and catchment lie south of the northern tropic and and are subject to monsoonal and mediterranean weather influences. As will be seen later, most study area and catchment rainfall occurs from March to May, and in larger amounts from July to September. The underlying weather systems are different during each of these two seasons.

Spring rainfall is thought to arise from the convergence over the Red Sea of cool air (generally of mediterranean origin) with warmer air. The warmer air may be northern monsoon air flow (eg. from the Indian subcontinent) or may be polar air warmed and/or moistened by passage over the Arabian area. This convergence is known as the Red Sea Convergence Zone (RSCZ). On occasion the convergence may produce sufficient lifting of the air mass for it to spill over on to the Arabian plateau. In spring the diurnally different heating of land and sea surfaces can give rise to thunderstorms in the Yemeni mountains.

Summer rainfall is caused by warm, moist southwesterly monsoon air. It is diverted along the Red Sea trough where it is lifted and converges with northerly air streams. The limit of this Intertropical Convergence Zone (ITCZ) activity lies to the north of Jeddah. Its greatest impact is felt along the southern coast of the peninsular and in the western part of the Yemeni mountains.

Tropical cyclones, originating off the west coast of India between 10° and 15°N, are said to penetrate as far as the Gulf of Aden (see Watts, reference 17), but only rarely. There is no suggestion that the study area has ever been affected by cyclone-related rainfall.

2.2 RAINFALL

2.2.1 Station network and available data

Figure 2.1 shows the network of rainfall stations relevant to the present studies. They are also listed in Table 2.1. Station locations have been checked as far as possible with the available mapping (see chapter 1). Many locations are not certain. Particular doubt surrounds Khalla, which has been provisionally placed on the Bana near the YAR/PDRY border following Sogreah's (ref 24) reference to a settlement of this name.

With few exceptions the stations are concentrated near the main centres of population or along the principal lines of communication. Apart from Khalla, only one station, Yarim, lies (just) within the Bana catchment. El Kod lies just to the south-west of the study area. Three stations (Sarar, Alirgah and Sha'b al Baari) have recently been established in the upper Hassan catchment and have been reporting intermittently since August 1981. If continued, they should ultimately provide invaluable information. Although a climate station is known to have existed at Giar, centrally located in the study area, no rainfall data are apparently available for it.

Sources of rainfall data are quoted in Table 2.1. Direct access to YAR data was not possible. For the stations in PDRY most monthly data came from MAAR files and old UK Meteorological Office rainfall summaries. GDC (ref 4) have provided a useful summary table of annual rainfall.

Data quality is probably not high. Discrepancies between different sources of the same record were noted on several occasions. A frequent source of confusion arose between months of no record and months of no rainfall. Given a choice the oldest data source was always taken. Study area rainfall is insignificant in water resources terms (see section 2.2.2) and there are, to all intents and purposes, no catchment rainfall records. It was therefore not considered worthwhile to undertake any formal quality checks.

2.2.2 Annual rainfall

Annual rainfall in arid and semi-arid climates tends to be highly variable. It was noted that coefficients of variation of "long" records were typically 30-40% for high rainfall stations (eg Dhala) to 100-120% at low rainfall stations (eg Aden, El Kod). This exacerbates the sampling error problem inherent in the use of short records. Coupled with the inadequacies of the station network, construction of a useful isohyetal map in this area is made extremely difficult.

Recognizing this, Griffiths and Hemming (ref 18) made extensive use of vegetation information when drawing their isohyetal map. Rainfall data collected in the 20 years since their pioneering work have not filled the gaps in the network to any great extent. Accordingly, the isohyets plotted on Figure 2.1 still follow the pattern mapped by Griffiths and Hemming. The main changes are shifts to the north and west, respectively, of the 100 mm and 300 mm isohyets. The 1760 mm average rainfall quoted for Ibb was ignored for isohyetal purposes: the town is surrounded by high mountains and the rainfall figure, if true, probably only applies to a very small area. GDC (ref 4) attempted to relate rainfall to altitude but the results were not encouraging and we have not tried to follow suit.

Station rainfalls shown in Figure 2.1 are averages of record. Consideration was given to adjusting them by comparing means of record periods with long term means at index stations. El Kod and Dhala suggested themselves as suitable index stations in low and high rainfall areas respectively. However, comparision of individual years' totals at individual stations indicated that even annual rainfall shows such spatial variation that attempts at adjustment were abandoned.

Any catchment rainfall estimates must inevitably be very crude but, equally, must be attempted. Use of Figure 2.1 gave the following values:

Catchment	Area km^2	Rainfall mm	Rainfall input $M.m^3/yr$
Bana	7 200	360	2 590
Tuban	5 090	530	2 700
Suhaybiyah	1 400	200	290
Hassan	3 300	200	660

Figure 2.1 suggests that study area rainfall lies between 50 and 100 mm. If we take average point study area rainfall as 80 mm and assume that its percentiles can be inferred from the frequency distribution of Lahej annual rainfall (average 63 mm), then we obtain:

Non-exceedance probability, %	Study area point rainfall, mm
20	40
50	70
80	105

Total median rainfall (no reduction for effectiveness) represents only about one-tenth of the Kharif gross seasonal irrigation application, and does not actually affect the magnitude of the latter. In water resources terms, then, study area rainfall is insignificant.

2.2.3 Monthly rainfall

Figure 2.2 shows the seasonal distribution of average monthly rainfall at Dhala, Mukeiras, Lahej and El Kod. The two peaks, in spring and summer, are clearly visible at the high altitude stations, rather less so at Lahej and El Kod. The second, ITCZ related, peak is the more pronounced. The use of averages for low rainfall stations has a definite drawback in that (as to a lesser extent with annual rainfall) one or two heavy rainfall events can impart a large positive skew and consequently increase the average considerably. Thus the February and October El Kod averages are in both cases strongly influenced by single historic days of heavy rainfall.

Under these circumstances, medians are better indicators of "average expected conditions". Estimated median monthly study area rainfalls are therefore shown in Table 2.3 and Figure 2.3. They were estimated from median monthly rainfalls at El Kod, Lahej and Jol Madram. Median rainfall is insignificant in all months and is therefore considered ineffective in satisfying crop water requirements. As the nearest station to the study area, the entire El Kod record is given in Appendix A.

2.3 STUDY AREA CLIMATE

Although the study area has a hot, arid climate, diurnal and seasonal variations are moderated by the proximity of the sea. The climate is characterized by:

- low and highly unreliable rainfall (see previous section)
- high sunshine and incident radiation
- gusty wind conditions in June, July and August leading to dust storms and generally poor visibility
- high humidity

2.3.1 Adopted climatic means

All stations in PDRY known to have recorded some climate data other than merely rainfall are shown in Figure 2.1. Only Giar and El Kod lie close to or within the study area. Giar was apparently operated for 3½ years, from 1965 to 1968. The exact site of the station is not known but is thought to have been at Giar Experimental Farm, just north of Jebel Khanfar. Both shortness of record and general lack of information regarding exposure, times of observation, etc, ruled out use of the Giar data to describe mean study area climate.

The El Kod station has been operated since 1958. Table 2.2 lists station details. In general the station is run well under difficult circumstances. Current problems with instruments are:

(i) the evaporation pan is very corroded.

(ii) a thermohygrograph, recently supplied by FAO, can only be accommodated by leaving the Stevenson screen open.

(iii) the sunshine recorder needs resetting.

The station site is fair, being between irrigated fields and low trees. It has bare sandy soil cover. Although not ideally situated to represent study area conditions, lack of a suitable alternative led to its adoption. With the exception of rainfall, then, all study area climatic values have been taken from the El Kod record. Rainfall values were derived as explained in 2.2.

Records were obtained from three sources:

(i) El Kod files for 1967-82

(ii) Empire Cotton Growing Corporation publications (ref 19) for 1961-5.

(iii) Dar Al-Handasah (ref 1) for 1958-60 and 1966.

The record was scrutinized for obvious errors and inconsistencies. Where possible the original daily records were used to correct them. In general the quality appears fair: certainly good enough for a number of detailed crop water requirement experiments in the 1950s and 1960s. The main problem arose with relative humidity values. Quoted monthly means appeared to increase suddenly and become more variable around 1967/8. Subsequent investigation suggested a likely cause: originally, observations were at 0630h and 1300h and were averaged, but currently the practice is to make only a single observation, at about 0700h. Only records up to 1967 were used, therefore. Where later values were needed for evapotranspiration estimates, 1958-67 monthly means were used.

The complete records of temperature, relative humidity, sunshine and run of wind are given in Appendix A. The adopted monthly means are summarized in Table 2.3. Although six years of Gunn-Bellani incoming radiation data are available between 1959 and 1966 the values presented by Dar Al-Handasah (ref 1), their principal source, appear suspect and have not been shown.

Seasonal variations show through quite clearly in Figure 2.3. Temperatures and evapotranspiration rates peak, and are nearly constant, over the summer period from May to August, and reach their lowest values in December and January. Somewhat surprisingly, sunshine hours are greatest in May, during the latter part of the Seif flood season. Low values in July are probably attributable to dusty atmospheric conditions.

Absolute highest and lowest air temperatures recorded either at Giar or El Kod are:

Absolute maximum 41.7°C (May 1965 at Giar)

Absolute minimum 10.0°C (November 1972 at El Kod)

2.4 EVAPOTRANSPIRATION ESTIMATES

Estimates of reference potential crop evapotranspiration (ETo) were required for irrigation agronomy studies. The Penman formula is widely recognized as a satisfactory method of estimating ETo and it was used here.

The formula may use either measured incoming radiation directly, or a regression equation enabling radiation to be estimated from sunshine measurements. About three years of monthly radiation values were available but, after some consideration, it was decided that this was too short a period either to establish a local sunshine-radiation relationship with any confidence or to be used as a basis for ETo estimates. Regional sunshine-radiation relations were therefore used.

The Penman formula can be written

$$ETo = B\ (Hi - Hb) + (1 - B)\ Ea$$

where Hi = nett incoming short-wave radiation, mm/day

Hb = nett long-wave outgoing radiation, mm/day

Ea = aerodynamic term, mm/day

B = D/(D+G) (D = slope of saturated vapour pressure curve in mb/°C, and G = psychrometric constant in mb/°C)

The weighting factor B (a function of air temperature and altitude) can be read from tables (eg McCulloch, reference 21). The radiation and aerodynamic terms are estimated from meteorological data as follows:

<u>Hi</u> $Hi = (1 - r)\, Ra\, (a_1 + a_2 n/N)$

where r = albedo (0.25 for crops, 0.05 for open water)

Ra = solar radiation at outer edge of atmosphere in mm/day (from McCulloch's tables)

n/N = no of bright sunshine hours/max possible hours of bright sunshine (from tables)

a_1, a_2 = regression constants

<u>Hb</u> $Hb = s\, Ta^4 (a_3 - a_4 \sqrt{he_a})(a_5 + a_6\, n/N)$

where s = 2.01×10^{-9} (Stefan-Bolzmann constant relating black-body radiation to temperature)

Ta = air temperature, °abs

h = relative humidity (as a fraction)

e_a = saturated vapour pressure, mb (function of air temperature, from tables).

$a_3 - a_6$ = constants

<u>Ea</u> $Ea = a_7 e_a (1 - h)(a_8 + a_9 u_2)$

where u_2 = wind run in km/day at 2m height

$a_7 - a_9$ = constants

Values of the constants a_1 to a_9 are shown in Table 2.4. They were taken from equation (5) of Faulkner and Evans (ref 20). This form of the equation is the same as Penman's original but incorporates Glover and McCulloch's sunshine-radiation relation (ref 22). Faulkner and Evans found in the course of experiments in Saudi Arabia that this equation (used in conjunction with crop factors from ref 23) agreed well with observed crop evapotranspiration rates. The widely used Doorenbos and Pruitt procedure (ref 23) was found by Faulkner and Evans to give substantial overestimates.

ETo values were estimated for each month of record with values of sunshine, wind run, relative humidity and temperature. Daily mean values were used in each case. This gave approximately 21 years of ETo estimates; they are shown in Appendix A. Monthly means appear in Table 2.3 and Figure 2.3. The annual total (rounded to three significant figures) is

Annual ETo = 1960 mm (5.37 mm/day)

Other annual ETo estimates seen were:

Dar Al-Handasah (ref 2)	:	1902 mm (El Kod)
GDC (ref 4)	:	1980 mm (El Kod)
GDC (ref 5)	:	1970 mm (Tuban delta)

In each of the above cases period climatic means were used rather than the more accurate approach, adopted here, of calculating ETo for each historic month of record. In Dar Al-Handasah's case, incorrect values of saturated vapour pressure were also used.

No frequency analyses of monthly ETo values were carried out, for two reasons:

(a) the variability of ETo is small beside inaccuracies in estimates of irrigation efficiency and readily available soil moisture.

(b) each field receives, generally, only one water application per growing season and so no response is possible to subsequent weather conditions.

Annual open water evaporation (Eo) was estimated (putting r = 0.05 and a_8 = 0.5) for three years whose annual ETos were close to the long term mean, from which was obtained:

annual Eo = 2380 mm (6.52 mm/day)

TABLE 2.1 RAINFALL RECORDS

Station	Latitude	Longitude	Grid ref	Alltitude (m)	Record	Total no of years	Av.ann. rainfall (mm)	Source
El Kod	13°05'N	45°22'E	NK3947	13	1958-83	25	49	a
Aden	12°47'N	45°02'E	NK0413	27	1870-1938	62	49	b
Khormaksar	12°49'N	45°02'E	NK0417	4	1940-66	27	38	b
Fiyush	12°59'N	44°57'E	MK9536	65	1973-82	10	51	c
Jawala	12°56'N	44°55'E	MK9130	52	1973-5	3	99	c
Little Aden	12°45'N	44°50'E	MK8210	12	1955-60	6	32	b
Sheik Othman	12°52'N	44°59'E	MK9923	14	1946-9	4	34	e
Lahej	13°03'N	44°53'E	MK8843	129	1973-82	10	63	c
Dhala	13°42'N	44°44'E	ML7114	1 500	1955-63, 1973-82	18	397	b,c,e
Jol Madram	13°21'N	44°42'N	MK6775	450	1972-81	9	152	c
Musaymir	13°25'N	44°37'E	MK5886	600	1972-9	8	288	d
Al Kirsh	13°22'N	44°30'E	MK4578	750	1972-9	8	192	d
Milah	13°25'N	44°50'E	MK8184	600	1972-8	7	202	d
'Arisa	13°30'N	44°28E	MK4292	900	1972-9	8	369	d
Qarad	13°45'N	44°36'E	ML5720	1 100	1972-9	8	298	d
Khalla	Location doubtful - see text				1972-9	8	258	d
Mukeiras	13°52'N	45°41'E	NL7341	2 150	1954-9, 1977-81	8	214	c,e
Beihan	14°47'N	45°44'E	NM7845	1 150	1955-9	2	194	f
Sha'b al Baari	13°46'E	45°17'E	NL3121	ca 1 700	1981-2	1	-	c
Alirgah	13°47'N	45°21'E	NL3824	ca 1 400	1981-2	1	-	c
Sarar	13°41'N	45°19'E	NL3512	ca 1 500	1981-2	1	-	c
Ibb*	13°59'N	44°11'E	ML1248	1 900	1969-80	12	1 760	d
'Udayn*	13°56'N	44°03'E	LL9741	1 800	1970-9	10	594	d
Sumarah*	14°07'N	44°12'E	ML1361	1 650	1969-77	9	803	d
Yarim*	14°18'N	44°23'E	ML3381	2 650	1969-80	12	691	d
Taiz*	13°34'N	44°01'E	LL9201	1 350	1944-7	4	521	b
Rihab*	14°14'N	44°07'E	ML0573	1 250	1969-76	8	516	d
Rida*	14°25'N	44°51'E	ML8394	2 150	1976-7	2	200	d

Stations marked * are in the YAR.

Sources:
- a = station observer
- b = Griffiths and Hemming (ref 18)
- c = MAAR files, Aden
- d = various sources quoted by GDC (ref 4)
- e = Meteorological Office, UK
- f = Abyan Board files

TABLE 2.2 - EL KOD CLIMATE STATION DETAILS

Location:	13°05'N 45°22'E (grid reference NK392474)
Altitude:	15 m
Observer:	Hasson Hadi Hamada
Observations:	currently once daily at 0700 h originally twice daily at 0630 h and 1300 h
First observations:	September 1958
Exposure:	open country to west and north, low trees to east.
Ground cover:	bare sandy soil

	Instrument	Condition
1.	Campbell-Stokes sunshine recorder (Negretti & Zambra model)	Table needs replacement and relevelling
2.	Standard raingauge (N & Z 200 mm dia.)	Satisfactory. Rim approx. 300 mm above ground.
3.	Psychrometer (non-aspirated)	Satisfactory
4.	Max and min thermometers	Minimum not working in May 1983.
5.	Piche evaporimeter (N & Z)	Satisfactory. Mounted in screen.
6.	Evaporation pan	Very corroded and dirty
7.	Anemometer (N & Z, 3 cup pattern)	Mounted approx 2.3 m above ground. Cups are battered but turn freely.
8.	Thermohygrograph (Seiki model, supplied recently by FAO).	Hygrograph pen not working, May 1983. Instrument too big for screen which is therefore propped open.

TABLE 2.3 STUDY AREA MONTHLY CLIMATE SUMMARY

Note: All values are averages except rainfall, for which median values are quoted.

	Years of Record	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Year
1. Rainfall, mm	--	0	0	0	2	5	1	9	4	16	0	0	1	70
2. Mean air temp, °C	20-23	23.8	24.4	25.7	27.4	29.3	30.7	30.5	29.7	29.6	26.7	25.3	24.3	27.3
3. Daily max temp, °C	22-24	28.0	28.6	30.0	31.8	34.1	35.7	34.9	34.4	34.4	32.5	30.8	28.8	32.0
4. Daily min temp, °C	20-23	19.4	20.3	21.4	23.0	24.4	25.6	26.2	25.2	24.7	20.9	19.8	19.8	22.6
5. Bright sunshine, h/day	20-22	8.4	8.9	8.7	9.3	10.3	9.0	7.8	8.8	8.7	9.6	9.9	8.7	9.0
6. Wind run, km/day (at 2m)	20-22	197	199	206	189	154	153	176	173	147	151	157	169	173
7. Relative humidity, %	8-10	72	73	75	74	74	70	71	70	73	70	69	70	72
8. ETo, mm (r=0.25)	18-21	128	131	162	176	195	185	184	189	176	166	140	125	1957
9. ETo, mm/day (r=0.25)	18-21	4.13	4.64	5.23	5.87	6.29	6.17	5.94	6.10	5.87	5.35	4.67	4.03	5.36

Notes:

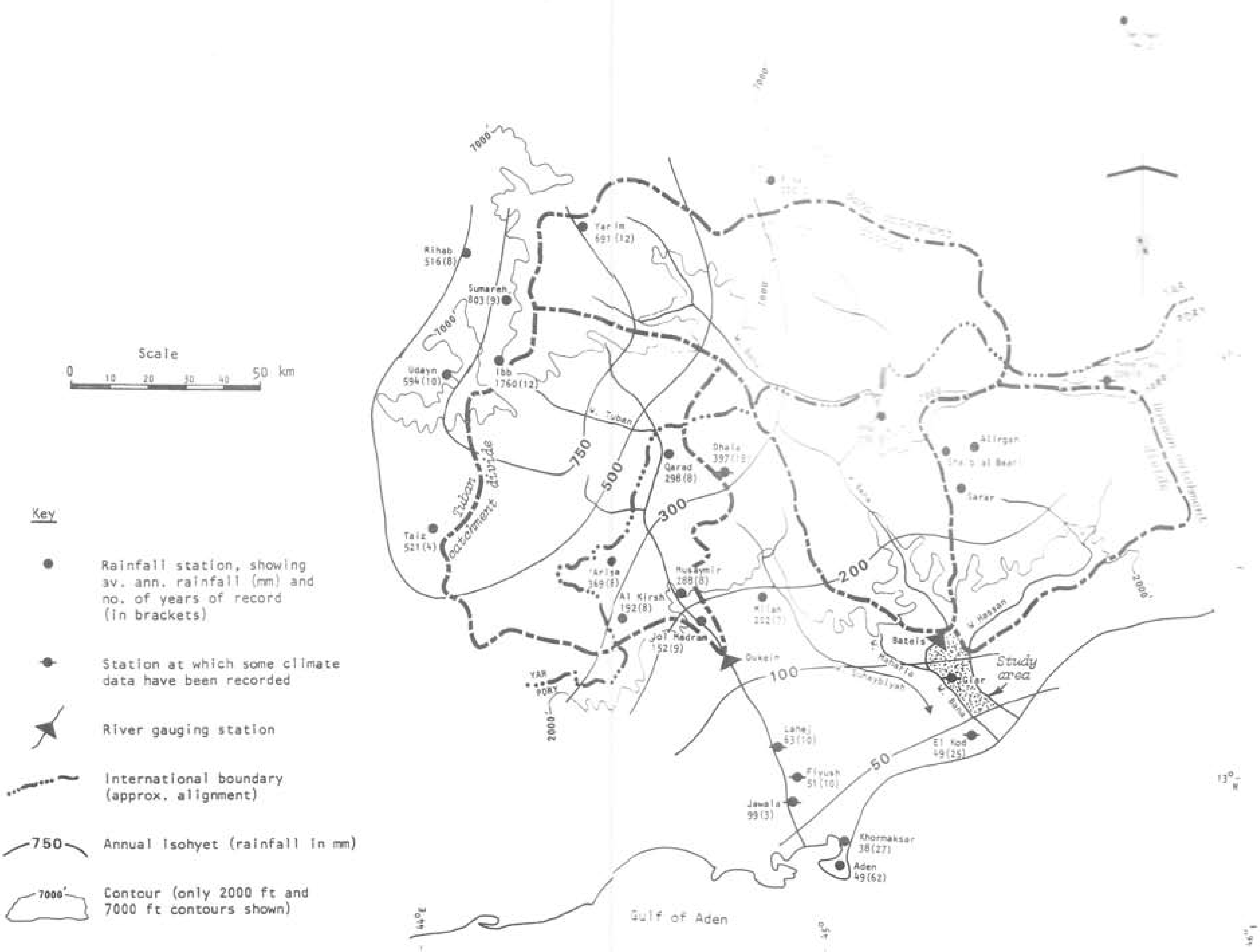
1. Items 2-7 observed at El Kod. See text for items 1, 8 and 9.
2. Daily mean air temp. =0.5 (Tmax + Tmin).
3. Annual means for items 2 - 7 and 9 are averages of monthly means. Total is given for item 8.
4. Observation periods are 1958-82 for items 2-6, 8 and 9, and 1958-67 for item 7.
5. Items 8 and 9: r = albedo.

TABLE 2.4 ADOPTED PENMAN CONSTANTS

Term	Constant	Value
Incoming radiation, H_i	a_1	0.28
	a_2	0.52
Back radiation, H_b	a_3	0.56
	a_4	0.08
	a_5	0.10
	a_6	0.90
Aerodynamic, E_a	a_7	0.26
	a_8	1.0/0.5
	a_9	0.0062

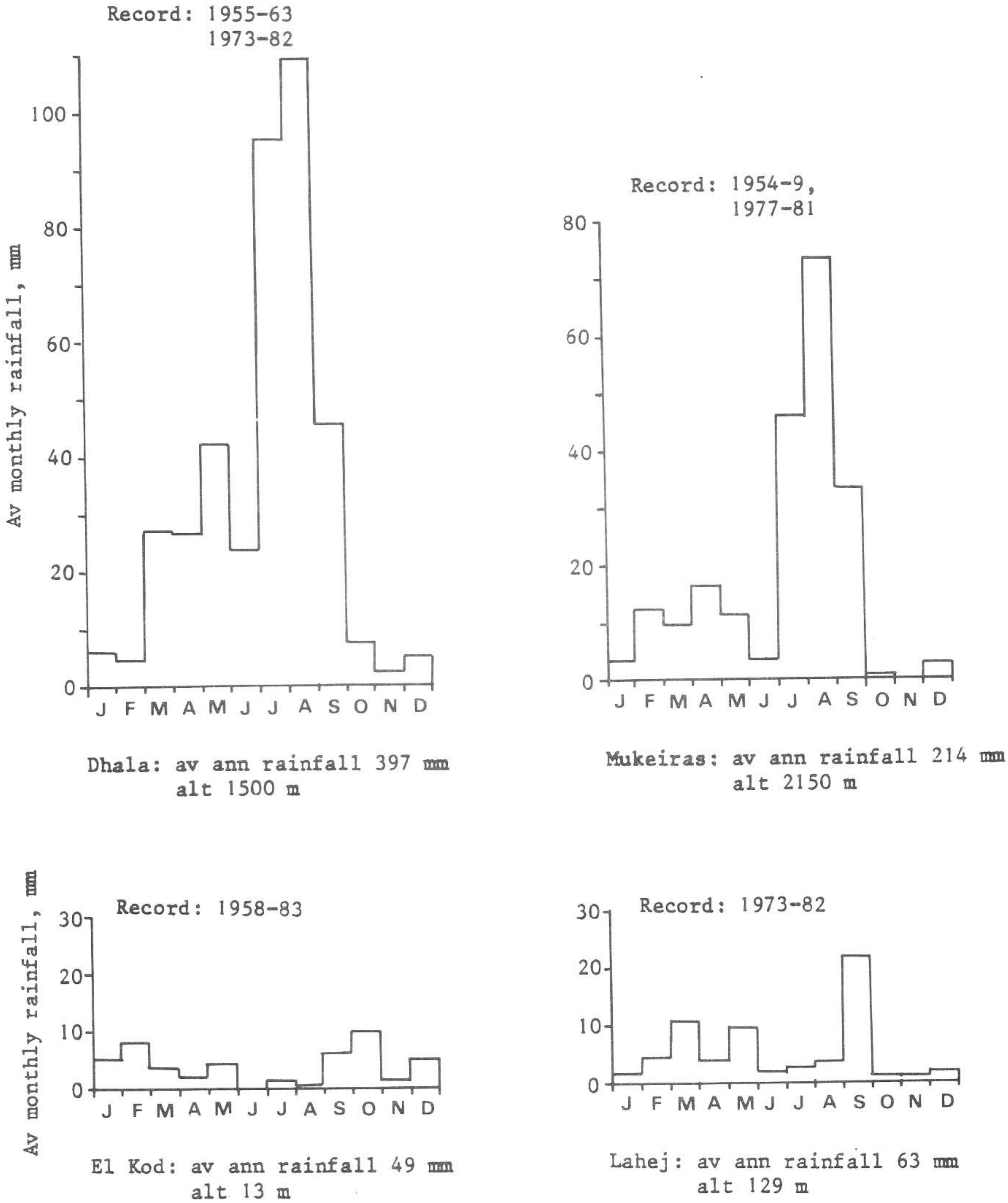
Notes

1. Units: pressures in mb, wind run in km/day.
2. a_1 derived from 0.29 cos (latitude).
3. a_8 = 1.0 for crops;
   a_8 = 0.5 for open water evaporation.



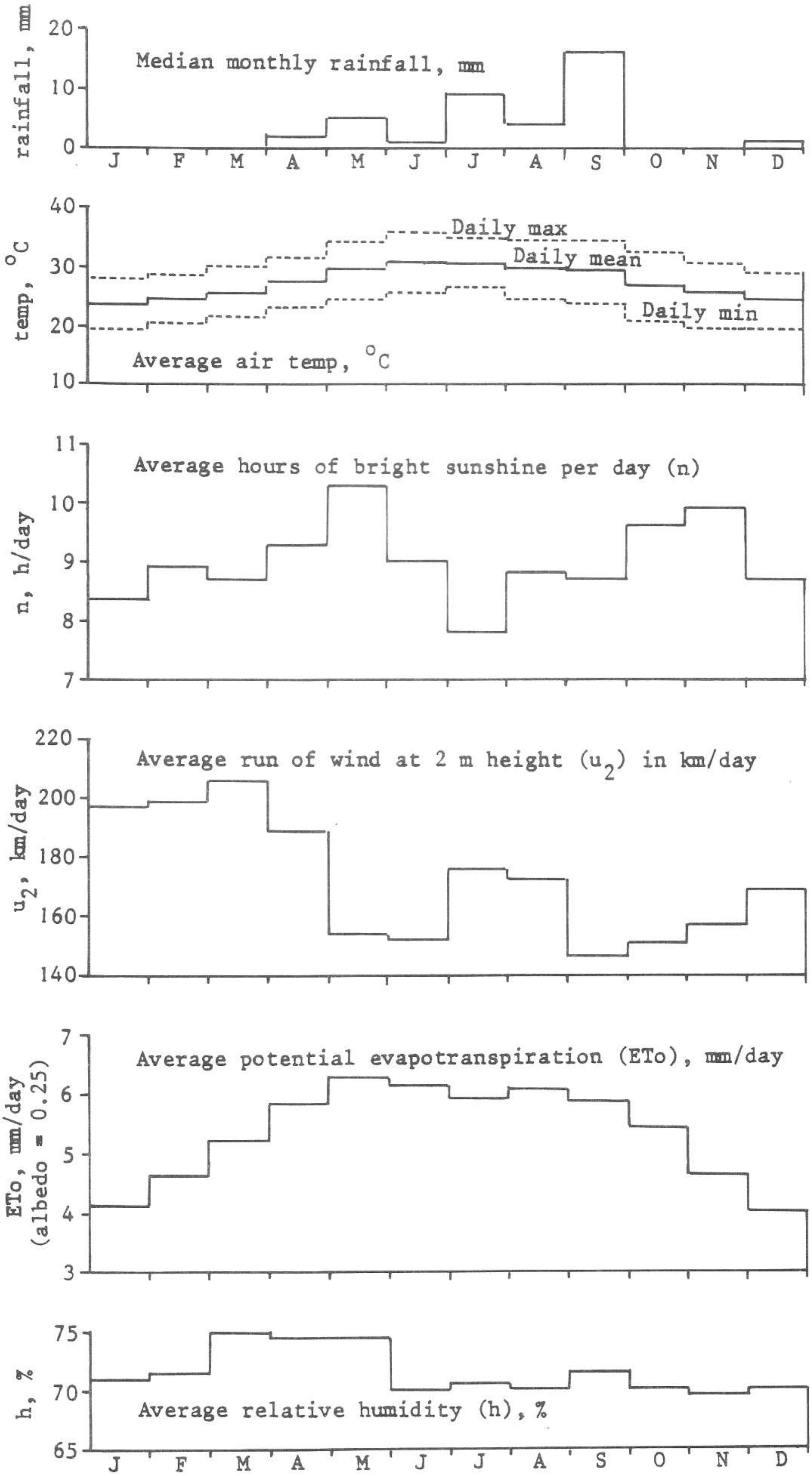
CATCHMENT AND PROVISIONAL ISOHYETAL MAP

Figure 2.1



MONTHLY RAINFALL DISTRIBUTIONS

Figure 2.2



Note

1. See Table 2.3 for tabulated values

STUDY AREA CLIMATE

Figure 2.3

3. SURFACE RUNOFF

3.1 INTRODUCTION

3.1.1 Available surface water resources

Two major wadis discharge regularly into the Abyan delta: Wadi Bana and Wadi Hassan (see Figure 2.1). Based on the adopted 1951-65 record (see below) the mean annual runoff (MAR) of Wadi Bana at Bateis is approximately 162 $M.m^3$, or about 6% of the estimated catchment rainfall (section 2.2). There are no records of Wadi Hassan flow. Assuming that percentages of rainfall emerging as surface runoff are similar for both wadis, Wadi Hassan's MAR at Ad Dirjaj may be of the order of 40 $M.m^3$, assuming no substantial upstream diversions. These figures may be summarized as follows:

Wadi	Area km^2	Rainfall input $M.m^3/yr$	MAR $M.m^3$
Bana (at Bateis)	7 200	2 590	162
Hassan (at Ad Dirjaj)	3 300	660	40

(Catchment areas planimetered on 1:100 000 1-GSGS sheets and 1:500 000 TPC sheet K-6AG).

Wadis Suhaybiyah and Maharia approach the delta from the west (Figure 2.1). Surface flow in these wadi probably only reaches the delta during rare floods, being otherwise entirely diverted for irrigation or lost as wadi bed infiltration upstream. Their significance for Abyan delta water resources lies chiefly in their contribution to groundwater recharge.

The irrigation area commanded by Wadi Hassan amounts to about 4 400 ha within the Abyan delta (Dar Al-Handasah, ref 2). GDC (ref 3) report a further 1 200 ha being cropped in 1978 at the Yeramis cooperative, well upstream of Ad Dirjaj. Assuming a Kharif season gross irrigation depth of 0.7 m, approximately 40 $M.m^3$ would be needed to irrigate this area.

There is thus no scope for transfers of water to supplement Wadi Bana flows, and to the best of our knowledge no such transfers have been made. Additional evidence to support this comes from the practice of transferring water in the other direction, i.e. from the Bana to the Hassan (see below).

3.1.2 Nature of Wadi Bana runoff

Approximately 90% of the mean annual runoff occurs during two main flood seasons from March to May and from July to October. The catchment is steep and largely covered by bare rock of low permeability: storm rainfall thus emerges as sudden spates in the wadi. (Hydrograph shape is discussed in more detail in chapter 4). Numbers of individual flood peaks (regardless of magnitude) are available for 1951 and 1953-5 (tallied and recorded in the Abyan Board water books) and have been counted for 1958 and 1963 (driest and wettest years respectively of the adopted 1951-65 record). The six year average was 115 floods/year. The number of floods counted in this way and the total annual runoff appear to be unrelated.

Reports and records indicate that some surface flow is available throughout most years at Bateis. This appears to be groundwater which emerges as surface water just upstream of Bateis; at Ligma, some 3 km upstream of Bateis (see Figure 3.1), the wadi bed is said to be dry for most of the dry season. GDC (ref 3) estimated the flow at Bateis to be about 50 l/s (4 000 m^3/day) at some time during the 1979/80 dry season. (The timing of the present study precluded any such measurements).

A number of other springs in this area may have an origin similar to that of the Bateis dry season flow. Flow (measured as 300 l/s in June 1983) emerges in the hitherto dry Wadi Hurub bed about 400 m above the Bana/Hurub confluence. At this point the Hurub follows what may be an old Bana channel and it is probable that water still moves through the alluvium between the present and the former watercourse. Similarly a small perennial spring flow emerges just south of a marshy area near Shakat ba Omer and is used locally for irrigation. The locations of these points are shown in Figure 3.1.

More deep-seated springs also exist in the area. Spring flow was seen in a limestone gorge in the Hurub catchment, about 5 km upstream of the Bana confluence, and two springs, one of which was hot and very saline, were noted on the right bank of the Wadi Bana about 10 km upstream of Bateis.

3.1.3 Other water users

Considerable areas are known to be irrigated from small-scale diversion works in the upper Bana catchment, both in the YAR and in PDRY. Unfortunately, information on the quantities of water involved is not readily available and we have had to assume that runoff characteristics at Bateis will remain substantially the same as during the adopted runoff record from 1951 to 1965. The El Gebla irrigation immediately above Bateis (Figure 3.1) has an area of only 130 ha and its requirements are negligible by comparison with offtakes further downstream.

There are no other existing, or, to our knowledge, potential users of Wadi Bana surface water between Bateis and the sea. Transfers to Wadi Hassan must be mentioned, however. Up to the flood of March 1982 transfers could be made by two canals:

(i) Shakat ba Omer (SBO) canal

(ii) Bani-Hassan canal

The arrangement is sketched in Figure 3.1. Both canals have small irrigation commands in their own right: the gross seasonal requirement of Shakat ba Omer's command is about 1 $M.m^3$. Of the two canals only Bani-Hassan is currently serviceable, but Shakat ba Omer will be reinstated once the new Bateis weir is complete. There is also a possibility that a new 40 m^3/s link canal will be built, also to be supplied from the new Bateis headworks.

Values for Bani-Hassan flows are not available: they are included in Main Canal totals. However, when Main Canal diversions are compared with estimated irrigation demands of its command area, it is clear that transferred volumes must be very small. Shakat ba Omer, however, has a significant nominal capacity of 10 m^3/s (Dar Al-Handasah, reference 2). For seven years for which data were readily available, Shakat ba Omer volumes were compared with total Seif and Kharif seasonal runoffs (see section 3.4 for discussion of irrigation seasons):

Year	Seif volumes ($M.m^3$) W Bana	SBO	Kharif volumes ($M.m^3$) W Bana	SBO
1952	19.2	3.7	83.9	8.3
1953	28.5	3.2	108.5	10.8
1954	23.2	0	163.8	4.5
1955	13.9	3.0	118.8	2.2
1960	70.8	4.8	41.7	0.2
1961	7.3	0	77.6	0.3
1962	10.6	0	131.0	2.1

Shakat ba Omer volumes are small compared with total irrigation season runoffs. This accords with what we understand to be the operating policy: that transfers to Wadi Hassan are only made when there is no demand for water in the area command by Wadi Bana.

3.2 WADI FLOW RECORDS

3.2.1 Records available

Published Wadi Bana runoff data are available from two main sources: Dar Al-Handasah (reference 1) and Sogreah (reference 24). Dar Al-Handasah compiled and reproduced Abyan Board and MAAR monthly runoff volumes for the period 1948-71, and daily volumes for March 1951 to September 1971. Sogreah extended the record, again using MAAR and Abyan Board data, to 1977. For 1978 and 1979 only annual totals are available. Published monthly data are summarized in Table 3.1.

For this study estimates of flows averaged over much shorter periods than one day were needed (because of the extremely flashy nature of runoff - see section 3.1). It was fortunate, then, that we were able to acquire the original Abyan Board water books for 1951-65, which contain complete sets of Bateis staff gauge readings. (No routine staff gauge readings have been made at any of the weirs below Bateis).

In addition, a number of miscellaneous Wadi Bana gaugings have been reported by Dar Al-Handasah (1971), Sogreah (1970) and GDC (1979). They are listed in Appendix B. Significant amounts of runoff data for comparable catchments in PDRY are, to our knowledge, limited to Wadi Tuban (see Figure 2.1 for catchment location). For this catchment GDC (references 4 and 5) have worked up daily flows for 1973-80 and have also estimated annual totals for 1955-61 and 1968-72. Monthly totals from 1980 to June 1983 are available in MAAR files in Aden.

3.2.2 Gauging arrangements; data quality

The bulk of the available Wadi Bana runoff estimates are based on staff gauge readings in four canals at Bateis and in the wadi below the old Bateis headworks as follows:

1. Bateis Canal
2. Maincanal
3. Shakat ba Omer Canal
4. Massani Canal
5. Wadi Bana

Added together, the flows at these gauges represent the total runoff available at the old Bateis weir.

The sketch in Figure 3.1 shows the gauging arrangements as they are thought to have existed for most of the period of record. There was evidently no means of recording water level at the old Bateis weir, presumably because the procedure began before any permanent weir existed. In September 1981 flood waters removed the Wadi Bana staff gauge, while in March 1982 the upper reaches of Shakat ba Omer canal were destroyed, also by floods. The Massani canal headworks have also been destroyed in recent years. Thus, only Bateis and Maincanal staff gauges are read at present, Wadi Bana stages being estimated by the gauge reader. Despite rumours to the contrary we have seen no evidence that a water level recorder at Ligma has ever existed.

At least for the early part of the record gauges were read several times a day, generally at 6h intervals during low flow periods and increasing to typically 10-20 times per day (including the night) during periods of high flow. Gauge plates appear to have been marked only at 50 mm intervals. Nevertheless, the very frequency of observations is encouraging.

The same rating curves have been in use since at least 1951. In the case of the canal drop structures these were theoretical weir ratings and, despite Dar Al-Handsasah's findings in 1971, were probably satisfactory for the structures in existence during the early part of the the record.

The origin of the Wadi Bana rating is unknown: there are no records of any early flow measurements, and it may therefore have been based on slope-area estimates. There is no stable control anywhere in this reach of the wadi, although it is said that earthmoving equipment was used to reestablish the section following a flood. Records of flows passing the old Bateis weir are therefore of quite unknown reliability. In practice this means any flows above the combined Bateis and Maincanal capacity of about 30 m^3/s, and later in the irrigation season, all flow. Despite this, Dar Al-Handasah's review (in ref 1) of flow measurement indicated only an 18% overestimate, using the Abyan Board ratings, of a measured Ligma discharge of 112 m^3/s (although their method of measuring this flow is unknown).

The only improvement which could be made to the Wadi Bana rating during this study was to realign the high flow section above 500 m^3/s to pass through the 17 September 1981 estimated peak stage (4m) and discharge (2 450 m^3/s). Other improvements are now impossible . (Although Sogreah (ref 24) produced a new rating in 1978, it would not necessarily be any more applicable to the bulk of the record than the Abyan Board rating). For want of a practicable alternative, then, it was decided to adopt the Abyan Board ratings, the high flow Wadi Bana rating having been adjusted as described above. They are tabulated in Appendix B.

3.2.3 Adopted record; reworked flows

Many of the recessions between the main flood seasons appeared highly suspect. Daily flows from the water books (and published by Dar Al-Handasah in reference 1) were apparently constant for weeks and even months. They also appeared far too high in the light of dry season flow observations (section 3.1): flows at Bateis at the ends of dry seasons were frequently recorded as 5 to 10 times GDC's value of 50 l/s.

Although unimportant beside flood season runoffs, recessions were fitted to replace particularly suspect dry season flows in order to obtain a more realistic picture of the seasonal runoff pattern. The very lack of more than a few credible recessions made this a rather crude operation. The recession equation can be written

$$Q_t = Q_o K^t,$$

where Q_o is the initial flow, Q_t the flow after t days and K is the daily recession constant. After plotting a number of recessions on semilogarithmic paper, the following set of K values was adopted:

Range of Q_o (1 000 m³/day)	K
150 to 100	0.70
100 to 30	0.73
30 to 10	0.75
10 to 3	0.90
less than 3	0.96

Adopted daily flows for 1951-65 using the above correction for recessions and the adjusted rating curve are shown in Appendix B. Values reworked during this study or replaced by a fitted recession are clearly indicated. The remainder are Abyan Board water book values and are in nearly all cases identical with those tabulated by Dar Al-Handasah. Adopted monthly and half-monthly values appear in Tables 3.2 and 3.3 respectively. For reasons already discussed above it will be apparent why the values are on average slightly lower (5% for the 1951-65 period) than the previously published estimates shown in Table 3.1.

3.2.4 Short duration flow data

For this study it was necessary to have hourly (or similar) flows for flow-duration work and the operation studies, as well as estimates of Seif and Kharif flood volumes. Scrutiny of the published and unpublished data led us to the conclusion that the record from 1951 to 1965 was by far the most reliable, as it has few gaps and a well documented stage record, and is the period to which the Abyan Board ratings are most likely to apply. This period was therefore adopted for all flow-duration and seasonal runoff frequency studies. The question of representativeness is discussed below.

To get the hourly flows referred to above and to study hydrograph shape in any detail, considerable time was spent reworking basic stage data. A program was written for the HP9825A to handle up to 15 stage readings per day on each of 5 staff gauges. Six entire flood seasons were reprocessed in this way: these seasons were selected after frequency studies of seasonal runoffs (see below). In addition, many individual high flow periods were reprocessed, for two reasons:

(a) in order to study hydrograph shape;

(b) because the original Abyan Board calculations frequently appear to have overestimated the time to peak of a spate. This arose because stages immediately before a flood were often not noted. In this study a time to peak of 1h (based on hydrographs reproduced by Sogreah (ref 24)) was assumed if no better figure could be inferred from the water book records.

