INSTITUTE OF HYDROLOGY

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SUDAN

New Halfa rehabilitation scheme

ANNEX 2 Water resources

A report on the present and future
availability of water for irrigation
and power in Khashm el Girba reservoir.

Prepared for Agrar und Hydrotechnik
by the
Institute of Hydrology,
Wallingford, UK.

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Ministry of Irrigation and Hydroelectric Power

Department of Nile Waters (Khartoum)
- Director, Kamal Ali Mohammed
- Engineer, Mohammed Nur Ahmed

Department of river gauging
- Ibrahim Elmansouri

Department of Dams (Khartoum)
- Director, Abbas Hidayfallah
- Resident engineer (Sennar), Ahmed Elfatih Saad

Department of Dams (Khashm el Girba)
- Resident engineer, Dasougi Ahmed Hashim

Department of Irrigation Services
- Deputy Director (Khashm el Girba), Abu Elgasim Elamil
- Divisional Engineer (New Halfa), Abdalaziz Elmubarak

Meteorological Department

- Director, Fadlallah Khidir
- Assistant, Kh. I. Khalil

Public Electricity and Water supply Corporation

- Engineer, Siddig Hassan Abu Gedairi

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SUMMARY

In assessing the availability of water for irrigation and power from Khashm el Girba reservoir, all hydrological records on the Atbara in Sudan have been examined together with selected data on rainfall, evaporation and sediment concentration. All available reports from the Ministry of Irrigation and from the French consulting firm of Sogreah have also been studied.

It was decided to carry out reservoir simulation studies with 50 years of flow data to assign probabilities to various degrees of irrigation shortfall. The two main tributaries of the Atbara (the Setit and Upper Atbara) are gauged just above their confluence at Showak near the head of the reservoir. 21 years of record were made available by the Ministry of Irrigation and by correlation with flows at the Lower Atbara station (at K3), where there are records from 1905, a stochastic model of the tributary flows was derived. The model was used to generate 50 year sequences of synthetic 10 day flows.

Estimates of average rainfall and evaporation were based on data provided by the Sudan Meteorolgoical Department and were used in conjunction with the tributary flows as basic data for the reservoir simulation program. Table S.1 summarises the hydrology of the Atbara catchment and Khashm el Girba reservoir and shows that a small proportion of the runoff if stored and used for irrigation and power.

As the sediment concentration of the runoff from the Atbara catchment is high, the low ratio of storage to inflow has resulted in rapid siltation of the reservoir. To minimize the effect, the water level in the reservoir is lowered to 462 m at the start of the flood season, thereby confining sediment deposition to the central channel through the reservoir. The reservoir is also drawn down to bed level two or three times during the flood season with the aim of flushing sediment deposits through the bottom gates of the dam. Refilling to the maximum operating level of 473 m is started after the peak of the sediment load has passed and as late in the season as is compatible with the need to complete the filling with the remaining inflow.

The rate of siltation was assessed from estimates made during the first twelve years of reservoir operation. During this time the available storage volume was decreased from 1.3 to .78 milliard m^3. From a model of sediment inflow and deposition and making a pessimistic estimate of the amount to be removed by flushing, it is estimated that the

Table S.1

Summary of hydrological statistics
(annual averages)

Catchment :	Setit	Upper Atbara
Area, km^2	70,800	29,600
Rainfall, mm	1,104	844
Runoff, mm	103	170
Percentage runoff	9	20

Reservoir :	milliard m^3	
Total runoff	12.32	
Rain on reservoir	.05	12.37
Evaporation from reservoir	.20	
Water diverted to canal (1972-77)	1.38	
Water released through Kaplan	.25	
Spillage	10.54	12.37
Available storage (1964)	1.30	
Available storage (1976)	.78	

storage could decline further to .66 milliard m^3 by 1982 and to .5 milliard m^3 by about 1997.

However, calculations of storage based on the water balance reveal some discrepancies in the data. The actual rate of storage loss should be calculated from the difference between accurate estimates of sediment volume stored in the reservoir made at two or three year intervals. To date, there has been only one bathymetric survey, in 1976, and a further survey is needed soon. Meanwhile the estimates, given above, of the dates when the storage is likely to have fallen to .66 and .5 milliard m^3 must be regarded as approximate and provisional.