3.3 WADI BANA RUNOFF CHARACTERISTICS

3.3.1 Annual runoff

Annual runoffs for 1951-65 are shown in Table 3.4, while estimated values for other years between 1948 and 1979, and Wadi Tuban values, are shown in Table 3.5. Annual runoffs for various non-exceedance probabilities were estimated on the basis of the 1951-65 data only. The annual totals were ranked and plotted on log normal probability paper and the following estimates obtained:

Non-exceedance probability, %	Annual runoff $M.m^3$
20	110
50	155
80	210

Mean annual runoff (MAR) for the adopted 1951-65 record is 162 $M.m^3$, or 6% of the estimated catchment rainfall. MARs as percentages of rainfall for two comparable wadis are 4% for Wadi Tuban (1973-80 record) and 7% for Wadi Najran (1967-74 record; see reference 25). Whilst providing some reassurance for the Wadi Bana value, it should be remembered that each of these percentages compounds errors in both rainfall and runoff estimates.

Comparison of the adopted 1951-65 period with the longer record from 1948 to 1979 in Table 3.5 does not suggest that it is unrepresentative of long-term conditions, either in terms of mean or spread. In view of the poor quality of the data, no firmer conclusions can be drawn. Long records of rainfall or of runoff from other wadis, which might have helped, are not available.

Figure 3.2 shows plots of cumulative departures from the mean of Wadi Bana and Wadi Tuban annual runoffs, and of annual rainfall averaged for various combinations of stations. The only sign of persistence is the four year run of lower than average Wadi Tuban annual runoffs from 1972 to 1976. There is no indication that the Sahel drought of the late 1960s and early 1970s affected conditions here. The apparent lack of correlation between runoffs from the two wadis (Figure 3.2) probably arises from the fact that the overlapping period is drawn from the least reliable part of each record.

Years of notably low Wadi Bana runoff were 1976 and 1958: the latter is remembered locally. Unfortunately data for the very recent years are not available. If we may assume that Tuban and Bana annual runoffs are correlated, then the Tuban data suggest that, relative to average conditions, 1977-8 was wet, 1979-80 was dry and 1981 was around average. The March 1982 floods place that year in the "wet" category.

3.3.2 Monthly and half-monthly runoff

Adopted monthly and half-monthly runoffs for 1951-65 are shown in Tables 3.2 and 3.3. Half-monthly means are plotted in Figure 3.3. This figure shows clearly the two flood seasons the predominance of the later, July to October, season. The Wadi Tuban seasonal pattern (Table 3.1 in reference 5) differs somewhat in that the two flood seasons merge and mean monthly runoffs build up steadily from April to September. This may be attributable to more permeable rock types in the Tuban catchments, or of course to differences in seasonal rainfall patterns.

3.3.3 Daily and hourly flows

Daily flow hydrographs for the representative Kharif years, 1961 and 1962, (section 3.4) are shown in Figures 3.4a and 3.4b. The frequent flood peaks and steep recessions are clearly shown. The same features are evident in Figures 3.5a and 3.5b, which show hourly flows for a selection of Seif and Kharif seasons used in the operation studies.

3.4 IRRIGATION SEASON RUNOFFS

The timing of the Seif and Kharif irrigation seasons are determined both by expectations of high wadi flows and by agricultural practices. The Kharif season is the more important, both agriculturally and in terms of available runoff, and the timing is laid down in an irrigation programme issued in late June or early July. The Seif season appears to be less rigidly defined and the period adopted here was derived from hydrological considerations.

The adopted seasons are:

(i) Kharif season : 1 July to 15 October

(ii) Seif season : 16 March to 31 May

The hydrological sense behind these seasons is shown clearly in Figure 3.3, which shows the seasonal distribution of average half-monthly runoffs, and in Figure 3.6, which shows the frequencies of high runoff pentads (ie 5 day periods with a total runoff exceeding 5 $M.m^3$). During the period 1951-65 the two irrigation seasons accounted for 90% of the annual runoff. 66% was accounted for by the Kharif season alone.

Table 3.4 lists annual and irrigation season runoff volumes. Although the series are short, a number of simple statistical tests were carried out to assist in understanding the nature of seasonal runoff. The following results, all quoted at the 5% level of significance, were obtained:

(i) positive correlations obtained between Seif and annual volumes, and between Kharif and annual volumes, are significant.

(ii) there is no significant correlation between Seif and Kharif volumes occurring in the same year.

(iii) wetter or drier than average seasons occur randomly.

These results lend support to the argument in chapter 2 that quite separate weather systems are responsible for the two flood seasons.

For the operation studies and flow-duration work it was necessary to carry out frequency analyses of irrigation season runoffs. The ultimate objective of this was to assess the reliability with which a given area might be irrigated by Wadi Bana. Seasonal volumes from Table 3.4 were therefore ranked and plotted, using unbiased plotting probabilities, on normal probability paper. Arithmetic probability paper was satisfactory for the Kharif values, but even a three parameter log normal distribution was not entirely suited to the Seif seasonal runoffs.

Values with 20%, 50% and 80% non-exceedance probabilities were estimated from the plots, and historic years with seasonal runoffs close to these values were identified for further analysis:

	Non-exceedance probability (%) 20	50	80
Kharif runoff, M.m^3	77	108	140
Closest recorded season	1961	1953	1962
Recorded volume, M.m^3	77.6	108.5	131.0
Corresponding non-exceedance probability (%)	21	50	73
Seif runoff, M.m^3	13	22	52
Closest recorded season	1962*	1954	1960
Recorded volume, M,m^3	10.6	23.2	70.7
Corresponding non-exceedance probability (%)	12	55	85

(* 1962 was not the closest recorded season but was chosen because it contained fewer infilled recession values).

3.5 FLOW DURATION STUDIES

A flow duration curve shows the relationship between a given flow and the proportion of time that this flow is exceeded. It may be used to estimate the proportion of total flow in a river which can be diverted by a canal intake of known capacity. In this study one of the objectives was to estimate volumes which could be diverted from Wadi Bana at Bateis (the only point at which flows are known), and the flow duration curve approach was ideally suited to this. The time step over which flows are averaged is important: too long a step will give an over-optimistic impression of the efficiency of diversion. An hourly time interval was used here.

In the time available for the study it was not possible to derive hourly flows for the entire 1951-65 period. Instead, hourly flows were derived only for the three Kharif and three Seif seasons identified for further study in section 3.4, i.e a total period of 18 months. Discharges were expressed as proportions of the average daily flow (ADF) for the season concerned: this enabled comparisons to be made between seasons of higher or lower than average flow.

Flow duration curves were drawn for each of the six seasons (Figure 3.7) and from them the following conclusions were drawn:

(i) no consistent pattern distinguishes between the flow duration characteristics of the dry, average or wet Kharif or Seif seasons chosen.

(ii) Kharif and Seif seasons do have different flow duration characteristics, the Seif season flows showing greater variability.

For general use, then, it was decided to pool hourly flows for each season. The result is Figure 3.8, plotted on log normal probability paper. It can be seen that the logarithms of hourly flow ratios are approximately normally distributed.

The final stage was to use the flow duration curves to estimate proportions of ADFs which could be diverted for given intake capacities, also expressed as proportions of the ADF. Figure 3.9 shows the diversion curves for each of the six seasons and Figure 3.10 the two curves using the pooled Seif and Kharif season data. Use of these curves is described in chapter 5.

The flow duration charactistics of the selected seasons were compared with those of other seasons with similar total runoffs. The results were used to aid interpretation of operation study results. In the absence of hourly flows for all seasons, daily data were used to make the comparison. Figure 3.11 shows the results, graphically, for the more important Kharif season. Daily flow duration data for the selected season are in each case plotted alongside those for three other seasons with similar total runoffs.

The differences in variability of Kharif daily flows are not great, as Figure 3.11 shows. Qualitative results are summarized below.

Selected Kharif season	Non-exceedance prob of total runoff (%)	Comparison with variability of other Kharif seasons
1961	21	Similar
1953	50	Slightly less variable
1962	73	Slightly more variable

A similar exercise for Seif seasons gave the following results:

Selected Seif season	Non-exceedance prob of total runoff (%)	Comparison with variability of other Seif seasons
1962	12	Slightly less variable
1954	55	Slightly less variable
1960	85	Similar

TABLE 3.1 <u>PREVIOUSLY PUBLISHED WADI BANA MONTHLY RUNOFF ESTIMATES</u>

All values in million cubic metres ($M.m^3$)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
1948	-	-	-	-	2.8	3.7	15.1	34.6	7.6	3.0	0.3	0.6	-
1949	0.1	-	0.9	0.4	20.9	2.9	28.6	17.6	9.0	-	2.6	4.9	-
1950	0.6	0.4	2.5	18.7	16.0	7.8	48.9	88.4	20.4	2.2	1.6	1.6	209
1951	-	-	(14.0)	10.4	10.9	1.6	13.8	115.4	14.6	3.7	1.5	2.0	-
1952	1.5	0.8	10.7	11.2	2.7	3.7	11.7	54.3	32.6	0.5	0.4	1.0	131
1953	0.2	0.1	0.2	33.3	2.4	3.3	50.1	38.5	32.4	3.8	3.9	10.8	179
1954	1.4	2.4	13.5	10.6	8.8	14.6	66.6	88.1	43.2	16.3	7.3	6.1	279
1955	14.6	2.6	6.1	4.5	6.0	8.6	20.2	37.5	54.8	4.3	2.8	4.2	166
1956	2.3	1.3	0.6	12.9	1.1	2.0	14.8	51.3	18.4	20.5	1.5	1.2	128
1957	1.3	4.8	6.1	56.0	88.2	18.1	18.1	62.4	13.8	5.7	7.3	5.2	287
1958	5.7	3.8	2.5	10.3	0.3	2.1	17.3	31.5	6.4	2.2	2.1	1.8	86
1959	1.8	1.6	1.0	0.5	8.8	3.0	12.8	52.0	39.8	4.2	2.4	2.9	131
1960	1.9	1.7	13.5	21.2	30.3	2.0	10.0	11.7	17.8	1.4	1.1	2.3	115
1961	1.1	1.5	1.0	5.4	1.1	4.8	12.1	39.7	18.2	2.1	2.4	1.3	91
1962	0.4	0.4	3.1	5.8	2.8	11.6	8.0	67.8	46.7	2.1	1.4	1.2	151
1963	2.2	1.0	0.6	77.0	49.3	8.8	37.4	57.0	17.1	6.7	5.6	2.1	265
1964	2.0	1.5	0.5	37.3	4.3	4.5	50.6	62.3	33.6	12.5	2.5	3.9	215
1965	2.9	0.6	0.2	25.8	0.6	0.1	20.9	46.1	15.5	3.4	7.4	1.4	125
1966	2.2	7.6	(1.2)	(4.6)	-	(3.1)	11.7	29.5	32.3	2.7	1.9	(0.2)	-
1967	-	-	(3.8)	(18.2)	(50.7)	-	(41.4)	(20.9)	(13.6)	-	-	-	-
1968	(0.3)	(6.1)	(1.8)	(24.7)	(11.0)	(7.0)	48.4	40.7	27.5	4.9	6.0	4.8	-
1969	3.1	4.8	12.8	(6.7)	(8.7)	-	(4.2)	57.7	31.6	(0.7)	(1.6)	4.5	-
1970	(3.9)	(0.9)	(30.5)	(15.6)	(5.3)	-	(22.3)	39.8	(12.3)	6.7	(0.1)	(0.3)	-
1071	(0.2)	-	(5.2)	5.1	(27.6)	11.0	9.4	13.5	10.4	-	-	-	-
1972	-	-	-	-	-	-	-	-	-	-	-	-	-
1973	0.2	-	-	-	0.8	0.7	0.8	8.7	20.0	64.2	0.2	-	-
1974	-	2.0	2.6	0.2	5.9	6.2	10.3	-	-	1.2	-	3.2	-
1975	-	-	-	-	-	-	-	-	-	-	-	-	-
1976	-	13.0	1.0	19.7	13.3	5.6	8.8	5.4	3.3	2.0	6.8	0.9	-
1977	0.6	1.7	0.7	19.4	2.3	6.0	5.6	36.0	17.3	-	-	-	-
1978	-	-	-	-	-	-	-	-	-	-	-	-	219
1979	-	-	-	-	-	-	-	-	-	-	-	-	97

<u>Notes:</u>
1) Brackets signify a month whose data are known to be incomplete
2) - = no data, or data not available
3) Sources : 1948-71 Abyan Board records and Dar Al-Handasah (ref.1). 1973-9 Sogreah (ref.24)

TABLE 3.2 ADOPTED WADI BANA MONTHLY RUNOFF VOLUMES IN M.m^3 AT OLD BATEIS WEIR, 1951-65

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
1951	-	-	(17.03)	8.07	11.67	1.61	14.09	99.05	13.93	3.24	0.31	0.94	-
1952	0.15	0.03	10.04	10.51	2.46	3.24	11.60	47.37	23.53	1.46	0.32	0.46	111
1953	0.04	0.01	0.09	25.96	2.40	3.40	37.81	37.79	30.53	3.75	3.34	9.71	155
1954	1.42	2.30	7.23	7.91	9.43	11.54	40.73	72.61	43.40	16.32	7.34	6.14	226
1955	15.26	2.59	6.08	4.49	5.87	8.74	22.51	41.80	51.99	4.16	0.56	2.98	167
1956	1.23	1.33	0.62	13.02	1.07	3.07	14.62	57.49	20.26	20.07	0.84	0.05	134
1957	0.00	2.46	6.05	51.56	86.12	16.90	17.02	59.91	13.69	5.72	4.65	3.15	267
1958	4.85	3.77	2.99	9.86	0.15	1.95	18.76	31.90	6.37	2.17	0.92	0.05	84
1959	0.47	0.11	0.57	0.25	12.04	2.91	15.10	56.43	47.32	3.96	1.30	2.10	143
1960	0.55	0.06	12.86	25.32	35.50	2.03	10.50	11.76	18.83	0.72	0.43	1.66	120
1961	0.50	0.86	0.73	5.44	1.18	4.85	12.85	42.98	20.04	1.94	2.42	0.94	95
1962	0.16	0.23	3.50	6.27	2.91	11.71	8.55	72.31	48.93	1.91	1.23	0.56	158
1963	1.55	0.45	0.22	83.16	48.95	7.42	30.28	72.82	19.34	4.28	5.09	0.93	274
1964	0.43	0.04	0.02	23.35	5.02	4.48	57.55	65.52	33.52	19.08	1.71	3.74	214
1965	2.90	0.64	0.24	26.57	0.72	0.19	19.64	48.73	15.51	3.35	7.40	1.06	127
Average	2.11	1.06	3.66	20.12	15.03	5.60	22.11	54.56	27.15	6.14	2.52	2.30	162
% of MAR	1.3	0.7	2.3	12.4	9.3	3.4	13.6	33.6	16.7	3.8	1.5	1.4	

TABLE 3.3 ADOPTED WADI BANA HALF-MONTHLY RUNOFFS AT OLD BATEIS WEIR, 1951-65

Runoffs expressed in $M.m^3$

	Jan		Feb		Mar		Apr		May		Jun		Jul		Aug		Sep		Oct		Nov		Dec	
	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2
1951	-	-	-	-	-	(17.03)	7.79	.28	10.52	1.15	.25	1.37	4.19	9.90	51.15	47.89	10.39	3.54	2.36	.88	.24	.07	.23	.70
1952	.11	.04	.02	.01	3.80	6.24	.10	10.41	2.34	.12	.04	3.21	3.58	8.02	15.91	31.46	20.84	2.69	1.37	.09	.03	.30	.39	.06
1953	.03	.02	.01	0	0	.09	3.24	22.71	1.89	.52	1.93	1.46	9.81	28.00	19.03	18.76	16.77	13.76	2.36	1.38	1.72	1.62	1.31	8.40
1954	1.01	.41	.89	1.41	1.34	5.89	6.55	1.36	7.63	1.80	.96	10.58	10.60	30.13	30.85	41.76	26.68	16.72	7.09	9.24	4.23	3.10	2.93	3.21
1955	4.59	10.67	1.54	1.06	2.55	3.53	1.30	3.19	3.55	2.32	5.56	3.17	12.15	10.35	3.79	38.02	19.45	32.54	2.51	1.65	.14	.42	.35	2.63
1956	.66	.57	.86	.47	.36	.26	.59	12.43	.92	.15	.03	3.04	2.03	12.59	42.68	14.81	6.35	13.90	19.70	.38	.43	.41	.04	.01
1957	0	0	.12	2.34	3.85	2.20	14.79	36.76	31.67	54.44	11.91	5.00	6.83	10.18	36.88	23.03	10.13	3.55	2.67	3.05	1.89	2.75	1.96	1.19
1958	2.44	2.41	2.31	1.46	1.01	1.99	8.92	.94	.12	.04	1.11	.84	1.88	16.88	16.90	15.00	4.12	2.25	1.05	1.12	.83	.09	.03	.02
1959	.01	.46	.08	.03	.36	.21	.22	.04	1.50	10.55	1.83	1.07	5.67	9.43	29.63	26.80	39.98	7.33	2.54	1.42	.16	1.14	1.09	1.01
1960	.26	.29	.04	.02	2.89	9.97	12.04	13.29	16.55	18.94	.99	1.04	2.18	8.32	4.63	7.12	11.76	7.07	.66	.06	.24	.19	1.41	.25
1961	.21	.29	.72	.14	.04	.69	3.85	1.60	.72	.46	1.32	3.53	4.98	7.87	30.47	12.51	16.73	3.30	1.76	.18	.49	1.93	.45	.49
1962	.12	.04	.15	.08	2.13	1.37	.06	6.21	2.55	0.36	9.66	2.05	4.64	3.90	19.75	52.55	35.44	13.50	1.20	.71	.30	.93	.10	.46
1963	1.46	.09	.03	.42	.19	.04	42.09	41.07	43.56	5.38	2.99	4.44	6.07	24.20	27.24	45.58	12.27	7.07	4.10	.18	2.83	2.27	.88	.05
1964	.35	.08	.03	.02	.01	0	22.94	.40	.07	4.96	.57	3.92	1.12	56.43	28.61	36.91	20.20	13.32	5.71	13.37	1.13	.59	1.20	2.54
1965	2.01	.89	.38	.26	.19	.05	4.78	21.78	.65	.07	.03	.16	9.97	9.67	9.04	39.69	12.24	3.27	.75	2.60	3.22	4.18	1.00	.06
Average	.95	1.16	0.51	0.55	1.34	2.32	8.62	11.50	8.28	6.75	2.61	2.99	5.71	16.39	24.44	30.13	17.56	9.59	3.72	2.42	1.19	1.33	0.89	1.41
% of MAR	.6	.7	.3	.3	.8	1.4	5.3	7.1	5.1	4.2	1.6	1.8	3.5	10.1	15.1	18.6	10.8	5.9	2.3	1.5	.7	.8	.6	.9

Notes: 1. Half months are 1-15th and 16th-end of each month.
2. Total for second half of March is for period 19th-31st March 1951 (earlier values not available).

TABLE 3.4 ADOPTED WADI BANA ANNUAL AND IRRIGATION SEASON RUNOFFS, 1951-65

Year	Annual runoff $M.m^3$	Seif season runoff (16 Mar-31 May) $M.m^3$	Kharif season runoff (1 July-15 Oct) $M.m^3$
1951	-	36.8	129.4
1952	111	19.2	83.9
1953	155	28.5	108.5
1954	226	23.2	163.8
1955	167	13.9	118.8
1956	134	14.4	112.1
1957	267	139.9	93.3
1958	84	12.0	58.1
1959	143	12.5	121.4
1960	120	70.8	41.7
1961	95	7.3	77.6
1962	158	10.6	131.0
1963	274	132.1	126.5
1964	214	28.4	162.3
1965	127	27.3	84.6
Average	162	38.5	107.5

Note 1. 1951 Seif season total is for 19 March-31 May (earlier data not available).

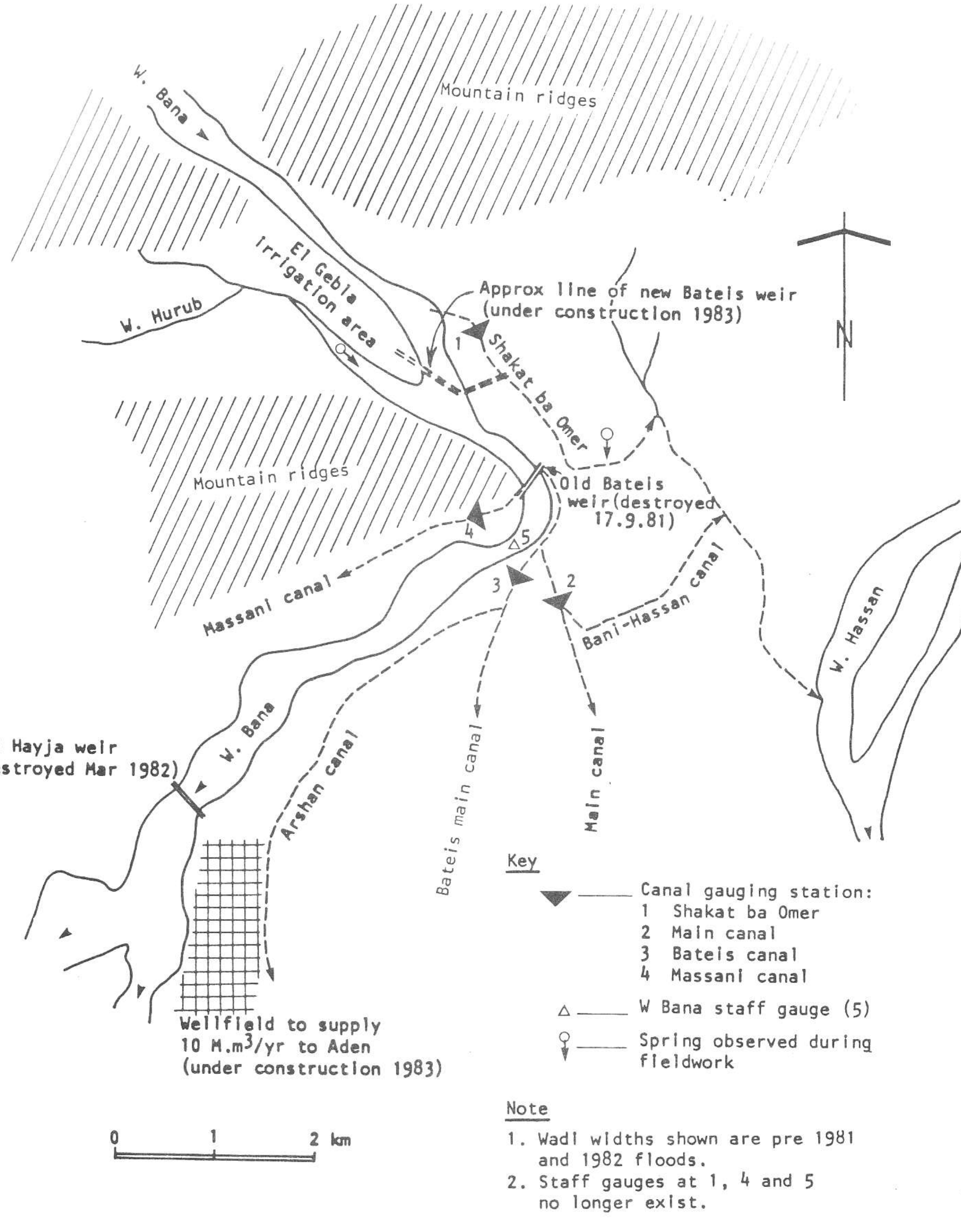
TABLE 3.5 - ANNUAL WADI BANA AND WADI TUBAN RUNOFFS, 1948-82

Year	W.Bana at Bateis $M.m^3$	W.Tuban at Dukeim $M.m^3$	Year	W.Bana at Bateis $M.m^3$	W.Tuban at Dukeim $M.m^3$
1948	(95)	-	1966	(135)	-
1949	(95)	-	1967	-	-
1950	209	-	1968	(188)	128
1951	(173)	-	1969	(166)	90
1952	111	-	1970	(149)	126
1953	155	-	1971	(97)	145
1954	226	-	1972	-	140
1955	167	103	1977	(123)	63
1956	134	138	1974	-	81
1957	267	120	1975	-	116
1958	84	74	1976	(79)	46
1959	143	183	1977	(121)	222
1960	120	206	1978	219	170
1961	95	150	1979	97	92
1962	158	-	1980	-	86
1963	274	-	1981	-	118
1964	214	-	1982	-	322
1965	127	-			

Notes

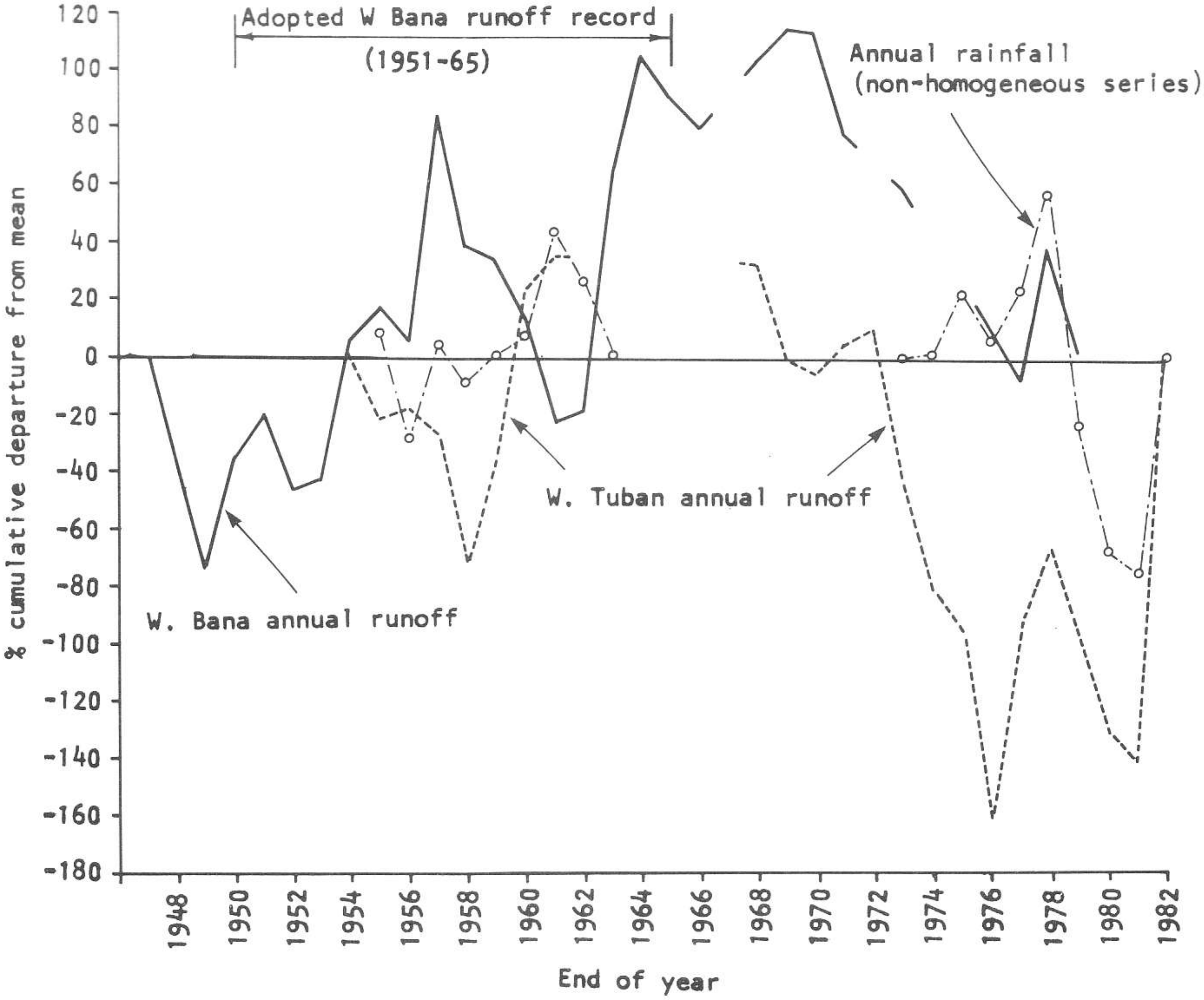
1. Brackets signify incomplete years infilled by monthly means

2. Sources: W Bana - see Table 3.1
   W Tuban - 1955-80, GDC (reference 5)
   1981-2, MAAR files, Aden



SKETCH MAP OF BATEIS–LIGMA AREA

Figure 3.1

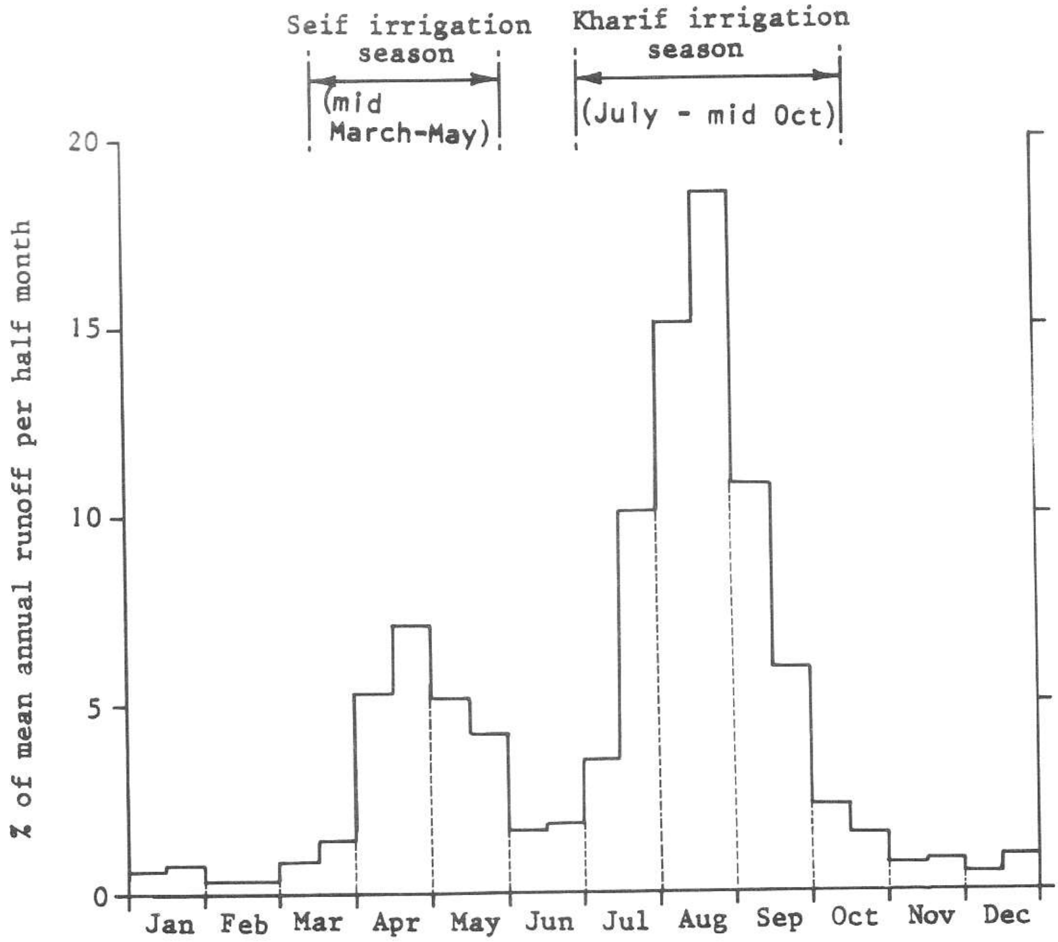


Notes

1. Rainfall series:

1955-9, mean of Khormaksar, Dhala and Mukeiras.
1960-3, mean of Khormaksar, El Kod and 2 x Dhala.
1973-82, mean of El Kod, Dhala and Lahej.

CUMULATIVE DEPARTURES FROM MEAN
Figure 3.2

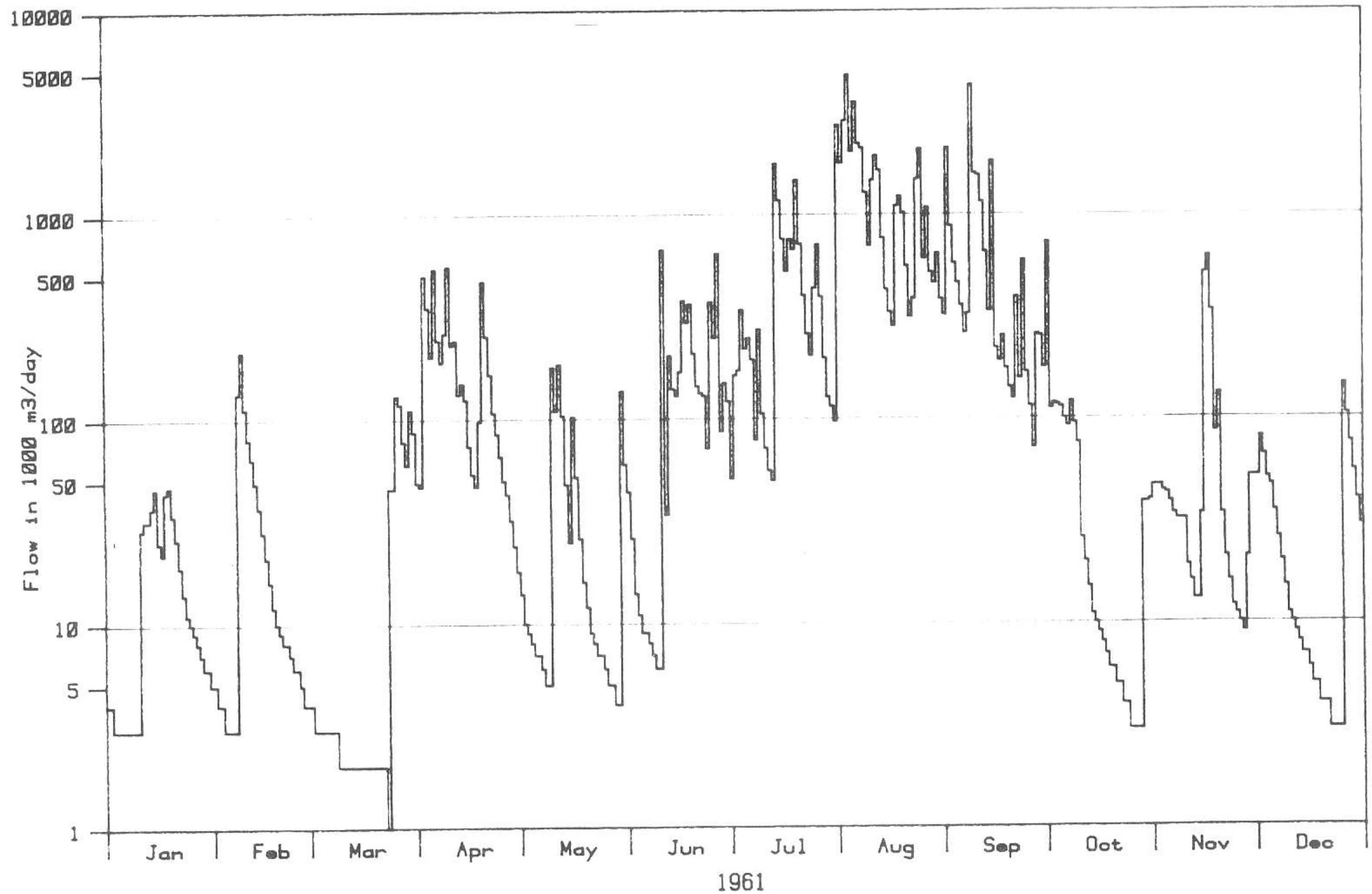


Notes

1. Based on adopted record 1951-65 at old Bateis weir.
2. Mean annual runoff = 162 $M.m^3$
3. Values are also shown in Table 3.2.

SEASONAL DISTRIBUTION OF WADI BANA RUNOFF

Figure 3.3



Notes

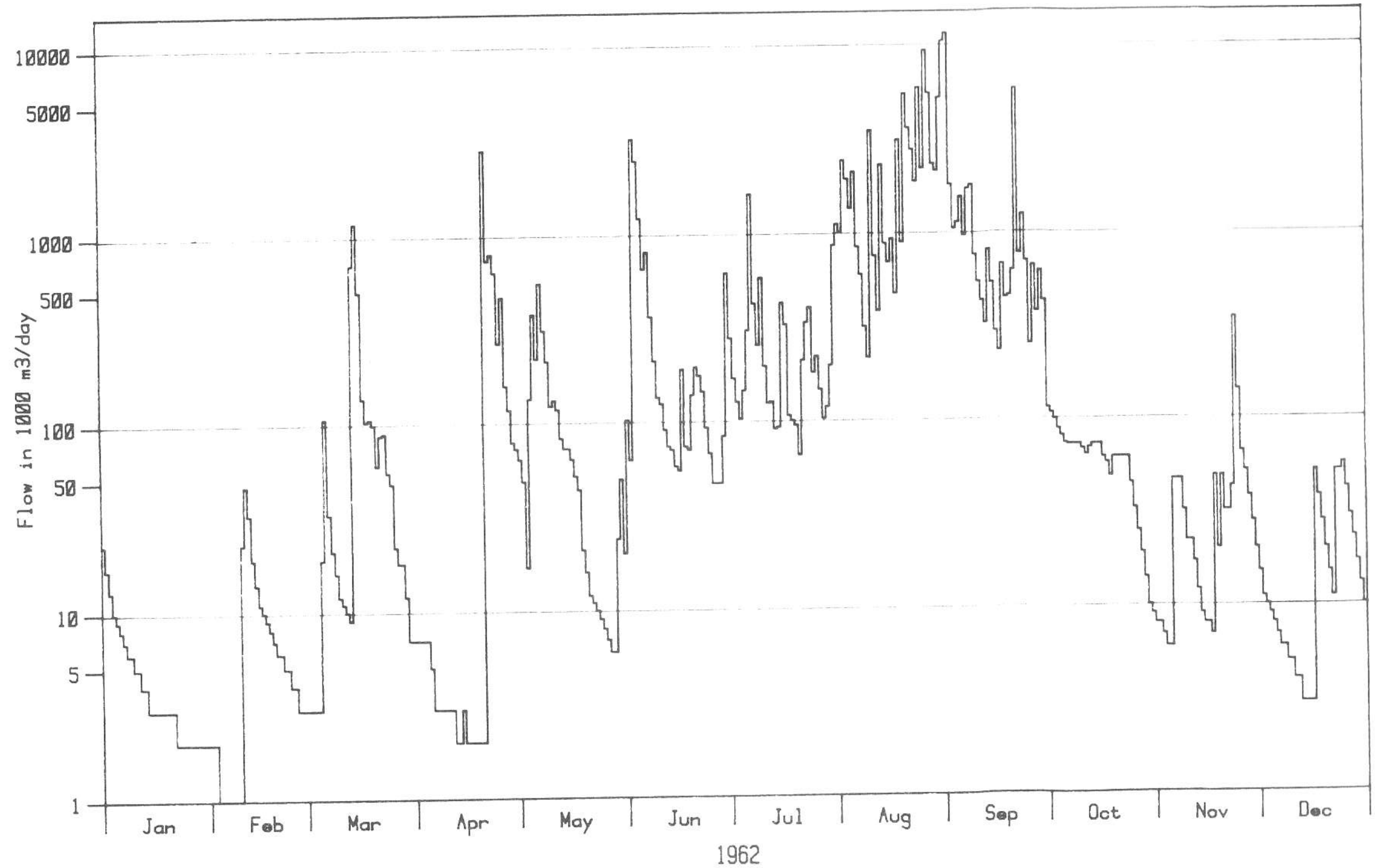
1. 100 000 m^3/day = 1.16 m^3/s
2. Flows are tabulated in Appendix B.
3. See Appendix B tables for details of days where recessions have been fitted.

Khairif P = 21%

Seif P =

WADI BANA DAILY FLOW HYDROGRAPHS, 1961

Figure 3.4a



Notes

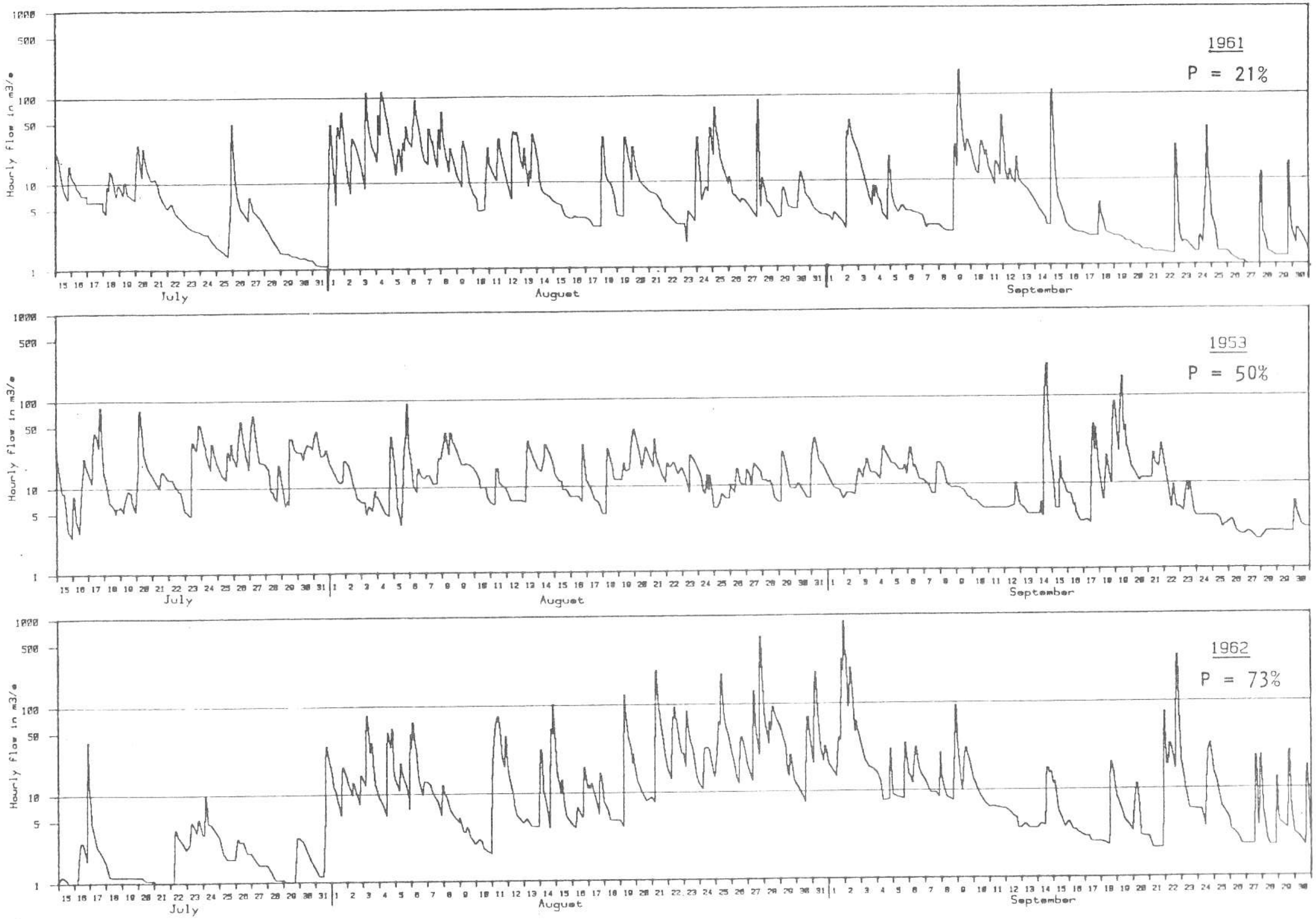
1. 100 000 m^3/day = 1.16 m^3/s
2. Flows are tabulated in Appendix B.
3. See Appendix B tables for details of days where recessions have been fitted.

Khairif P = 73%

Seif P = 12%

WADI BANA DAILY FLOW HYDROGRAPHS, 1962

Figure 3.4b



WADI BANA KHARIF SEASON HOURLY FLOW HYDROGRAPHS

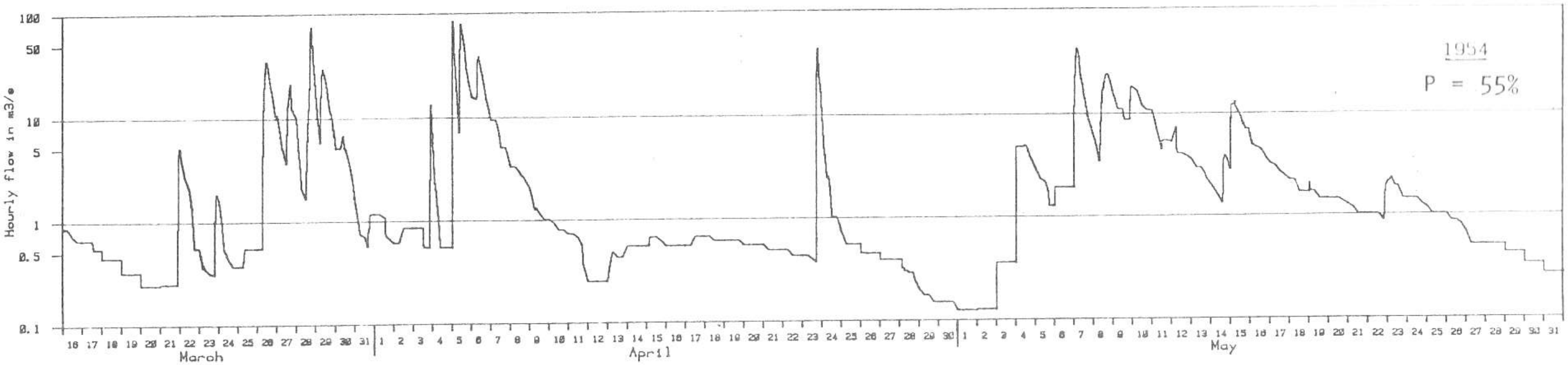
Figure 3.5a

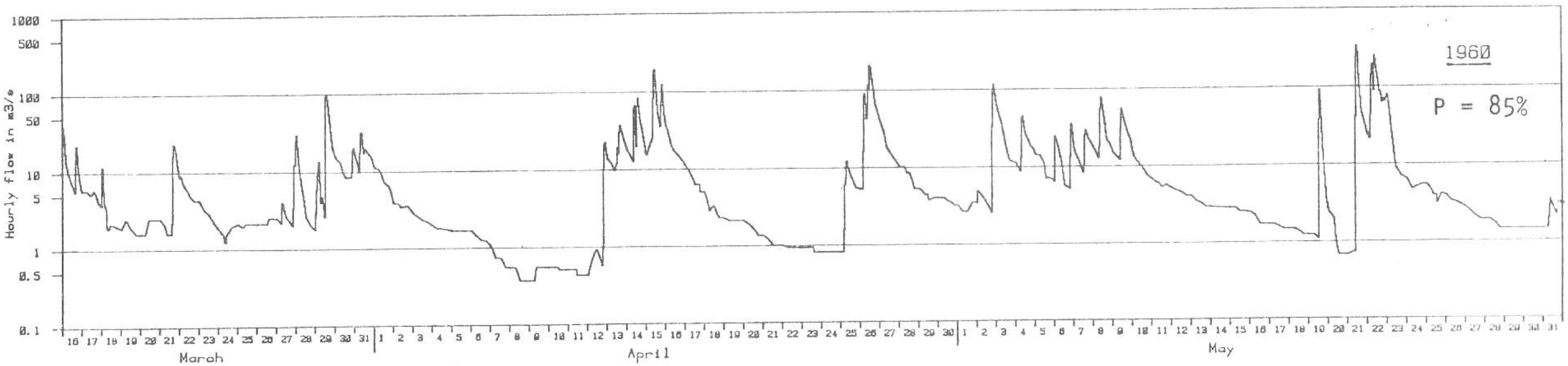
Notes

1. Flows shown are those used as operation study inflows.
2. For clarity, only central 2½ months of each season shown.
3. Expressed as total seasonal runoff, 1961 was driest, followed by 1953 and 1962.

WADI BANA SEIF SEASON HOURLY FLOW HYDROGRAPHS

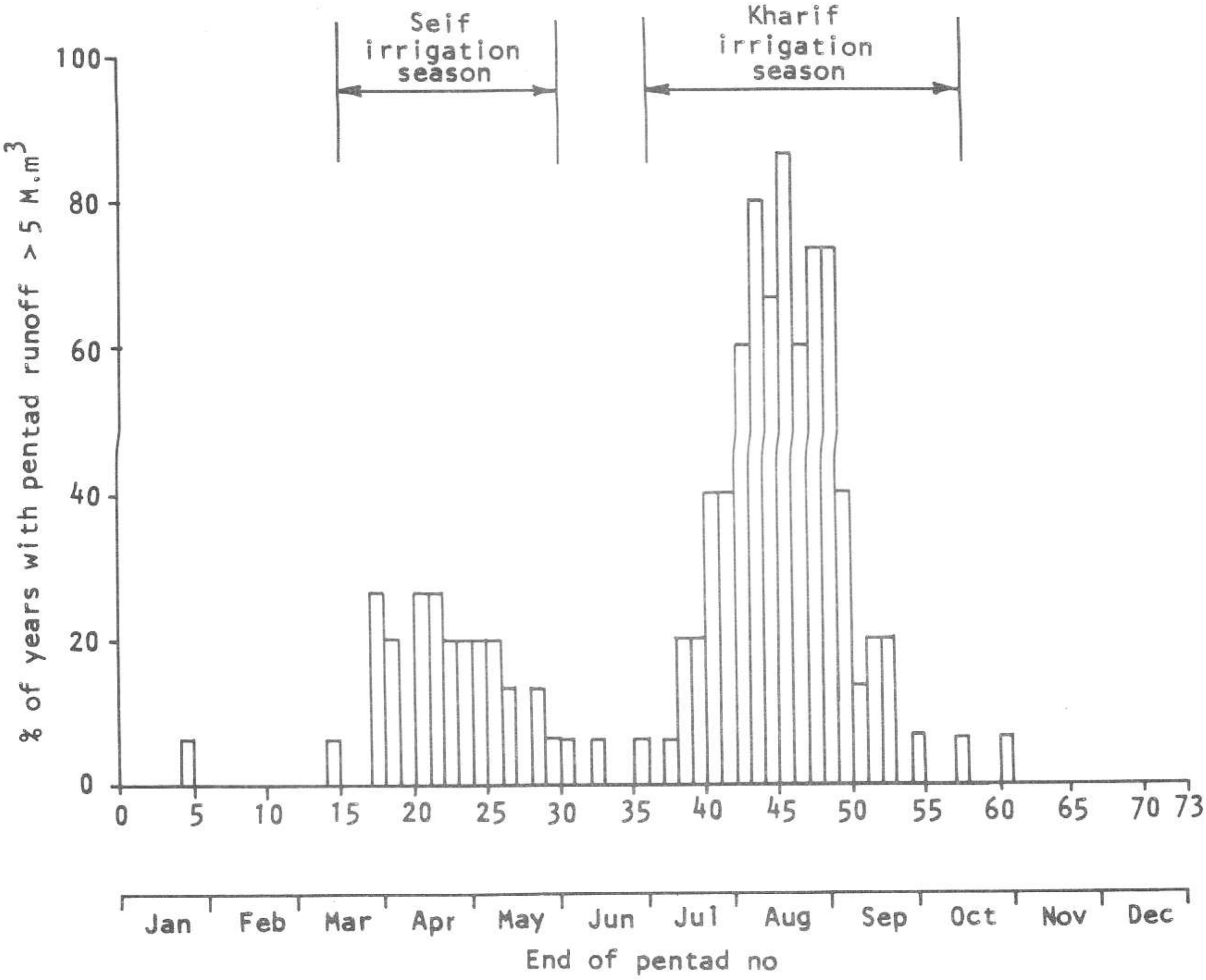
Figure 3.5b





Notes

1. Flows shown are those used as operation study inflows.
2. 1962 seif season hourly flows not shown as many days were infilled by fitting daily recessions : see Figure 3.4b.



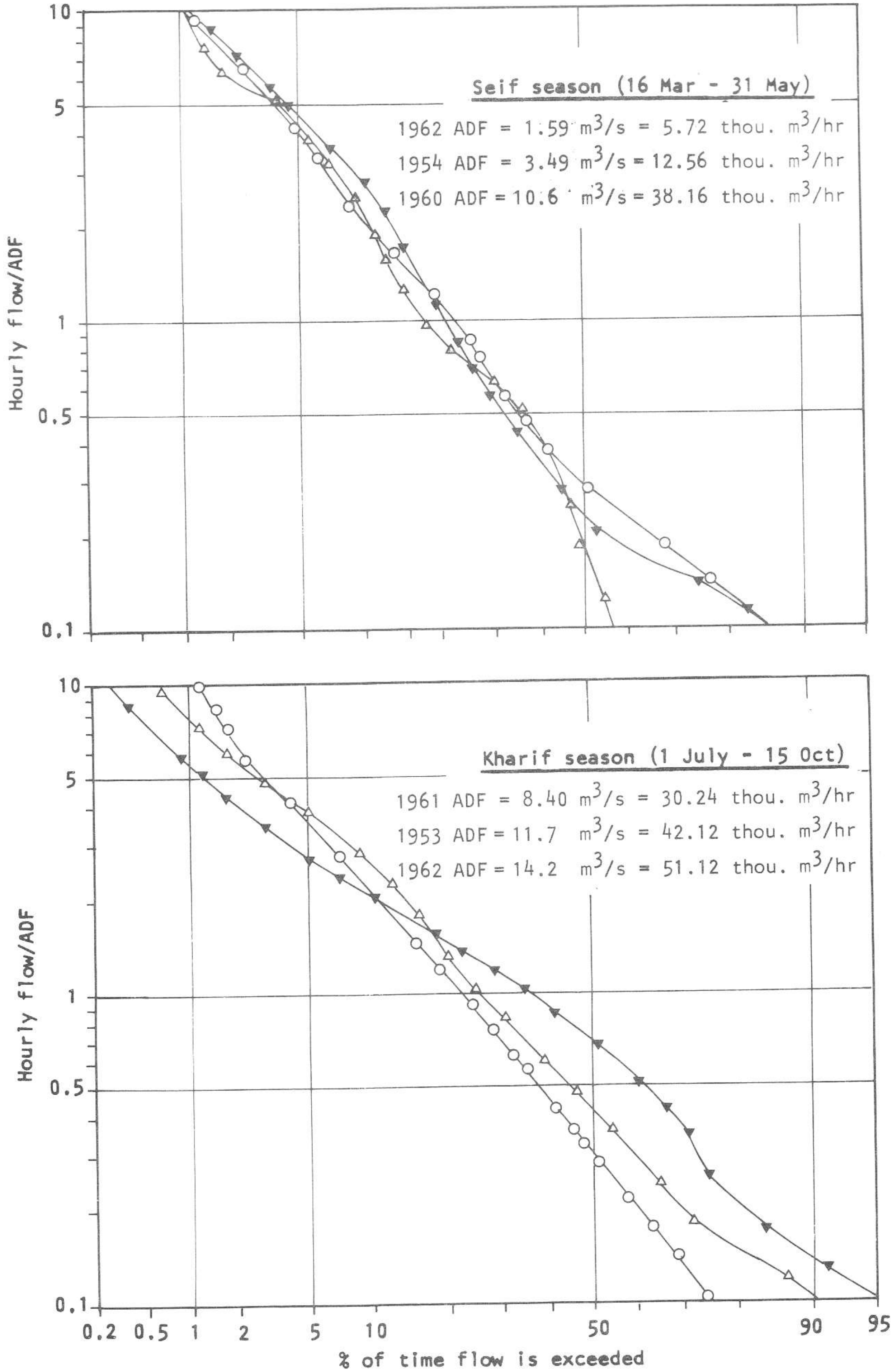
Notes

1. A high runoff pentad is a 5 day period with a total runoff > 5 M.m^3 (11.6 m^3/s).

2. Frequencies based on adopted record 1951-65 at old Bateis weir.

FREQUENCIES OF HIGH RUNOFF PENTADS

Figure 3.6

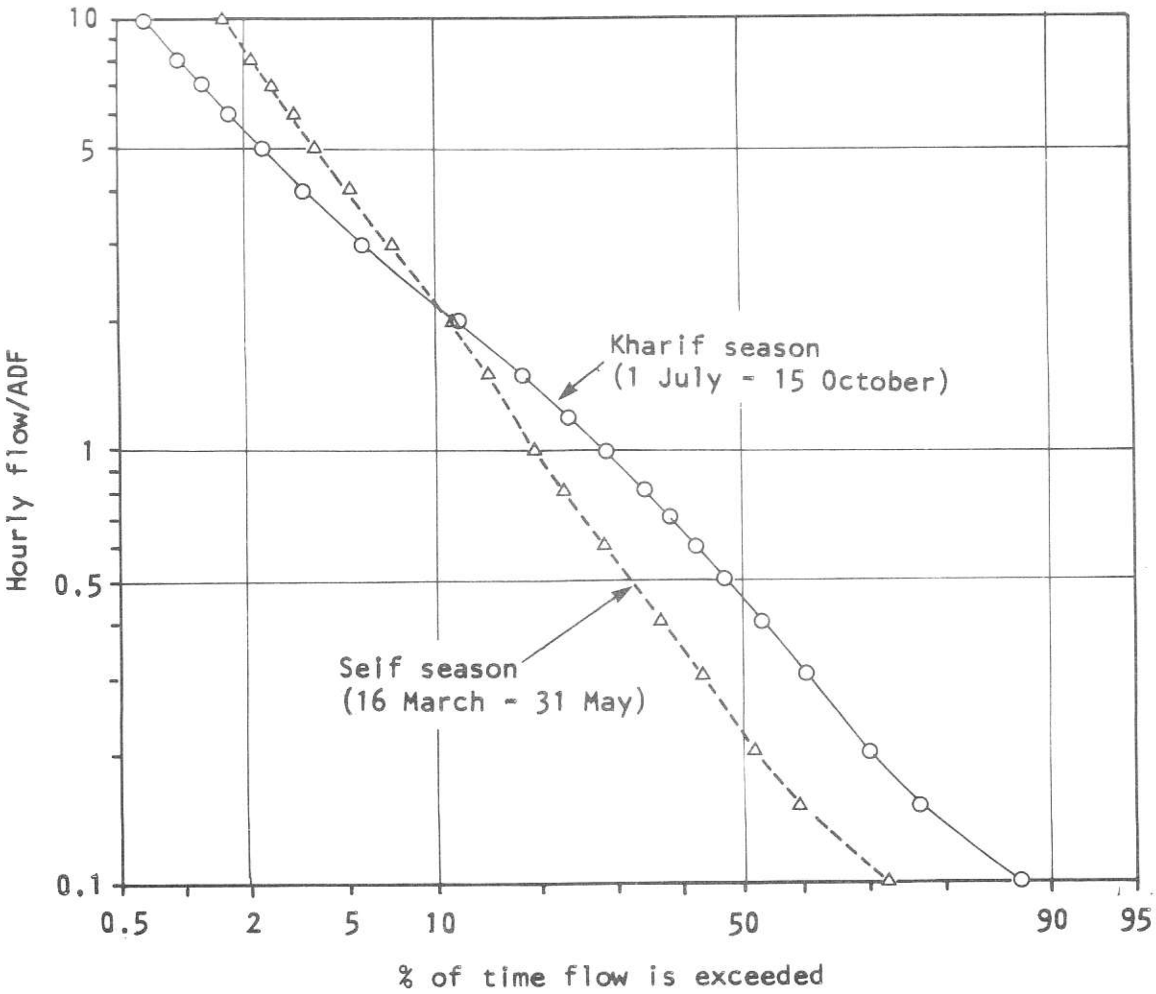


Notes

1. ADF = average daily flow over season concerned

HOURLY FLOW DURATION CURVES FOR INDIVIDUAL IRRIGATION SEASONS

Figure 3.7

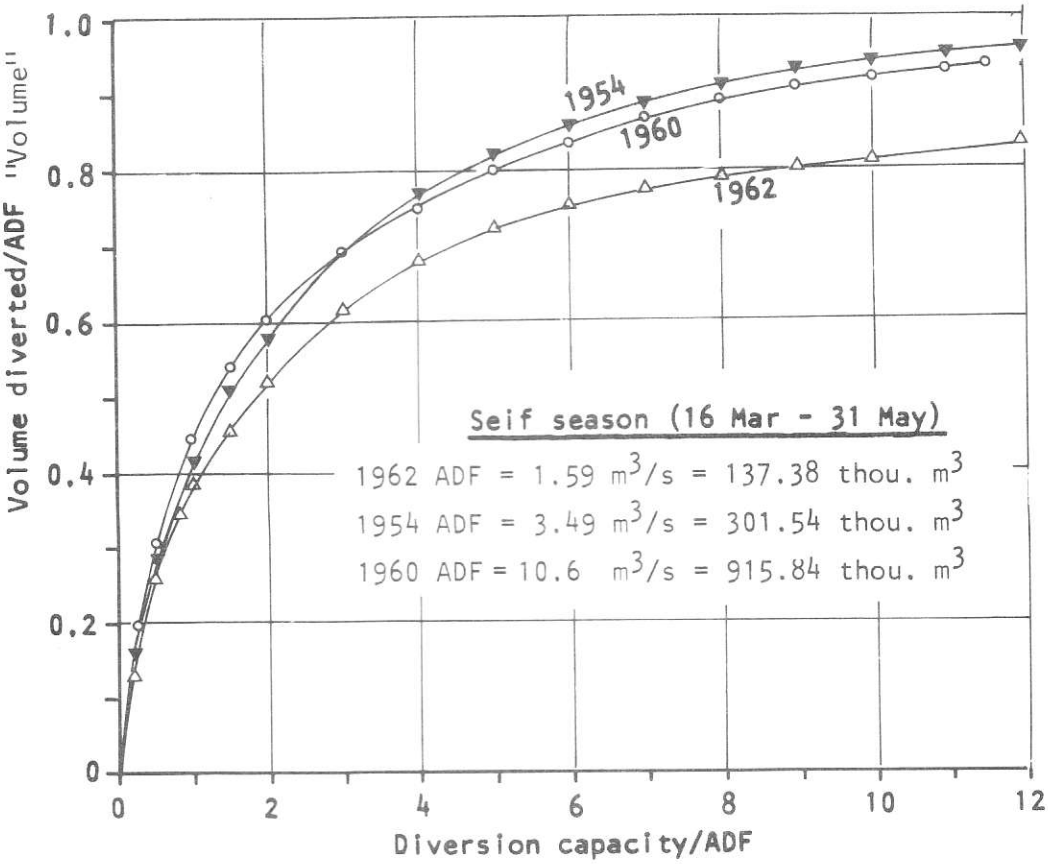


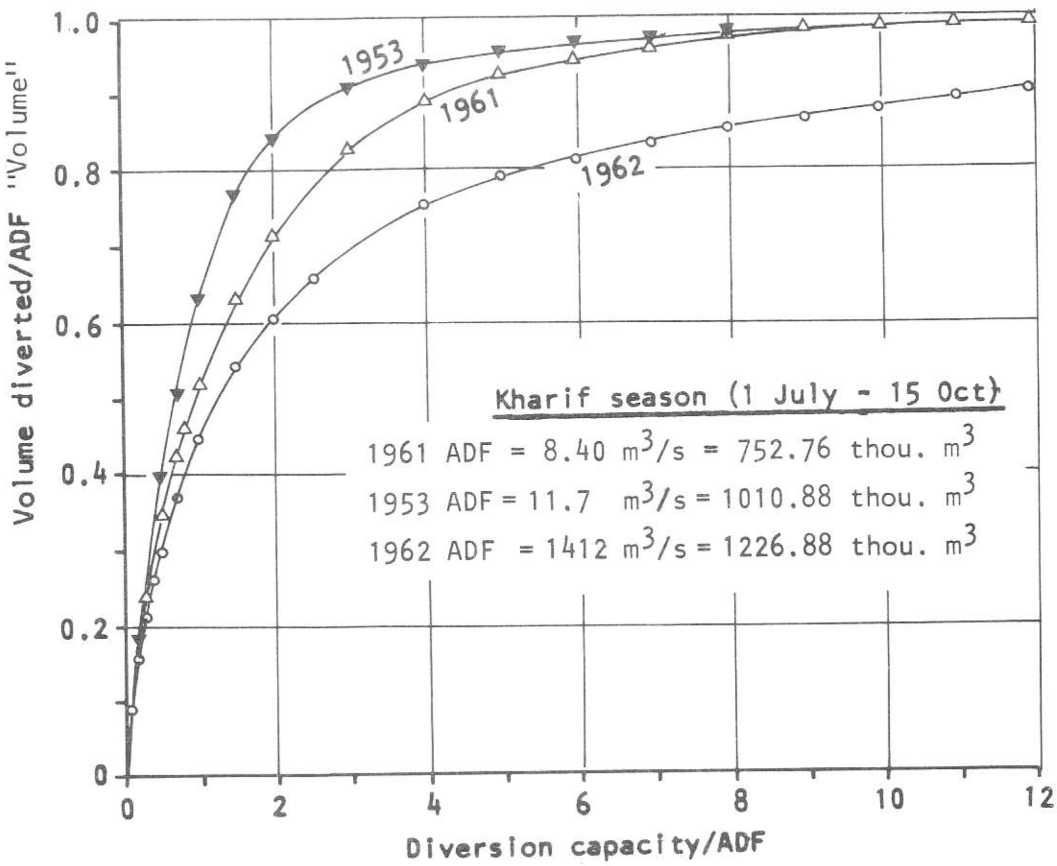
Notes

1. ADF = average daily flow of three Kharif or Seif seasons (see Figure 3.7)

HOURLY FLOW DURATION CURVES FOR SEIF AND KHARIF SEASONS, USING POOLED SEASONAL DATA

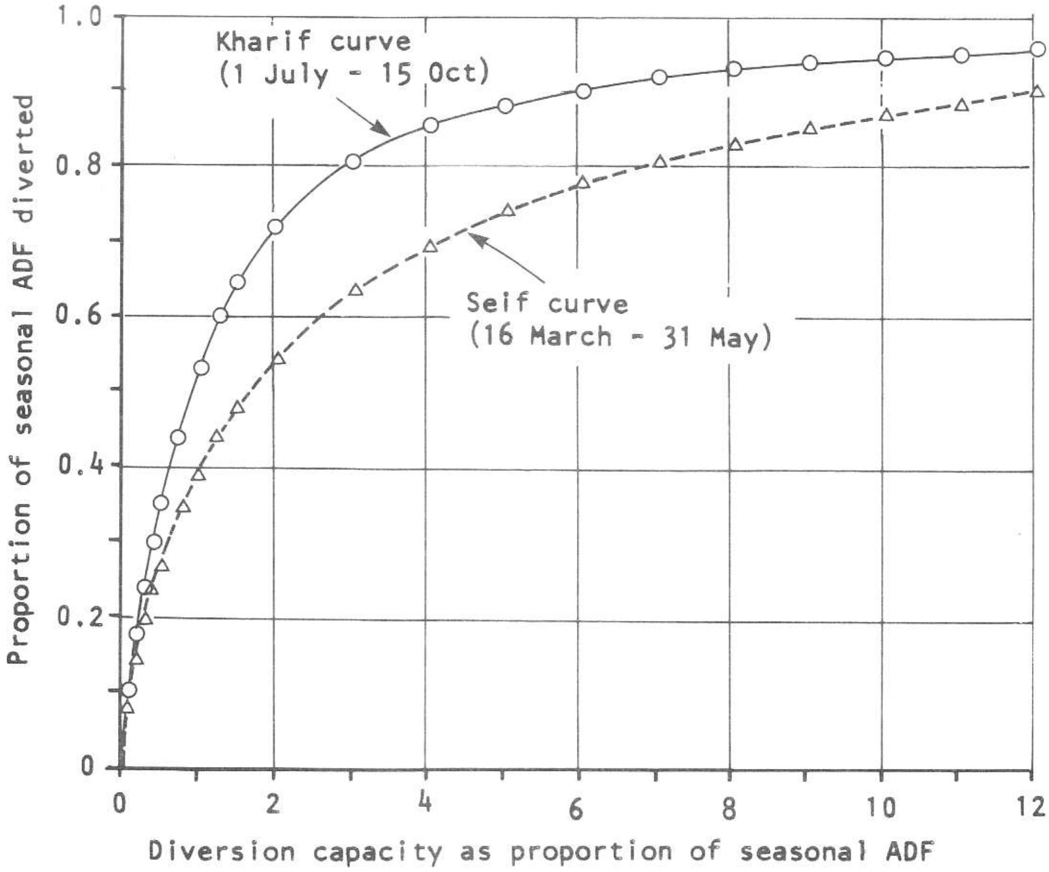
Figure 3.8





BATEIS DIVERSION CURVES FOR INDIVIDUAL IRRIGATION SEASONS

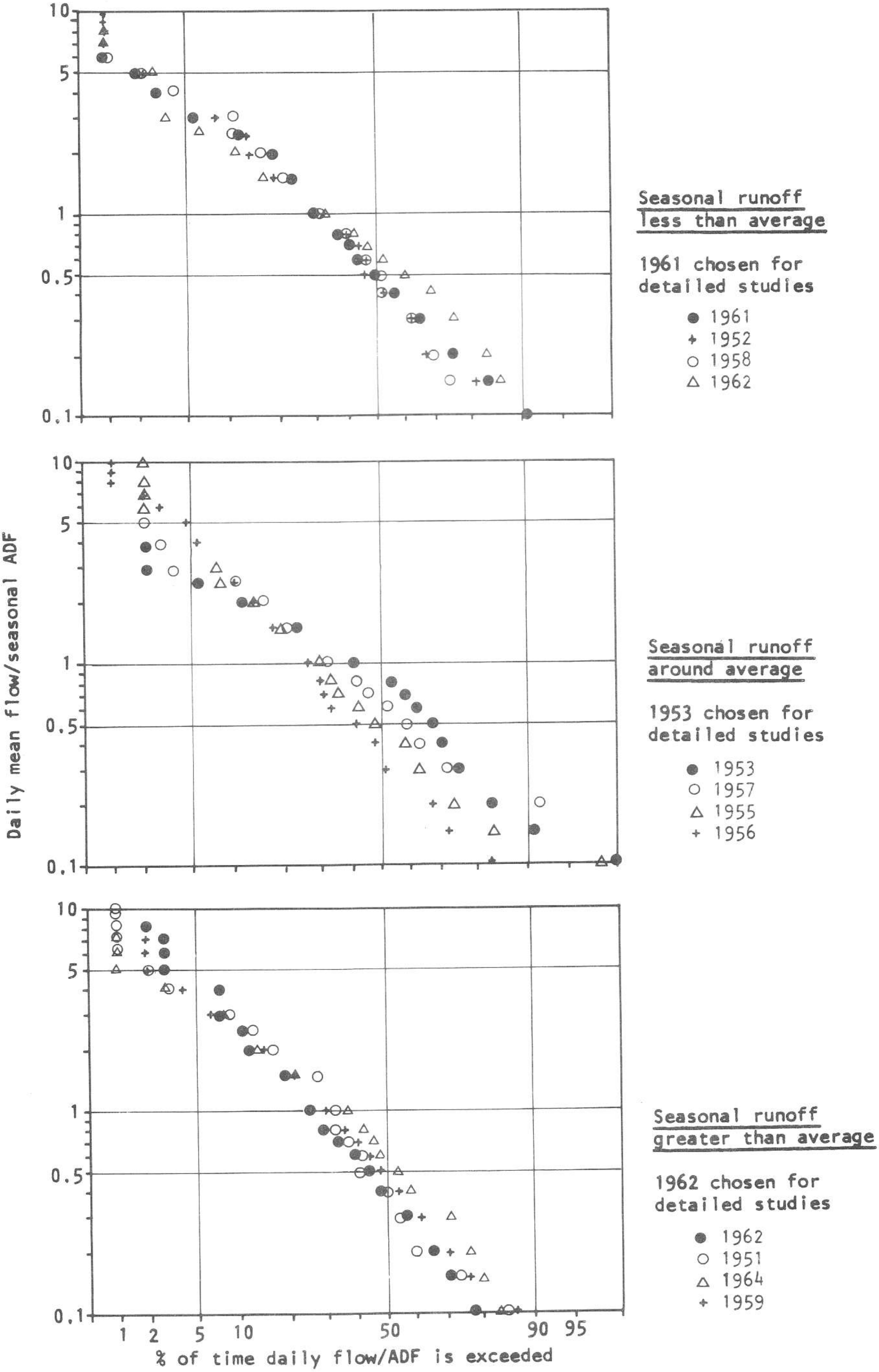
Figure 3.9



Notes

1. Curves derived from hourly flow duration data on Figure 3.8.
2. Flows are at Bateis, i.e. do not allow for any en route losses below Bateis.

BATEIS DIVERSION CURVES
Figure 3.10



COMPARISON OF KHARIF SEASON DAILY FLOW DURATION DATA

Figure 3.11

4. FLOOD STUDIES

4.1 INTRODUCTION

Design flood estimates were required for:

(a) the design of new weirs on Wadi Bana below Bateis and any associated river training works, and

(b) the design of a cross-drainage structure on Wadi Maharia.

The terms of reference required the Consultant to take into consideration the design adopted by Soviet engineers for the new Bateis weir. For this design the following floods have been used:

(i) a weir design flood of 2 500 m^3/s, estimated by the designers to have a return period (T) of 20 years (ref 7)

(ii) an emergency fuseplug spillway allowing passage of a total flood of 5 000 m^3/s, estimated by the designers to have a return period of 100 years.

4.2 AVAILABLE DATA

Peak discharge data are available for three wadis in PDRY:

Wadi	Catchment area, km^2	Period of record	No of years
Bana	7 200	1949-82*	25
Hajr	9 300	1959-65	7
Tuban	5 090	1957-79*	14

(* with gaps)

The locations of the Bana and Tuban catchments are shown in Figure 2.1. Wadi Hajr lies further east and enters the Gulf of Aden at 48°40'E. The Hajr data were obtained from Camacho (ref 6) and the Tuban data from GDC (ref 4). Other, minor data sources for PDRY flood values were Sogreah (ref 24) and Camacho (ibid). Although major floods occurred on Wadi Tuban in March 1982, at the same time as the Bana floods, no authoritative estimates of their magnitude are yet available.

4.3 DATA QUALITY

4.3.1 Wadi Bana

The 1981 and 1982 peak discharges were estimated using the slope-area method, by Soviet personnel (ref 7). In each case the work was carried out a few days after the event, and the values obtained are considered fairly reliable.

Sogreah's 1978 and 1979 values (ref 24) are based on stage readings at Bateis. Their Bateis rating curve was evidently not the same as the Abyan Board rating, but they give no details of its derivation. Estimated side wadi and canal flows were added by Sogreah to get the totals shown in Table 4.1.

Values for 1951-66 are based on peak stages extracted from the original water books and the Abyan Board ratings, modified (as described in chapter 3) in the case of Wadi Bana to pass through the estimated 1981 peak stage and discharge. Stages at Bateis and on the various canals were read at very frequent intervals during spates (sometimes every quarter hour). Recorded peak stages are therefore probably close to true peaks. The validity of the Wadi Bana rating curve, however, remains extremely doubtful.

The remaining five annual maxima (1949-50, 1970, 1975-6) were taken from ref 7 which in turn quotes Bulgarian work, dated 1976, which was not seen. The 1949 value (2 120 m^3/s) stands out. Unfortunately, local questioning did not confirm a major flood in that year.

4.3.2 Wadi Tuban and Wadi Hajr

Wadi Tuban data (Table 4.2) were taken from GDC (ref 4). The sources used by GDC were:

- 1957-60 : Barraud (ref 11), apparently based on the number of irrigation offtakes which could be supplied by the wadi.

- 1968-72 : Italconsult (ref 12), method of computation not known.

1973-79 :	GDC values for 1973-7 estimated from daily mean flows using a peak/daily volume relationship for 1979. Details of estimate of 1977 "flood of record" not known.

Wadi Hajr data were taken from Camacho (ref 6). Camacho gives no details of methods used in their estimation. In addition to the annual maxima listed in Table 4.3, Camacho tabulates all Wadi Hajr discharges greater than 180 m^3/s.

4.4 1982 WADI BANA FLOOD

The Bana flood of 29 and 30 March 1982 was a major event. In terms of its effects on Wadi shape it was clearly the single most important event since at latest the 1940s.

Peak discharge has been estimated as 3 810 m^3/s (ref 7), and its return period (see calculations presented below) as lying in the range 50 to 70 years. However, not only the peak but also the duration and hence the volume of the flood was remarkable. Stages during the flood could only be estimated as the Wadi Bana staff gauge had already been destroyed by the flood of 17 September 1981, but the following gives an idea of the sequence of events:

Date	Events
29 March	Wadi starts rising late morning and reaches peak at 1400h (est. stage 2.7 m), followed by a slight drop.
30 March	Est. stage 4.5 m at 0900h, rising to second peak, est at 6.5 m at 1900h.
31 March	Stage falls to 1.5 m at 2400h.
1 April	stage falls to 0.4 m at 2400h.

(local questioning suggested that stages were substantially over-estimated and that the peak stage was not in fact greatly in excess of 4 m).

Table 4.4 shows daily rainfall amounts associated with the flooding. The impression gained is of storm cells moving slowly south or south-east over several days. Amounts received dropped sharply on the coastal plain. The second, higher, flood peak may have been the result of a translatory flood wave produced by runoff in the eastern part of the catchment on the 29th-30th March and superimposed on the already swollen river, but may equally be connected with the breach of an alluvial blockage 18 km upstream of Bateis (see section 4.5 below). Major flood damage was apparently confined to the area around Dhala (see reference 8) and to the Abyan Delta.

The Dhala point rainfall is the largest shown in Table 4.4. It is 3.9 times the mean of 10 years' annual maximum daily falls at this station (68 mm) and about twice the 50 year value estimated using Wan's procedure (reference 9). It is possible that it approaches a point PMP for areas with average annual rainfalls between 125 and 500 mm and not subject to tropical cyclones. (see note by Mansell-Moullin on Wadi Najran design floods (ref 10)).

4.5 WADI BANA FLOOD FREQUENCY ESTIMATES

4.5.1 Introduction

Wadi Bana has a main stream length of 180 km from the catchment divide in the YAR to Bateis, and an average slope of 17 m/km. Catchment geology is dominated by Precambrian metamorphics of low permeability as far as Bateis, below which the wadi flows in alluvial deltaic deposits.

At a point approximately 18 km upstream of Bateis (grid reference NK205860) the river currently flows around both sides of a rock island. Formerly only the gorge-like right hand branch (with a bed width of about 20 m) was open, the other branch being blocked by alluvium which was breached by flood waters in March 1982. How this feature affects Bateis flood peaks is difficult to say. Probably low to medium return period floods are attenuated once the alluvial bank is reestablished, while its collapse may increase peak flows during major floods. Unfortunately neither effect was apparent in the low quality data available to this study and the analyses could not take them into account.

The two flood seasons have already been described in chapter 3. Major floods have occurred in both seasons, but of the 20 annual maxima listed in Table 4.1 whose dates are known, 13 have occurred in the July to October (Kharif) season.

Some details of the history of earlier Wadi Bana structures are available. The original Bateis weir dated from about 1953 and survived until the September 1981 flood. The lower weirs are said to have been built between 1961 and 1966. Hayja, Makhzan and Gharaib survived until the 1982 flood without major damage, but Diyyu (the earliest weir after Bateis) had to be completely rebuilt in 1968 and again partially in 1974 or 1975. The 1982 flood also destroyed the two narrow bridges (span approximately 120 m) built side by side to carry the Aden-Zingibar road across the wadi. The earlier of these bridges dated from the 1950s and the later from the 1970s. That a need was (and is) perceived for a high level bridge is some evidence of a significant flood risk at this point, despite the irrigation diversions and conveyance losses over the 34 km from Bateis.

4.5.2 Approaches

Three approaches were tried:

(a) frequency analysis of Bateis annual maximum discharges

(b) frequency analyses of values of annual maxima divided by mean annual floods (Q/Qbar) for Wadis Bana, Tuban and Hajr

(c) comparison with flood estimates and envelope curves for comparable areas.

Unit hydrograph approaches were ruled out by the lack of rainfall and storm loss data.

Approach (a) - frequency analysis of Bateis maxima

Table 4.1 maxima were ranked and plotted, using unbiased plotting probabilities, on EV1 (Gumbel) paper. An eye-fit to the points plotted on Figure 4.1 was adopted, using as a guide to its alignment those points considered most reliable: the mean annual flood (940 m^3/s) and the 1981 and 1982 maxima. Estimates obtained using this approach appear in Table 4.5.

Approach (b) - frequency analyses of pooled Q/Qbar values.

In order to make the best use of the three, relatively short, records on Wadi Bana, Wadi Tuban and Wadi Hajr, it was decided to pool the values of Q/Qbar from each series. Inherent in the use of this station-year approach are the assumptions that the catchments are homogeneous (i.e. that values of Q/Qbar are drawn from the same population) and that the flood events are independent.

Mean annual floods were estimated from the annual maxima in the cases of Wadi Tuban and Wadi Bana. In the case of Wadi Hajr the record was so short (7 years) that the partial duration series of all peaks over 284 m^3/s was analysed instead, using the UK Flood Studies Report Model (ref 13). Values obtained were:

	Wadi Bana	Wadi Tuban	Wadi Hajr
Area, km^2	7 200	5 090	9 300
Mean ann flood, m^3/s	940	560	1 110

The resulting series of 46 values of Q/Qbar were ranked and plotted on EV1 (Gumbel) paper. As with the Bateis peaks, an eye-fit line guided by the mean annual flood and the 1981 and 1982 Wadi Bana maxima was adopted.

In a revised calculation the data of flood peaks (where known) were scrutinized and where annual maxima from different wadis occurred on the same day a single, average, value of Q/Qbar was used in their place. This reduced the series to 44 values. These values were ranked and plotted on log normal probability paper (Figure 4.2). The line shown was fitted using the mean and standard deviation of the transformed series. The line fitted the plotted points well, and indeed the log normal distribution provided a more convincing description of the recorded floods than did the EV1 distribution described above. A danger with a logged observed variable, however, is that extrapolation to large return periods may yield unrealistically large predicted floods. Growth factors (Q(T)/Qbar) obtained from the two frequency analyses are summarized in Table 4.5.

Approach (c) - regional comparisons

Figure 4.3 shows various envelope curves and observed or estimated floods from comparable climatic zones plotted against catchment area. The Creager C=100 curve formed an envelope for (chiefly United States) maximum recorded flows when it was conceived over 40 years ago. It ignores all catchment characteristics except area. Despite these limitations, Creager C values are still widely quoted and provide a useful frame of reference for comparing flood estimates.

The Creager C=20 curve shown in Figure 4.3 has been quoted elsewhere (Mansell-Moullin, ref 14) as an envelope curve for various Middle Eastern data and for data from arid regions of South Africa (ref 15). In both cases records are likely to be very short, however. The 1982 Wadi Bana estimated flood peak corresponds to C=23.

Other points shown in Figure 4.3 are:

(i) maximum recorded floods from Wadis Tuban, Hajr and Hassan (Camacho, ref 6) in PDRY, and from a number of Saudi Arabian catchments with comparable rainfall quoted in reference 25. The Saudi Arabian records are of only 5-7 years duration.

(ii) mean annual floods from PDRY and Saudi Arabian records as in (i) above.

(iii) low return period floods estimated by Sogreah (ref 24) for small catchments in the Bana and Hassan basins.

(iv) a curve representing rare floods, possibly of about 100 years return period, derived by Maslov (ref 16) for small Syrian catchments. The curve corresponds to Creager C=20 for an area of 160 km^2.

(v) a major flood on 3 May 1981 from Wadi Adai (catchment area 370 km^2) in Oman, with an estimated peak flow of 1 150 m^3/s (Wheater and Bell, ref 27). The storm which produced this flood contained rainfall amounts for certain durations with return periods estimated at 100-300 years. The flood peak has a Creager C of 27.

Although the quantity of information contained in Figure 4.3 is not great, it does suggest that:

(i) Although a Creager C=20 curve forms an envelope to all but two of the historic maxima, the records used are short and a 100 year flood could reasonably be expected to correspond to a rather greater C value.

(ii) A line through the Wadi Bana mean annual flood forms an envelope to the other plotted values. The Tuban value is noticeably lower and may arise from its more permeable rock types.

4.5.3 Adopted flood frequencies at Bateis, Hayja and Gahaisa weir sites

Hayja and Gahaisa weir sites are, respectively, 6 and 8.5 km downstream of the new Bateis weir. For much of the main July-October flood and irrigation season the water table is near the wadi bed over this reach and the opportunities for infiltration limited. Contributions from small intervening side wadis can be ignored. Flattening of the peak would probably also be negligible at the high Froude numbers occurring. It was therefore decided to adopt flood discharges at the three sites identical with those at Bateis.

It was decided to adopt growth factors from the log normal plot on Figure 4.2, as the most convincing of the three frequency plots drawn, with the Wadi Bana mean annual flood of 940 m^3/s. This gave a 100 year flood of 4 890 m^3/s, corresponding to a Creager C of 30. This appeared a reasonable value in the light of other values plotted on Figure 4.3. The adopted flood frequencies, shown below and in Figure 4.1, remain rough approximations, however, in view of the poor quality of the basic data.