The question of accuracy of the inflow and outflow data is also raised by these studies and it is recommended that the hydrometric data are investigated in greater depth than has previously been possible.

By studying the typical recession curve of inflows, rules were devised for choosing the date of raising the reservoir level to 473 m and for rationing of irrigation releases. At any time after 1 September, it is possible to estimate the future expectations in terms of the current inflow rate and the available storage. These may be compared with the future requirements for irrigation and the evaporation from the reservoir surface. If expectations are less than requirements, rationing is required; if they are greater, the surplus can be used to generate power through the Kaplan turbine. On this basis the statistics of irrigation supply efficiency and power production can be estimated.

The reservoir simulation studies, using 50 years of data and three alternative irrigation demand patterns (the original planned pattern, the average recorded pattern of the past 5 years and the proposed pattern), were carried out at storage states of .78, .66 and .5 milliard m^3.

For the proposed cropping pattern, it is estimated that average annual irrigation supply efficiency (the ratio of water supplied to water required) changes from 98 percent in the present storage state to 94.4 percent when the storage is reduced to .66 milliard m^3 and to 88 percent when it is .5 milliard m^3. Raising the top operating level to 473.5 m increases these figures by about 1.5 percent.

By using the 50 year record, it is possible to study the range of irrigation supply which naturally varies according to the inflow in the critical period from November to June. When storage is .66 milliard m^3, for example, an irrigation supply of 90 percent or better would be achieved with 84 percent reliability. This is equivalent to an irrigation supply during the November-June period of 83 percent or better. In other words, there would probably be a 16 percent chance by 1982 that rationing in excess of 17 percent will be required during the wheat growing season.

This emphasis on shortages during the wheat growing season can be given even more force if all of the rationing is assumed to apply solely to the wheat crop rather than shared with the sugarcane, forests, etc. The 17 percent rationing requirement mentioned above then becomes a 58 percent reduction in the water available to the wheat. With 80 percent reliability (the wheat irrigation demand to be met in four years out of five) the corresponding reductions are 15 percent in the 1976 storage state, 56 percent when the storage has fallen to .66 milliard m^3 and 93 percent when it has reached .5 milliard m^3. In other words, by 1997 or thereabouts, it is estimated that only 7 percent of the planned wheat crop could be irrigated with the usual 80 percent reliability. The extra storage which could be achieved by raising the dam .5 m would increase this to 15 percent approximately. The effect of raising the dam would be equivalent to a delay of between three and five years in reaching a given state of reduced water availability.

Assuming that the pump turbines are working to design specifications, they would produce an average 12 Gwh/year in the storage state forecast for 1982. The Kaplans would produce 14.1 Gwh, but of this, 9.4 Gwh would be required for pumping to the main canal when the reservoir is drawn down. Despite a net surplus of energy over the year, the installed capacity is insufficient to meet even the local peak demand and diesel generators are used when the irrigation demand is high and the reservoir is low; they are also needed to supplement the electrical baseload of the local grid system, since the hydro-electric power is unreliable for the whole of the year.

A graphical method of predicting the date for raising reservoir level and the possible need for rationing is presented in Annex 2.

Recommendations for further work include an investigation of the basic hydrometric data as mentioned above, a repeat bathymetric survey of the reservoir, a closer study of various evaporation estimates, and a possible extension to the proposal that one or two reservoirs are constructed upstream.

1. Introduction

The water resources development of the Atbara has been studied by the Ministry of Irrigation for a number of years. Since the construction of the Khashm el Girba reservoir (originally designed to store only one tenth of the average annual yield) the studies have been concerned primarily with proposals for further dams on the upstream tributaries and with the rate of siltation in the existing reservoir. Sogreah has produced many reports on these topics and on other matters concerned with the operation and maintenance of equipment at the dam; several of these reports, (1), (2), (3), (4), were made available to the Institute by the Ministry of Irrigation. In 1976 , a sediment survey of the reservoir was conducted and although the report itself was unavailable, a set of preliminary graphs and diagrams was supplied.

The Institute's programme of work has been designed to supplement the previous work, and has therefore included a different approach to some of the calculations and key predictions in the Sogreah reports. It is clear that sedimentation in Khashm el Girba reservoir is continuing at a rate which suggests that upstream regulation will be required within 10-20 years if the rationing of irrigation water to the New Halfa scheme is to stay within acceptable limits. Although it has been necessary to concentrate on the single reservoir case at this stage, preliminary discussions have been held with Sogreah and it is possible to offer broad agreement with the Sogreah proposals, as they relate to the Rumela and Burdana reservoirs.

Chapter 2 of this report is concerned with river flow data and Chapter 3 with rainfall and evaporation.

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1) SOGREAH, R11728. Upper Atbara Project, Preliminary Studies. Report on Comparative Studies on the Burdana and Rumela Dam Sites. February, 1974.
2) SOGREAH, R12040. Upper Atbara Project, Preliminary design report on the siltation control, sizing and operation of the finally selected Rumela-Burdana reservoirs, for power generation and irrigation in conjunction with Khashm el Girba reservoir protection. December, 1974.
3) SOGREAH, R12534. Upper Atbara Project, Report giving the setting-out of canal headreaches. May, 1976.
4) SOGREAH, R11835. Upper Atbara Project, Preliminary Studies. Report on siltation of Khashm el Girba Reservoir. April, 1974.

Sedimentation in Khashm el Girba reservoir is discussed in Chapter 4 and power generation in Chapter 5. Irrigation demand is the subject of Chapter 6 but this is covered more extensively in Annex 3. The reservoir simulation studies used to establish data on irrigation and power reliability are described in Chapter 7 and the results discussed in Chapter 8. Chapter 9 brings together recommendations for further studies.

2. River flow data

The Atbara is gauged at three locations on the main river and on each of the two main tributaries, the Upper Atbara and the Setit. The location of gauging stations is shown in Figure 1 and the records from each station are briefly described in this chapter.

2.1 Atbara at K3

The lowest gauging station on the Atbara, known as K3, is three kilometres from the junction with the Nile and is sometimes affected by backwater from the larger river. Gauge readings and discharge measurements are available from 1905 and 10-day average flows have been published up to 1967 (5). For recent years, 10-day flows have been derived from the basic data supplied by the Ministry of Irrigation. This was done with confidence only up to 1973 since current meter measurements in recent years have been rather few and inconsistent. The 10-day flows from January 1968 to December 1973 as calculated by the Institute are listed in Appendix A, Table A.1.

2.2 Atbara at Khashm el Girba

Gauge readings are available from 1905 and discharge measurements from 1962. The stage-discharge relationship developed during the 1962-73 period has apparently been used to calculate 10-day flows for the earlier years (6) but there is some doubt as to the confidence with which this record is regarded. According to the Ministry of Irrigation, Khashm el Girba flows have also been estimated from the station at K3 by adding a 5 percent 'transmission loss'. Since 1964 the measured discharges have been influenced by reservoir operation. Correction for storage effects and abstraction would be needed to derive a natural flow record.

We consider that the long term record at Khashm el Girba is less reliable and therefore less useful than that at K3 and it has not been used in this report.