Return period, T (years)	Q(T) m^3/s
Mean ann. flood	940
5	1 320
10	1 950
20	2 680
50	3 840
100	4 890

(In view of the logarithmic scale of Figure 4.2, extrapolation beyond T=100 years is not recommended)

Using the different approaches in Table 4.5, the return periods of various key floods are:

(i) Bateis fuseplug design flood (5 000 m^3/s): 100-300 years

(ii) Bateis weir design flood (2 500 m^3/s): 10-20 years

(iii) flood of March 1982: 50-70 years

4.5.4 Flood estimates at Diyyu and Makhzan weir sites

Diyyu and Makhzan sites are 19 km and 23.5 km, respectively, below the new Bateis weir. Under the usual irrigation regime the water table would, prior to a major flood be well below the wadi bed over much of the reach downstream of Hayja or Gahaisa. Average bed slopes also slacken considerably, averaging 7.1 m/km from Bateis to Gahaisa, but only 4.0 m/km from Gahaisa to Makhzan. Flood peaks will therefore be significantly reduced by routing effects and conveyance losses. In addition, differences in catchment response time and aspect mean that for all practical purposes contributions from the Maharia catchment (which joins the Bana 2 km above Diyyu) can be ignored.

Given the imprecision of both the Bateis flood peak estimates and the adopted hydrograph shape (see section 4.7 below) and the complete absence of any observed hydrographs below Bateis, it was decided not to attempt any routing calculations. An allowance for infiltration losses was made, however. The method adopted was that used for the operation studies (section 5.5.2). Infiltration was considered to take place from the wetted perimeter at a rate of 75 mm/h (ie a rather lower, and hence conservative, value than that used in the operation studies of 200 mm/h), and to take place over a 13 km reach below Gahaisa.

The adopted procedure for relating wetted perimeter to overall bed width and discharge (see chapter 5) gave an almost constant inflow rate for any flows above the mean annual flood. This amounted to about 110 m^3/s (or 8.5 $m^3/s/km$). This discharge was therefore subtracted from the Bateis floods, giving the values shown below.

T (years)	Q(T) (m^3/s)
Mean ann. flood	830
5	1 210
10	1 840
20	2 570
50	3 730
100	4 780

4.6 WADI MAHARIA FLOOD ESTIMATES

Wadi Maharia is shown in Figure 2.1. At its confluence with the Bana it has a catchment area of approximately 260 km^2. Of this, 150 km^2 is made up of small steep limestone catchments, which drain in a southerly direction and are picked up by the main west-east Maharia drainage line. The lower 110 km^2 of the catchment, lying below about 250 m contour, is in the alluvium of the coastal plain and likely to be highly permeable. It may be, as reported locally, that Wadi Suaybiyah sometimes captures Maharia runoff and diverts it towards the sea before reaching the Bana.

For flood estimation it is reasonable to assume that only the upper 150 km^2 of the catchment is significant in producing floods. Losses sustained in the lower reaches must prevent many floods ever reaching the Bana. There are no discharge data for this wadi, nor, to our knowledge, for any comparable wadis. A major historic flood, possible of 300 m^3/s peak flow, is mentioned in reference 17.

For a catchment area of 150 km^2, Figure 4.3 indicates a mean annual flood of 150 m^3/s. This may be combined with Wadi Bana growth factors from Table 4.5. Loss rates are highly uncertain: in order to be on the conservative side a flow rate loss of 75 m^3/s has been assumed, representing

5 $m^3/s/km$ over the 15 km reach below the 250 m contour. Resulting flood frequencies are listed below:

Return period, T (years)	Q(T) m^3/s
Mean annual flood	75
10	240
20	350
50	540
100	710

4.7 HYDROGRAPH SHAPE

To assist the weir and wadi training studies some knowledge of hydrograph shape was necessary. No great accuracy can be claimed for the results of the work described below, for the three reasons:

(i) catchment rainfall is unknown

(ii) times to peak were frequently not recorded (see chapter 3)

(iii) to make the problem tractable only single peaked events were considered, whereas in reality events are frequently multi-peaked.

21 Wadi Bana hydrographs recorded at Bateis were chosen from the adopted 1951-65 record. Their more important features are summarized in Table 4.6. Fourteen had single peaks. The remainder had minor secondary peaks which were easily replaced by recessions from single-peaked hydrographs. A fixed base time of 20 hours was chosen as a compromise between a base time long enough for the discharge to drop to an insignificant proportion of the peak flow yet short enough to contain just one flood peak.

A procedure was sought whereby hydrograph shape could be predicted from peak discharge (Qp) alone. The first step was to plot total runoff volume (V) over the 20h base time against Qp (Figure 4.4). The line shown in Figure 4.4 differs slightly from the line originally determined by least squares regression and was decided by the need for simple expressions for recession constants. The relation between V and Q_p is

$$V = 0.076\, Q_p^{0.732} \quad (M.m^3 \text{ for } Q_p \text{ in } m^3/s)$$

Comparable peak-volume relations are also shown in Figure 4.4 for Wadi Tuban (GDC, reference 4) and Wadi Najran on the YAR/Saudi Arabian border (Binnie & Partners, ref 25). The latter uses the entire recession volume down to 1 m^3/s and so, quite apart from different catchment response characteristics, understandably gives higher volumes for given peak flows. The Wadi Tuban relation was intended to relate peak to daily mean flows. The fact that it is very close to the Bana relationship is probably because fixed calendar days include both multi-peaked events and late afternoon or evening events whose recessions are largely excluded, and these two effects tend to cancel each other out. Both the Najran and Tuban relations help to confirm the present work, however.

It should be stressed that Figure 4.4 cannot be used to estimate runoff volume from peak flow values. Although no figures are available for Wadi Bana, preliminary MAAR estimates for Wadi Tuban suggest that around 200 $M.m^3$ was discharged by that wadi during the March 1982 floods. Assuming similar peak flows for both wadis, ie 3 000-4 000 m^3/s, it can be seen that Figure 4.4 would underestimate the runoff volume by between 5 and 7 times.

Having fixed a peak-volume relation, the second step was to define a shape which would satisfy it. As already stated, times to peak (Tp) are not known with any reliability. Excluding the value of 10.25h for hydrograph C, the average of Table 4.6 Tp values is 1.3h, and it was therefore decided to adopt a constant Tp of 1h.

The falling limb was divided into two parts. Above Qp/2 the discharge was assumed to drop in direct proportion to time, while below Qp/2 a recession curve defined by

$$Q_t = 0.5\ Q_p K^t$$

was adopted, where Q_t is the flow t hours after dropping to Qp/2 and K is an hourly recession constant. In effect, the division is between the end of surface inflow into streams and the start of flow resulting from withdrawal of water from storage.

Use of Qp/2 as the dividing point arose from the fact that W, the time taken for the flow to drop from Qp to Qp/2, appeared promising as a hydrograph characteristic which could be predicted from Qp alone. Plotting W against Qp gave the relation

$$W = 1 + 8.93e^{(-\ 0.0144\ Q_p)} \text{ hours}$$

Given the adopted simplification of just one recession constant between time Tp + W and 20 hours it seemed reasonable to suppose that K would decrease with increasing Qp. After much trial and error, two relations were found which enabled hydrograph shapes to be defined which would satisfy the peak-volume relation of Figure 4.4:

$$Q_p > 400\ m^3/s \qquad K = 1.68\ Q_p^{-0.115}$$

$$Q_p < 400\ m^3/s \qquad K = 1.066\ Q_p^{-0.039}$$

The complete procedure is shown in Figure 4.5

TABLE 4.1 ANNUAL MAXIMUM WADI BANA DISCHARGES AT BATEIS, 1949-82

Year	Peak flow m^3/s	Peak stage at W Bana RGS m	Time and date	Source
1949	2 120	-	-	a
1950	660	-	-	a
1951	280	1.70	2300h, 13 Aug	b
1952	110	1.25	1000h, 1 Sep	b
1953	460	2.10	1345h, 19 Apr	b
1954	470	2.10	1515h, 17 Oct	b
1955	980	2.80	0600h, 17 Sep	b
1956	1 900	3.60	1645h, 2 Oct	b
1957	1 750	3.50	2315h, 27 May	b
1958	250	1.65	1830h, 1 Apr	b
1959	1 010	2.80	0430h, 2 Sep	b
1960	540	2.20	1545h, 22 Sep	b
1961	210	1.55	0600h, 9 Sep	b
1962	1 190	3.00	2230h, 1 Sep	b
1963	590	2.28	1045h, 26 Aug	b
1964	1 000	2.80	1300h, 4 Apr	b
1965	340	1.85	0730h, 25 Apr	b
1966	1 200	3.00	1430h, 8 Sep	b
1970	110	-	-	a
1975	1 000	-	-	a
1976	600	-	-	a
1978	195	-	0845h, 16 Feb	d
1979	240	-	1020h, 11 Sep	d
1981	2 450	4m approx	1800h, 11 Sep	c
1982	3 810	-	1900h, 30 Mar	c

Notes

1. Stages are on W Bana "old gauge". Value for 1959 is water book value +0.2m, in line with note in water book.

2. Sources:
   - (a) Bulgarian work, quoted in reference 7.
   - (b) Water book peak stages and Bana rating curve (see chapter 3). Discharges include canal flows.
   - (c) 1981 and 1982 values are slope-area estimates (ref 7).
   - (d) Sogreah (ref 24).

3. Values for 1952 and 1979 may not be annual maxima.

TABLE 4.2 ANNUAL MAXIMUM WADI TUBAN DISCHARGES, 1957-79

Year	Date	Discharge m^3/s	Year	Date	Discharge m^3/s
1957	April	250	1971	14 Sep	350
1958	July	320	1972	15 Aug	450
1959	Sep	1 000	1973	11 Sep	350
1960	Sep	750	1975	1 April	962
1968	25 July	200	1976	25 April	206
1969	24 Aug	500	1977	24 May	2 150
1970	29 July	150	1979	8 Sep	233

Notes

1. Source: GDC (reference 4).
2. Measurement sites: 1972 and earlier at Ras al Wadi weir site, remainder at Dukeim gauging station.

TABLE 4.3 ANNUAL MAXIMUM WADI HAJR DISCHARGES, 1959-65

Year	Date	Discharge m^3/s
1959	2 Sep	1 310
1960	24 July	390
1961	2 June	610
1962	28 Sep	210
1963	8 May	450
1964	4 April	3 400
1965	23 April	1 360

Notes
1. Source: Camacho (reference 6).

TABLE 4.4 <u>RAINFALL ASSOCIATED WITH MARCH 1982 WADI BANA FLOODS</u>

Station	Lat/Long	Alt m	Rainfall (mm) on 27-28th	28-29th	29-30th	30-31st	Total mm
Dhala	13°42'N 44°44'E	1500	0	265	15	0	280
* Sha'b al Baari	13°46'N 45°17'E	ca 1700	0	50	150	0	200
* Alirgah	13°47'N 45°21'E	ca 1400	0	17	120	42	179
* Sarar	13°41'N 45°19'N	ca 1500	29	68	78	81	256
Lahej	13°03'N 44°53'E	129	0	28	1	36	65
El Kod	13°05'N 45°22'E	15	0	0	7	29	36
Fiyush	12°58'N 44°57'E	65	0	38	0	29	67
Flood peaks at Bateis					1400h on 29th	1900h on 30th (max flow)	

Notes

1. Station locations appear in Figure 2.1. Locations of upper Hassan catchment stations (marked *) not certain.

2. Rainfall thought to be entered in Irrigation Dept records against day of observation. In table above, rainfall appears below presumed day of occurrence, eg 29 mm fell at Sarar between morning of 27th and morning of 28th.

3. Sources: El Kod from station records, remainder from Irrigation Dept records.

TABLE 4.5 SUMMARY OF WADI BANA FLOOD FREQUENCIES AT BATEIS

Return period T (years)	Growth factors Q(T)/Q bar				Adopted values of Q(T) m^3/s
	Bateis data EV1	Pooled Data EV1	Pooled Data LN	Reference 7	
Mean ann. flood	1.0	1.0	1.0	1.0	940
5	1.78	1.78	1.40	1.27	1 320
10	2.43	2.45	2.07	2.09	1 950
20	3.06	3.13	2.85	3.12	2 680
50	3.85	3.95	4.09	4.01	3 840
100	4.45	4.55	5.20	6.23	4 890

Notes

1. Q(T) = annual peak of return period T. Qbar = mean annual flood.

2. EV1 = Gumbel (extreme value) type 1. LN = log normal.

3. Adopted values are Qbar = $940m^3/s$ multiplied by LN growth factors.

4. Reference 7 is Soviet hydrological note. Estimates obtained by eye-fit curve to Bateis maxima on EV1 paper. Soviet hydrologist used Q = $802m^3/s$.

TABLE 4.6 DETAILS OF SELECTED HYDROGRAPHS

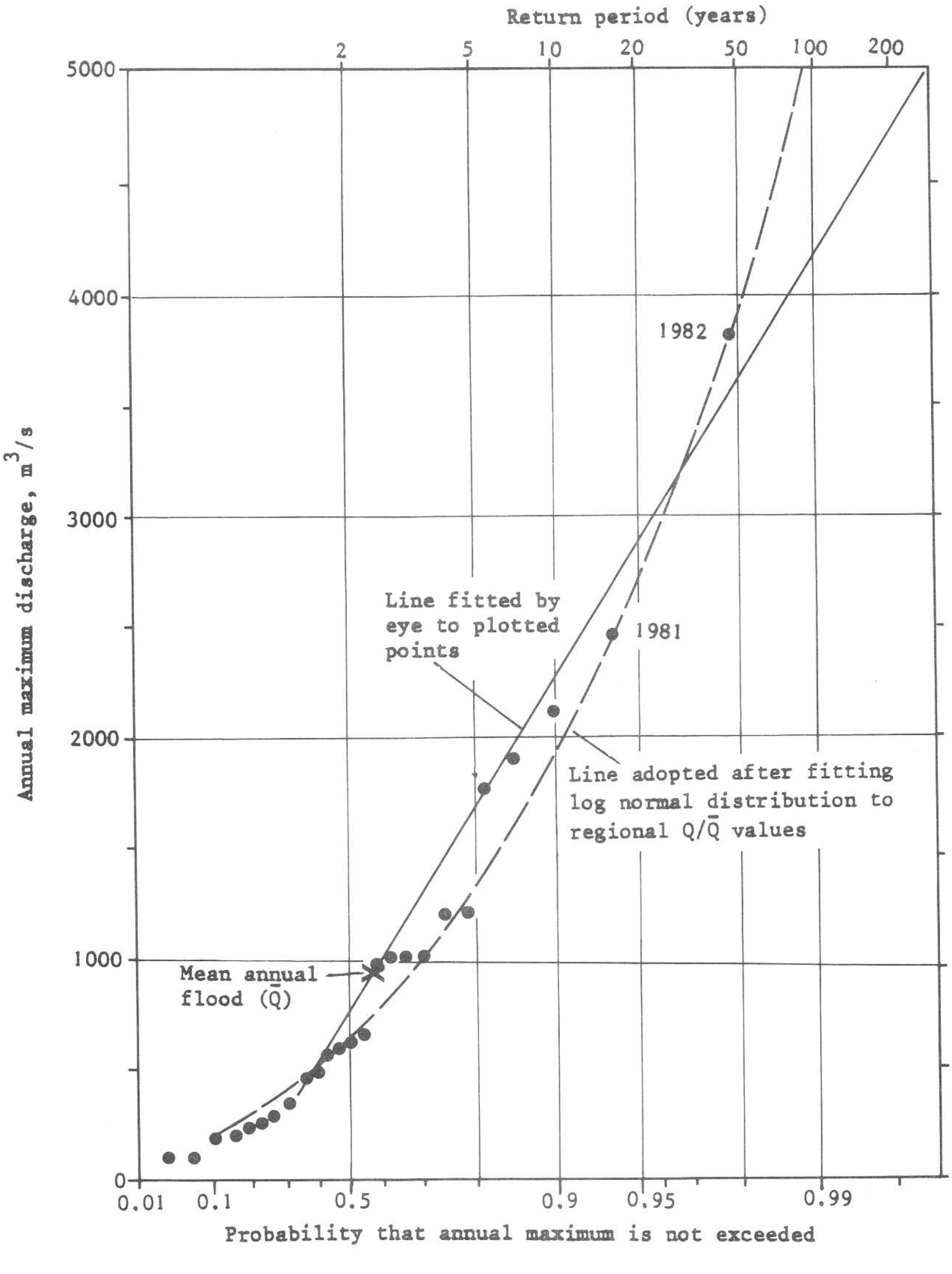
Ref	Date	Q_p	T_p	W	V	Ref	Date	Q_p	T_p	W	V
		(m^3/s)	(h)	(h)	($M.m^3$)			(m^3/s)	(h)	(h)	($M.m^3$)
A	6. 9.52	60	2.0	5.0	2.02						
B	12. 7.53	289	1.25	0.6	2.86	M	17.8.62	19	0.75	5.0	0.61
C	21. 8.54	130	10.25	3.2	3.35	N	19.8.62	160	1.5	1.0	3.14
D	7. 9.54	152	0.25	1.6	2.23	P	21.8.62	285	1.5	1.0	5.44
E	17.10.54	470	0.5	0.7	3.33	Q	31.8.62	238	2.25	1.6	4.74
F	4. 4.56	997	0.25	1.6	8.38	R	1.9.62	1 190	0.25	1.2	12.24
G	24. 4.56	140	2.0	1.2	2.61	S	11.5.63	185	1.0	1.2	3.21
H	2.10.56	1 900	1.25	1.4	15.57	T	18.8.63	101	2.75	3.8	2.98
I	15.4.60	133	1.25	2.1	2.73	U	5.4.64	347	1.5	2.0	7.10
J	4.5.60	46	1.5	7.0	1.62	V	25.4.65	314	0.5	-	6.04
K	9.9.61	210	2.0	1.2	3.74						
L	7.8.62	13	2.0	10.0	0.57						

Q_p = peak discharge.

T_p = time from first sustained rise to peak discharge.

W = time for discharge to drop from Q_p to $Q_p/2$.

V = total runoff volume from time of rise to 20h later.

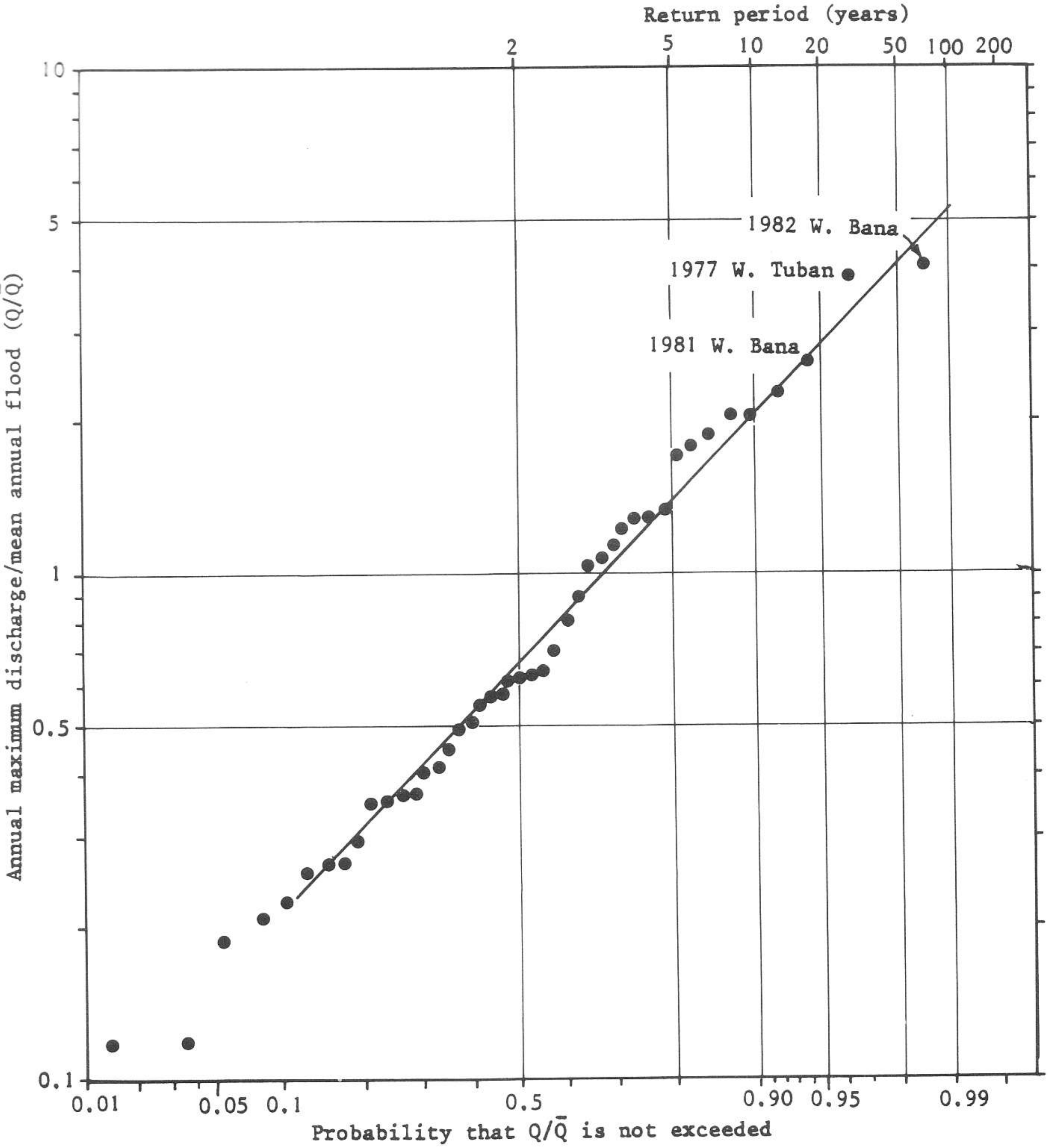


Notes

1. Plotted points are 1948-82 annual maxima from Table 4.1
2. x axis is Gumbel extreme value scale

WADI BANA AT BATEIS : FLOOD FREQUENCIES

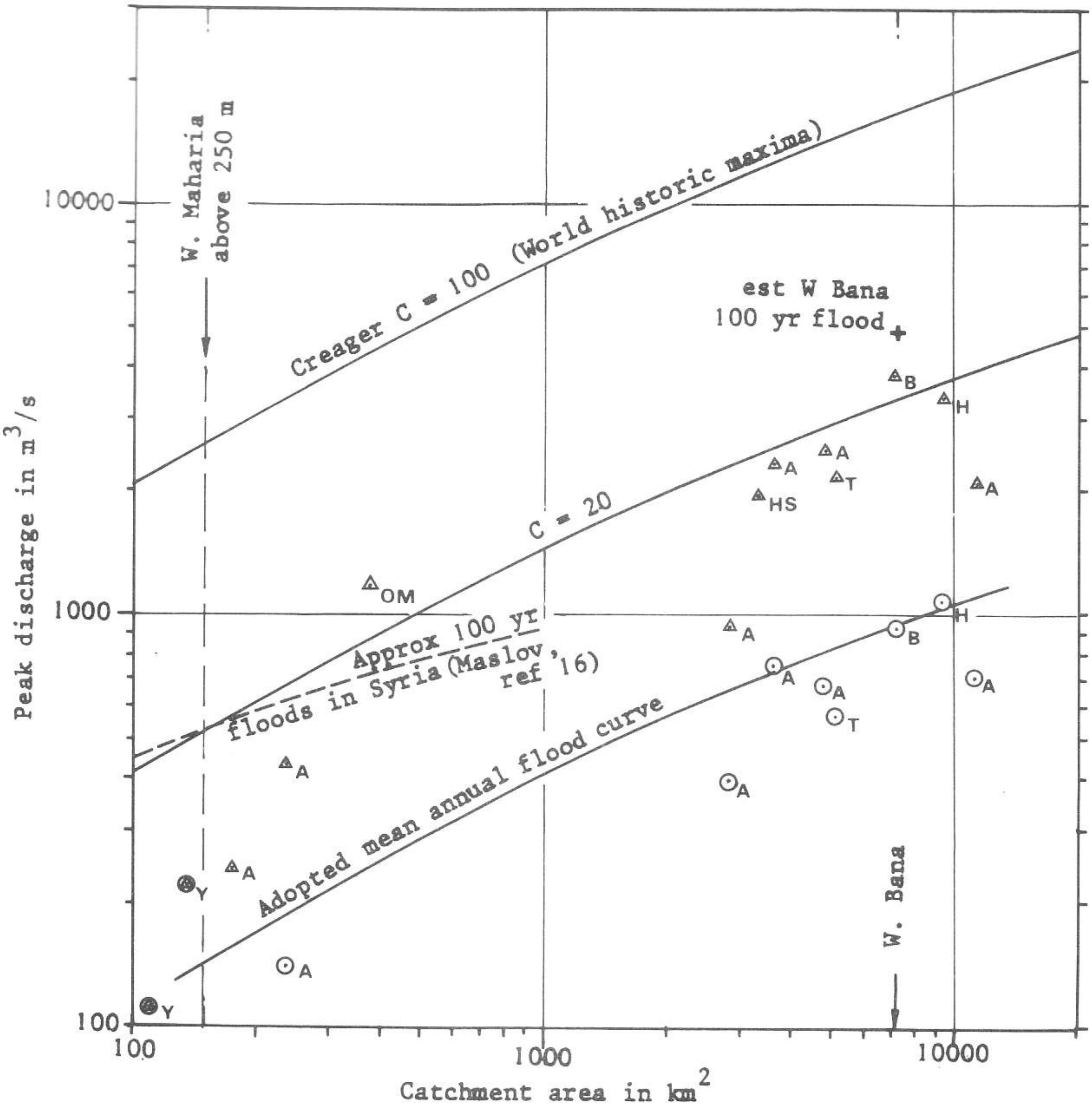
Figure 4.1



Notes

1. Points plotted are Bana, Tuban and Hajr annual maxima divided by respective mean annual floods.
2. Annual maxima occurring on same day in different wadis plotted as a single mean value of $Q/\bar{Q}$.
3. x axis is normal probability scale

FREQUENCY ANALYSIS OF Q/Q VALUES
Figure 4.2



Key :

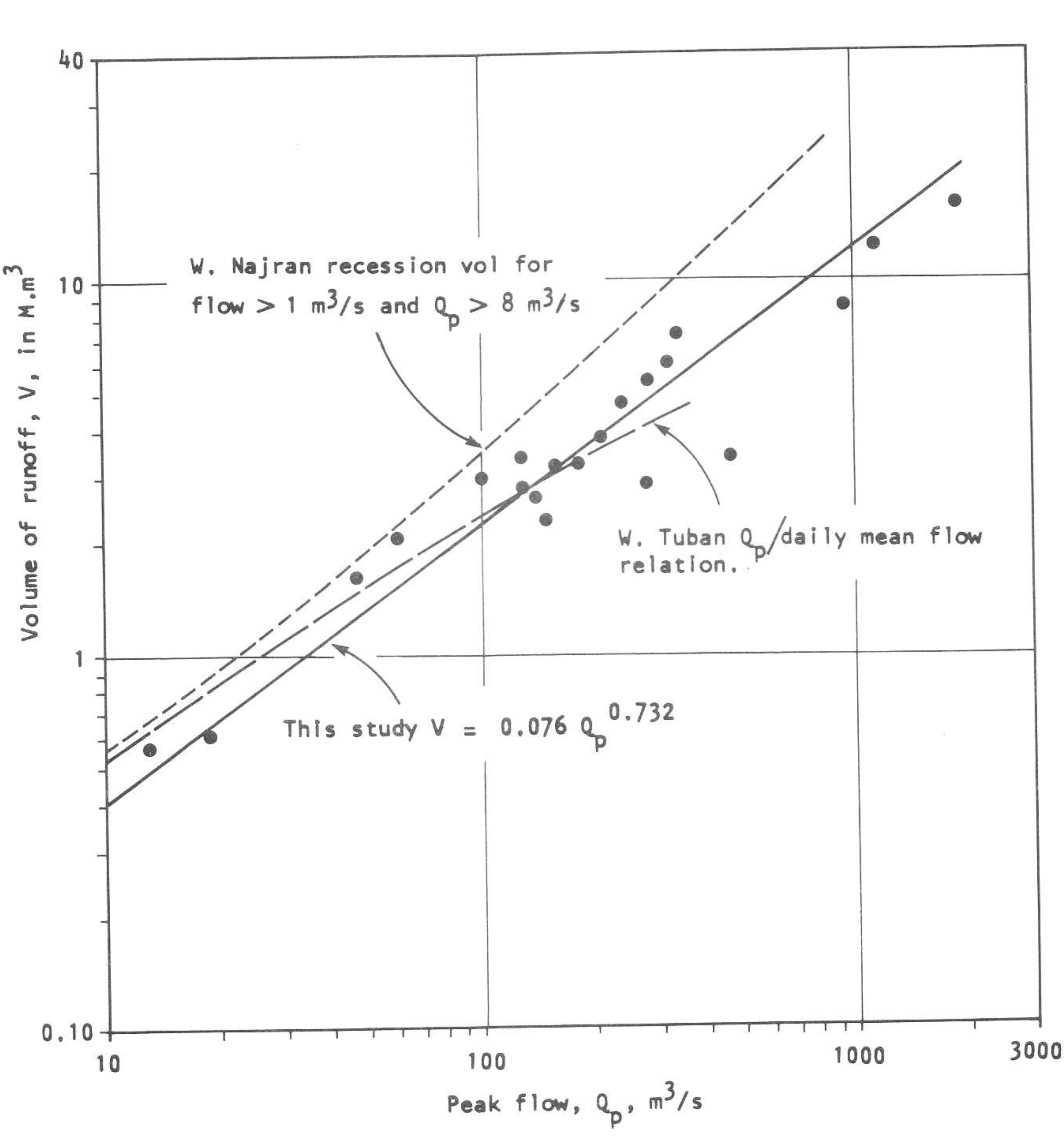
- ⊙ mean annual flood
- △ max recorded flood
- ⊛ estimated low return period (2-10 yrs) flood

Locations:

A	Saudi Arabian data
B	W Bana
H	W Hajr
HS	W Hassan
T	W Tuban
Y	Other PDRY data
OM	W Adal, Oman

REGIONAL FLOOD PEAK DATA

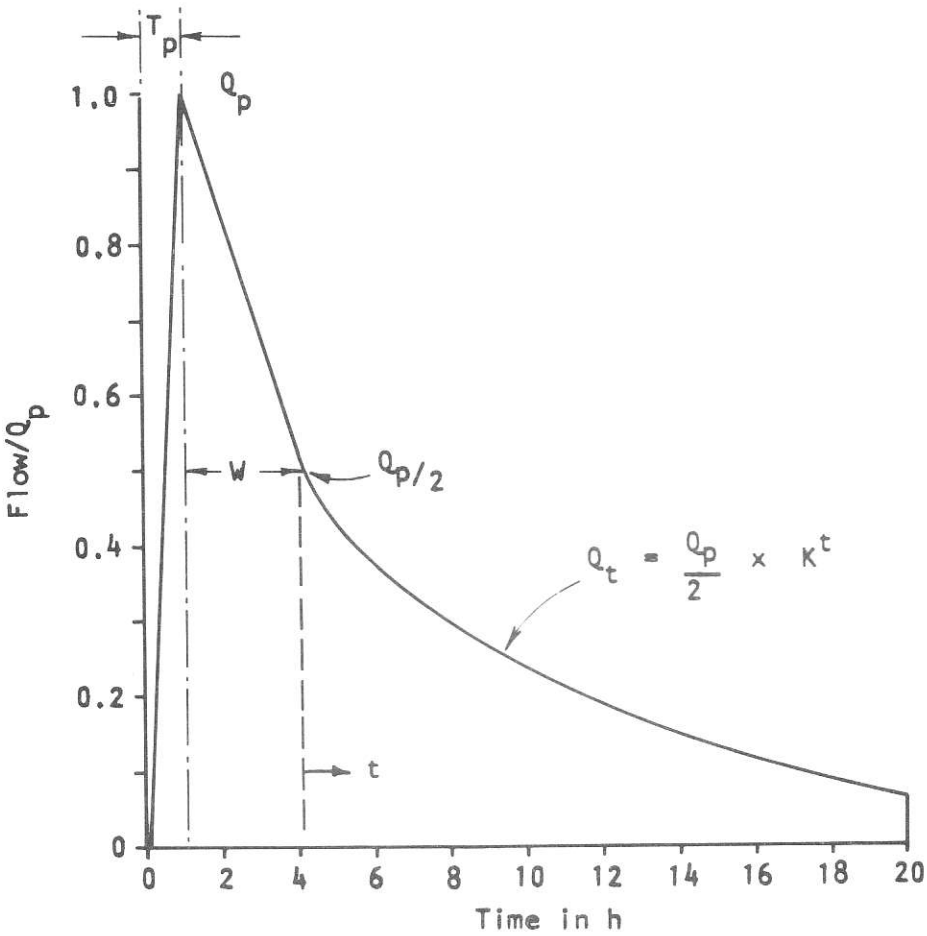
Figure 4.3



Notes

1. See Table 4.6 for plotted data.
2. Najran relation from Figure A31 of ref.25.
3. Tuban relation from Figure 11.15 of ref. 4.

RELATION BETWEEN PEAK FLOW AND RUNOFF VOLUME
Figure 4.4



Procedure, given Q_p in m^3/s

1. T_p = 1 h.
2. $W = 1 + 8.93e^{(-0.0144\ Q_p)}$
   (time in h for flow to drop from Q_p to 0.5 Q_p).
3. Find hourly recession const, K
   $Q_p > 400\ m^3/s \quad K = 1.68\ Q_p^{-0.115}$
   $Q_p \leq 400\ m^3/s \quad K = 1.066\ Q_p^{-0.039}$
4. Find flows at hourly intervals from
   $Q_t = \frac{Q_p}{2} \times K^t$ (flow t hours after dropping $Q_p/2$)
5. Volume below hydrograph over a base time of 20 h = volume from Figure 4.4.

HYDROGRAPH SHAPE
Figure 4.5

5. MATCHING RESOURCES AND REQUIREMENTS

5.1 INTRODUCTION

The objective of this chapter is to assess the areas which can be irrigated by the available wadi flows, under various proposed weir and canal systems. To achieve this it has been necessary to estimate all demands on Wadi Bana flows, including those from outside the study area.

Figure 5.1 is a schematic layout of the areas irrigable from Wadi Bana, and these are summarised in Table 5.1. Areas quoted in this annexe are wetted areas (equivalent to 95% of planimetered gross areas, which include roads, bunds and canals but exclude villages and other major non-agricultural features). The extent of the old right bank traditional areas (RBTA) is very approximate, since they have not been studied to feasibility level.

Having established the required irrigation depths, irrigable areas have been related to available water resources in three stages:

(i) simple estimates of irrigable areas assuming no wadi or diversion losses. This gives an upper bound solution which might in reality be approached if the entire area were irrigated from one very large diversion at Bateis.

(ii) diversions at Bateis. These can be studied in isolation as Bateis diversions have first call on Wadi Bana resources and are limited only by canal and headworks capacities.

(iii) the operation study approach. So far as is possible with the serious lack of data, the operation study aims to account for intake and canal capacities and wadi and diversion losses, thereby modifying and making more realistic the upper bound solution in (i) above.

5.2 WATER REQUIREMENTS

5.2.1 Field requirement

Experimental work at El Kod indicates that the depth of water needed in the field for a cotton crop is 50 cm, see Annexe D. However, since crop growth depends entirely upon soil moisture retained in the plant root zone before sowing, the capacity of the soil profile to retain water is crucial.

Combining these capacities (from Annexe C) with the expected rooting depths of the principal crops we get the following totals, as maxima for potential evapotranspiration. Up to 5% will probably be lost by surface evaporation between irrigation and planting:-

Soil type texture	Water holding cap: cm per m	Cotton root depth cm	Cotton available water cm	Water Melon root depth	Water Melon available water	Sorghum root depth	Sorghum available water
Fine	15 or more	300	45	150	23	200	30
Medium	11-15	300	39	150	20	200	26
Coarse	11 or less	300	33	150	17	200	22

It can be seen that the desirable moisture requirement of 50 cm for cotton is only approached in the fine textured soils. It is furthermore apparent that to apply 50 cm or more for crops other than cotton, or for any crop on the medium or coarse textured soil, is wasteful in that water will not be used for evapotranspiration. However the recharge of the groundwater body which results from over-irrigation will form a valuable part of the overall water resources cycle, provided it does not lead to an excessively high water table. We therefore assume a net field requirement of 45 cm for all soils and crops.

5.2.2 Diversion requirement

(a) Diversion depth

In the past it has not been considered feasible to restrict irrigation quantities to correspond to the lesser water holding capacities of medium and coarse textured soils, as compared with the fine textured ("heavy") soils. However, with an improved distribution system controlled water application becomes possible: depths should be calculated according to both soil moisture capacity and infiltration rate of the soils in any field. The effect of infiltration during the time needed to flood a field is considered in Chapter 14 of Annexe B: for typical fields it amounts to an average additional application of some 3 cm, giving a gross field application of 48 cm.

In the traditional irrigation areas, that is the entire left bank area and the RBTA, we consider that an additional application depth of 20% must be allowed for the effects of poor water control: i.e. 57 cm field application is assumed. This compares with an average application depth of 68 cm recorded in our field trial at Miyuh, in the northern part of Maincanal area: the latter figure includes conveyance losses downstream of the main canal.

Conveyance efficiencies are always difficult to estimate, but the high velocities and short total times of canal flows must mean that infiltration losses are less than in conventional slow-moving systems where canals are full for much of the year. Conventional systems having efficiencies of 50% to 65% lose water also from discharges to waste occurring through negligence and/or the inability of sub-areas to accept the whole flow delivered; such operating losses are most unlikely to occur with a spate system. We therefore consider an overall conveyance efficiency of 80% to be reasonable.

The diversion requirement for irrigating the Phase I ares (with improved distribution system) is therefore taken as 60 cm (48 cm at 80% efficiency). Likewise the diversion requirement for the traditional areas is 20% higher at 72 cm.

Available data on actual diversion depths is extremely sparse, but the selected values are consistent with those appearing in early Department of Agriculture and El Kod research station reports, which range from 59 to 91 cm.

Listed below are gross irrigation depths taken from Department of Agriculture and El Kod reports:

(i) 1957 (Dept of Agriculture)

Kharif season: total of 13 000 ha irrigated by 83 $M.m^3$ diverted (0.64 m depth)

(ii) 1959/60 (El Kod)

Seif season: 11.8 $M.m^3$ diverted to irrigate 1 300 ha (0.91 m depth)

Kharif season: average application 0.82 m ("compared with 0.60 m in the previous season with more restricted supply").

(iii) 1960/1 (El Kod)

Kharif season: average application 0.59 m

(iv) 1961/2 (El Kod)

Kharif season: average application 0.66 m

(b) Diversion volumes

The layout of the Wadi Bana command is shown schematically in Figure 5.1, and the command areas are given in Table 5.1. The command area progressively increased during the 1950's and 1960's, with the construction of permanent diversion weirs. With a diversion requirement of 72 cm depth the required volumes would have been as follows:

Year of construction	Weir	Irrigable area, ha		Diversion requirement $M.m^3$	
		Command	Cumulative	Command	Cumulative
1953	Bateis	8740	8740	62.9	62.9
1961	Diyyu	3650	12390	26.3	89.2
1964	Makhzan	3300	15690	23.8	113.0
1965	Hayja	3260	18950	23.5	136.5
1966	Gharaib	3220	22170	23.2	159.7

Re-development of parts of the right bank (the Phase I areas) took place during the 1970's, with the remaining RBTA being exluded from the project. This work has never been commissioned but would have created a reduced project diversion requirement as follows:

Weir	Irrigable area, ha	Required depth, cm	Diversion requirment, $M.m^3$
Bateis	8740	72	62.9
Hayja	2030	60	12.2
Diyyu	2130	60	12.8
Makhzan	3300	72	23.8
TOTAL	16200		111.7

5.3 IRRIGABLE AREAS IGNORING WADI AND DIVERSION LOSSES

If wadi and diversion losses are ignored, then the diversion requirements calculated in the previous section can be compared directly with the seasonal runoffs quoted in Table 3.4. It is apparent that after construction of Hayja weir there would very rarely have been sufficient water to complete Makhzan irrigation, let alone to irrigate from Gharaib weir. This is borne out by the annual reports from El Kod Research Station (which lies within Gharaib command) and by the fact that all of Gharaib and parts of Makhzan command have been converted to borehole irrigation.

Table 5.2 shows the areas that could have been irrigated each year, following the Phase I re-development. It can be seen that even if wadi and diversion losses are ignored, and if no peak flood water was lost, the whole 16200 ha project could only have been irrigated in 8 of the 15 years. On average less than 14000 ha could be irrigated in the kharif season.

5.4 BATEIS DIVERSIONS

The diversion curves in Figures 3.9 and 3.10 (based on hourly flows) were used to estimate the Kharif and Seif season volumes which could have been diverted into Bateis canal and Maincanal between 1951-65, assuming the current approximate combined canal capacity of 28 m^3/s. The values obtained are shown in Tables 5.3 and 5.4, and are compared in each case with volumes (found from Abyan Board water book records) actually diverted. Shakat ba Omer was deliberately excluded as its capacity is disproportionately large for the area which it commands.

Volumes diverted cannot be directly related to areas actually irrigated, since these are unknown in all but one case (1957, when a Kharif total of 5 300 ha was irrigated). They are also affected by diversion arrangements at Bateis, which are known to have been improved during the course of the adopted record, at least up until the late 1950s.

Actual diverted Kharif volumes average 48 $M.m^3$ and range from 29 to 68 $M.m^3$. These may be compared with Bateis and Maincanal command requirements used in this study of 62 $M.m^3$. The adopted requirements thus appear realistic.

Examination of diverted and divertible volumes in Table 5.3 suggests that only in 1960 (the driest Kharif season of the adopted record) and 1958 (second driest) were diversions limited by available runoff and, possibly, by diversion capacity. Even so, some 8 - 9 $M.m^3$ were apparently "wasted" (ie could have been diverted but were not) in both years and explanations were sought in the Abyan Board water books.

In 1960 irrigation from Maincanal did not start until 3 August and approximately 6 $M.m^3$ were thus "wasted" during July. Shakat ba Omer diversions were negligible (see values tabulated in section 3.1.3). For 1958 the explanation lies in excessive Shakat ba Omer diversions: 3.6 $M.m^3$ were diverted in July and August 1958 (and halted on 31 August). In addition 1.4 $M.m^3$ were diverted by the Massani canal (not accounted for in Tables 5.3 and 5.4). The discrepancies between diverted and divertible volumes during the 1958 and 1960 Kharif seasons are thus largely explained.

Diverted Seif volumes (Table 5.4) average only 9.5 $M.m^3$ and range from 1 to 21 $M.m^3$. Only in 1961 (the driest Seif season of the adopted record) did lack of runoff or diversion capacity appear to limit diversions. In all other years diverted volumes were far less than those which could have been diverted, evidently for reasons not connected with water availability.

From the foregoing discussion it may be concluded that full requirements of the two main canals supplied from Bateis can be met in 80 - 90% of Kharif seasons and that there is little direct benefit in increasing the diversion capacity at Bateis. (However, the operation runs show that there is an indirect benefit to downstream areas, which thereby receive a full supply earlier).

5.5 OPERATION STUDY PROCEDURES

5.5.1 Outline description

The operation study program was written for a Hewlett-Packard 9825A desk-top computer. An hourly time step was used. Hourly Bateis inflows were available for three Kharif and three Seif irrigation seasons, as described in chapter 3. Each hourly flow was treated as a discrete volume of water, ie no routing (other than infiltration loss) was assumed. With the quality of flow data available this was considered an acceptable simplification, the result of which is to underestimate slightly the divertible volumes at lower intakes.