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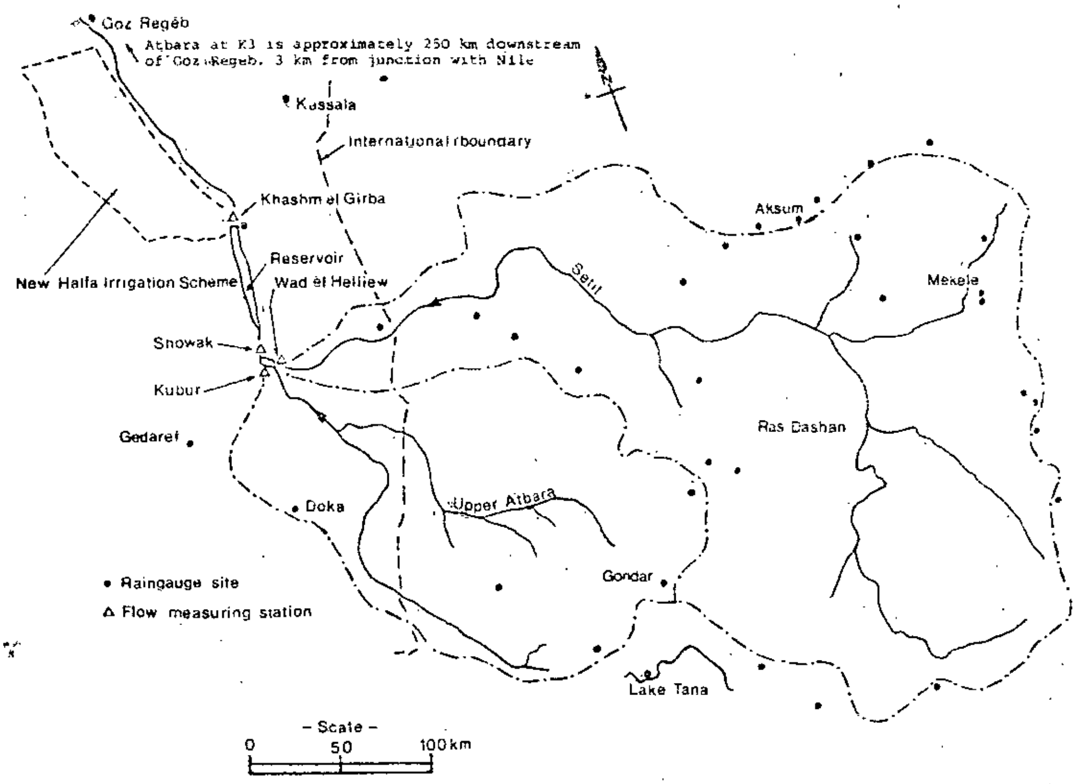
5) CAIRO, The Nile Basin, Vol. IV and supplements. 'Ten-day mean discharges of the Nile and its tributaries'. Government Press, 1933 to 1967.

6) MINISTRY OF IRRIGATION. Preliminary survey of land and water resources, Upper Atbara. April, 1973.

ANNEX 2
FIGURE 1

Map showing gauging stations



Atbara at K3 is approximately 250 km downstream of Goz Regeb. 3 km from junction with Nile

2.3 Atbara at Showak

Showak is a few kilometres downstream of the confluence between the two main tributaries, the Upper Atbara and the Setit. Gauge readings began in 1937 and discharge measurements in 1962. Backwater from the reservoir affects the stage discharge relationship for several months each year and causes changes in the sandbed control. 10-day flows are available but they have not been used in this report.

2.4 Upper Atbara

The Upper Atbara has gauge records from 1956 at Abu Reida which was found to be a poor site for discharge measurement and Kubur station was established further upstream in 1966. Flow measurement was initially confined to low flows but cableway construction in 1973 has enabled the development of a full range rating curve. This stage discharge relationship is understood to be stable and regularly checked but, although a request was made for access to the internal Ministry papers which describe the quality of the data and its processing (1), no further information was provided and no indication can be given of the likely accuracy of the 10-day flows.

A correlation between levels at Kubur and Abu Reida was developed from the period of overlapping record (1966-69) and used to calculate discharges back to 1956. Again, no details are available and the consequent and inevitable increase in error associated with these earlier data cannot be estimated.

The 10-day mean flows are listed in Appendix A, Table A.2. They have been taken from (1) for the period 1956-73 and were provided by the Ministry of Irrigation for 1974-77. The data for certain months from 1964/5 were provided by the Ministry through Sir Alexander Gibb & Partners.

2.5 Setit

Gauging history on the Setit parallels that on the Upper Atbara. Wad el Helliew is now the main site with a cableway for discharge measurement and records exist from 1966. Setit village is the site of an earlier record of levels dating from 1956. Estimates of 10-day flows are given in Appendix A, Table A.2, and were obtained from the same sources as given above for the Upper Atbara.

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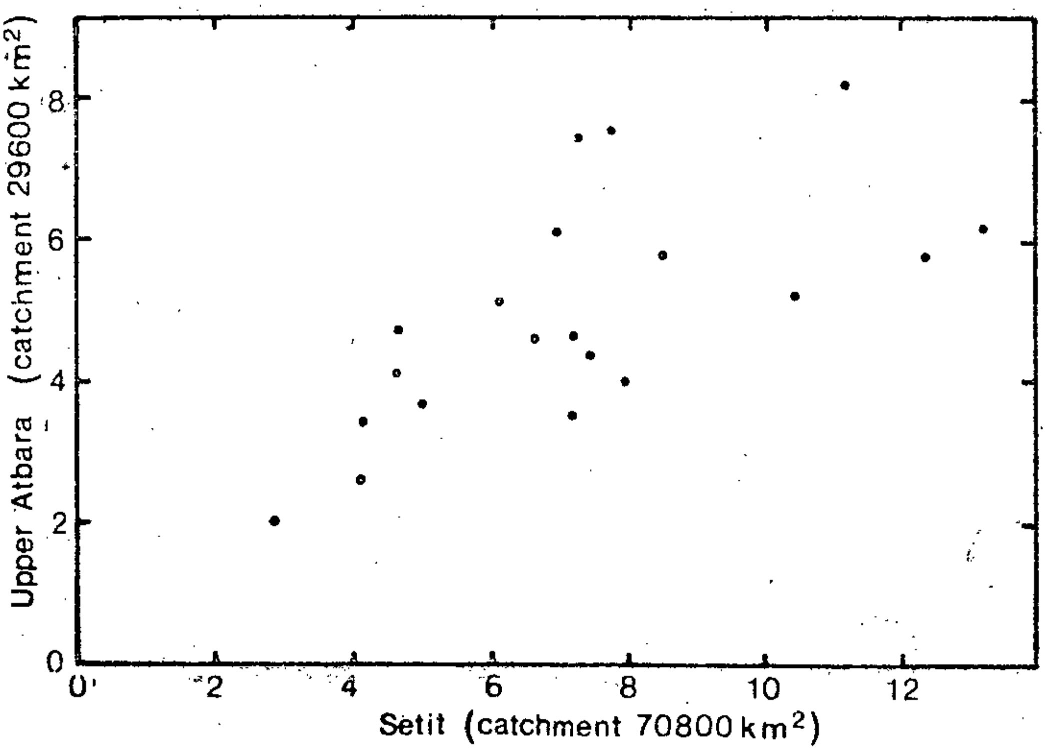
1) SOGREAH, op.cit. Chapter 7.

ANNEX 2
FIGURE 2

Correlation of annual runoff volumes
between the Upper Atbara and the Setit
(milliards m^3)



2.6 Comparison of tributary yields

Runoff producing rainfall in the drier parts of the African tropics is rarely widespread and the shape of the annual hydrograph on large catchments is determined by the amalgamation of many different tributary flood hydrographs arising from separate storms each covering only part of the catchment. It is not surprising therefore that there is little correlation between 10-day flows from adjacent catchments. When annual runoff totals are compared, the correlation should improve because it will reflect the occurrence of a generally wet or dry year over a large region, (Figure 2).

The most surprising aspect of the tributary flows concerns their average yields over the period of record. The Upper Atbara has an average yield of 5.03 milliard m^3 which is equivalent to 170 mm over its 29,600 km^2 catchment area; this is 20 percent of its mean annual rainfall of 844 mm (c.f. Figure 4). In contrast, the Setit has an average yield of 7.29 milliard m^3 which is equivalent to 103 mm over its 70,800 km^2 catchment area; this is 9 percent of its mean annual rainfall of 1,104 mm. This difference in percentage runoff is rather large and difficult to explain particularly in view of the fact that the Setit catchment seems generally steeper and has fewer trees.

2.7 Data 'rehabilitation' by Sogreah

Sogreah (1) give tables of 'rehabilitated' discharge data in addition to the data received from the Ministry of Irrigation. Their modifications ensured that the two tributary flows summed to equal Khashm el Girba flows in each 10-day period but no details are given as to the method of adjusting the individual records. In the present report, only data obtained directly or indirectly from the Ministry of Irrigation have been used.