The system handled by the program is shown in Figure 5.1. Each hourly volume is moved down the wadi from weir to weir, reduced en route by infiltration and evaporation losses. A distance increment of 0.5 km is used. The procedure for estimating losses is described in more detail in section 5.5.2 below. In accordance with current practice, considered unlikely to change, abstraction priorities are fixed in an upstream to downstream order, although the program user may "remove" any specified weir(s).

The program allows up to four canals to be supplied by one weir. Their priority order is that in which they are specified. Supply into an individual canal is thus determined by:

(i) the hourly flow arriving at the weir.

(ii) the headworks capacity of the weir.

(iii) the priority of the canal relative to others supplied by the same weir.

(iv) the canal capacity

(v) the remaining volume of irrigation water required by the canal's commanded area.

Table 5.5 lists the weirs and canals in the order in which they are specified for use by the basic program. Variations associated with particular options are described in Section 5.5.3.

5.5.2 Wadi losses

Wadi losses comprise infiltration and evaporation, the former being by far the most important. The following factors affect infiltration loss:

(i) area of the infiltrating surface

(ii) infiltration rate

(iii) volume to be recharged below the wadi bed

(iv) rate of subsurface movement away from the wadi bed.

In order to estimate the infiltrating surface area a relationship was sought between discharge, Q, and wetted perimeter, P. A number of current wadi bed cross-sections between Bateis and Makhzan were plotted. Using mean bed slopes and a Manning's n of 0.03, relationships between Q and P were established. Although there was considerable variation for different sections, the following expression gave reasonable results:

$$P = B - Be^{-0.00539Q}$$

|| RUBBISH. P less than B!

In this formula Q is in m^3/s and P and B (wadi bed width) are in metres.

Dar Al-Handasah (reference 1) carried out five wadi bed infiltration tests, in each case about 200 m below a diversion weir. In the last hour of each test (ie after about 4h) they obtained the following rates:

Bateis	0.36 m/h
Hayja	0.12 m/h
Diyyu	1.13 m/h
Makhzan	0.13 m/h
Gharaib	0.18 m/h

Dar Al-Handasah themselves dismissed these results as "too high". If the Diyyu result is excluded as being possibly the result of cobblestones immediately below the infiltrometer, an average of 0.20 m/h is obtained. This is still a high value: Binnie & Partners (ref 25) quote equilibrium rates of between 0.06 and 0.07 m/h measured in Wadi Najran and Wadi Jizan, and an initial rate of 0.15 m/h in Wadi Najran. However, equilibrium rates of over 0.1 m/h have been accepted (see Annexe B (Soils) of this report) for coarse textured agricultural soils in the study area, and a wadi bed value of 0.20 m/h may therefore be reasonable. During operation study runs both 0.10 m/h and 0.20 m/h were tried: run results proved fairly insensitive to which of the two values was used and 0.20 m/h was used for all definitive runs.

The procedure for estimating the volume to be recharged was of necessity extremely approximate. Long sections of wadi bed levels before and after the 1982 flood were plotted. These long sections were compared with the water table elevation along the wadi bed estimated from Sogreah's Figure 2.III.1 (ref 24). Sogreah's water levels are representative of pre-kharif flood season conditions in 1980. To estimate recharge volumes the wadi was divided into 0.5 km lengths. The gross volume per 0.5 km length was estimated as the product of the length, current (1983) bed width, and the depth from a mean wadi bed (average of bed levels before and after the 1982 flood) to the water table. Recharge is thus envisaged as filling a prism below the wadi bed: any subsurface flow away from the prism during a flood season has been neglected.

For Kharif season recharge a fairly high specific yield of 20% was used to convert the gross volume below the wadi bed to a rechargable water volume. Potential recharge at the start of the Seif season would clearly be greater and a specific yield of 30% (ie close to the likely porosity) was assumed. Water level data known to refer to pre-Seif conditions were not available.

Account had also to be taken of the Aden water supply well field abstractions. Construction of this wellfield is currently (October 1983) under way. It is intended ultimately to supply 10 $M.m^3$/year. Its location, on the left bank of Wadi Bana and close to Hayja weir site, is shown in Figure 3.1. Recharge to meet abstractions will come from Wadi Bana runoff and irrigation water. Some reduction in evaporation losses by phreatophytes is also envisaged (Sogreah, ref 24).

Although very close to Wadi Bana it is the opinion of one of the hydrogeologists involved (Dr S E Sutton, personal communication) that lateral subsurface flow from the wadi bed area is slight (as assumed here) and that most recharge is from irrigation. We have assumed that 5 $M.m^3$ is met by additional wadi bed infiltration, and that this is divided seasonally in rough proportion to preceding dry season lengths. This gives:

Seif season: 4 $M.m^3$ additional wadi bed recharge

Kharif season: 1 $M.m^3$ additional wadi bed recharge

Table 5.6 shows potential recharge volumes for both seasons between successive pairs of weirs down the wadi. The annual total is 18 $M.m^3$ or about 11% of the MAR at Bateis. This is a low figure (GDC (ref 3) assumed 30-35%) but most of any water escaping over the lowest weir (which depends on diversion capacities and demands) also contributes to recharge.

Evaporation loss was assumed to take place over the wetted perimeter, P, estimated from B and Q (see above). A constant rate of

$$Eo = 0.3 \text{ mm/h}$$

was used for all runs. It was derived from the estimated average annual Eo of 2 380 mm (chapter 2).

The procedure can be summarized as follows:

(i) recharge takes place over the wetted perimeter estimated from inflow, Q, into the 0.5 km reach, and B, wadi bed width) at the prescribed infiltration rate until the recharge prism is full, whereupon recharge stops.

(ii) evaporation takes place over the wetted perimeter at the prescribed rate as long as there is surface inflow into the 0.5 km reach.

5.5.3 Options studied

A number of operation runs were carried out in 1983 and their results incorporated in the December 1983 draft final report. Following discussions on the draft report, water application depths and project options have been refined, therefore these earlier results are not reproduced in the final report. Conclusions from the early series of runs were:

(i) the requirements of Bateis weir commands and the right bank Phase I areas can be satisfied with a high degree of reliability using existing intake and canal capacities.

(ii) there is normally insufficient water to irrigate all of Makhzan and/or the RBTA.

(iii) reducing the Makhzan intake capacity from 37 m^3/s to 15 m^3/s only increases the shortfall slightly.

(iv) seif season flows are taken almost entirely within Bateis command, and therefore do not affect the choice of alternative development options.

A new series of operation runs was carried out in April 1984, to study the effect of various supply options, and using the water application depths given in Section 5.2.2. Following the earlier studies it was clear that:

(i) it is not economic to reconstruct Hayja weir to supply only its Phase I command area of 2030 ha.

(ii) if Diyyu weir is replaced, it is cheaper to provide a left bank supply to Makhzan at Diyyu than to reconstruct Makhzan weir.

The new options studied fall into three main groups, each excluding one or more command areas.

Option A

New weirs at Hayja and Diyyu (see Figure 5.2). Hayja command area is increased by including 1050 ha at Hawashib. This leaves insufficient water to justify a double crested Diyyu weir to supply Makhzan, therefore the remaining water is supplied to Nusheera. (Note: the 180 ha at Malaha could also be included in this option, but, with the general uncertainty of the RBTA area figures, its omission is not significant).

Option B

One new weir at Diyyu serving both banks; Hayja command excluded (see Figure 5.3). Under Option B' Makhzan is supplied from Bateis weir instead of Diyyu weir; diversions for Makhzan therefore take priority over Diyyu diversions.

Options C-H

One new weir at Hayja (see Figure 5.4) to supply all the right bank Phase I areas. Makhzan supplied from Bateis weir via Maincanal and Bateis main canal. The options investigate the effect of various permutations of canal size, which are given in Table 5.7.

Under the traditional system Makhzan was supplied from the weir furthest downstream and had lowest priority, so the operation runs for options C-H have been modelled to reflect the traditional water rights so far as practicable.

It has been assumed that after the Bateis and Maincanal commands have been satisfied the Bateis intake would be closed to allow diversions from Hayja weir; only the excess above Hayja intake capacity would be diverted for Makhzan until all the Hayja demands were satisfied. This method of operation would be difficult to control and if adhered to would inevitably lead to higher diversion losses. It has been modelled in the operation study program using a dummy Makhzan intake 0.5 km downstream of Hayja weir: since Makhzan cannot be irrigated simultaneously with Bateis/Maincanal commands, all volumes recorded by the program as having been diverted before Bateis/Maincanal irrigation is completed have been re-allocated to losses.

Option I

This option was not analysed using the operation study program. It is a low cost scheme with no new headworks, but Makhzan is supplied via Maincanal, as in Options G & H. Maximum divertible volumes at Bateis have been taken from Table 5.3, assuming a single 28 m^3/s intake capacity; this is not strictly correct because there is a 16 m^3/s supply to Bateis, until that is satisifed, in addition to the Maincanal capacity (costed at 25 m^3/s), but the figures can be used for approximation purposes. Oqma diversions at Diyyu are assumed to irrigate 400 ha in favourable years, as at present.

Option O

Option O is included as the base (without project) case against which other options can be compared. It assumes completion of the new Bateis headworks, but no other construction work. It is assumed that the Diyyu main canal will be breached by wadi bank erosion so that no land can be irrigated there, even with oqma diversions.

5.6 OPERATION STUDY RESULTS

Table 5.8 summarizes the operation study results: the program deals with volumetric demands, rather than areas, thus the table lists results in terms of volumes diverted at each headworks. Tables 5.9 to 5.11 present the results in terms of irrigable areas for each option, broken down into the separate commands. Table 5.12 summarizes the areas to be developed under each option, with the expected average cultivated areas.

5.6.1 Significance of results

It can be seen in Table 5.8 that the total volume diverted (supply) is not directly related to seasonal runoff (inflow). The following table summarises some of the data:

Kharif season		1953		1962		1961	
Total runoff $M.m^3$		108.5		131.0		77.6	
Option	Intake capacity (m^3/s)	Diverted Vol	%	Diverted Vol	%	Diverted Vol	%
A	100.5	101.4	93	104.3	80	73.3	94
B	98.0	99.0	91	100.1	76	72.8	94
C	45.5	96.4	89	83.7	64	69.4	89
I	28.0	89.1 (demand)	82	77.0	59	61.7	80

Clearly as the total intake capacity is reduced the amount which can be diverted is more susceptible to the variability of the seasonal flow. Figure 3.5a shows that 1962 kharif flows were more variable than the others. Although seasonal runoffs have been assigned a given probability (Sects 3.4 and 3.5), the same probabilities cannot be applied to the divertible volume which is dependent on intake capacities and hydrograph forms. Therefore we have assumed that the three years selected for hourly flow analysis may be considered representative, in terms of divertible volumes, as follows:

1953, 1962 - median and high divertible volumes (depending on intake capacity)

1961 - low divertible volume

It is not economic to provide engineering infrastructure and carry out annual ploughing on land that will only rarely be irrigated, therefore the area to be developed is taken as the lesser of the areas irrigable in 1953 or 1962. The average area that will be irrigated is taken as:

$$\frac{1}{4} \times \text{(1961 area)} + \frac{3}{4} \times \text{(developed area)}$$

5.6.2 Option A

Option A uses the existing canal capacities (including the newly constructed Hawashib and Nusheera canals) and assumes new weirs at Hayja and Diyyu. The model was actually run with a 15 m^3/s intake at Diyyu weir to serve Makhzan, but since this would supply less than 100 ha on average, the supply is clearly uneconomic and the diverted volumes have been re-allocated as losses. As it is, less than half the Nusheera command is normally irrigated. Progress of the irrigation throughout the season is shown on Figures 5.5a and 5.5b for runs E1 and E2 respectively.

5.6.3 Option B

For Option B the 17.5 m^3/s intake at Hayja is replaced by a 15 m^3/s supply to Makhzan at Diyyu weir. The total volumes diverted are only slightly reduced. Progress of irrigation is shown on Figures 5.6a and 5.6b, with a little over half of Makhzan being irrigated by the end of the wetter kharif seasons.

Under Option B' diversions for Makhzan are increased, largely at the expense of Nusheera. Although divertible volumes are increased, the average cultivated area is less, because flows to individual commands are particularly variable.

5.6.4 Options C-H

Option C uses the existing Ahbush-Jabalein canal capacities to supply all the right bank Phase I areas from a new weir at Hayja. Makhzan is supplied at 8.1 m^3/s from Bateis via Maincanal. Under this arrangement less than half the Diyyu area is normally irrigated, and only about 200 ha at Makhzan.

Option D doubles the capacity to Makhzan by extending Bateis main canal at 8.3 m^3/s, but this only adds 100 ha to the irrigable area.

Option E increases the Ahbush-Jabalein canal capacity to 17.5 m^3/s throughout. This results in a much improved supply to Diyyu, but means that less water can be diverted for Makhzan. Option F further increases the Ahbush-Jabalein canal capacity: this effects a small improvement in the Diyyu supply, but also a much larger improvement in the supply to Makhzan. This is brought about because the increased AJC capacity allows the Hayja demands to be satisfied earlier in the season, so that diversions for Makhzan can begin earlier.

Under Options G and H Makhzan is supplied by Maincanal, uprated to 25 m^3/s throughout. For Option G the AJC is at 17.5 m^3/s, as in Option E, but the Diyyu supply is improved because Maincanal has been satisfied earlier in the season; the increased Maincanal capacity permits significantly more irrigation at Makhzan. For Option H the AJC is also uprated: this improves Makhzan supply because of the timing effect noted above, but the improvement is relatively small.

5.6.5 Option I

Option I assumes no right bank weirs and a 25 m^3/s supply to Makhzan via Maincanal. As noted in Section 5.5.3, the results for this option are approximate, since they are not from the operation study program. However, as expected in the absence of competing right bank demands, the results demonstrate the highest area irrigated at Makhzan.

5.6.6 Concluding remarks

From the results presented in this Chapter relating to Kharif season irrigation we may conclude that:

(i) the requirements of Bateis, Maincanal and Shakat ba Omer commands can be satisfied with a high degree of reliability.

(ii) Makhzan command cannot reliably be satisfied using any of the options considered. If a substantial part of Makhzan is to be developed, then major portions of the right bank must be excluded from the project in order to make adequate water available.

(iii) Diyyu command cannot adequately be irrigated from a weir at Hayja using the existing Ahbush-Jabalein canal capacity.

(iv) reliability of diverting a given volume is reduced with reduced total intake capacity.

TABLE 5.1 COMMAND AREAS

	Command	Gross 100%		Irrigable 95% (wetted area)		Agricultural 80%	
Bateis							
	Bateis canal	5158		4900		4125	
	Maincanal	3847		3660		3077	
	Shakat ba Omer	187		180		150	
	Sub-total		9182		8740		7352
Hayja							
	Ahbush (Ph I)	890		840		712	
	Jabalein (Ph I)	1250		1190		1000	
	Malaha	190		180		150	
	Hawashib	1100		1050		880	
	Sub-total		3430		3260		2742
Gahaisa Island (Ph I)			130		120		100
Diyyu							
	Diyyu (Ph I)	2240		2130		1792	
	Nusheera	1600		1520		1280	
	Gharaib	(3390)		(3220)		(2710)	
	Sub-total		3840		3650		3072
Makhzan			3470		3300		2776
TOTAL			20062		19070		16042

NOTES:

1. Massani (350 ha gross) was supplied by a right bank intake at the old Bateis weir. Much of the land was destroyed by the 1982 flood, and the remainder will not be commanded by the new weir.

2. Figures for the RBTA (Malaha, Hawashib and Nusheera) areas are very approximate. Malaha has been excluded from the Option A operation runs, but may be considered as part of Hawashib.

3. Gahaisa island, originally 190 ha, was served by an oqma. Following destruction during the 1982 flood, the reduced area has been excluded.

4. Gharaib was originally commanded by its own weir but the land is now irrigated from groundwater. It is shown here under Diyyu to allow for the possibility of leaching flows when water is available in very wet years, but its area is not included in the totals.

TABLE 5.2 - TOTAL IRRIGABLE AREAS IF WADI AND DIVERSION LOSSES IGNORED, 1951-65

	Seif season		Kharif season	
Year	Runoff $M.m^3$	Irrigable area ha	Runoff $M.m^3$	Irrigable area ha
1951	36.8	5 110	129.4	16 200
1952	19.2	2 670	83.9	12 240
1953	28.5	3 960	108.5	15 760
1954	23.2	3 220	163.8	16 200
1955	13.9	1 930	118.8	16 200
1956	14.4	2 000	112.1	16 200
1957	139.9	16 200	93.3	13 650
1958	12.0	1 670	58.1	8 070
1959	12.5	1 740	121.4	16 200
1960	70.8	10 050	41.7	5 790
1961	7.3	1 010	77.6	11 190
1962	10.6	1 470	131.0	16 200
1963	132.1	16 200	126.5	16 200
1964	28.4	3 940	162.3	16 200
1965	27.3	3 790	84.6	12 350
AVERAGE		5 000		13 900

NOTE: Irrigable areas are calculated assuming the priority and water depths given in the table in Section 5.2.2 (b), up to 16 200 ha maximum.

TABLE 5.3 - VOLUMES DIVERTED INTO BATEIS AND MAIN CANALS, 1951-64 (KHARIF SEASON)

Year	Kharif runoff (1 July-15 Oct) M.m^3	Max. volume divertible M.m^3	Actual volume diverted M.m^3
1951	129.4	91.6	38.2
1952	83.9	68.0	36.3
1953*	108.5	95.2	48.3
1954	163.8	106.6	67.8
1955	118.8	88.1	57.5
1956	112.1	84.0	39.8
1957	93.3	73.5	42.3
1958	58.1	49.9	41.7
1959	121.4	88.3	60.1
1960	41.7	37.8	28.9
1961*	77.6	66.2	44.5
1962*	131.0	80.0	45.2
1963	126.5	91.4	53.6
1964	162.3	106.1	63.0
1965	84.6	68.4	-

NOTES

1. Diversion capacity of 28 m^3/s assumed
2. Years marked * used in operation studies. For these years divertible volumes estimated from Figure 3.9. For other years Figure 3.10 used.

TABLE 5.4 - VOLUMES DIVERTED INTO BATEIS AND MAIN CANALS, 1951-64 (SEIF SEASON)

Year	Seif runoff (16 Mar-31 May) M.m^3	Max volume divertible M.m^3	Actual volume diverted M.m^3
1951	36.8	27.3	12.4
1952	19.2	16.5	11.4
1953	28.5	22.5	11.0
1954*	23.2	21.3	8.2
1955	13.9	12.7	9.6
1956	14.4	13.0	9.8
1957	139.9	63.0	20.9
1958	12.0	11.2	3.9
1959	12.5	11.6	1.2
1960*	70.8	47.2	13.3
1961	7.3	7.1	6.5
1962*	10.6	9.3	6.6
1963	132.1	61.4	14.3
1964	28.4	22.5	4.5
1965	27.3	21.8	-

NOTES

1. Diversion capacity of 28 m^3/s assumed
2. 1951 seasonal total is for 19 March-31 May (earlier data not available)
3. Years marked * used in operation studies. For these years divertible volumes estimated from Figure 3.9. For other years Figure 3.10 used.

TABLE 5.5 - LIST OF WEIRS AND CANALS IN PRIORITY ORDER USED BY PROGRAM

Weir	Canal
Bateis	1. Shakat ba Omer 2. Bateis 3. Maincanal
Hayja	1. Ahbush 2. Malaha
Gahaisa oqma	1. Gahaisa
Diyyu	1. Diyyu 2. Nusheera
Makhzan	1. Makhzan

TABLE 5.6 - POTENTIAL WADI BED RECHARGE

Weir	km d/s of Bateis	km between weirs	Potential recharge ($M.m^3$) Kharif	Seif
Bateis	0			
		6.0	1.3	3.5
Hayja	6.0			
		2.5	1.0	2.4
Gahaisa	8.5			
		10.5	1.4	2.2
Diyyu	19.0			
		4.5	2.4	3.6
Makhzan	23.5			
		TOTAL	6.1	11.7

TABLE 5.7 DEVELOPMENT OPTIONS - KEY ENGINEERING FEATURES

Option	Weirs Bateis, Hayja, Diyyu			Maincanal		Bateis extension	Ahbush-Jabalein canal			Makhzan link canal
				a	b	c	d	e	f	g
A	B	H	D	12	-	-	17.5	10	10	-
B	B	-	D	12	-	-	-	-	-	15
B'	B	-	D	12	8.1	8.3	-	-	-	-
C	B	H	-	12	8.1	-	17.5	10	10	-
D	B	H	-	12	8.1	8.3	17.5	10	10	-
E	B	H	-	12	8.1	8.3	17.5	17.5	17.5	-
F	B	H	-	12	8.1	8.3	25	25	21	-
G	B	H	-	25	25	-	17.5	17.5	17.5	
H	B	H	-	25	25	-	25	25	21	-
I	B	-	-	25	25	-	-	-	-	-
O	B	-	-	12	-	-	-	-	-	-

NOTES:

1. Canal capacities a-g in m^3/s

2. See Figure 5.4 for locations

TABLE 5.8 OPERATION STUDY RESULTS

Option	Run no.	Year	Inflow	Losses		Total Supply	Total Demand	Bateis weir		Hayja weir		Diyyu weir		Makhzan (3)	
				Wadi bed + evap.	Diversion			Supply	Demand	Supply	Demand	Supply	Demand	Supply	Demand
A	E1	1953	108.5	4.1	3.0	101.4	106.3	62.9	62.9	19.7	19.7	18.8	23.7	-	-
	E2	1962	131.0	4.1	22.6	104.3		62.9		19.7		21.7			
	E3	1961	77.6	3.8	0.5	73.3		61.7		8.6		3.0			
B	E4	1953	108.5	4.1	5.4	99.0	110.4	62.9	62.9	-	-	23.7	23.7	12.4	23.8
	E5	1962	131.0	4.2	26.7	100.1		62.9				23.7		13.5	
	E6	1961	77.6	3.9	0.9	72.8		61.7				10.7		0.4	
B'	F1	1953	108.5	3.8	2.7	102.0	110.4	62.9	62.9	-	-	15.3	23.7	23.8	23.8
	F2	1962	131.0	3.8	25.6	101.6		62.9				23.6		15.1	
	F3	1961	77.6	3.7	1.1	72.8		61.7				6.9		4.2	
C	D11	1953	108.5	1.5	10.7	96.4	111.7	62.9	62.9	25.0	25.0	-	-	8.5	23.8
	D12	1962	131.0	1.5	45.8	83.7		62.9		19.2				1.6	
	D3	1961	77.6	1.5	6.7	69.4		61.7		7.7				0.0	
D	D1	1953	108.5	1.5	8.7	98.3	111.7	62.9	62.9	25.0	25.0	-	-	10.4	23.8
	D2	1962	131.0	1.5	45.0	84.5		62.9		19.2				2.4	
	D3	1961	77.6	1.5	6.7	69.4		61.7		7.7				0.0	
E	D5	1953	108.5	1.5	8.3	98.7	111.7	62.9	62.9	25.0	25.0	-	-	10.8	23.8
	D6	1962	131.0	1.5	40.9	88.6		62.9		24.3				1.4	
	D7	1961	77.6	1.5	5.7	70.4		61.7		8.7				0.0	
F	D25	1953	108.5	1.5	7.7	99.3	111.7	62.9	62.9	25.0	25.0	-	-	11.4	23.8
	D26	1962	131.0	1.5	37.6	91.9		62.9		25.0				4.0	
	D27	1961	77.6	1.4	4.4	71.8		61.7		10.1				0.0	
G	D16	1953	108.5	1.5	6.2	100.8	111.7	62.9	62.9	25.0	25.0	-	-	12.9	23.8
	D17	1962	131.0	1.5	33.9	95.6		62.9		25.0				7.7	
	D18	1961	77.6	1.5	3.5	72.6		62.9		9.4				0.3	
H	D19	1953	108.5	1.5	6.0	101.0	111.7	62.9	62.9	25.0	25.0	-	-	13.1	23.8
	D20	1962	131.0	1.5	32.3	97.2		62.9		25.0				9.3	
	D21	1961	77.6	1.4	2.2	74.0		62.9		10.3				0.8	
I		1953	108.5	4.1	15.3	89.1	89.1	62.9	62.9	-	-	2.4	2.4	23.8	23.8
		1962	131.0	4.2	44.4	82.4		62.9				2.4		17.1	
		1961	77.6	3.9	7.5	66.2		62.9				0.0		3.3	

NOTES:
1. All volumes in $M.m^3$
2. Runs are kharif season (1 July to 15 October)
3. Makhzan supplied from Diyyu weir for Option B and from Bateis weir for Options B' and C-I
4. Figures for Option I are derived from Table 5.3.

TABLE 5.9 IRRIGABLE AREAS, OPTION A

Command		Bateis/Maincanal/SBO			Ahbush/Jabalein			Hawashib			Diyyu			Nusheera			Total	
Available area, ha			8 740			2 030			1 050			2 130			1 520		15 470	
Gross depth, m			0.72			0.60			0.72			0.60			0.72			
Gross demand, M.m^3			62.9			12.2			7.5			12.8			10.9		106.3	
Run No.	Year	Supply	%	Area	Supply	%	Area	Supply	%	Area	Supply	%	Area	Supply	%	Area	Supply	Area
E1	1953	62.9	100	8 740	12.2	100	2 030	7.5	100	1 050	12.8	100	2 130	6.0	55	850	101.4	14 800
E2	1962	62.9	100	8 740	12.2	100	1 050	7.5	100	1 050	12.8	100	2 130	8.9	81	1 240	104.3	15 190
E3	1961	61.7	98	8 570	8.6	70	1 430	0.0	0	0	3.0	23	500	0.0	0	0	73.3	10 500
Average cultivated area, ha				8 700			1 880			790			1 720			640		13 730

TABLE 5.10 IRRIGABLE AREAS, OPTION B AND B'

Command		Bateis/Maincanal/SBO			Diyyu			Nusheera			Makhzan			Total	
Available area, ha			8 740			2 130			1 520			3 300		15 690	
Gross depth, m			0.72			0.60			0.72			0.72			
Gross demand, M.m^3			62.9			12.8			10.9			23.8		110.4	
Run No.	Year	Supply	%	Area	Supply	%	Area	Supply	%	Area	Supply	%	Area	Supply	Area
Option B															
E4	1953	62.9	100	8 740	12.8	100	2 130	10.9	100	1 520	12.4	52	1 720	99.0	14 110
E5	1962	62.9	100	8 740	12.8	100	2 130	10.9	100	1 520	13.5	57	1 870	100.1	14 260
E6	1961	61.7	98	8 570	10.7	84	1 780	0.0	0	0	0.4	2	60	72.8	10 410
Average cultivated area, ha				8 700			2 040			1 140			1 320		13 200
Option B'															
	1953	62.9	100	8 740	12.8	100	2 130	2.5	100	350	23.8	100	3 300	102.0	14 520
	1962	62.9	100	8 740	12.8	100	2 130	10.8	100	1 500	15.1	64	2 100	101.6	14 470
	1961	61.7	98	8 570	6.9	84	1 150	0.0	0	0	4.2	0	580	72.8	10 300
Average cultivated area, ha				8 700			1 890			260			1 720		12 570

NOTES:
1. Developed area is lesser of areas irrigable in 1953 and 1962
2. Average cultivated area taken as 0.25 x (1961 area) + 0.75 x (developed area)

TABLE 5.11 IRRIGABLE AREAS OPTIONS C-I

			Bateis/Maincanal/SBO			Ahbush/Jabalein			Diyyu			Makhzan			Total	
Available area, ha			8 740			2 030			2 130			3 300			16 200	
Gross depth, m			0.74			0.60			0.60			0.72				
Gross demand, $M.m^3$			62.9			12.2			12.8			23.8				
Option	Run No.	Year	Supply	%	Area	Supply	%	Area	Supply	%	Area	Supply	%	Area	Supply	Area
C	D11	1953	62.9	100	8 740	12.2	100	2 030	12.8	100	2 130	8.5	36	1 180	96.4	14 080
	D12	1962	62.9	100	8 740	12.2	100	2 030	7.0	55	1 170	1.6	7	220	83.7	12 160
	D3	1961	61.7	98	8 570	7.7	63	1 280	0.0	0	0	0.0	0	0	69.4	9 850
Average cultivated area, ha					8 700			1 840			880			170		11 590
D	D1	1953	62.9	100	8 740	12.2	100	2 030	12.8	100	2 130	10.4	44	1 440	98.3	14 340
	D2	1962	62.9	100	8 740	12.2	100	2 030	7.0	55	1 170	2.4	10	330	84.5	12 270
	D3	1961	61.7	98	8 570	7.7	63	1 280	0.0	0	0	0.0	0	0	69.4	9 850
Average cultivated area, ha					8 700			1 840			880			250		11 670
E	D5	1953	62.9	100	8 740	12.2	100	2 030	12.8	100	2 130	10.8	45	1 500	98.7	14 400
	D6	1962	62.9	100	8 740	12.2	100	2 030	12.1	95	2 020	1.4	6	190	88.6	12 980
	D7	1961	61.7	98	8 570	8.7	71	1 450	0.0	0	0	0.0	0	0	70.4	10 020
Average cultivated area, ha					8 700			1 840			1 510			150		12 240
F	D25	1953	62.9	100	8 740	12.2	100	2 030	12.8	100	2 130	11.4	48	1 580	99.3	14 480
	D26	1962	62.9	100	8 740	12.2	100	2 030	12.8	100	2 130	4.0	26	560	91.9	13 460
	D27	1961	61.7	98	8 570	10.1	83	1 680	0.0	0	0	0.0	0	0	71.8	10 250
Average cultivated area, ha					8 700			1 940			1 600			420		12 660
G	D16	1953	62.9	100	8 740	12.2	100	2 030	12.8	100	2 130	12.9	54	1 790	100.8	14 690
	D17	1962	62.9	100	8 740	12.2	100	2 030	12.8	100	2 130	7.7	32	1 070	95.6	13 970
	D18	1961	62.9	100	8 740	9.4	77	1 570	0.0	0	0	0.3	1	40	72.8	10 350
Average cultivated area, ha					8 740			1 910			1 600			810		13 060
H	D19	1953	62.9	100	8 740	13.1	100	2 030	12.8	100	2 130	13.1	55	1 820	101.0	14 720
	D20	1962	62.9	100	8 740	12.2	100	2 030	12.8	100	2 130	9.3	39	1 290	97.2	14 190
	D21	1961	62.9	100	8 740	10.3	85	1 720	0.0	0	0	0.8	3	110	74.0	10 570
Average cultivated area, ha					8 740			1 950			1 600			1 000		13 290
I	-	1953	62.9	100	8 740	-	-	-	2.4	19	400	23.8	100	3 300	89.1	12 440
	-	1962	62.9	100	8 740	-	-	-	2.4	19	400	17.1	72	2 370	82.4	11 510
	-	1961	62.9	100	8 740	-	-	-	0.0	0	0	3.3	14	460	66.2	9 200
Average cultivated area, ha					8 740						300			1 890		10 930

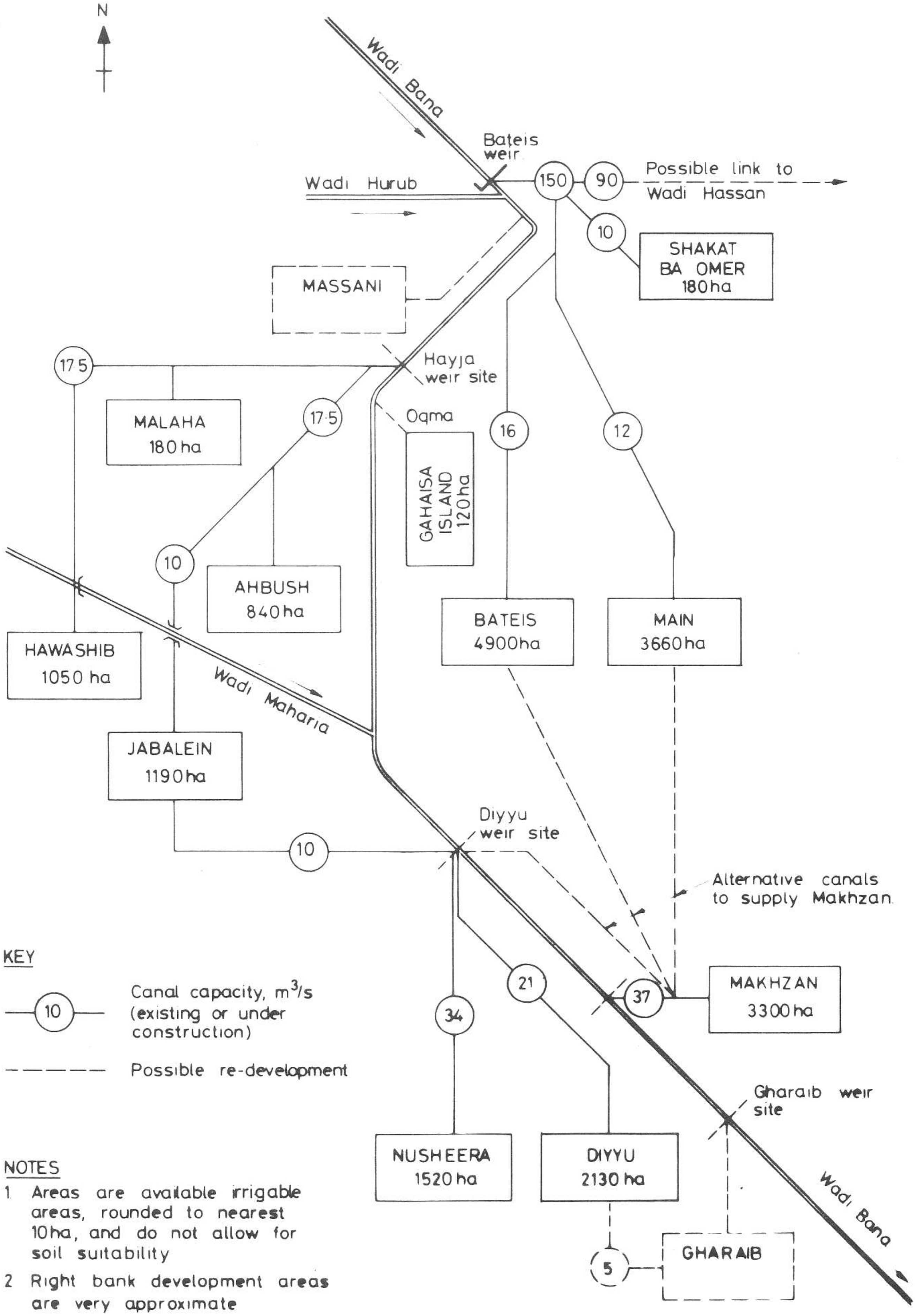
NOTES:
1. Developed area is lesser of areas irrigable in 1953 and 1962
2. Average cultivated area taken as 0.25 x (1961 area) + 0.75 x (developed area)

TABLE 5.12 IRRIGATION AREAS SUMMARY (ha)

Commands Option	Bateis Maincanal SBO	Ahbush Jabalein	Hawashib	Diyyu	Nusheera	Makhzan	Total
A	8 740	2 030	1 050	2 130	850	-	14 800
	8 700	1 880	790	1 720	640	-	13 730
B	8 740	-	-	2 130	1 520	1 720	14 110
	8 700	-	-	2 040	1 140	1 320	13 200
B'	8 740	-	-	2 130	350	2 100	13 320
	8 700	-	-	1 890	260	1 720	12 570
C	8 740	2 030	-	1 170	-	220	12 160
	8 700	1 840	-	880	-	170	11 590
D	8 740	2 030	-	1 170	-	330	12 270
	8 700	1 840	-	880	-	250	11 670
E	8 740	2 030	-	2 020	-	190	12 980
	8 700	1 880	-	1 510	-	150	12 240
F	8 740	2 030	-	2 130	-	560	13 460
	8 700	1 940	-	1 600	-	420	12 660
G	8 740	2 030	-	2 130	-	1 070	13 970
	8 740	1 910	-	1 600	-	810	13 060
H	8 740	2 030	-	2 130	-	1 290	14 190
	8 740	1 950	-	1 600	-	1 000	13 290
I	8 740	-	-	400	-	2 370	11 510
	8 740	-	-	300	-	1 890	10 930
O	8 740	-	-	-	-	-	8 740
	8 740	-	-	-	-	-	8 700

NOTES:

1. For each option and command, top figure is area to be developed and bottom figure is the average cultivable area.

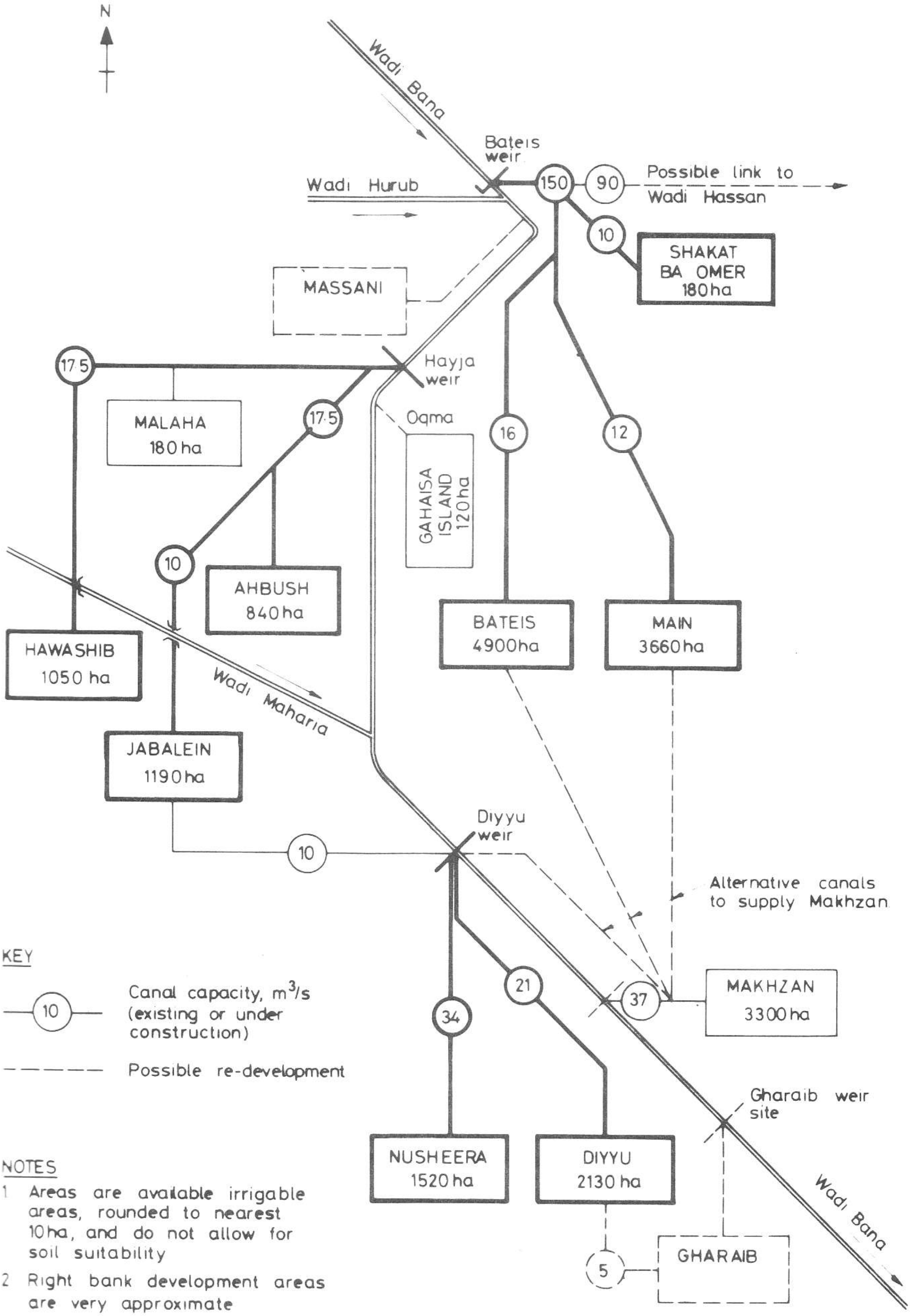


NOTES

1. Areas are available irrigable areas, rounded to nearest 10 ha, and do not allow for soil suitability
2. Right bank development areas are very approximate
3. Gharaib is now irrigated from groundwater.