2.8 Data extension

The data to be used in the reservoir operation studies described in Chapter 7 are the two sets of tributary inflows. We have adopted a form of sequential analysis whereby long sequences of data are input to a computer model of the system. The statistics of the output can

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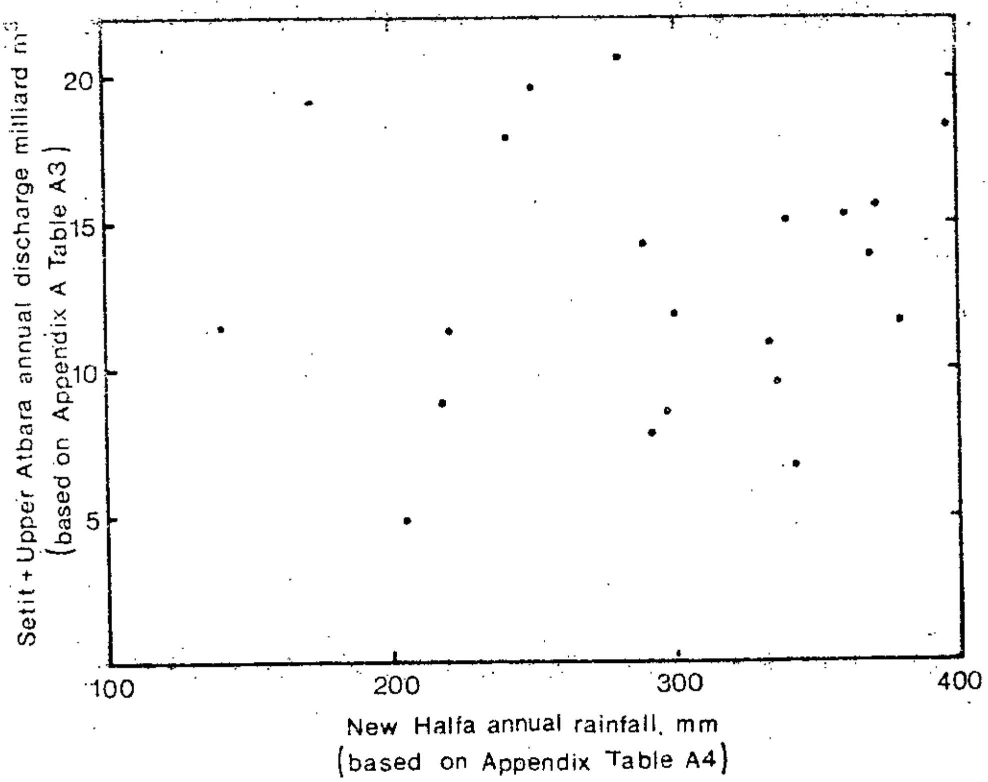
1) SOGREAH, op.cit. R11728

ANNEX 2
FIGURE 3

Khashm el Girba inflows compared with New Halfa rainfall



then be estimated directly. This procedure avoids the prior definition of representative years and offers a more reliable assessment of the effects of changing the reservoir operating strategy.

While there are 21 years of actual record available for the tributaries, it is preferable to use a longer record in reservoir operation studies as it is not only necessary that the 'lumped' sample statistics (mean and standard deviations) should be good estimates of their long term values but also that the variety of possible flow sequences should be well sampled. In other studies of the Nile basin it is becoming accepted that 50 years of data are a suitable basis for analysis and so the K3 record has been used to extend the tributary flows backwards in time. When extending a record in this way it is necessary to preserve the variance unexplained by the relationship between the long and short period stations, the cross correlation between the two short period stations and the serial correlation between one 10-day flow and the next. Details of the data extension model are given in Appendix B.

3. Rainfall and evaporation

3.1 Use of monthly average data

This chapter concerns data on rainfall and evaporation as they relate to gain and loss from storage in the reservoirs. In both cases, it is intended to use average monthly figures rather than estimate the actual or synthetic values in each of the 50 years to be used in reservoir operation studies. Evaporation in a particular month does not vary much from one year to another and this is particuarly true in Sudan. Rainfall is naturally more variable but most of it occurs at a time when the reservoirs are spilling the annual flood and that which falls in November, April, May or early June and which has some theoretical benefit to storage is so little that the error induced by ignoring its annual variation is well within the range of error associated with storage estimation. Of course, the use of average values must reduce the range of annual totals of available water but the effect may be dismissed as trivial. As shown in Figure 3, there is little correlation between local rainfall and reservoir inflows and therefore no danger of consistently overestimating rainfall when inflows are low.