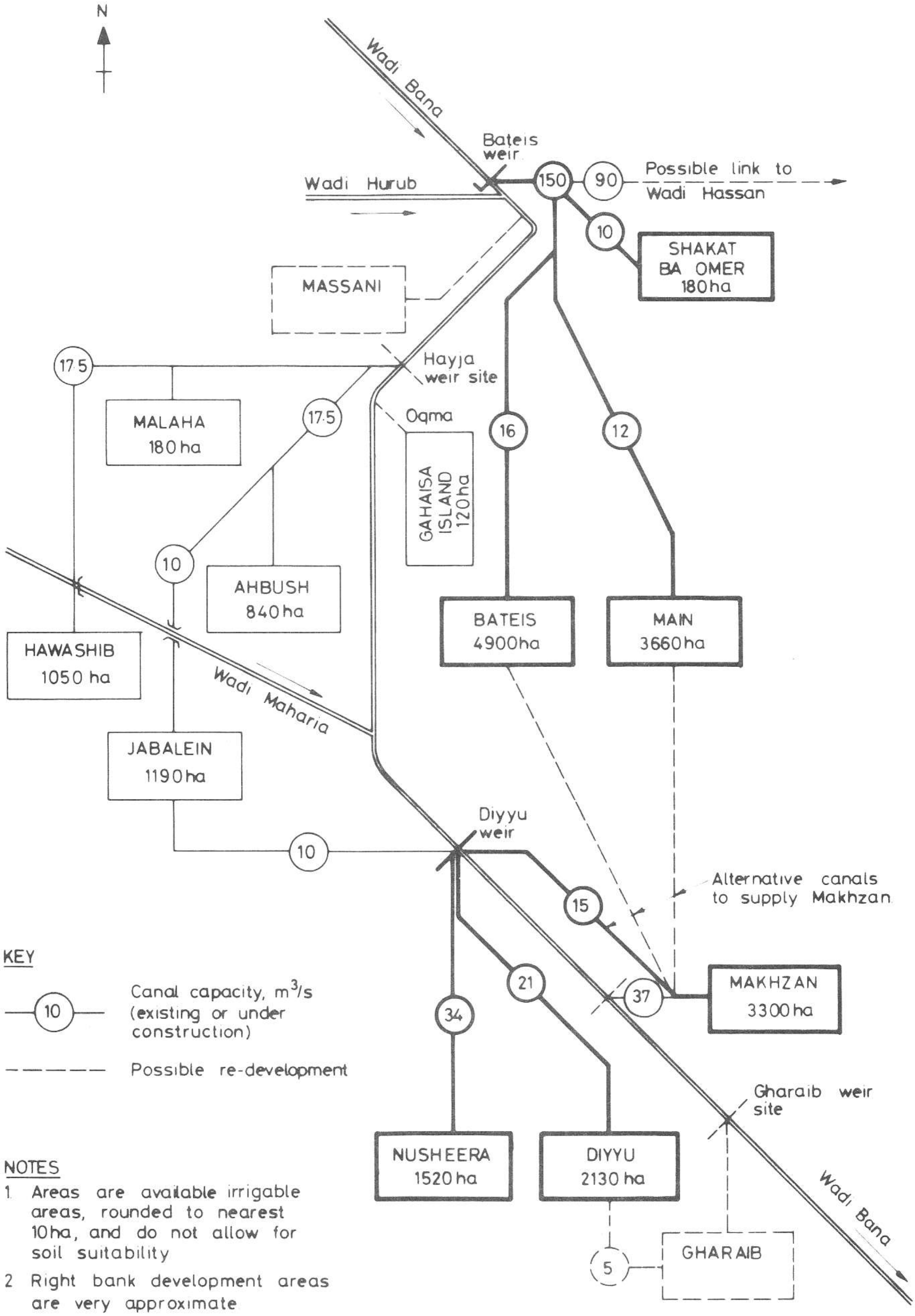
EXISTING SYSTEM
SCHEMATIC LAYOUT

FIGURE 5.1



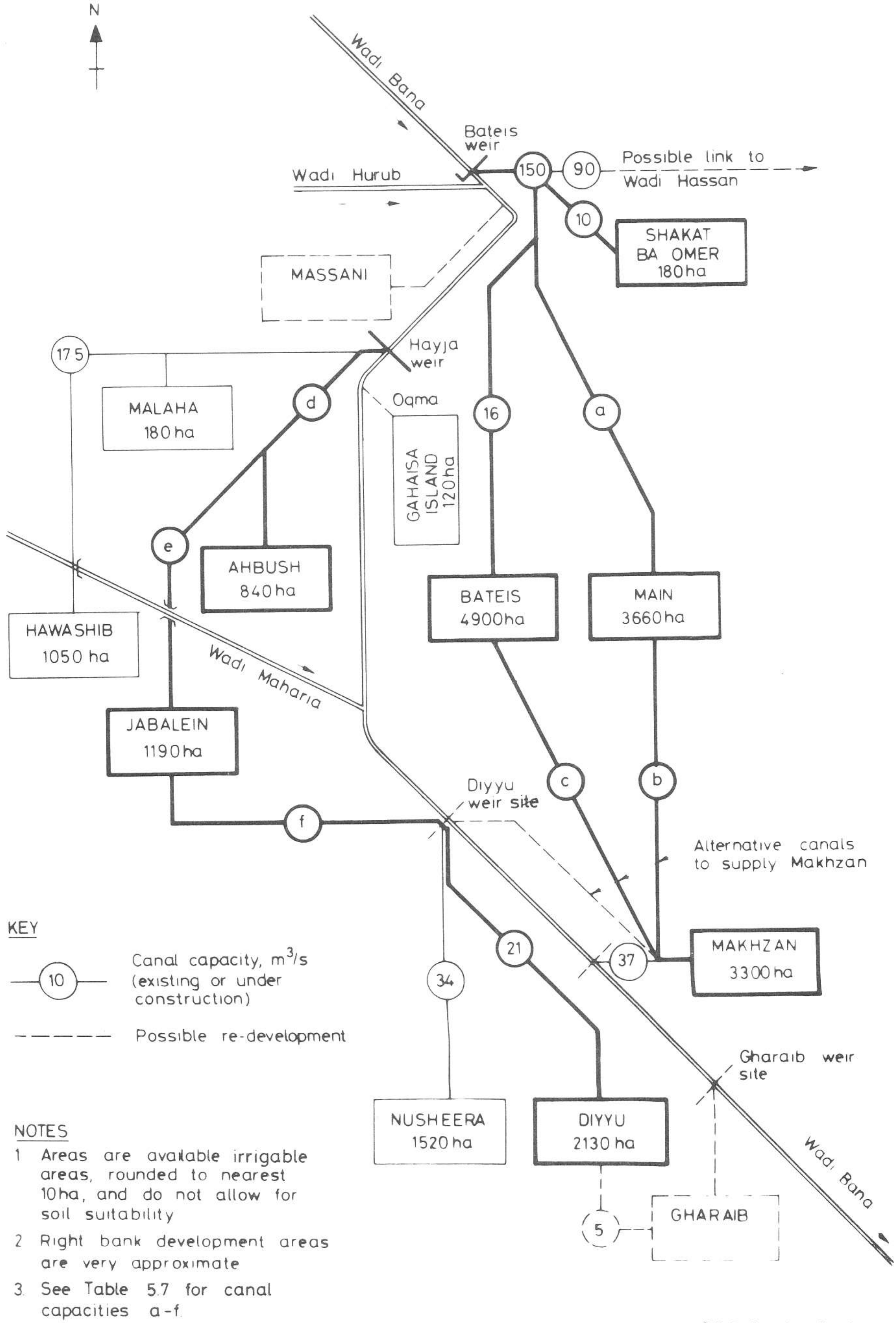
OPTION A
SCHEMATIC LAYOUT

FIGURE 5.2



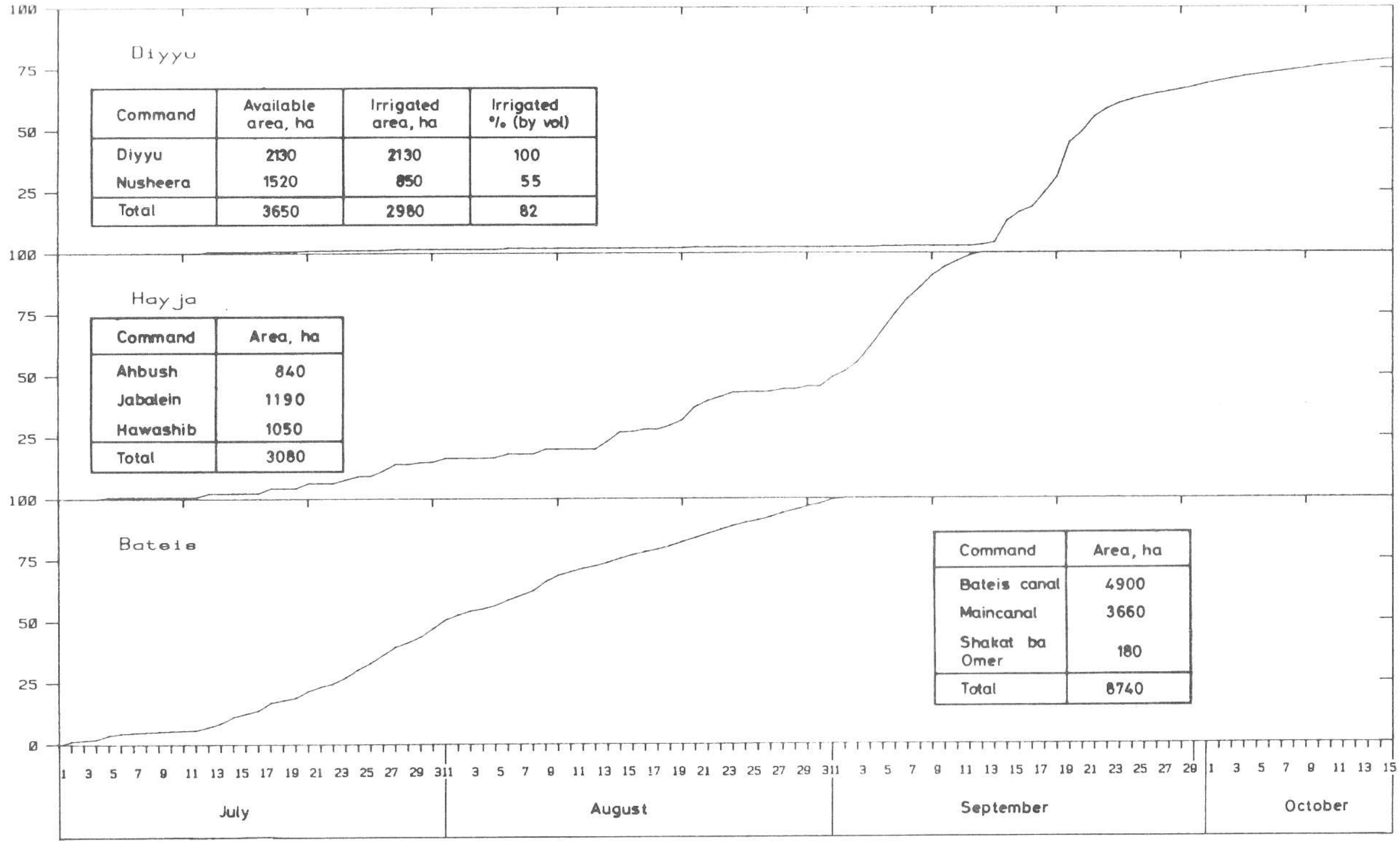
OPTION B
SCHEMATIC LAYOUT

FIGURE 5.3



OPTIONS C-I
SCHEMATIC LAYOUT

FIGURE 5.4



Diyyu

Command	Available area, ha	Irrigated area, ha	Irrigated % (by vol)
Diyyu	2130	2130	100
Nusheera	1520	850	55
Total	3650	2980	82

Hayja

Command	Area, ha
Ahbush	840
Jabalein	1190
Hawashib	1050
Total	3080

Bateis

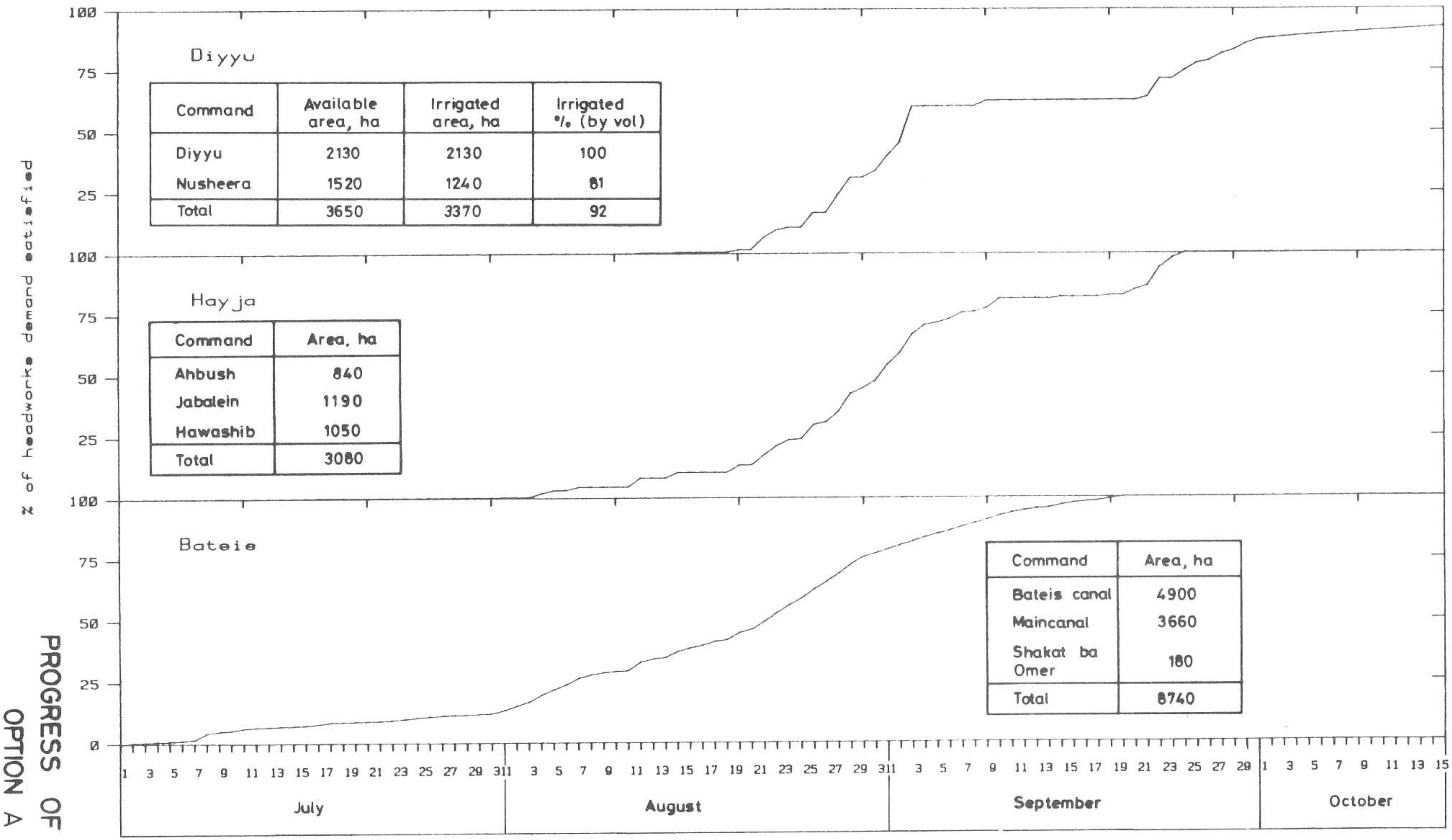
Command	Area, ha
Bateis canal	4900
Maincanal	3660
Shakat ba Omer	180
Total	8740

NOTES

1. Inflow season 1953 Kharif.
2. Plotted lines show cumulative progress towards satisfying irrigation demands at each intake.

PROGRESS OF IRRIGATION
OPTION A (RUN E1)

Figure 5.5a



Diyyu

Command	Available area, ha	Irrigated area, ha	Irrigated % (by vol)
Diyyu	2130	2130	100
Nusheera	1520	1240	81
Total	3650	3370	92

Hayja

Command	Area, ha
Ahbush	840
Jabalein	1190
Hawashib	1050
Total	3080

Bateis

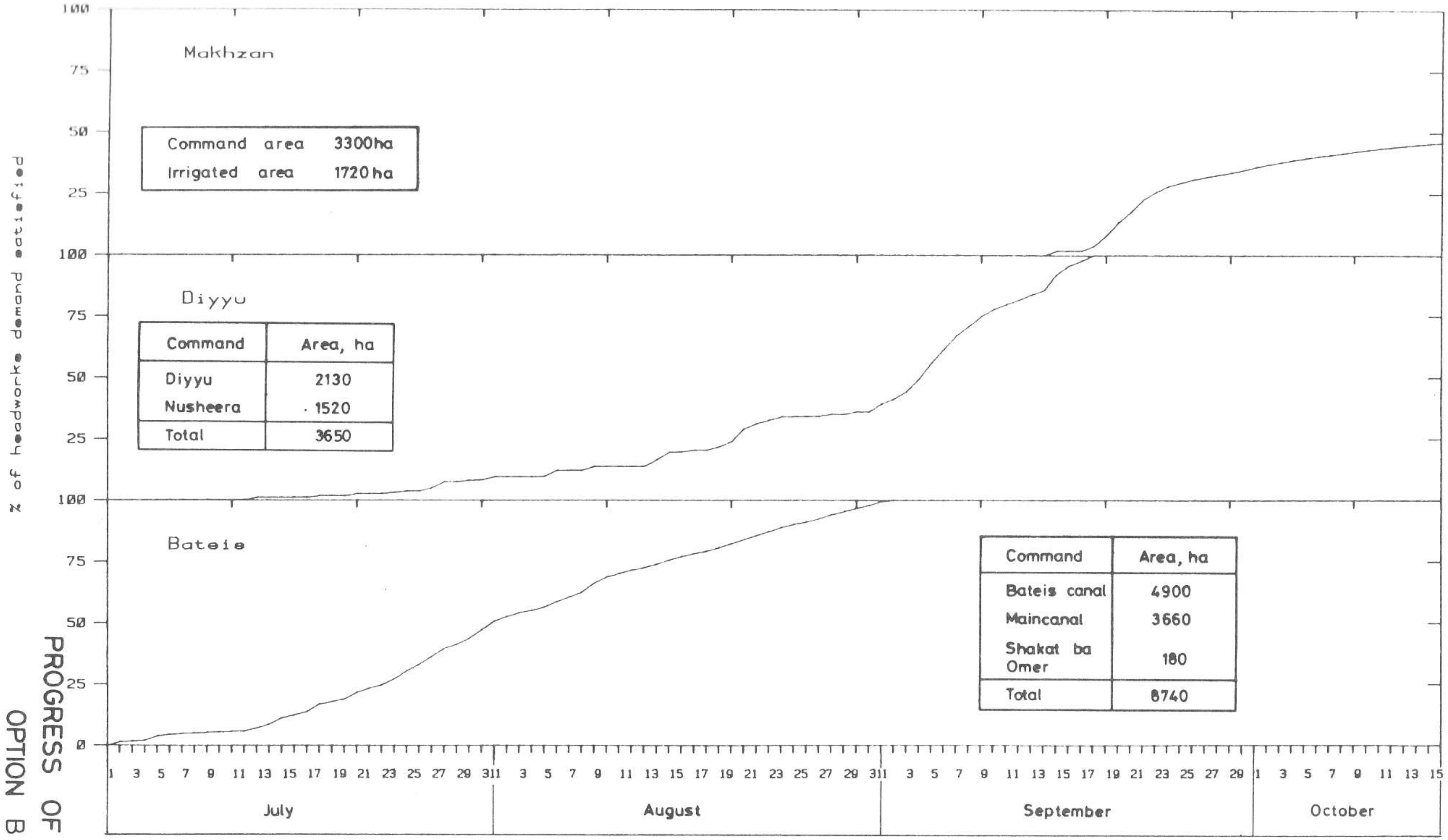
Command	Area, ha
Bateis canal	4900
Maincanal	3660
Shakat ba Omer	180
Total	8740

NOTES

1. Inflow season 1962 Kharif.
2. Plotted lines show cumulative progress towards satisfying irrigation demands at each intake.

PROGRESS OF IRRIGATION
OPTION A (RUN E2)

Figure 5.5b



PROGRESS OF IRRIGATION
OPTION B (RUN E4)
Figure 5.6a

NOTES

1. Inflow season 1953 Kharif.
2. Plotted lines show cumulative progress towards satisfying irrigation demands at each intake.

6. GROUNDWATER

6.1 INTRODUCTION

Groundwater has only been studied to the extent necessary to assess its importance as a source of irrigation water. Subsurface water resources have been studied in the past by Gear (1961, ref 26), Dar Al-Handasah (1971, ref 1), GDC (1970, ref 3) and Sogreah (1981, ref 24), and what follows is largely drawn from these reports. The most extensive of these studies, by GDC and Sogreah, were directed at identifying future water supplies for Greater Aden.

6.2 AQUIFER DESCRIPTION

Knowledge to date is limited to the alluvial aquifer in the delta, although it is recognized (ref 24) that important sandstone and limestone aquifers may underlie it. There is general agreement that it may be divided into an upper, unconfined aquifer, tapped by open wells, and a lower, semi-confined aquifer, tapped by tubewells. There is slow, leaky recharge from the upper into the lower water body.

Water level fluctuations are confined to the upper aquifer. Apparent water level changes between well surveys in 1964, 1971, 1979 and 1980 are thought to be largely attributable to seasonal fluctuations, rather than long term changes, over most of the area. There may however be some general drop in static water level in the south of the delta where abstraction is heaviest. Sogreah put the drop at 2-4 m. Levels are highest in the northern part of the delta, generally 0-10 m below ground level. Piezometric gradients are also steep in this area, approximately 10m/km, and slacken off to about half this value south of Makhzan. The general direction of flow is parallel to the main road from Bateis to Zingibar.

Water quality is said to be similar in both upper and lower aquifers (GDC, ref 3), although Sogreah show a number of results indicating an increase in conductivity with depth. Groundwater conductivity maps have been produced by Dar Al-Handasah, GDC and Sogreah. The main features are common to all of them. Conductivities are generally low in the north of the delta, and lowest (< 2mS/cm) in the Maincanal command area. Values are higher in the south and away from the main sources of recharge to the east and west of the delta. Areas of particularly high conductivity are: between Giar and Wadi Hassan (3-5 mS/cm), Al Jawl (5 mS/cm), and immediately north-east of Zingibar (3-5 mS/cm). GDC conclude that there is no evidence of any significant long term decline in quality. A number of samples were collected and analysed during the present study. The results are given in chapter 7.

6.3 ABSTRACTIONS

Small scale domestic water abstractions from open wells have no doubt always been a feature of life in the Abyan delta. Abstractions for irrigation on any scale appear to have only started in the early 1960s, however. The concentration of wells in the southern part of the delta strongly suggests that the poor reliability of irrigating with surface water encouraged this form of investment.

Estimates of total annual pumped groundwater abstraction from 1961-83 are shown in Table 6.1. Details of methods used to estimate 1982/3 abstractions are given below. Different definitions of "in use" and different assumed pump discharges and hours of operation no doubt account for the apparently erratic development of groundwater. Table 6.1 can therefore only give a rough impression, but is sufficient to define the scale of development. This may be summarised as:

(i) total groundwater abstraction is 70-100 $M.m^3$ per year.

(ii) the area irrigated is of the order of 3 000-4 000 ha and is predominantly in the southern and central parts of the delta.

(iii) land irrigated from wells receives approximately 2 m (gross) of water annually (using GDC's 1979/80 figures), compared with 0.6-0.7 m received by flood irrigated land.

Table 6.2 lists numbers of irrigation wells in 1979/80 and in 1982/3. The indication is that the number of wells owned by the state farms has remained roughly constant but that Giar and Makhzan cooperatives have substantially increased their dependence on groundwater. This is further evidence of the poor reliability of surface water supplies in these areas. GDC's 1979/80 average flow rates and operating hours were used to convert the 1982/3 numbers of wells in Table 6.2 into abstractions in Table 6.1. The GDC data for pumped wells were:

(i) State farms

Discharge 28 l/s
Operating hours: 15 h/day over 296 days/year

(ii) Cooperatives

Discharge 16 l/s
Operating hours: 10 h/day over 264 days/year

There is insufficient information available at present to define the water balance for the delta. There is no evidence that long-term depletion of groundwater resources is taking place.

TABLE 6.1 ANNUAL PUMPED ABSTRACTIONS OF GROUNDWATER IN THE ABYAN DELTA, 1961-83

Year	Source	No of irrigation wells in use Open	Tubewells	Total	Irrigated area ha	Annual abstraction $M.m^3$
1961	Gear	-	-	-	190	2.25
1971	DAH	292	91	383	-	45
1979/80	GDC	77	154	231	3 793	76*
Mar 1980	Sogreah	-	-	312	3 260	104
1982/3	This study	97	154	251	-	74*

Note: abstractions marked * include 3.8 $M.m^3$ for water supply

TABLE 6.2 NUMBERS OF IRRIGATION WELLS IN USE IN THE ABYAN DELTA, 1979/80 and 1982/3

Location in delta	Name of co-operative or state farm	Number of wells: 1979/80 Open and tubewells	1982/3 Open	1982/3 Tubewells
South	Zingibar co-op	42	10	34
	El Kod dairy farm	11		13
	El Kod research farm	6		9
	7th October farm Mustaqbal farm	29		16
	4th Congress farm	16		16
	Al 'Adoun farm	8		10
	Dahl Ahmed farm	3		4
	Lenin dairy farm	7		7
	Lenin state farm	16		16
	Muraqed farm	5		0
Central	Makhzan co-op	18	23	7
	Al Tariyah farm	17		18
	Giar co-op	43	54	2*
	Giar research farm	2		2
	Giar agricultural college	1		0
North	Al Husn co-op	5	5	0
	Bateis co-op	1	5	0
	Grand totals	230	251	

Sources: 1979/80 data from Groundwater Development Consultants (reference 3).
1982/3 data from interviews with officals of state farms and cooperatives

* a third tubewell is used for water supply

7. WATER QUALITY

7.1 CHEMICAL WATER QUALITY

Eleven water samples were collected during the field work period from pumped irrigation wells and from wadi flows. Locations of sampling points are listed in Tables 7.2 and 7.3 and in the case of wadi samples are shown in Figure 7.1. Chemical water quality analyses were carried out by staff at El Kod research station and the results are shown in Table 7.3. Analysis for potassium and boron content, requested by the consultants, could not be carried out for technical reasons. Table 7.3 also shows the results of analyses of wadi samples collected by Dar Al-Handasah in 1971 (reference 1) and by El Kod research station in 1955/6 (ECGC, reference 19).

Discussion here is confined to the suitability of surface water for irrigation used. The criteria used have been taken from Ayers and Westcot (ref 28) and are reproduced here as Table 7.1. The quality of groundwater is discussed in the wider context of Abyan delta soils in the Soils Annex.

7.1.1 Conductivity

Surface water conductivity (ECw) drops with increasing wadi discharge, from approximately 1.5 mS/cm during dry season flows to 0.5 mS/cm during flood flows. GDC (reference 5) noted similar characteristics in Wadi Tuban. By Ayers and Westcot's criteria an ECw of 1.5 mS/cm constitutes an "increasing problem" while 0.5 mS/cm is "no problem". As the bulk of irrigation water derives from flood season flows, there should be no problem solely by virtue of the salinity of applied water. Dry season low flows are used almost exclusively in the Bateis area but groundwater quality mapping (see chapter 6) does not show appreciable salinity build-up in this area.

7.1.2 Sodium adsorption ratio (SAR)

High SAR values in combination with low conductivities may reduce the permeability of the clay layers of soils. High SAR values may also pose a specific toxicity problem. All the combinations of SAR and conductivity in Table 7.3 fall into the "no problem" category of Ayers and Westcot. As far as specific toxicity is concerned, most Table 7.3 values fall just within the "increasing problem" band (SAR from 3 to 9).

7.1.3 Chloride

High concentrations of chloride are toxic to certain crops. Concentrations in Table 7.3 drop with increasing discharge. At low flows they fall into the "increasing problem" category (4-10 meq/l) but pose no problem at high flows.

7.1.4 Boron

Boron concentrations in surface water are seldom high enough to cause a toxicity problem, and Dar Al-Handasah's analyses found no boron present. However, GDC's analyses of Wadi Tuban water (reference 5) came up with average concentrations of 1.1 mg/l during dry season low flows and 0.5 mg/l during flood season flows. Tuban water quality otherwise resembles that of Wadi Bana and it is therefore recommended that further boron anaylses are undertaken if boron-sensitive crops are to be considered.

7.1.5 Bicarbonate

High bicarbonate concentrations may cause problems under certain specialized sprinkler irrigation regimes unlikely to be encountered in the Abyan delta. Bicarbonate concentrations in Table 7.3 are high: all fall within Ayers and Westcot's "increasing problem" category (1.5-8.5 meq/l).

7.1.6 Nitrogen

Excessive levels of nitrogen may upset crop growth and maturity. In Table 7.3 nitrate nitrogen and ammoniacal nitrogen have been summed. Samples S2 and S3 both lie just within Ayers and Westcot's "increasing problem" range (5-30 mg/l).

7.1.7 Conclusion

Dry season low flows have slight salinity and chloride hazards but flood season flows, which provide the bulk of irrigation supplies, are generally suitable for irrigation.

7.2 SEDIMENT LOAD

Five suspended sediment samples were collected during the fieldwork period. The samples were filtered, oven dried at 100°C and weighed on site. The results are shown in Table 7.4. Unfortunately, no major floods occurred while the team was present and the 1983 samples were taken from relatively minor spates. They were collected using a suspended, wide-mouthed pickle jar of approximately 400 ml capacity. In each case the sample was collected from highly turbulent water.

Table 7.4 also reproduces Dar Al-Handasah's results (from Table III-3 of reference 1). The value of their work is greatly reduced by the lack of flow data. Flows given in Table 7.4 are daily mean total wadi flows for the sampling day, taken from Dar Al-Handasah's Table III-12: obviously, they may bear little relation to the flow at the actual time of sampling. No data are available on canal flows. The locations of sampling points are shown in Figure 7.1. Particle size distributions of Dar Al-Handasah's samples are shown in Figure 7.2.

Figure 7.3 shows sediment concentration plotted against flow. Relations suggested for Wadi Tuban (reference 5) and Wadi Najran (reference 25) have also been plotted. The available data are quite inadequate, both in terms of quantity and quality, to define a relation between sediment concentration and flow. It was decided provisionally to adopt an upper envelope curve to the plotted points, which may be written

$$S = 530\ Q^{1.075}$$

where S is sediment concentration in mg/l and Q is total flow in m^3/s. All but two of the plotted points in Figure 7.3 apply to wadi, rather than canal flow. However, Dar Al-Handasah found, perhaps surprisingly, that canal concentrations were at least as high as those in the wadi on the same day and it was therefore considered that the same curve could serve for both.

The adopted curve implies concentrations of 100 000 mg/l at 130 m^3/s, and 250 000 mg/l (or about 25% by weight) at 300 m^3/s. Such concentrations are possible but rare in natural streams. At our present level of knowledge it seemed sensible to impose a maximum concentration of 100 000 mg/l.

Total catchment sediment yield was estimated by applying the concentration-flow relation to hourly wadi flow during median Seif and Kharif flood seasons (wadi water is substantially clear during the rest of the year). The results of this calculation were:

Seif season total	(1954)	0.32 Mt
Kharif season total	(1953)	2.16 Mt
Approx median annual yield		2.48 Mt

An annual yield (Y) of 2.48 Mt is equivalent to 340 $t/km^2/year$. This may be compared with GDC's estimate for Wadi Tuban of 3.5-4.0 Mt/year, equivalent to 690-790 $t/km^2/year$.

A number of procedures are available for estimating suspended sediment yield from simple catchment properties (such as area, climatic zone, etc). The phenomena which these procedures seek to describe are so complex that they can only indicate an order of magnitude. The results of three approaches are given below:

Fleming (1969) (reference 29)

Fleming related suspended load to catchment area and average daily flow for 253 catchments throughout the world. His yield-area regression gave a mean yield of

$$Y = 0.77 \text{ Mt/year} \quad (110 \text{ t/km}^2\text{/year})$$

(regression based on all catchments except those in India). A further regression on average daily flow for catchments with desert and scrubland vegetation gave a mean yield of

$$Y = 1.58 \text{ Mt/year } (220 \text{ t/km}^2\text{/year}).$$

and a 95% confidence limit range of 1.05-2.40 Mt/year (150-330 $t/km^2/year$).

Langbein and Schumm (1958) (reference 30)

Langbein and Schumm related sediment yield to average annual precipitation. Use of their graph gives a mean yield of 260 $t/km^2/year$.

The various approaches tried, including the Wadi Tuban estimates, give a range of 100-800 $t/km^2/year$. This provides some slight confirmation of the Wadi Bana figure, which lies within this range. None of the figures quoted include any bedload, for which no data are available. Allowing a nominal 10% increase for bed load gives a total yield of about 400 $t/km^2/year$ or 3 Mt/year.

TABLE 7.1 GUIDELINES FOR INTERPRETATION OF WATER QUALITY FOR IRRIGATION (from Ayers and Westcot (Ref 28))

Irrigation problem	Degree of problem: No Problem	Degree of problem: Increasing Problem	Degree of problem: Severe Problem
Salinity			
ECw (mS/cm)	<0.75	0.75-3.0	>3.0
Permeability (affects soil infiltration rate)			
ECw (mS/cm)	>0.5	0.5-0.2	<0.2
SAR[1]			
Mountmorillonite[2]	<6	6-9[3]	>9
Specific toxicity			
Sodium (SAR)	<3	3-9	>9
Chloride (meq/l)	<4	4-10	>10
Boron (mg/l)	<0.75	0.75-2.0	>2.0
Miscellaneous effects			
NO_3-N or NH_4-N (mg/l)	<5	5-30	>30
HCO_3 (meq/l)	<1.5	1.5-8.5	>8.5
pH	[Normal range 6.5-8.4]		

1. Ayers and Westcot use an adjusted SAR. Sufficient data were not available in this study to make the adjustment.
2. Ayers and Westcot quote SAR values for three types of dominant clay mineral, but only the cost sensitive is shown here.
3. Use the lower range if ECw <0.4 mS/cm
   Use the intermediate range if ECw = 0.4-1.6 mS/cm
   Use upper limit if ECw >1.6 mS/cm

TABLE 7.2 GROUNDWATER SAMPLES COLLECTED FOR WATER QUALITY ANALYSIS

Sample no	Soil obs. no	Grid ref	Date	Field ECw mS/cm	Sogreah (1981) Well no	ECw mS/cm	Date
G1	55	NK416486	29.6.83	2.2	689	-	-
G2	61	NK411490	29.6.83	1.1	703	1.5	6.3.78
G3	53	NK402508	29.6.83	3.6	714	-	-
G4	70	NK381528	4.7.83	3.0	743	3.2	21.6.80
G5	-	NK390522	4.7.83	3.4	737	4.1	-
G6	59	NK415464	4.7.83	1.4	686	1.4	-
G7	60	NK412481	4.7.83	1.2	704	1.1	1.4.80

TABLE 7.3 SURFACE WATER SAMPLES COLLECTED FOR WATER QUALITY ANALYSIS

Sample no	Wadi	Location	Flow m^3/s	Field ECw mS/cm	Date	Notes
S1	Bana	U/s Hurub confluence	Low	1.5	30.6.83	Clear water; little surface runoff
S2	Hurub	U/s Bana confluence	0.3	1.4	30.6.83	
S3	Bana	Bateis	10 approx*	-	9.8.83	Regression following minor spate
S4	Bana	Bateis	10-20	-	17.8.83	As above

* Sum of Bateis and Maincanal flows

TABLE 7.4 CHEMICAL WATER QUALITY ANALYSES

Source	Well	Well	Well	Well	Well	Well	Well	W Bana	W Hurub	W Bana	W Bana	W Bana	W Bana	W Bana	SBO canal	Arshan canal
Sample No	G1	G2	G3	G4	G5	G6	G7	S1	S2	S3	S4	See note 3			See note 4	
Date collected	29.6.83	29.6.83	29.6.83	4.7.83	4.7.83	4.7.83	4.7.83	30.6.83	30.6.83	9.8.83	17.8.83	April 1956	1971	1971	1971	1971
Flow, m^3/s (approx)	-	-	-	-	-	-	-	low	0.3	10	10-20	med-high	-	-	-	-
pH value	7.9	7.4	7.3	7.6	7.4	8.2	7.7	7.8	8.0	8.25	-	-	7.9	7.5	7.5	8.0
Conductivity, mS/cm	2.80	1.30	4.25	3.30	3.90	1.50	1.35	1.70	1.60	0.95	0.71	-	0.49	0.58	0.58	0.49
Chemical analysis (results in meq/l except where stated):																
Carbonate, Co_3	5.6	2.0	2.4	1.6	2.0	Nil	1.6	0.8	Nil	0.8	-	-	Nil	1.0	Nil	0.8
Bicarbonate, HCO_3	2.0	5.0	4.4	3.8	4.0	6.2	3.8	1.6	3.4	2.9	-	3.4	3.5	3.8	4.0	3.3
Chloride, Cl	8.0	3.8	24.0	16.0	21.4	4.0	4.2	7.6	6.8	4.4	-	-	2.6	3.2	3.4	2.8
Sulphate, SO_4	8.0	4.2	9.6	11.8	12.4	3.4	3.4	6.2	6.2	2.1	-	-	3.3	1.3	0.4	0.5
Calcium, Ca	1.2	2.2	7.0	6.2	7.0	2.0	2.0	4.0	4.0	2.2	-	-	1.7	1.5	1.3	1.9
Magnesium, Mg	6.4	1.4	16.2	11.8	17.4	1.4	1.4	3.2	3.2	1.9	-	-	1.0	1.3	1.8	0.9
Sodium, Na	18.6	8.6	17.2	12.8	15.0	10.4	9.0	7.2	7.2	6.4	-	-	6.5	5.2	4.2	4.1
Ammonium, NH_4	0.20	0.10	0.05	0.025	trace	0.15	trace	0.05	0.05	0.10	-	-	-	-	-	-
Nitrate, NO_3	0.85	trace	3.0	1.25	2.0	0.25	0.10	0.20	0.40	0.375	-	-	-	-	-	-
Ammoniacal nitrogen, N (mg/l)	2.8	1.4	0.7	0.4	trace	2.1	trace	0.7	0.7	1.4	-	-	-	-	-	-
Nitrate nitrogen, N (mg/l)	11.9	trace	42.0	17.5	28.0	7.0	1.4	2.8	5.6	5.3	-	-	-	-	-	-
Total nitrogen, N (mg/l)	14.7	1.4	42.7	17.9	28.0	9.1	1.4	3.5	6.3	6.7	-	-	-	-	-	-
Boron, B	-	-	-	-	-	-	-	-	-	-	-	-	Nil	Nil	Nil	Nil
Potassium, K	-	-	-	-	-	-	-	-	-	-	-	-	0.2	0.4	0.3	0.3
Total dissolved solids	-	-	-	-	-	-	-	-	-	-	-	6.9 (4.4-10.6)	-	-	-	-
SAR	9.5	6.4	5.1	4.3	4.3	8.0	6.9	3.8	3.8	4.5	-	3.8 (2.0-6.8)	5.6	4.4	3.4	3.5

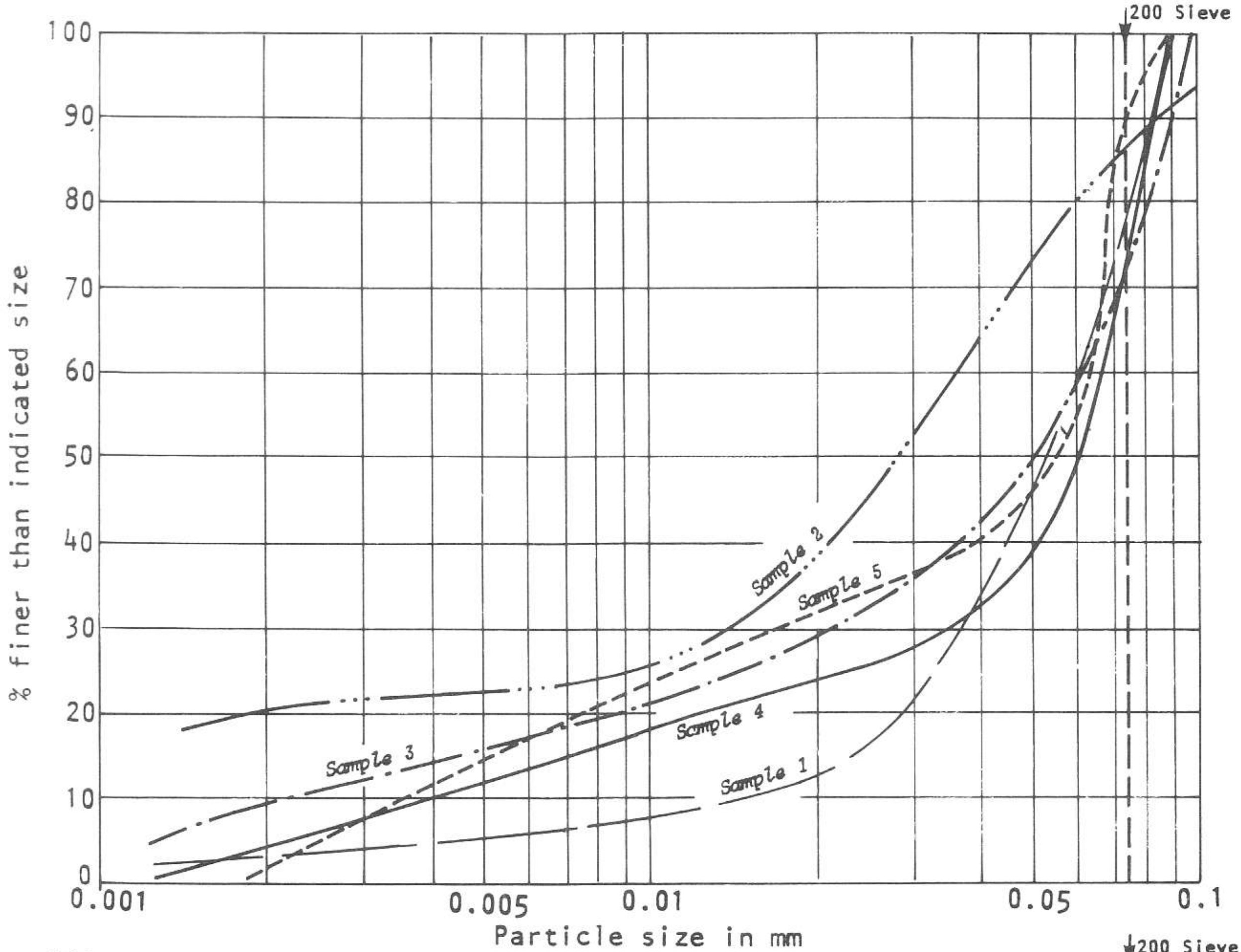
Notes

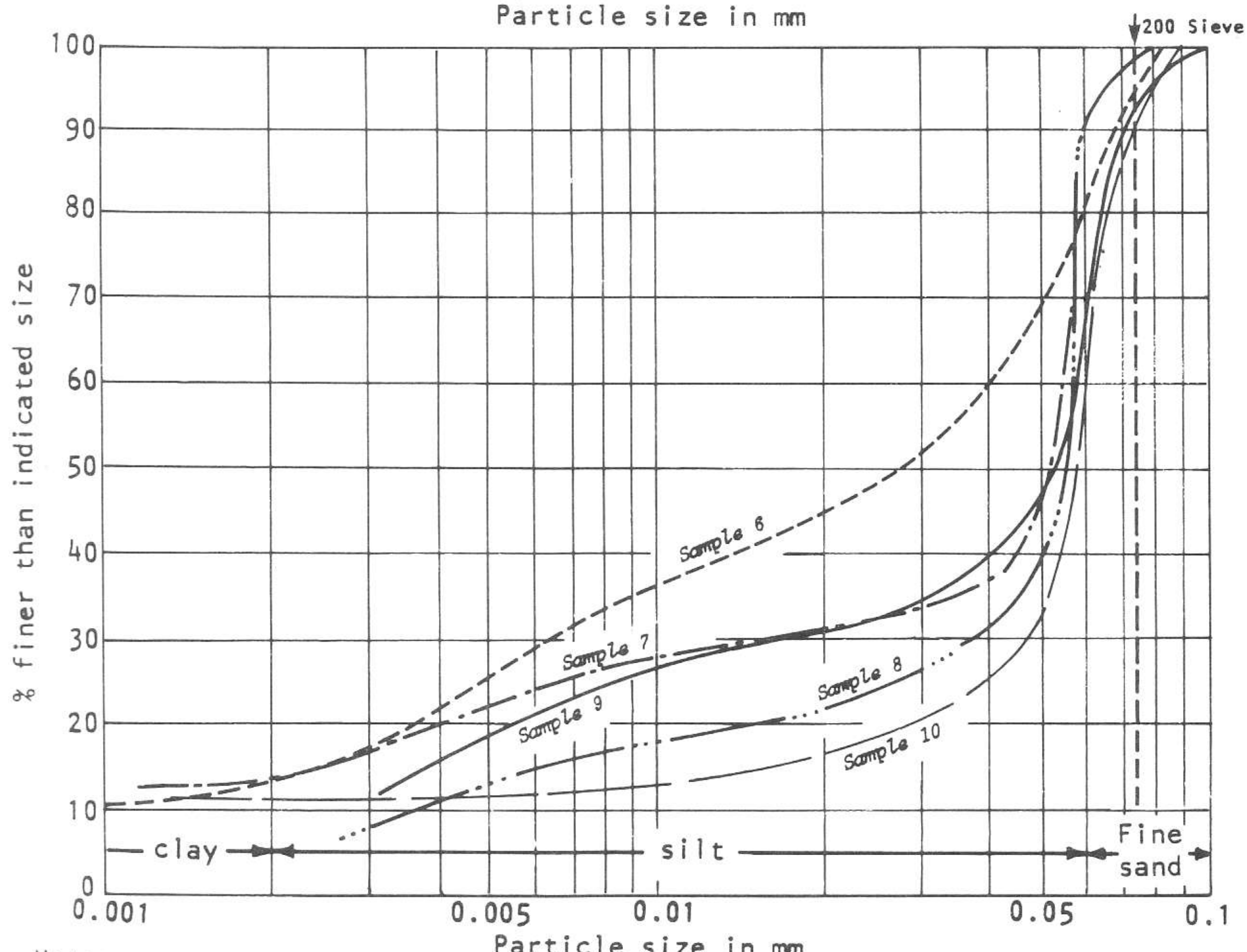
1. See Figure 7.1 and Tables 7.1 and 7.2 for details of locations of collection points
2. Samples G1 - G7 and S1 - S4 analysed at El Kod research station, PDRY
3. Taken from 1955/6 El Kod progress report. 12 samples were collected from flood flows, of which 10 were taken from Wadi Bana. Values shown are averages, and ranges (in brackets), for all 12 samples.
4. Dar Al-Handasah (1971). Samples thought to originate from flood flow. Dates of collection not stated.