The discussion in 6.1 on the use of average crop water requirements is also relevant.

3.2 Evaporation

In estimating open water surface evaporation, Sogreah (1) used data from Piche evaporimeters and regional ratios relating Piche data to Penman estimates. They used data from New Halfa for Khashm el Girba and from Showak for the proposed Burdana and Rumela reservoirs. At the time when these estimates were made (1973) data from the Class A evaporation pans at both New Halfa and Showak were available for a few months only and were not used. The Sogreah estimate of annual evaporation at New Halfa was 2,012 mm and it is now possible to compare this with the pan figure of 4,290 mm and the Penman estimates derived from recent New Halfa data (Appendix A, Table A.3) which suggest an annual total slightly over 2900 mm. The latter two figures are compatible in that derived pan coefficients for various months are, as expected, in the range 0.6-0.7. Additional support for the newer and higher figure comes from the Blue Nile Study (7) where average (1941-70) Penman open water evaporation is quoted as 2,740 mm for the Northern Zone (Khartoum to Wad Medani). On the other hand, Adam and Farbrother (8) give Penman data for Gedaref (100 km to the south-west of the reservoir) which suggests an annual total of only 2,470 mm.

In deriving estimates of the long term average monthly evaporation from the reservoir we have taken account of the year to year variation indicated by the pan data and adjusted the Penman estimates derived in Appendix A. These adjusted figures, giving an annual total of 2,880 mm, are shown in the third row of Table 1.

Pan evaporation is 10 percent higher at Showak than New Halfa but, due to lack of wind data, it is not possible to check this with Penman calculations. Until these data are available, it will be assumed that the New Halfa estimates apply to all three reservoirs.

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1) SOGREAH, op.cit. R11728

7) BLUE NILE STUDY CONSULTANTS. Blue Nile Waters Study. September, 1977.

8) ADAM H.S. and FARBROTHER H.G. 'Crop water use in irrigated and rainfall agriculture in Sudan'. Technical Notes on Water Use, No. 12. Agricultural Research Corporation, Ministry of Agriculture. July, 1976.

Table 1

Average monthly evaporation totals
(mm)

	J	F	M	A	M	J	J	A	S	O	N	D	Year
Showak, pan	362	409	557	545	560	385	300	229	252	313	355	366	4633
New Halfa pan	273	314	415	467	508	477	356	282	294	322	312	270	4290
New Halfa Penman	190	216	285	297	307	299	250	197	206	226	213	189	2880

3.3 Rainfall

Monthly rainfall data for 1941-77 were obtained from the Sudan Meteorological Department for the stations at Khashm el Girba (moved to New Halfa in 1970), Showak (Appendix A, Table A.3), Kassala, Doka, and Goz Regeb (see Figure 1). Data from other stations in the catchment area are available at the British Meteorological Office, Bracknell. Preliminary studies relating monthly and annual rainfall at Gondar to Atbara runoff gave disappointing results; clearly a large number of raingauges would be needed to reflect the highly variable rainfall over the catchment. There are other gauges (Figure 1) and much data at Bracknell but, as flow in the Atbara river has been gauged for longer than rainfall anywhere in the catchment, the study of rainfall/runoff relationships is of limited direct interest. Figure 4, showing annual average rainfall isohyets over the catchment, was used to compute average annual runoff percentages as already discussed in 2.6.

Average (1941-70) monthly rainfalls at Khashm el Girba and Showak are shown in Table 2. It is suggested that the mean of the two should be used for Khashm el Girba reservoir and that Showak should be used for the Upper Atbara.