TABLE 7.5 SUSPENDED SEDIMENT CONCENTRATIONS

Ref no	Date	Source	Wadi or canal	Location	Flow m^3/s	Concentration mg/1	Ref no	Date	Source	Wadi or canal	Location	Flow m^3/s	Concentration mg/1
-	9.8.83	This study	Bateis C.	C4	3	1 500	15	27.8.71	DAH	Main C	C5	-	4 800
-	"	"	Bateis C.	C3	3	1 900	16		"	Bateis C	C8	-	4 400
-	"	"	W Bana	W2	10	2 500	17		"	Arshan C	C9	-	4 000
-	17.8.83	This study	W Bana	W2	10-20	6 300	18		"	Arshan C	C10	-	4 000
-	"	"	W Bana	W2	10-20	3 800	19	5.9.71	DAH	W Bana	W1	23	4 800
1	31.7.71	DAH	W Bana	W1	17	9 100	20		"	W Bana	W2	23	5 200
2		"	W Bana	W2	17	9 900	21		"	SBO	C1	-	5 600
3		"	SBO	C1	-	9 500	22		"	Main + Bateis	C2	-	5 600
4		"	Main + Bateis	C2	-	10 300	23		"	Main C	C5	-	6 400
5		"	Main C	C5	-	10 700	24		"	Bateis C	C8	-	6 400
6		"	Bani-Hassan	C6	-	11 100	25		"	Arshan C	C9	-	6 000
7		"	Bani-Hassan	C7	-	13 400	26		"	Arshan C	C10	-	5 600
8		"	Bateis C	C8	-	7 900	27	14.9.71	DAH	W Bana	W1	13	6 800
9		"	Arshan C	C9	-	9 500	28		"	W Bana W2	W2	13	7 500
10		"	Arshan C	C10	-	9 100	29		"	SBO	C1	-	6 800
11	27.8.71	DAH	W Bana	W1	11	4 400	30		"	Main + Bateis	C2	-	6 400
12		"	W Bana	W2	11	3 200	31		"	Main C	C5	-	7 500
13		"	SBO	C1	-	4 800	32		"	Bateis C	C8	-	7 200
14		"	Main + Bateis	C2	-	4 000							

Notes: 1) Dar Al- Handasah data from Table III-3 of reference 1. Corrresponding daily mean flows taken from Table AIII-12.

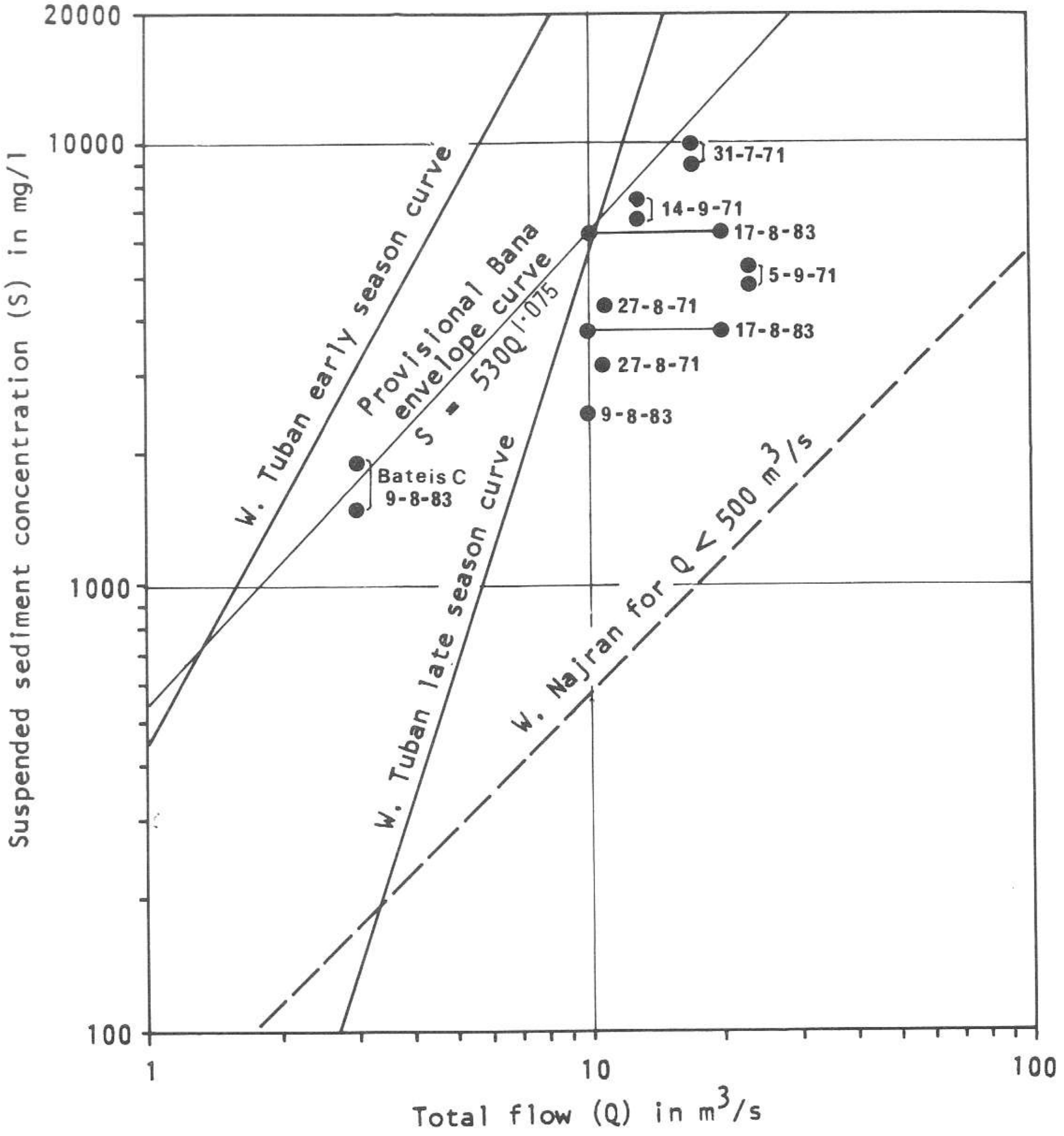




Notes

1. Reproduced from Dar Al-Handasah (ref 1)
2. See Table 7.4 for details of samples.
4. Samples analysed by hydrometer.

SUSPENDED SEDIMENT PARTICLE SIZE DISTRIBUTIONS
Figure 7.2



Notes

1. Najran line from Binnie & Partners et al (reference 25)
2. Tuban lines from GDC (reference 5)
3. All plotted points refer to Wadi Bana samples except where shown.

WADI BANA SUSPENDED SEDIMENT LOAD
Figure 7.3

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APPENDIX A

El Kod monthly climate data and

evapotranspiration estimates

Notes on Appendix A tables

1. In all cases annual means are computed as the sum of monthly means.

2. Data sources in all cases are:

   (i) 1958 - May 1961 and June 1965 - December 1966 from Dar Al-Handasah (reference 1).

   (ii) June 1961 - May 1965 from Empire Cotton Growing Corporation reports (reference 19).

   (iii) 1967-1982 from El Kod station records.

TABLE A1 - EL KOD MONTHLY RAINFALL, 1958-83

Units: mm

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
1958	-	-	-	-	-	-	-	-	0	0	6.0	0	-
1959	49.2	4.8	4.2	0	-	-	-	0	37.5	0	0	2.0	-
1960	2.2	0	12.0	0.8	65.8	0	6.8	0	5.5	0	5.2	0	98
1961	2.0	0.8	0	0	0	0	1.0	0.8	2.5	0	3.8	38.9	50
1962	0	0	0	0	0	2.8	0	0	1.3	0	0	0.3	4
1963	1.8	0	0	0.5	1.5	0	0.6	3.4	0.3	0	0	0	8
1964	13.6	6.3	0	2.6	5.3	0	1.4	0.1	13.7	0	0	13.8	57
1965	0.7	0	0	1.7	0	0	0	0	0	0	0	0.1	3
1966	0.7	2.4	25.5	0	0	-	-	-	-	-	-	-	-
1967	0	40.4	11.5	8.9	0	0	0.2	0.3	0	59.3	9.3	14.8	145
1968	6.4	0	0	0	0	0	0.2	0	3.9	0	0.5	20.0	31
1969	6.0	5.2	0	0	0	0	0	0	0.3	19.3	0	0	31
1970	17.2	0	0	0.2	0.6	0	0	0.5	2.7	0	0	0	21
1971	0	0	0	0	0	0	0	1.0	1.0	0	0	2.7	5
1972	1.0	2.1	0.1	3.0	0	0	0	0	43.6	150.02	0	0	200
1973	0	0	0	0	8.0	0	0	0	0	0	2.8	0	11
1974	0	0	0	0	4.7	0	0	0	6.9	0	0	2.0	14
1975	0.7	0.2	0	3.5	0	0	8.3	7.5	20.0	0	0	1.3	42
1976	0	0	0	33.5	2.4	0	0	2.9	0	0	0	0	39
1977	3.3	0	2.1	0	0.7	0	3.2	0	0	4.6	0	0.3	14
1978	6.0	4.1	0	0	0	0	11.5	0	0	3.4	3.9	3.4	32
1979	1.9	0	0	0	0	0	0	0	0	0	0	10.7	13
1980	1.0	2.5	0	6.0	0	0	0	0	2.0	0	0	1.0	13
1981	0	0	7.0	0	10.5	0	0.5	2.0	3.0	0	0	0.4	23
1982	10.0	0	35.5	0	0	0	0.5	0.3	1.0	1.7	0.2	8.5	58
1983	3.4	138.0	0	-	-	-	-	-	-	-	-	-	-
Average	5.1	8.3	3.9	2.5	4.3	0.1	1.6	0.8	6.1	9.9	1.3	5.0	49

Note: - indicates no data available

TABLE A2 EL KOD MONTHLY MEAN AIR TEMPERATURES, 1958-82

Units: ^{o}C

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Average
1958	-	-	-	-	-	-	-	-	31.1	27.7	24.7	24.9	-
1959	25.0	24.8	25.5	26.8	-	-	-	29.6	29.5	27.6	25.2	24.1	-
1960	23.6	23.0	26.8	27.4	29.1	30.3	30.2	30.9	30.7	26.8	25.1	24.7	27.4
1961	24.8	24.7	25.5	28.8	29.9	31.8	29.9	29.7	30.8	27.9	26.4	24.3	27.9
1962	23.7	23.3	25.1	27.2	29.2	30.9	30.0	30.2	30.2	25.6	25.3	24.1	27.1
1963	23.8	25.1	25.2	29.1	30.5	31.5	31.7	30.7	29.9	27.2	26.4	24.2	27.9
1964	25.2	24.8	25.1	26.9	29.2	30.7	30.2	30.0	29.6	27.2	24.8	23.5	27.3
1965	22.8	22.7	23.2	27.3	27.6	30.3	30.6	30.2	30.1	26.4	25.8	23.5	26.7
1966	24.1	25.4	25.7	27.3	28.4	31.1	31.8	31.1	29.8	27.4	24.6	23.7	27.5
1967	22.8	23.9	25.7	27.0	28.6	29.9	30.3	30.0	30.3	26.9	25.6	23.9	27.1
1968	23.0	25.1	24.9	27.7	28.1	29.8	29.3	30.1	29.7	29.4	27.4	26.9	27.6
1969	25.2	26.1	25.4	24.6	28.8	30.4	30.1	25.2	24.3	24.2	24.8	24.5	26.1
1970	-	-	-	-	-	-	-	-	-	-	-	-	-
1971	22.1	22.7	24.8	26.8	30.1	30.6	30.9	30.3	29.5	27.0	25.3	23.5	27.0
1972	24.0	24.6	26.7	27.7	28.5	30.5	30.5	27.8	26.1	22.7	21.8	24.9	26.3
1973	20.3	-	27.8	28.0	29.5	30.6	30.6	29.7	29.9	26.1	27.5	23.7	-
1974	24.8	22.7	25.9	-	28.8	30.8	30.4	-	30.6	25.9	22.1	22.7	-
1975	23.5	24.9	25.0	27.1	30.7	30.2	30.6	28.9	29.5	26.3	24.9	23.7	27.1
1976	22.7	25.0	27.1	27.5	29.6	30.7	30.4	29.2	27.6	27.4	24.9	26.1	27.4
1977	24.8	23.0	25.6	29.4	30.7	31.5	30.9	30.7	30.5	27.2	25.0	24.8	27.8
1978	24.0	24.5	25.3	26.0	29.3	29.9	28.9	28.8	29.2	26.1	26.3	23.8	26.8
1979	-	-	-	-	-	-	-	-	-	-	-	-	-
1980	-	-	26.1	27.4	29.4	-	-	-	-	-	-	24.1	-
1981	24.2	25.5	26.3	27.7	29.9	30.4	31.5	30.2	30.4	27.2	25.3	24.8	27.8
1982	25.3	26.2	26.8	28.4	29.6	31.7	32.0	31.2	31.1	27.6	26.6	25.6	28.5
Average	23.8	24.4	25.7	27.4	29.3	30.7	30.5	29.7	29.6	26.7	25.3	24.3	27.3

Notes:

(1) Daily means estimated as (Tmin + Tmax) /2

(2) - indicates no data

TABLE A3 EL KOD MEAN MONTHLY RELATIVE HUMIDITIES, 1958-82

Values are %

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Average
1958	-	-	-	-	-	-	-	-	72	66	69	72	-
1959	73	76	84	70	-	-	-	70	76	78	73	78	-
1960	78	74	73	70	71	68	68	71	70	72	66	71	71
1961	70	75	76	68	68	71	68	71	78	73	72	76	72
1962	71	74	75	73	78	69	81	72	77	67	69	74	73
1963	72	70	79	88	82	78	75	72	72	70	73	67	75
1964	73	70	72	79	78	71	71	73	74	69	65	66	72
1965	75	73	70	76	69	63	68	66	71	65	70	65	69
1966	68	72	70	69	68	62	65	67	69	68	66	64	67
1967	66	70	78	72	76	74	69	68	70	68	68	66	70
1968	81	82	77	84	81	72	81	79	76	78	73	71	78
1969	82	87	88	92	87	84	91	86	95	81	76	77	86
1970	-	-	-	-	-	-	-	-	-	-	-	-	-
1971	81	81	84	81	81	80	80	78	75	80	82	85	81
1972	78	77	80	79	85	81	76	78	79	77	72	79	78
1973	77	76	80	83	86	71	67	83	77	88	92	79	80
1974	79	79	82	-	89	78	83	-	86	82	85	83	-
1975	88	80	81	81	80	80	75	81	82	86	88	80	82
1976	75	82	80	84	84	72	71	68	68	78	69	76	76
1977	73	70	71	70	71	65	70	66	68	69	67	70	69
1978	70	70	72	72	81	75	73	76	86	83	72	71	75
1979	71	72	79	78	76	74	71	72	77	74	60	65	72
1980	72	69	69	76	77	81	(97)	92	88	68	56	51	-
1981	75	77	79	76	80	77	77	78	74	78	77	76	77
1982	82	82	83	81	78	79	75	80	83	83	81	83	81
Average	75	76	77	77	78	74	74	75	77	75	73	73	75
1958-67 Average	72	73	75	74	74	70	71	70	73	70	69	70	72

Notes:

(1) 1958-67 period adopted for study pruposes - see chapter 2 text.

(2) All values derived from unaspirated psychrometer data.

(3) - indicates no data.

(4) Values in brackets rejected and not used in means.

TABLE A4 EL KOD HOURS OF BRIGHT SUNSHINE, 1958-82

Units: h/day

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Average
1958	-	-	-	-	-	-	-	-	9.0	10.1	10.7	9.9	-
1959	6.9	7.4	9.4	11.0	-	-	-	8.7	9.2	9.9	10.0	9.2	-
1960	8.5	10.4	7.5	10.2	10.0	10.1	7.4	9.5	9.0	10.3	10.3	9.3	9.4
1961	9.7	8.7	9.6	9.4	10.3	8.2	5.6	9.2	9.5	9.8	9.0	8.5	9.0
1962	9.0	10.1	9.0	10.3	10.0	10.3	7.9	8.1	8.8	10.7	10.1	9.9	9.5
1963	9.4	9.7	9.9	8.4	9.4	9.2	8.2	8.3	9.9	11.0	9.9	8.7	9.3
1964	6.4	8.3	9.7	10.1	9.8	9.3	7.8	8.8	8.9	10.1	8.8	8.1	8.8
1965	8.9	9.9	10.6	9.8	11.6	10.4	9.2	9.2	9.6	10.7	10.4	10.1	10.0
1966	9.4	7.2	8.5	9.7	10.9	10.0	8.0	8.7	8.9	10.3	10.5	9.0	9.3
1967	9.4	8.9	8.2	8.5	10.3	8.4	6.3	8.0	8.7	9.8	8.8	8.6	8.7
1968	-	-	-	-	-	-	-	-	-	-	-	-	-
1969	-	-	-	-	-	-	-	-	-	-	-	-	-
1970	-	-	-	-	-	-	-	-	-	-	-	-	-
1971	6.7	6.7	8.6	9.9	9.9	8.8	7.8	9.2	8.3	9.7	9.3	8.5	8.6
1972	9.1	7.1	7.0	8.0	10.4	5.5	9.2	8.2	8.6	9.3	9.5	9.3	8.4
1973	10.9	(12)	9.0	10.3	11.7	6.3	6.3	8.5	8.0	10.5	10.4	5.3	-
1974	6.2	9.3	7.2	-	9.7	10.4	8.2	-	6.4	9.3	10.3	9.2	-
1975	8.5	8.4	8.4	8.2	10.1	9.2	7.6	8.2	8.9	9.5	10.2	9.6	8.9
1976	8.5	9.9	7.9	9.2	10.2	9.9	8.8	9.7	8.9	9.9	9.8	9.8	9.4
1977	8.7	10.4	9.8	9.9	9.6	8.1	8.0	9.3	9.3	9.6	10.6	8.7	9.3
1978	8.8	8.0	8.6	10.4	10.9	9.1	8.7	9.6	9.5	9.6	10.0	9.2	9.4
1979	7.5	10.2	9.4	9.1	10.9	8.6	8.8	9.2	9.1	10.4	10.4	7.8	9.3
1980	6.3	9.2	9.3	8.9	9.3	8.6	7.1	8.8	8.4	9.6	10.4	7.6	8.6
1981	9.3	9.2	8.0	8.3	10.2	10.2	7.7	9.1	8.2	9.4	9.6	8.6	9.0
1982	8.2	8.3	8.1	7.2	10.2	8.8	7.0	6.8	7.2	9.6	9.2	7.3	8.2
Average	8.4	8.9	8.7	9.3	10.3	9.0	7.8	8.8	8.7	9.6	9.9	8.7	9.0

Notes:

(1) - indicates no data.

(2) Values in brackets rejected and not used to compute averages.

TABLE A5 EL KOD MEAN MONTHLY RUN OF WIND, 1958-82

Units: km/day

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Average
1958	-	-	-	-	-	-	-	-	174	178	187	221	-
1959	226	184	200	202	-	-	-	219	153	157	188	197	-
1960	185	181	206	199	158	159	197	170	152	154	164	196	177
1961	216	164	200	231	144	175	210	196	165	164	223	171	188
1962	180	169	207	199	170	159	179	201	180	137	196	183	180
1963	191	230	188	209	172	157	193	184	167	152	191	173	184
1964	217	197	204	154	149	155	189	195	147	139	159	210	176
1965	189	160	168	227	167	154	174	169	159	198	196	179	178
1966	214	203	206	210	175	126	179	168	146	173	162	149	176
1967	179	182	185	202	115	123	136	138	129	120	164	123	150
1968	(456)	192	(504)	187	(456)	144	144	144	168	-	-	-	-
1969	-	-	-	-	-	-	-	-	-	-	-	-	-
1970	-	-	-	-	-	-	-	-	-	-	-	-	-
1971	240	214	276	192	163	144	180	156	98	142	221	130	180
1972	257	249	264	264	160	195	178	140	141	160	117	162	191
1973	245	200	191	142	135	113	147	132	168	133	128	199	161
1974	192	271	242	-	264	170	216	-	170	154	156	204	-
1975	223	283	269	295	204	178	194	211	156	156	156	175	208
1976	194	257	247	190	146	170	156	154	127	163	120	168	174
1977	185	149	192	163	125	149	175	214	142	190	144	149	165
1978	150	190	150	140	120	140	180	160	120	110	120	140	140
1979	160	-	-	130	140	160	160	170	130	150	110	170	-
1980	161	182	194	156	130	163	190	175	142	120	114	125	154
1981	156	175	175	134	125	151	178	166	120	125	108	142	146
1982	168	154	158	144	125	120	149	161	132	144	130	144	144
Average	197	199	206	189	154	153	176	173	147	151	157	169	173

Notes:

(1) - indicates no data

(2) Values in brackets rejected and not used to compute averages.

(3) Run of wind measured approximately 2 m above ground level.

TABLE A6 ESTIMATED POTENTIAL REFERENCE CROP EVAPOTRANSPIRATION RATES AT EL KOD, 1958-82

Units: mm/month

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
1958	-	-	-	-	-	-	-	-	189	177	144	138	-
1959	129	123	158	187	-	-	-	193	177	167	141	124	-
1960	122	130	161	185	193	193	183	200	185	168	143	132	1 995
1961	142	128	166	193	199	187	170	194	187	171	147	121	2 005
1962	128	129	161	183	191	198	174	188	180	163	145	129	1 969
1963	131	144	163	168	192	188	192	190	188	175	147	127	2 005
1964	126	132	167	172	188	187	183	191	175	168	135	128	1 952
1965	122	125	160	180	198	196	196	196	186	177	149	131	2 016
1966	138	129	165	183	199	193	196	196	178	175	141	125	2 018
1967	129	130	154	170	185	171	166	180	177	162	137	119	1 880
1968	-	-	-	-	-	-	-	-	-	-	-	-	-
1969	-	-	-	-	-	-	-	-	-	-	-	-	-
1970	-	-	-	-	-	-	-	-	-	-	-	-	-
1971	119	117	164	176	197	182	185	193	165	164	145	117	1 924
1972	138	129	161	175	191	162	195	169	155	143	118	130	1 866
1973	126	-	174	180	205	158	167	180	173	163	150	114	-
1974	122	133	157	-	200	199	191	-	163	157	126	124	-
1975	130	140	163	177	208	187	184	184	176	161	139	127	1 976
1976	123	145	168	175	195	194	188	190	163	171	133	139	1 984
1977	132	128	167	188	194	182	187	204	183	171	140	125	2 001
1978	125	127	154	170	196	180	182	188	175	155	140	122	1 914
1979	-	-	-	-	-	-	-	-	-	-	-	-	-
1980	-	-	167	168	184	-	-	-	-	-	-	115	-
1981	129	136	157	163	194	192	188	192	171	161	132	124	1 939
1982	130	132	158	159	192	185	180	178	168	167	139	122	1 910
Average	128	131	162	176	195	185	184	189	176	166	140	125	1 957

Notes:

(1) Albedo = 0.25. For other constants and calculation procedure see chapter 2 text

(2) - indicates insufficient data for evapotranspiration estimate.

APPENDIX B

WADI FLOW DATA

NOTES ON TABLES B1-B15

1. - indicates no data

2. + indicates that the daily volume was worked up during the present study (see Chapter 3 text).

3. r indicates that a recession has been fitted (see Chapter 3 text).

TABLE B1 ADOPTED WADI BANA DAILY RUNOFF VOLUMES AT OLD BATEIS WEIR IN 1 000 m^3

Year: 1951

Day	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	-	-	-	647	161	7r	29	1 944r	2 048+	310	8r	3r
2	-	-	-	621	95	7r	25	1 977+	1 358+	180	7r	3r
3	-	-	-	790	64	6r	22	1 045+	761	107	6r	3r
4	-	-	-	240	36	5r	116	1 764+	652	84	6r	3r
5	-	-	-	2 360+	858	35	253	2 137+	498	90	5r	2r
6	-	-	-	1 174+	826	26r	514	2 869+	366	120	5r	2r
7	-	-	-	474	253	54	381	2 793+	239	172	4r	2r
8	-	-	-	307	232	26	464	2 464+	398	146	4r	2r
9	-	-	-	287	926	20r	810	3 509+	895	142	58	2r
10	-	-	-	287	1 034	15r	505	3 042+	450	134	42r	2r
11	-	-	-	148	2 754+	11r	340	1 939+	231	121	31r	65
12	-	-	-	133	638	10r	205	1 768+	214	359	23r	54
13	-	-	-	164	427	9r	153	13 251+	203	114	17r	39r
14	-	-	-	90	1 275r	8r	165	6 774+	204	173	13r	29r
15	-	-	-	66r	939+	7r	209	3 877+	1 871+	106	10r	22r
16	-	-	-	51	450	6r	704	2 327+	964	79	9r	16r
17	-	-	-	37r	166	6r	500	1 747+	474	84	8r	12r
18	-	-	-	28r	114	14	1 218+	2 054+	490	99	7r	9r
19	-	-	2 328+	21r	73	64	959+	2 450+	207	84	6r	8r
20	-	-	3 876+	16r	53r	50	652	3 633+	186	92	6r	7r
21	-	-	54	12r	39r	55	195	3 916+	147	84	5r	7r
22	-	-	74	10r	28r	435	183	4 410+	134	79	5r	6r
23	-	-	64	9r	40	229	801	3 721+	94	79	4r	48
24	-	-	2 082+	8r	50	142	487	2 275+	78	58r	4r	51
25	-	-	1 424+	7	40	129	301	4 326+	82	42r	4r	179
26	-	-	623	8	29r	71	205	5 147+	76	31r	3r	94
27	-	-	212	7r	22r	50	187	3 064+	65	23r	3r	95
28	-	-	1 940+	6r	16r	50	250	2 598+	181	17r	3r	65
29	-		2 738+	6r	12r	34	169	2 219+	143	13r	3r	47r
30	-		859	56	9r	32	617	1 481+	222	10r	3r	35r
31	-		755		8r		2 470+	2 526+		9r		25r
Total ($M.m^3$)	-	-	-	8.07	11.67	1.61	14.09	99.05	13.93	3.24	0.31	0.94

TABLE B2 ADOPTED WADI BANA DAILY RUNOFF VOLUMES AT OLD BATEIS WEIR IN 1 000 m^3

Year: 1952

Day	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	19^{r}	2^{r}	1^{r}	15^{r}	360	3^{r}	178	374	$4\,417^{+}$	90	3^{r}	47
2	14^{r}	2^{r}	1^{r}	11^{r}	174	3^{r}	336	313	$2\,506^{+}$	90	2^{r}	47
3	11^{r}	2^{r}	0^{r}	10^{r}	141	3^{r}	211	$1\,143^{+}$	$2\,246^{+}$	90	2^{r}	47
4	9^{r}	1^{r}	0^{r}	9^{r}	306	3^{r}	29	984	$1\,685^{+}$	90	2^{r}	47
5	9^{r}	1^{r}	0^{r}	8^{r}	337	3^{r}	783	844^{+}	$1\,210^{+}$	473	2^{r}	47
6	8^{r}	1^{r}	0^{r}	8^{r}	432	3^{r}	191	519	$2\,198^{+}$	215	2^{r}	30
7	7^{r}	1^{r}	0^{r}	7^{r}	210	2^{r}	151	$1\,047^{+}$	675^{+}	75	2^{r}	30
8	6^{r}	1^{r}	73	6^{r}	86	2^{r}	118	$2\,412^{+}$	956	62	2^{r}	23^{r}
9	6^{r}	1^{r}	101	5^{r}	70	2^{r}	118	$1\,240^{+}$	$1\,120^{+}$	50	2^{r}	17^{r}
10	5^{r}	1^{r}	94	5^{r}	49	2^{r}	102	711	802	39	2^{r}	13^{r}
11	5^{r}	1^{r}	94	4^{r}	33	2^{r}	384	558	790	22	2^{r}	11^{r}
12	4^{r}	1^{r}	75	4^{r}	49	2^{r}	384	593	769	22	2^{r}	10^{r}
13	4^{r}	1^{r}	164	4^{r}	35	2^{r}	254	$1\,309^{+}$	705	22	2^{r}	9^{r}
14	4^{r}	1^{r}	$1\,423^{+}$	3^{r}	27	2^{r}	196	$1\,827^{+}$	507	18	1^{r}	8^{r}
15	3^{r}	1^{r}	$1\,771^{+}$	3^{r}	27	2^{r}	144	$2\,033^{+}$	256	14	1^{r}	8^{r}
16	3^{r}	1^{r}	$1\,641^{+}$	3^{r}	20^{r}	2^{r}	111	$2\,859^{+}$	256	14	1^{r}	7^{r}
17	3^{r}	1^{r}	$1\,308^{+}$	2^{r}	15^{r}	2^{r}	83	$1\,045^{+}$	256	10	1^{r}	6^{r}
18	3^{r}	1^{r}	874	2^{r}	11^{r}	2^{r}	61	646	256	10	1^{r}	5^{r}
19	3^{r}	1^{r}	550	878	10^{r}	2^{r}	53	432	256	6	1^{r}	5^{r}
20	3^{r}	1^{r}	528	1 043	9^{r}	1^{r}	253	278	222	6	1^{r}	4^{r}
21	3^{r}	1^{r}	364	350	8^{r}	1^{r}	69	344	189	5^{r}	1^{r}	4^{r}
22	3^{r}	1^{r}	270	136	7^{r}	281	535^{+}	237	181	5^{r}	22	4^{r}
23	2^{r}	1^{r}	141	86	7^{r}	$1\,057^{+}$	$1\,499^{+}$	$2\,731^{+}$	156	4^{r}	17^{r}	3^{r}
24	2^{r}	1^{r}	141	793	6^{r}	479	$1\,076^{+}$	$2\,070^{+}$	134	4^{r}	12^{r}	3^{r}
25	2^{r}	1^{r}	133	$2\,575^{+}$	5^{r}	238	562	$1\,524^{+}$	135	4^{r}	9^{r}	3^{r}
26	2^{r}	1^{r}	93^{r}	$1\,561^{+}$	5^{r}	323	973	$2\,381^{+}$	136	3^{r}	44	3^{r}
27	2^{r}	1^{r}	68^{r}	$1\,138^{r}$	4^{r}	270	668	$2\,434^{+}$	134	3^{r}	44	3^{r}
28	2^{r}	1^{r}	49^{r}	653	4^{r}	121	525	$2\,813^{+}$	134	3^{r}	47	3^{r}
29	2^{r}	1^{r}	36^{r}	479	4^{r}	328	803	$1\,093^{+}$	124	3^{r}	47	3^{r}
30	2^{r}		27^{r}	711	3^{r}	99	341	$1\,357^{+}$	120	3^{r}	47	3^{r}
31	2^{r}		20^{r}		3^{r}		411	9 215		3^{r}		3^{r}
Total ($M.m^3$)	0.15	0.03	10.04	10.51	2.46	3.24	11.60	47.37	23.53	1.46	0.32	0.46

TABLE B3 ADOPTED WADI BANA DAILY RUNOFF VOLUMES AT OLD BATEIS WEIR IN 1 000 m^3

Year: 1953

Day	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	2^{r}	1^{r}	0	9^{r}	807	4	895^{+}	$1\ 224^{+}$	809^{+}	231^{+}	102	73
2	2^{r}	1^{r}	0	8^{r}	330	4	277^{+}	$1\ 057^{+}$	734^{+}	227^{+}	106	115
3	2^{r}	1^{r}	0	7^{r}	152	96	200^{+}	543^{+}	$1\ 237^{+}$	215^{+}	111	116
4	2^{r}	1^{r}	0	7^{r}	104	211	$1\ 476^{+}$	930^{+}	$1\ 541^{+}$	182^{+}	112	103
5	2^{r}	1^{r}	0	6^{r}	104	148	379^{+}	$1\ 944^{+}$	$1\ 313^{+}$	168^{+}	113	92
6	2^{r}	1^{r}	0	5^{r}	95	244	217^{+}	$1\ 210^{+}$	$1\ 350^{+}$	162^{+}	112	86
7	2^{r}	1^{r}	0	5^{r}	57	176	118^{+}	$1\ 194^{+}$	903^{+}	162^{+}	112	83
8	2^{r}	1^{r}	0	4^{r}	47	194	201^{+}	$2\ 714^{+}$	976^{+}	162^{+}	112	80
9	2^{r}	1^{r}	0	4^{r}	47	108	120^{+}	$1\ 580^{+}$	675^{+}	162^{+}	112	81
10	2^{r}	0	0	4^{r}	47	281	112^{+}	926^{+}	486^{+}	151^{+}	112	83
11	2^{r}	0	0	4^{r}	31	91	112^{+}	843^{+}	439^{+}	124^{+}	124	80
12	2^{r}	0	0	3^{r}	23^{r}	202	$2\ 326^{+}$	615^{+}	520^{+}	122^{+}	125	81
13	2^{r}	0	0	3^{r}	17^{r}	89	946^{+}	$1\ 578^{+}$	403^{+}	114^{+}	125	84
14	1^{r}	0	0	125	13^{r}	48	$1\ 623^{+}$	$1\ 768^{+}$	$4\ 537^{+}$	95^{+}	122	76
15	1^{r}	0	0	$3\ 050^{+}$	12^{r}	37	812^{+}	906^{+}	846^{+}	87^{+}	118	75
16	1^{r}	0	0	$2\ 432^{+}$	11^{r}	13	827^{+}	911^{+}	460^{+}	86	106	85
17	1^{r}	0	0	$1\ 988^{+}$	67	5	$2\ 756^{+}$	663^{+}	$1\ 397^{+}$	86	104	86
18	1^{r}	0	0	$1\ 703^{+}$	152	4	666^{+}	$1\ 166^{+}$	$1\ 704^{+}$	86	111	86
19	1^{r}	0	0	$8\ 041^{+}$	89	4	604^{+}	$1\ 547^{+}$	$4\ 530^{+}$	86	118	88
20	1^{r}	0	0	$1\ 630^{+}$	51	2	$2\ 454^{+}$	$2\ 274^{+}$	$1\ 027^{+}$	86	125	99
21	1^{r}	0	0	$1\ 384^{+}$	22	2	$1\ 099^{+}$	$1\ 521^{+}$	$1\ 426^{+}$	82	125	646^{+}
22	1^{r}	0	0	892^{+}	22	2	857^{+}	$1\ 361^{+}$	769^{+}	73	125	$2\ 344^{+}$
23	1^{r}	0	0	$1\ 724^{+}$	22	190	$1\ 889^{+}$	$1\ 330^{+}$	554^{+}	73	120	$2\ 845^{+}$
24	1^{r}	0	0	$1\ 246^{+}$	17	181	$2\ 385^{+}$	904^{+}	349^{+}	73	113	698
25	1^{r}	0	0	477	15	115	$1\ 595^{+}$	560^{+}	309^{+}	81	111	518
26	1^{r}	0	22	300	12	65	$2\ 558^{+}$	902^{+}	254^{+}	86	107	321
27	1^{r}	0	22	199	11	42	$2\ 834^{+}$	$1\ 201^{+}$	208^{+}	86	95	176
28	1^{r}	0	17^{r}	135	9	50	$1\ 059^{+}$	809^{+}	223^{+}	92	90	117
29	1^{r}		12^{r}	143	7	50	$1\ 642^{+}$	$1\ 085^{+}$	229^{+}	102	90	97
30	1^{r}		11^{r}	418	5	737	$2\ 275^{+}$	715^{+}	319^{+}	102	83	95
31	1^{r}		10^{r}		4		$2\ 498^{+}$	$1\ 806^{+}$		102		99
Total ($M.m^3$)	0.04	0.01	0.09	25.96	2.40	3.40	37.81	37.79	30.53	3.75	3.34	9.71

TABLE B4 ADOPTED WADI BANA DAILY RUNOFF VOLUMES AT OLD BATEIS WEIR IN 1 000 m^3

Year: 1954

Day	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	86	71	26^{r}	80^{+}	11^{+}	29	143	$2\ 279^{+}$	956	987	298	167
2	81	82	20^{r}	66^{+}	11	30	165	$2\ 295^{+}$	1 333	756	276	167
3	78	90	15^{r}	171^{+}	31	26	$1\ 311^{+}$	$3\ 824^{+}$	1 100	464	294	162
4	72	70	11^{r}	94^{+}	362^{+}	21	$1\ 256^{+}$	$4\ 411^{+}$	$3\ 016^{+}$	504	305	156
5	72	74	10^{r}	$3\ 220^{+}$	166^{+}	20	$1\ 465^{+}$	922^{+}	$2\ 204^{+}$	486	305	156
6	63	54	9^{r}	$1\ 726^{+}$	162	92	853	$3\ 036^{+}$	1 332	436	299	178
7	65	64	8^{r}	557^{+}	$1\ 574^{+}$	58	762	$1\ 290^{+}$	$2\ 345^{+}$	405	299	218
8	69	69	7^{r}	240^{+}	$1\ 142^{+}$	63	262	834	$1\ 498^{+}$	397	299	239
9	65	65	7^{r}	107^{+}	955^{+}	189	310	604	1 058	409	299	226
10	62	53	6^{r}	73^{+}	$1\ 112^{+}$	117	199	1 099	927	411	285	197
11	57	52	87^{+}	50^{+}	522^{+}	98	168	920	913	410	248	212
12	58	52	613^{+}	22^{+}	378^{+}	75	128	1 156	1 360	379	240	203
13	58	49	236^{+}	38^{+}	232^{+}	48	997	$3\ 623^{+}$	$3\ 594^{+}$	341	256	210
14	59	48	183^{+}	48^{+}	195^{+}	43	1 125	$3\ 116^{+}$	$3\ 055^{+}$	341	264	218
15	64	35^{r}	105^{+}	54^{+}	773^{+}	49	$1\ 454^{+}$	1 445	$1\ 989^{+}$	359	264	224
16	64	26^{r}	65^{+}	48^{+}	362^{+}	67	$1\ 179^{+}$	1 055	1 154	354	258	219
17	59	20^{r}	53^{+}	54^{+}	229^{+}	68	$2\ 520^{+}$	$2\ 350^{+}$	1 126	$3\ 501^{+}$	257	223
18	56	15^{r}	39^{r}	55^{+}	159^{+}	169	$1\ 465^{+}$	$2\ 991^{+}$	$4\ 285^{+}$	516	257	212
19	39	138	28^{r}	52^{+}	133^{+}	272	1 507	$1\ 747^{+}$	1 081	420	257	154
20	29^{r}	344	21^{r}	48^{+}	118^{+}	325	1 171	1 403	768	436	255	201
21	22^{r}	222	57^{+}	43^{+}	93^{+}	193	$1\ 925^{+}$	$3\ 636^{+}$	699	494	251	228
22	17^{r}	144	167^{+}	39^{+}	98^{+}	218	$1\ 900^{+}$	$3\ 012^{+}$	910	426	210	203
23	12^{r}	132	45^{+}	628^{+}	154^{+}	$1\ 982^{+}$	1 219	$2\ 070^{+}$	681	385	183	195
24	11^{r}	106	50^{+}	188^{+}	116^{+}	944^{+}	905	$4\ 080^{+}$	834	358	174	188
25	10^{r}	86	43^{+}	49^{+}	89^{+}	550	$1\ 650^{+}$	$6\ 331^{+}$	783	344	167	204
26	9^{r}	57	$1\ 276^{+}$	48^{+}	73^{+}	$2\ 250^{+}$	$2\ 594^{+}$	$2\ 024^{+}$	598	343	167	212
27	14	48	832^{+}	48^{+}	46^{+}	$1\ 892^{+}$	$2\ 758^{+}$	$2\ 522^{+}$	837	343	167	212
28	23	35^{r}	$1\ 476^{+}$	33^{+}	44^{+}	722^{+}	$1\ 453^{+}$	$2\ 585^{+}$	$1\ 588^{+}$	343	167	197
29	13		$1\ 279^{+}$	15^{+}	37	687	$1\ 858^{+}$	$1\ 353^{+}$	776	343	167	187
30	8		374^{+}	13^{+}	29	243	$4\ 426^{+}$	$2\ 772^{+}$	595	324	167	187
31	23		80^{+}		23		1 604	1 825		307		187
Total ($M.m^3$)	1.42	2.30	7.23	7.91	9.43	11.54	40.73	72.61	43.40	16.32	7.34	6.14

TABLE B5 ADOPTED WADI BANA DAILY RUNOFF VOLUMES AT OLD BATEIS WEIR IN 1 000 m^3

Year: 1955

Day	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	209	165	60	235	138	63	247	233	1 118	232	27^{r}	5^{r}
2	1 292^{+}	158	60	162	147	58	192	250	877	231	20^{r}	4^{r}
3	625	149	86	134	581	58	114	291	650	203	15^{r}	4^{r}
4	336	136	86	102	775	50	86	523	532	184	11^{r}	3^{r}
5	302	124	81	79	417	48	67	336	670	177	10^{r}	3^{r}
6	256	118	81	84	274	48	59	212	2 371^{+}	169	9^{r}	3^{r}
7	184	94	76	61^{r}	199	806	460	154	2 714^{+}	161	8^{r}	3^{r}
8	148	89	76	45^{r}	149	500	1 012	143	900	159	7^{r}	3^{r}
9	156	83	76	33^{r}	143	316	3 728^{+}	125	672	159	7^{r}	3^{r}
10	168	79	76	25^{r}	134	253	1 036^{+}	210	981	150	6^{r}	100
11	170	83	370	18^{r}	116	165	1 266	371	494	145	5^{r}	73^{r}
12	203	86	531	14^{r}	90	133	1 803^{r}	454	744	142	5^{r}	53^{r}
13	187	86	327	101	78	390	700	170	1 430	138	4^{r}	39^{r}
14	184	86	137	104	73	1 706^{r}	540	142	1 713	135	4^{r}	29^{r}
15	166	76	423	104	240	970^{+}	845	171	3 582^{+}	125	4^{r}	22^{r}
16	158	76	260	104	603	905	585	654	3 915^{+}	121	108	16^{r}
17	158	76	230	104	345	374	422	1 976^{+}	19 080^{+}	121	79^{r}	480
18	158	86	154	104	214	272	285	2 404^{+}	1 778^{+}	121	58^{r}	257
19	184	86	114	104	166	196	2 209^{+}	1 406^{r}	637	129	42^{r}	183
20	187	86	104	91	147	169	1 563^{+}	495	946^{+}	134	31^{r}	239
21	206	76	86	86	107	146	808	2 336^{+}	2 082^{+}	131	23^{r}	219
22	1 521^{+}	86	83	125	78	166	498	1 642^{+}	660	108	17^{r}	159
23	2 239^{+}	76	82	103	73	161	901	593	521	108	13^{r}	141
24	1 667^{+}	71	69	224	68	129	679	2 513^{+}	384	108	10^{r}	143
25	2 027^{+}	71	76	404	62	121	581	3 436^{+}	409	108	9^{r}	143
26	772	66	67	404	60	112	437	2 926^{+}	449	108	8^{r}	131
27	520	66	67	267	84	108	357	3 914^{+}	680	108	7^{r}	111
28	415	60	67	568	103	108	317	5 980^{+}	449	92	6^{r}	108
29	208		67	343	78	105	269	4 405^{+}	297	67^{r}	6^{r}	102
30	125		1 367	158	67	101	218	2 008	256	49^{r}	5^{r}	101
31	126		639		63		222	1 328		36^{r}		97
Total ($M.m^3$)	15.26	2.59	6.08	4.49	5.87	8.74	22.51	41.80	52.00	4.16	0.56	2.98

TABLE B6 ADOPTED WADI BANA DAILY RUNOFF VOLUMES AT OLD BATEIS WEIR IN 1 000 m^3

Year: 1956

Day	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	90	83	26	13	138	3	60	2 037[+]	607	1 000[+]	4[r]	6[r]
2	95	78	26	13	129	3	60	1 292	2 044[+]	15 820[+]	56	5[r]
3	98	69	22	13	103	2	60	2 379[+]	685	318	64	5[r]
4	81	70	22	67	84	2	59	1 487[+]	314	311	47[r]	4[r]
5	80	76	22	100	73	2	63	7 667[+]	263	234	34[r]	4[r]
6	58[r]	67	17	87	65	2	56	1 600[+]	214	251	26[r]	3[r]
7	43[r]	64	17	49	60	2	52	1 022	209	128	19[r]	3[r]
8	31[r]	64	17	30	51	2	52	3 836[+]	219	1 108[+]	14[r]	3[r]
9	23[r]	58	22	22	47	2	544	5 269[+]	214	136	11[r]	2[r]
10	18[r]	54	22	22	43	2	116	2 927[+]	284	82	10[r]	2[r]
11	13[r]	47	22	47	35	2	89	6 901[+]	219	65	9[r]	2[r]
12	10[r]	45	32	55	22	2	86	887	285	64	8[r]	2[r]
13	9[r]	43	32	37	22	2	387	1 936[+]	438	63	7[r]	2[r]
14	8[r]	43	32	22	22	2	225	2 238[+]	213	59	62	1[r]
15	7[r]	39	32	17[r]	22	2	117	1 203	147	56	62	1[r]
16	6[r]	39	32	12[r]	18	2	76	676	138	57	62	1[r]
17	6[r]	34	17	11[r]	17	2	108	568	154	54	66	1[r]
18	94	34	17	10[r]	17	2	150	714	213	52	73	1[r]
19	95	34	17	9[r]	17	2	95	600	2 079[+]	52	41[r]	1[r]
20	69	34	17	2 742[+]	13	1	188	1 374	499	38[r]	37	1[r]
21	58	30	15	605	13	1	255	605	351	28[r]	28[r]	1[r]
22	42[r]	30	15	760	10	1	182	469	234	21[r]	21[r]	1[r]
23	31[r]	30	15	558	8	1	148	524	167	16[r]	16[r]	1[r]
24	23[r]	26	15	2 174[+]	7	1	320	486	161	12[r]	12[r]	0[r]
25	17[r]	26	15	2 094[+]	7	53	495	862	122	9[r]	11[r]	0[r]
26	13[r]	26	15	1 760[+]	5	175	456	2 881[+]	108	8[r]	9[r]	0[r]
27	12[r]	30	15	858	5	507	2 216[+]	1 250	1 290[+]	7[r]	9[r]	0[r]
28	11[r]	30	13	413	3	2 135[+]	868	1 248	3 376[+]	7[+]	8[r]	0[r]
29	10[r]	30	13	235	3	96	500	702	256	6[r]	7[r]	0[r]
30	9[r]		13	186	3	60	296	540	4 754[+]	5[r]	6[r]	0[r]
31	70		13		3		6 236[+]	1 308[+]		5[r]		0[r]
Total ($M.m^3$)	1.23	1.33	0.62	13.02	1.07	3.07	14.62	57.49	20.26	20.07	0.84	0.05

TABLE B7 ADOPTED WADI BANA DAILY RUNOFF VOLUMES AT OLD BATEIS WEIR IN 1 000 m^3

Year: 1957

Day	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	0[r]	0[r]	425	423	2 344[+]	566	606	1 194	847	188	206	212
2	0[r]	0[r]	266	270	10 311[+]	473	696	2 469[+]	705	188	220	186
3	0[r]	0[r]	320	404	1 497[+]	482	702	1 411	684	188	227	164
4	0[r]	0[r]	247	487	569	430	718	2 349	610	188	206	164
5	0[r]	0[r]	164	208	7 119[+]	354	643	4 739[+]	542	188	144[r]	164
6	0[r]	28	106	247	4 224[+]	367	584	1 844	509	182	101[r]	164
7	0[r]	21[r]	115	210	1 259	324	216	1 873	1 361	179	74[r]	164
8	0[r]	16[r]	122	137	1 193[r]	322	164	2 212	1 616[+]	173	54[r]	138
9	0[r]	12[r]	88	974	1 235[+]	387	164	4 925[+]	745	170	39[r]	97[r]
10	0[r]	11[r]	108	875	1 050	1 249[+]	498	2 250[+]	495	170	29[r]	71[r]
11	0[r]	10[r]	1 222	700	264	3 358[+]	585	3 076[+]	467	170	22[r]	51[r]
12	0[r]	9[r]	263	932	175	1 827[+]	278	1 280	436	170	16[r]	38[r]
13	0[r]	8[r]	174	732	167	852	293	1 248	383	170	12[r]	27[r]
14	0[r]	7[r]	133	5 438[+]	134	608	244	4 079[+]	367	170	259	149
15	0[r]	6[r]	100	2 757[+]	134	307	443	1 929	361	176	285	173
16	0[r]	6[r]	67	8 219[+]	114	592	282	1 524	353	179	285	121[r]
17	0[r]	5[r]	37	6 926[+]	97	642	540	1 262	329	179	285	88[r]
18	0[r]	5[r]	138	737[+]	75	572	292	2 538	311	179	251	65[r]
19	0[r]	4[r]	110	469[r]	69	307	497	1 968	279	179	176[r]	47[r]
20	0[r]	4[r]	49	259	60	268	273	1 140	242	185	123[r]	34[r]
21	0[r]	3[r]	40	170	866	614	396	2 336	232	187	90[r]	26[r]
22	0[r]	3[r]	12	238	3 964[+]	272	307	1 855	232	187	66[r]	19[r]
23	0[r]	3[r]	9	2 273[+]	4 168[+]	208	269	2 239[+]	219	132	48[r]	15[r]
24	0[r]	3[r]	7	3 988[+]	2 418[+]	207	641	1 022	214	132	35[r]	11[r]
25	0[r]	3[r]	26	3 193[+]	3 632[r]	226	1 183[+]	864	197	132	26[r]	10[r]
26	0[r]	3[r]	32	880[+]	16 799[+]	261	1 161[+]	978	194	206	281	9[r]
27	0[r]	1 491[+]	24	492	11 673[+]	207	872	851	188	206	313	178
28	0[r]	802[+]	10	289	7 315[+]	264	461	758	188	243	251	185
29	0[r]		622	199	1 219[+]	194	831	722	188	285	251	173
30	0[r]		387	8 431[+]	1 324	164	1 417[+]	1 838[+]	188	230	272	121[r]
31	0[r]		628		647		759	1 135		206		88[r]
Total ($M.m^3$)	0	2.46	6.05	51.56	86.12	16.90	17.02	59.91	13.69	5.72	4.65	3.15

TABLE B8 ADOPTED WADI BANA DAILY RUNOFF VOLUMES AT OLD BATEIS WEIR IN 1 000 m^3

Year: 1958

Day	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	65^{r}	162	86	$5\ 528^{+}$	17^{r}	2^{r}	43	881	432	127	58^{r}	3^{r}
2	47^{r}	225	86	$1\ 107^{+}$	13^{r}	1^{r}	73	552	549	53	43^{r}	3^{r}
3	34^{r}	158	83	365	12^{r}	1^{r}	88	341	569	52	31^{r}	2^{r}
4	26^{r}	118	78	244	10^{r}	22	62	255	365	81	23^{r}	2^{r}
5	19^{r}	140	78	199	9^{r}	23	52	353	250	56	18^{r}	2^{r}
6	15^{r}	136	78	115	8^{r}	23	47	801	204	58	13^{r}	2^{r}
7	11^{r}	197	76	89	8^{r}	23	47	540	188	57	10^{r}	2^{r}
8	10^{r}	341	70	184	7^{r}	23	43	$2\ 262^{+}$	179	48	285	2^{r}
9	9^{r}	168	67	150	6^{r}	37	39	$1\ 860^{+}$	181	47	106	2^{r}
10	$1\ 170^{+}$	130	67	189	6^{r}	43	34	805	195	72	77^{r}	2^{r}
11	267	130	57	146	5^{r}	159	892	383	187	86	56^{r}	2^{r}
12	192	130	54	146	5^{r}	232	111	350	175	84	41^{r}	2^{r}
13	277	130	45	144	4^{r}	229	191	853	211	78	30^{r}	2^{r}
14	153	147	41	115	4^{r}	159	96	$3\ 745^{+}$	235	78	23^{r}	2^{r}
15	144	134	41	200	3^{r}	132	62	$2\ 922^{+}$	204	76	17^{r}	1^{r}
16	144	130	41	166	3^{r}	73	41	1 114	127	78	13^{r}	1^{r}
17	144	130	36	97	3^{r}	73	118	1 036	107	78	10^{r}	1^{r}
18	138	130	34	61	3^{r}	66	$1\ 639^{+}$	1 206	203	70	9^{r}	1^{r}
19	135	130	34	74	3^{r}	62	$1\ 588^{+}$	911	329	73	8^{r}	1^{r}
20	132	108	34	63	3^{r}	62	985	697	368	73	7^{r}	1^{r}
21	135	93	34	60	2^{r}	60	$1\ 950^{+}$	444	173	69	6^{r}	1^{r}
22	112	86	34	58	2^{r}	54	$1\ 736^{+}$	507	134	69	6^{r}	1^{r}
23	107	86	27	58	2^{r}	44	$1\ 910^{+}$	514	146	66	5^{r}	1^{r}
24	129	86	25	58	2^{r}	38	516	1 172	90	62	5^{r}	1^{r}
25	253	86	22	58	2^{r}	36	237	1 025	76	65	4^{r}	1^{r}
26	150	86	22	58	2^{r}	36	$1\ 713^{+}$	$2\ 687^{+}$	73	62	4^{r}	1^{r}
27	106	86	22	47	2^{r}	105	694	474	64	62	3^{r}	1^{r}
28	152	86	721	32	2^{r}	63	593	642	58	69	3^{r}	1^{r}
29	164		573	23	2^{r}	30	$1\ 939^{+}$	824	58	61	3^{r}	1^{r}
30	193		188	23	2^{r}	39	596	$1\ 241^{+}$	239	80	3^{r}	1^{r}
31	216		139		2^{r}		626	507		80		1^{r}
Total ($M.m^3$)	4.85	3.77	2.99	9.86	0.15	1.95	18.76	31.90	6.37	2.17	0.92	0.05

TABLE B9 ADOPTED WADI BANA DAILY RUNOFF VOLUMES AT OLD BATEIS WEIR IN 1 000 m^3

Year: 1959

Day	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	1^r	11^r	2^r	47	2^r	572	590	4 911$^+$	614	239	12^r	14^r
2	1^r	10^r	94	36	2^r	311	182	2 022$^+$	11 150$^+$	619	9^r	10^r
3	1^r	9^r	81	22	2^r	189	61	2 858$^+$	1 129$^+$	100	8^r	9^r
4	1^r	8^r	44	20	2^r	132	117	2 438$^+$	2 499$^+$	235	7^r	8^r
5	1^r	7^r	32^r	17	2^r	95	108	1 819$^+$	867	285	7^r	176
6	1^r	6^r	24^r	13^r	2^r	82	1 866$^+$	2 828$^+$	619	143	6^r	84
7	1^r	6^r	18^r	10^r	2^r	79	281	2 740$^+$	717	102	5^r	84
8	1^r	5^r	14^r	9^r	1^r	71	721	1 837$^+$	2 442$^+$	91	5^r	112
9	1^r	5^r	10^r	8^r	1^r	47	523	1 628$^+$	9 032$^+$	105	4^r	116
10	1^r	4^r	9^r	7^r	1^r	47	137	1 863$^+$	2 221$^+$	107	4^r	116
11	1^r	4^r	8^r	6^r	40	47	136	1 333	1 206	106	4^r	116
12	0^r	3^r	7^r	6^r	483	47	130	1 231	1 008	105	3^r	92
13	0^r	3^r	7^r	5^r	405	47	391	866	4 681$^+$	101	3^r	67^r
14	0^r	3^r	6^r	5^r	454	37	162	775	920	101	3^r	49^r
15	0^r	3^r	5^r	4^r	97	28^r	264	485	879	101	82	36^r
16	0^r	3^r	5^r	4^r	480	21^r	191	1 550$^+$	864	118	88	27^r
17	0^r	3^r	4^r	3^r	78	16^r	427	2 882$^+$	1 058	118	101	20^r
18	0^r	2^r	4^r	3^r	75	12^r	227	978	1 171	108	108	15^r
19	0^r	2^r	4^r	3^r	74	11^r	143	2 079$^+$	676	101	78	11^r
20	0^r	2^r	3^r	3^r	63	9^r	364	4 340$^+$	642	101	104	10^r
21	0^r	2^r	3^r	3^r	56	9^r	239	2 017$^+$	486	233	116	9^r
22	0^r	2^r	3^r	3^r	52	8^r	291	3 520$^+$	513	134	95	107
23	180	2^r	3^r	3^r	52	7^r	132	3 980$^+$	343	92	100	106
24	80	2^r	3^r	2^r	52	6^r	125	1 562	224	96	91	106
25	58^r	2^r	2^r	2^r	42	6^r	345	928	206	82	83	106
26	43^r	2^r	2^r	2^r	37	5^r	193	625	165	74	61^r	94
27	31^r	2^r	2^r	2^r	207	5^r	126	575	94	54^r	44^r	82
28	23^r	2^r	2^r	2^r	50	30	80	475	425	39^r	39^r	79
29	18^r		75	2^r	335	856	1 214	405	290	29^r	24^r	80
30	13^r		48	2^r	8 230$^+$	73	2 125$^+$	519	175	22^r	18^r	73
31	12^r		49		665		3 112$^+$	361		16^r		84
Total (M.m^3)	0.47	0.11	0.57	0.25	12.04	2.91	15.10	56.43	47.32	3.96	1.30	2.10

TABLE B10 ADOPTED WADI BANA DAILY RUNOFF VOLUMES AT OLD BATEIS WEIR IN 1 000 m^3

Year: 1960

Day	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	61^r	4^r	1^r	680^+	256	202	52	392	933	99	2^r	4^r
2	45^r	4^r	1^r	301^+	$1\ 998^+$	125	51	321	684	99	2^r	4^r
3	33^r	3^r	1^r	202^+	$2\ 135^+$	81	150	589	527	97	2^r	3^r
4	25^r	3^r	1^r	152^+	$1\ 716^+$	65	97	504	310	78	2^r	3^r
5	18^r	3^r	1^r	143^+	839^+	55	33	329	$1\ 073^+$	75	2^r	3^r
6	14^r	3^r	1^r	113^+	$1\ 234^+$	52	21	396	$1\ 079^+$	59	2^r	3^r
7	10^r	3^r	1^r	61^+	$1\ 418^+$	50	17	331	811	37	2^r	3^r
8	10^r	3^r	1^r	38^+	$2\ 423^+$	47	17	236	538	28^r	2^r	3^r
9	9^r	3^r	1^r	43^+	$2\ 112^+$	46	339	213	631	21^r	2^r	2^r
10	8^r	3^r	1^r	46^+	824^+	46	433	319	680	16^r	2^r	34
11	7^r	3^r	76^+	40^+	483^+	46	248	241	459	12^r	2^r	75
12	6^r	2^r	448^+	365^+	379^+	46	110	221	490	11^r	2^r	418
13	6^r	2^r	122^+	$1\ 580^+$	276^+	46	304	183	345	10^r	78	425
14	5^r	2^r	683^+	$2\ 797^+$	240^+	44	143	156	$2\ 337^+$	9^r	82	265
15	5^r	2^r	$1\ 551^+$	$5\ 476^+$	221^+	42	162	204	859	8^r	52	164
16	67	2^r	$1\ 144^+$	$1\ 619^+$	163^+	42	509	165	519	7^r	39^r	56
17	49^r	2^r	460^+	615^+	134^+	42	361	137	355	6^r	29^r	42^r
18	36^r	2^r	277^+	257^+	115^+	42	168	137	264^+	6^r	22^r	32^r
19	27^r	2^r	167^+	182^+	$1\ 120^+$	164	100	198	265	5^r	17^r	24^r
20	20^r	2^r	190^+	141^+	102^+	74	643	268	191	5^r	12^r	18^r
21	15^r	2^r	626^+	94^+	$5\ 282^+$	198	409	538	213	4^r	11^r	13^r
22	11^r	2^r	489^+	80^+	$8\ 585^+$	76	$2\ 133^+$	$1\ 198^+$	$3\ 742^+$	4^r	10^r	10^r
23	10^r	2^r	247^+	75^+	$1\ 582^+$	52	557	404	216	3^r	9^r	9^r
24	9^r	1^r	153^+	69^+	450^+	48	212	280	515	3^r	8^r	8^r
25	8^r	1^r	180^+	528^+	354^+	60	199	954	148	3^r	7^r	7^r
26	7^r	1^r	198^+	$6\ 646^+$	273^+	49	188	368	107	3^r	7^r	7^r
27	7^r	1^r	378^+	$1\ 648^+$	186^+	46	296	216	110	3^r	6^r	6^r
28	6^r	1^r	537^+	661^+	143^+	46	843	316	113	3^r	5^r	5^r
29	5^r	1^r	$2\ 308^+$	363^+	122^+	46	526	276	171	3^r	5^r	5^r
30	5^r		$1\ 001^+$	308^+	122^+	53	456	579	140	3^r	4^r	4^r
31	4^r		$1\ 492^+$		210^+		722	1 090		3^r		4^r
Total ($M.m^3$)	0.55	0.06	12.86	25.32	35.50	2.03	10.50	11.76	18.83	0.72	0.43	1.66

TABLE B11 ADOPTED WADI BANA DAILY RUNOFF VOLUMES AT OLD BATEIS WEIR IN 1 000 m^3

Year: 1961

Day	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	4^{r}	5^{r}	4^{r}	49	14^{r}	44^{r}	51^{+}	2 749^{+}	322^{+}	730^{+}	47	52
2	4^{r}	4^{r}	3^{r}	47	10^{r}	26	164^{+}	1 787^{+}	2 116^{+}	112^{+}	47	81
3	3^{r}	4^{r}	3^{r}	505	9^{r}	14	173^{+}	2 890^{+}	874^{+}	119^{+}	47	66
4	3^{r}	3^{r}	3^{r}	353	8^{r}	11^{r}	342^{+}	4 840^{+}	575^{+}	117^{+}	44	51
5	3^{r}	3^{r}	3^{r}	203	7^{r}	9^{r}	220^{+}	2 037^{+}	462^{+}	114^{+}	43	47
6	3^{r}	3^{r}	3^{r}	548	7^{r}	9^{r}	249^{+}	3 563^{+}	359^{+}	100^{+}	39	35^{r}
7	3^{r}	3^{r}	3^{r}	244	6^{r}	8^{r}	195^{+}	2 229^{+}	262^{+}	92^{+}	34	26^{r}
8	3^{r}	135	3^{r}	190	5^{r}	7^{r}	79^{+}	2 120^{+}	327^{+}	121^{+}	32	20^{r}
9	3^{r}	215	2^{r}	264	5^{r}	6^{r}	275^{+}	1 283^{+}	4 315^{+}	95^{+}	32	15^{r}
10	3^{r}	113	2^{r}	563	180	6^{r}	106^{+}	703^{+}	1 593^{+}	76^{+}	32	11^{r}
11	29	80	2^{r}	231	110	674	72^{+}	1 479^{+}	1 560^{+}	26	19	10^{r}
12	32	64	2^{r}	243	186	34	56^{+}	1 942^{+}	1 151^{+}	20^{r}	16	9^{r}
13	32	49	2^{r}	133	104	204	50^{+}	1 653^{+}	654^{+}	15^{r}	13	8^{r}
14	37	37^{+}	2^{r}	150	48	140	1 778^{+}	766^{+}	337^{+}	11^{r}	13	7^{r}
15	46	28^{r}	2^{r}	125	25	130	1 171^{+}	428^{+}	1 826^{+}	10^{r}	34	7^{r}
16	25	21^{r}	2^{r}	74	103	170	759^{+}	333^{+}	221^{+}	9^{r}	515	6^{r}
17	22	16^{r}	2^{r}	54	52	379	529^{+}	284^{+}	192^{+}	8^{r}	623	5^{r}
18	44	12^{r}	2^{r}	47	26	297	758^{+}	1 102^{+}	254^{+}	7^{r}	337	5^{r}
19	47	10^{r}	2^{r}	98	16	365	676^{+}	1 227^{+}	176^{+}	6^{r}	86	4^{r}
20	34^{r}	9^{r}	2^{r}	476	12^{r}	209	1 480^{+}	1 019^{+}	142^{+}	6^{r}	132	4^{r}
21	26^{r}	8^{r}	2^{r}	255	9^{r}	145	718^{+}	559^{+}	125^{+}	5^{r}	34	4^{r}
22	19^{r}	8^{r}	2^{r}	166	8^{r}	134	403^{+}	315^{+}	395^{+}	5^{r}	21	3^{r}
23	14^{r}	7^{r}	1^{r}	108	7^{r}	130	260^{+}	388^{+}	157^{+}	4^{r}	16	3^{r}
24	11^{r}	6^{r}	46	85	7^{r}	72	204^{+}	1 495^{+}	595^{+}	4^{r}	12^{r}	3^{r}
25	10^{r}	6^{r}	46	66	6^{r}	374	438^{+}	2 090^{+}	168^{+}	3^{r}	11^{r}	3^{r}
26	9^{r}	5^{r}	131	50	5^{r}	249	713^{+}	607^{+}	115^{+}	3^{r}	10^{r}	146
27	8^{r}	4^{r}	119	43	5^{r}	644	397^{+}	1 080^{+}	72^{+}	3^{r}	9^{r}	104
28	7^{r}	4^{r}	78	32	4^{r}	87	198^{+}	520^{+}	259^{+}	3^{r}	21	76^{r}
29	6^{r}		60	24^{r}	4^{r}	150	128^{+}	462^{+}	254^{+}	39	52	55^{r}
30	6^{r}		112	18^{r}	137	122	115^{+}	644^{+}	178^{+}	39	52	40^{r}
31	5^{r}		87		60		97^{+}	385^{+}		40		30^{r}
Total ($M.m^3$)	0.50	0.86	0.73	5.44	1.18	4.85	12.85	42.98	20.04	1.94	2.42	0.94

TABLE B12 ADOPTED WADI BANA DAILY RUNOFF VOLUMES AT OLD BATEIS WEIR IN 1 000 m^3

Year: 1962

Day	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	23^{r}	2^{r}	3^{r}	7	64^{+}	103	277^{+}	$1\ 116^{+}$	$10\ 525^{+}$	114^{+}	8^{r}	15^{r}
2	17^{r}	2^{r}	3^{r}	7	49^{+}	63	169^{+}	$1\ 005^{+}$	$11\ 581^{+}$	107^{+}	8^{r}	11^{r}
3	13^{r}	1^{r}	3^{r}	7	17^{+}	$3\ 229^{+}$	127^{+}	$2\ 437^{+}$	$1\ 789^{+}$	99^{+}	7^{r}	10^{r}
4	10^{r}	1^{r}	3^{r}	7	135^{+}	$2\ 461^{+}$	103^{+}	$1\ 937^{+}$	$1\ 043^{+}$	88^{+}	6^{r}	9^{r}
5	9^{r}	1^{r}	19^{+}	5	380^{+}	$1\ 217^{+}$	146^{+}	$1\ 346^{+}$	$1\ 127^{+}$	81^{+}	6^{r}	8^{r}
6	8^{r}	1^{r}	107^{+}	3	220^{+}	652	305^{+}	$2\ 113^{+}$	$1\ 541^{+}$	74^{+}	47	7^{r}
7	7^{r}	1^{r}	33^{+}	3	557^{+}	805	$1\ 624^{+}$	841^{+}	957^{+}	73^{+}	47	6^{r}
8	6^{r}	1^{r}	21^{r}	3	311^{+}	362	423^{+}	599^{+}	$1\ 707^{+}$	73^{+}	47	6^{r}
9	6^{r}	1^{r}	16^{r}	3	213^{+}	211	254^{+}	316^{+}	$1\ 783^{+}$	73^{+}	32	5^{r}
10	5^{r}	23	12^{r}	3	123^{+}	135	584^{+}	216^{+}	755^{+}	73^{+}	22	5^{r}
11	5^{r}	47	11^{r}	3	132^{+}	125	196^{+}	$3\ 508^{+}$	542^{+}	69^{+}	22	4^{r}
12	4^{r}	33	10^{r}	2	118^{+}	91	125^{+}	752^{+}	429^{+}	64^{+}	17^{r}	4^{r}
13	4^{r}	19	9^{r}	2	83^{+}	74	127^{+}	382^{+}	325^{+}	70^{+}	12^{r}	3^{r}
14	3^{r}	14^{r}	706^{+}	3	73^{+}	71	91^{+}	$2\ 306^{+}$	799^{+}	73	9^{r}	3^{r}
15	3^{r}	11^{r}	$1\ 174^{+}$	2	73^{+}	58	93^{+}	876^{+}	532^{+}	73	8^{r}	3^{r}
16	3^{r}	10^{r}	503^{+}	2	64^{+}	55	427^{+}	695^{+}	294^{+}	73	8^{r}	3^{r}
17	3^{r}	9^{r}	137^{+}	2	52^{+}	191	327^{+}	928^{+}	231^{+}	62	7^{r}	52
18	3^{r}	8^{r}	103^{+}	2	44^{+}	74	107^{+}	473^{+}	668^{+}	58	49	38^{r}
19	3^{r}	7^{r}	106^{+}	2	21^{+}	71	101^{+}	$3\ 120^{+}$	442^{+}	49	20	28^{r}
20	3^{r}	6^{r}	99^{+}	2	16^{r}	139	95^{+}	886^{+}	455^{+}	62	49	20^{r}
21	3^{r}	6^{r}	60^{+}	$2\ 863^{+}$	12^{r}	196	66^{+}	$5\ 501^{+}$	621^{+}	62	32	15^{r}
22	2^{r}	5^{r}	87^{+}	737^{+}	11^{r}	176	211^{+}	$3\ 602^{+}$	$5\ 782^{+}$	62	32	11^{r}
23	2^{r}	5^{r}	89^{+}	797^{+}	10^{r}	145	336^{+}	$2\ 768^{+}$	762^{+}	62	43	52
24	2^{r}	4^{r}	55^{+}	636^{+}	9^{r}	93	404^{+}	$1\ 863^{+}$	$1\ 230^{+}$	62	344	52
25	2^{r}	4^{r}	48^{+}	266^{+}	8^{r}	68	181^{+}	$5\ 926^{+}$	694^{+}	45^{r}	141	57
26	2^{r}	3^{r}	22	469^{+}	7^{r}	47	221^{+}	$2\ 195^{+}$	250^{+}	33^{r}	66	42^{r}
27	2^{r}	3^{r}	18	158^{+}	6^{r}	47	147^{+}	$9\ 400^{+}$	657^{+}	25^{r}	52	30^{r}
28	2^{r}	3^{r}	18	118^{+}	6^{r}	47	103^{+}	$5\ 521^{+}$	372^{+}	19^{r}	38^{r}	23^{r}
29	2^{r}		12	79^{+}	24	84	119^{+}	$2\ 319^{+}$	615^{+}	14^{r}	28^{r}	17^{r}
30	2^{r}		7	73^{+}	50	619	198^{+}	$2\ 130^{+}$	425^{+}	10^{r}	20^{r}	13^{r}
31	2^{r}		7		20		861^{+}	$5\ 228^{+}$		9^{r}		10^{r}
Total ($M.m^3$)	0.16	0.23	3.50	6.27	2.91	11.71	8.55	72.31	48.93	1.91	1.23	0.56

TABLE B13 ADOPTED WADI BANA DAILY RUNOFF VOLUMES AT OLD BATEIS WEIR IN 1 000 m^3

Year: 1963

Day	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	9^r	3^r	41^r	2^r	$1\ 340^+$	415	74	904	$4\ 949^+$	416	4^r	73
2	8^r	3^r	30^r	$2\ 765^+$	403	328	64	1 046	1 035	416	3^r	75
3	7^r	3^r	22^r	1 123	1 075	162	383	$1\ 472^+$	706	416	3^r	78
4	95	2^r	17^r	1 014	$6\ 795^+$	118	236	$1\ 586^+$	571	416	3^r	87
5	811	2^r	13^r	$9\ 989^+$	$1\ 416^+$	173	611	$3\ 529^+$	684	416	3^r	87
6	126	2^r	9^r	$3\ 981^+$	$1\ 065^+$	489	400	$2\ 799^+$	584	416	3^r	87
7	92	2^r	9^r	1 101	$2\ 944^+$	280	244	1 737	661	336	818	66
8	66	2^r	8^r	425	$4\ 613^+$	233	192	$5\ 596^+$	527	300	330	95
9	56	2^r	7^r	286	717	114	923^+	$2\ 981^+$	475	258	280	69^r
10	52	2^r	6^r	200	512	86	598	935	367	236	258	51^r
11	47	2^r	6^r	70	$3\ 768^+$	86	510	517	364	165^r	202	37^r
12	34^r	2^r	5^r	$2\ 093^+$	$11\ 520^+$	86	282	449	318	116^r	121	28^r
13	26^r	2^r	5^r	655^+	$2\ 489^+$	86	607	823^+	332	84^r	141	21^r
14	19^r	2^r	4^r	$9\ 493^+$	$3\ 806^+$	170	361	$2\ 131^+$	384	62^r	348	16^r
15	14^r	2^r	4^r	$8\ 894^+$	$1\ 100^+$	160	587^+	738	312	45	311	12
16	11^r	2^r	3^r	$15\ 669^+$	962	133	428	939	257	33^r	180	9^r
17	10^r	1^r	3^r	3 094	234	300	$1\ 778^+$	$1\ 567^+$	229	25^r	236	7^r
18	9^r	1^r	3^r	1 121	226	391	$1\ 253^+$	$3\ 364^+$	531	19^r	236	5^r
19	8^r	1^r	3^r	$1\ 599^+$	227	719	792	$1\ 934^+$	779	14^r	236	4^r
20	7^r	1^r	3^r	$1\ 065^+$	163	$1\ 762^+$	228	$1\ 744^+$	712	12^r	180	3^r
21	6^r	1^r	3^r	372	476	121	$8\ 008^+$	615^+	731^+	11^r	180	3^r
22	6^r	1^r	2^r	481	281	159	$1\ 280^+$	$1\ 174^+$	314	10^r	180	3^r
23	5^r	1^r	2^r	196	153	182	757	$6\ 963^+$	283	9^r	180	2^r
24	5^r	1^r	2^r	119	108	137	568	$4\ 469^+$	205	8^r	180	2^r
25	4^r	101	2^r	108	103	116	789^+	$3\ 072^+$	381	7^r	131	2^r
26	4^r	167	2^r	108	108	98	$1\ 631^+$	$13\ 623^+$	628	7^r	77	2^r
27	3^r	79	2^r	90	120	69	$2\ 719^+$	$1\ 928^+$	628	6^r	88	2^r
28	3^r	56	2^r	$4\ 642^+$	66	86	$1\ 825^+$	1 330	464	5^r	61	2^r
29	3^r		2^r	$10\ 110^+$	59	86	785	1 085	464	5^r	59	2^r
30	3^r		2^r	$2\ 300^+$	$1\ 810^+$	78	451	984	464	4^r	61	2^r
31	3^r		2^r		289		911	790		4^r		2^r
Total (M.m^3)	1.55	0.45	0.22	83.16	48.95	7.42	30.28	72.82	19.34	4.28	5.09	0.93

TABLE B14 ADOPTED WADI BANA DAILY RUNOFF VOLUMES AT OLD BATEIS WEIR IN 1 000 m^3

Year: 1964

Day	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	2^r	3^r	1^r	272	7	93	13	2 424$^+$	853	461	68	195
2	2^r	2^r	1^r	1 103$^+$	6	67	10^r	4 724$^+$	2 155$^+$	145	90	403
3	2^r	2^r	1^r	464$^+$	5	56	9^r	1 592$^+$	1 307	533	91	48
4	2^r	2^r	1^r	9 691$^+$	5^r	44	167	2 201$^+$	904	200	74	38
5	1^r	2^r	1^r	8 313$^+$	4^r	26	56	1 903$^+$	2 811$^+$	508	54^r	24
6	1^r	2^r	1^r	2 194$^+$	4^r	64	145	3 025$^+$	2 988$^+$	565	39^r	13
7	87	2^r	1^r	271	4^r	61	103	3 246$^+$	1 661	599	30^r	13
8	73	2^r	1^r	180	3^r	49	103	1 891$^+$	1 665	263	22^r	9
9	53^r	2^r	1^r	123	3^r	43	81	2 314$^+$	1 105	239	17^r	52
10	39^r	2^r	1^r	86	3^r	31	74	1 388	541	205	99	73
11	29^r	2^r	1^r	74	3^r	18	68	908	911	894	101	65
12	22^r	2^r	1^r	58	3^r	5	58	816	580	476	125	62
13	16^r	2^r	1^r	50	3^r	4^r	47	744	593	284	106	62
14	12^r	2^r	1^r	36	2^r	4^r	47	614	674	186	111	69
15	11^r	1^r	1^r	29	14	4^r	139	816	1 457	148	99	73
16	10^r	1^r	0^r	22	9	361	145	874	442	147	53	73
17	9^r	1^r	0^r	13	8^r	938	568	1 189	390	134	31	73
18	8^r	1^r	0^r	11	7^r	815	1 177$^+$	3 878$^+$	395	133	108	73
19	7^r	1^r	0^r	10	7^r	93	1 048	1 690	316	128	108	107
20	7^r	1^r	0^r	13	6^r	195	4 022$^+$	4 052$^+$	266	108	74	107
21	6^r	1^r	0^r	13	5^r	601	6 003$^+$	4 640$^+$	601	108	54^r	449
22	5^r	1^r	0^r	11	5^r	284	3 749$^+$	2 607$^+$	4 736$^+$	131	39^r	675
23	5^r	1^r	0^r	7	4^r	167	9 753$^+$	1 488	978	131	30^r	146
24	4^r	1^r	0^r	69	4^r	128	5 450$^+$	1 713	751	99	22^r	167
25	4^r	1^r	0^r	100	690$^+$	82	6 114$^+$	2 226$^+$	594	99	17^r	142
26	3^r	1^r	0^r	69	318	70	2 134$^+$	2 371	484	86	12^r	131
27	3^r	1^r	0^r	16	1 931$^+$	57	2 051$^+$	1 729	375	74	11^r	127
28	3^r	1^r	0^r	7	1 183$^+$	48	7 564$^+$	1 614	1 840	74	10^r	88
29	3^r	1^r	0^r	29	478	47	1 482$^+$	2 310$^+$	544	11 288$^+$	9^r	62
30	3^r		0^r	13	182$^+$	30	1 978$^+$	1 506	603	355	8^r	62
31	3^r		0^r		118		3 188$^+$	3 024$^+$		275		55
Total ($M.m^3$)	0.44	0.04	0.02	23.35	5.02	4.48	57.55	65.52	33.52	19.08	1.71	3.74

TABLE B15 ADOPTED WADI BANA DAILY RUNOFF VOLUMES AT OLD BATEIS WEIR IN 1 000 m^3

Year: 1965

Day	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	65	36	18	37	113	2^r	10	480	3 498$^+$	87	190	285
2	62	36	18	37	103	2^r	17	262	2 965$^+$	87	190	200^r
3	73	36	18	119	91	2^r	48	388	784	73	190	140^r
4	37	32	16	79	77	2^r	69	738	651	73	190	98^r
5	194	31	16	180	65	2^r	43	1 279$^+$	854	73	101	71^r
6	259	31	14	180	84	2^r	208	794	624	40	66	52^r
7	259	25	14	180	34	2^r	865	364	503	36	579	38^r
8	211	22	9	180	15	2^r	625	792	449	36	400	28^r
9	98	22	13	180	7	2^r	622	688	367	36	348	21^r
10	259	22	10	180	6	2^r	744$^+$	404	329	36	122	16^r
11	198	22	10	884	13	1^r	887$^+$	513	276	36	58	12^r
12	73	22	9^r	1 250$^+$	12^r	1^r	983$^+$	927	270	36	125	11^r
13	73	22	8^r	1 008$^+$	11^r	1^r	1 169$^+$	582	215	48	112	9^r
14	73	22	7^r	321	9^r	1^r	1 621$^+$	438	209	35	290	9^r
15	73	33	7^r	68	9^r	1^r	2 058$^+$	390	242	22	259	8^r
16	73	33	6^r	616	8^r	1^r	2 754$^+$	1 942$^+$	328	35	259	7^r
17	73	22	5^r	670	7^r	1^r	975$^+$	1 693$^+$	215	36	259	6^r
18	73	18	5^r	3 521$^+$	6^r	1^r	342	4 901$^+$	209	22	259	6^r
19	73	17	4^r	851	6^r	1^r	182	2 469$^+$	185	155	272	5^r
20	73	17	4^r	886	5^r	23	633	1 103$^+$	135	207	285	5^r
21	57	17	3^r	368	5^r	38	586	538	105	207	285	4^r
22	52	17	3^r	224	4^r	25	452	502	109	207	285	4^r
23	62	13	3^r	260	4^r	15	271	1 687$^+$	100	207	285	3^r
24	57	11	3^r	1 155$^+$	3^r	11^r	973	4 824$^+$	348	190	285	3^r
25	57	11	3^r	8 416$^+$	3^r	10^r	902	2 182$^+$	410	190	285	3^r
26	57	11	3^r	2 592$^+$	3^r	9^r	354	3 750$^+$	436	190	285	3^r
27	48	18	3^r	1 241$^+$	3^r	8^r	256	2 758$^+$	125	190	285	3^r
28	44	21	2^r	629	3^r	7^r	196	3 096$^+$	119	190	285	3^r
29	21		2^r	208	3^r	7^r	199	3 354$^+$	348	190	285	3^r
30	32		2^r	148	2^r	6^r	257	3 571$^+$	99	190	285	2^r
31	36		2^r		2^r		342	1 321$^+$		190		2^r
Total ($M.m^3$)	2.90	0.64	0.24	26.57	0.72	0.19	19.64	48.73	15.51	3.35	7.40	1.06

TABLE B16 RATING TABLES

See Figure 3.1 for locations of gauging points and chapter 3 text for descriptions.

(a) Wadi Bana

Stage m	Discharge m^3/s	Stage m	Discharge m^3/s	Stage m	Discharge m^3/s
0	0.0	1.3	120	2.6	800 (700)
0.1	1.5	1.4	147	2.7	890 (755)
0.2	5	1.5	178	2.8	980 (805)
0.3	9	1.6	219	2.9	1 075 (855)
0.4	14	1.7	265	3.0	1 170 (905)
0.5	19	1.8	304	3.1	1 270 (957)
0.6	26	1.9	360	3.2	1 380 (1 010)
0.7	34	2.0	402	3.3	1 500 (1 062)
0.8	44	2.1	456	3.4	1 620 (1 114)
0.9	54	2.2	520 (500)	3.5	1 750 (1 166)
1.0	66	2.3	585 (550)	3.6	1 880 (1 220)
1.1	80	2.4	650 (596)		
1.2	98	2.5	725 (653)		

Flows in brackets are Abyan Board values where they differ from those adopted - see text of Chapter 3.

(b) Shakat ba Omer

Stage m	Discharge m^3/s	Stage m	Discharge m^3/s
0	0.0	0.5	1.80
0.1	0.25	0.6	2.40
0.2	0.40	0.7	3.50
0.3	0.70	0.8	4.90
0.4	1.30	0.9	6.30

Source: 1960 Abyan Board Working-up Book

TABLE B16 (Cont'd)

(c) Maincanal

Stage m	Discharge m^3/s	Stage m	Discharge m^3/s	Stage m	Discharge m^3/s
0	0.44	0.6	6.80	1.2	16.3
0.1	1.00	0.7	8.26	1.3	18.0
0.2	1.83	0.8	9.80	1.4	19.8
0.3	2.92	0.9	11.4	1.5	21.4
0.4	4.11	1.0	13.0	1.6	23.1
0.5	5.41	1.1	14.6		

Abyan Board rating is shown, for 5 gates open and central sill 0.30 m below the remainder

(d) Bateis canal

Stage m	Discharge m^3/s	Stage m	Discharge m^3/s	Stage m	Discharge m^3/s
0	0	0.4	2.68	0.8	8.60
0.1	0.25	0.5	3.96	0.9	10.5
0.2	0.85	0.6	5.40	1.0	12.7
0.3	1.65	0.7	6.88	1.1	15.0

Source: Abyan Board

(e) Massani canal

Stage m	Discharge m^3/s	Stage m	Discharge m^3/s
0	0.0	0.4	1.39
0.1	0.14	0.5	1.90
0.2	0.50	0.6	2.48
0.3	0.93	0.7	2.78

Source: 1960 Abyan Board working-up book.

TABLE B17 WADI BANA MISCELLANEOUS FLOW MEASUREMENTS

Location	Source	Date	Discharge m^3/s	Gauge height m
Bateis?	DAH (ref 1)	29. 6.71	5.68	0.275
Bateis?	"	5. 9.71	5.30	0.17
Ligma	"	1971	112	1.34*
Ligma	GDC (ref 4)	27. 9.79	5.71	-
Ligma	"	30.12.79	0.602	-

* inferred from Dar Al-Handasah's text as stage corresponding to 132 m^3/s on Abyan Board rating.