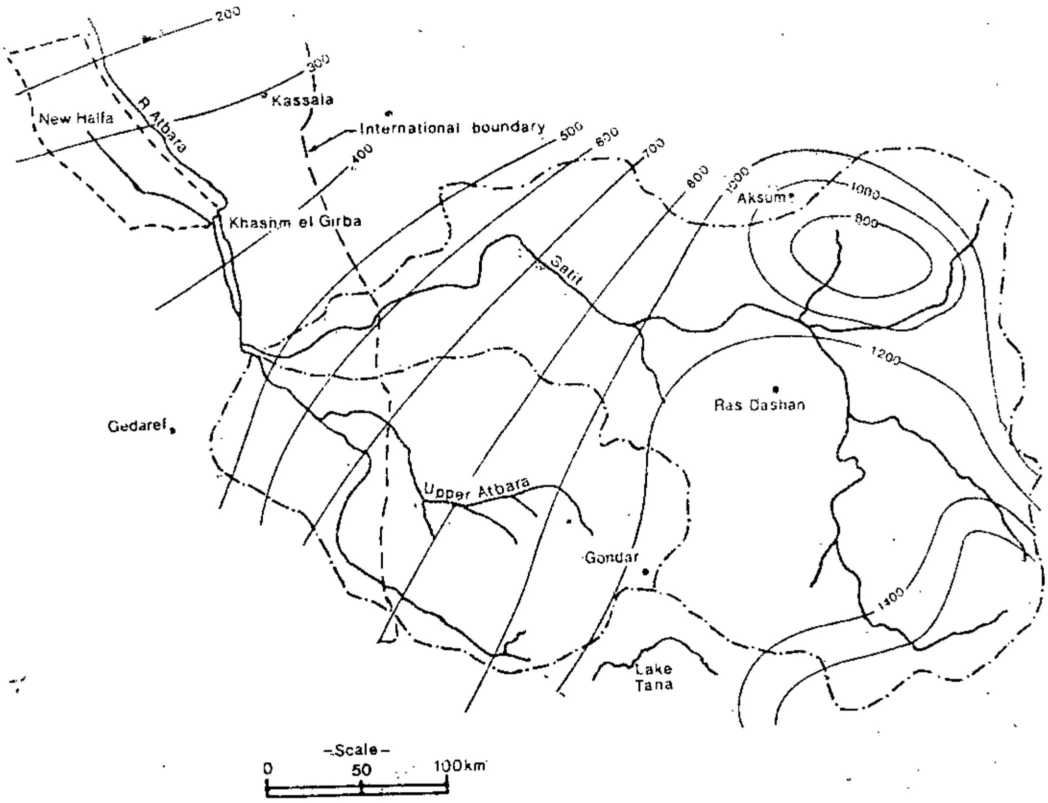
Table 2

Average monthly rainfall
(mm)

	J	F	M	A	M	J	J	A	S	O	N	D
Khashm el Girba:	-	-	-	2	11	25	118	133	60	9	-	-
Showak :	-	-	-	-	14	57	148	178	66	11	2	-
Mean :	-	-	-	1	12	41	133	156	63	10	1	-

ANNEX 2
FIGURE 4

Annual average isohyets over catchment area



3.4 Net evaporation

The monthly evaporation (Table 1) may be reduced by the average rainfall to give values of net evaporation for use in the reservoir operation studies; these are shown in Table 3.

Table 3

Average monthly net evaporation from reservoirs
(mm)

	J	F	M	A	M	J	J	A	S	O	N	D
Khashm el Girba :	190	216	285	296	295	258	117	41	143	216	217	189
Upper Atbara :	190	216	285	297	293	242	102	19	140	215	216	189

4. Progressive sedimentation of Khashm el Girba reservoir

This chapter reviews the evidence for the rate of sediment inflow and deposition in the reservoir. A forecast is made of future changes in the volume of available storage.

4.1 Past and present sedimentation

It had always been appreciated that a reservoir which could store as little as one tenth of its annual inflow from a catchment draining tropical highlands would be bound to have a sediment problem. From the beginning (1964), it was decided to pass as much as possible of the annual flood through the reservoir at a low level (462 m), thus minimising high level deposition and decreasing retention time. The reservoir is raised to its normal operating level as late in the season as will subsequently enable it to fill; this is normally after the peak of the sediment inflow has passed. The sediment peak usually occurs on the rising limb of the flow hydrograph, probably sometime in July; reservoir level is usually raised in September.

Despite these measures, sedimentation has progressed somewhat faster than anticipated and flushing by drawdown to bed level, begun in 1971, is now a regular feature of reservoir operation during the flood season (2) (3). By this means,

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2) SOGREAH, op.cit. R11835
3) SOGREAH, op.cit. R12040

ANNEX 2
FIGURE 5

Storage level curves, 1964-1976

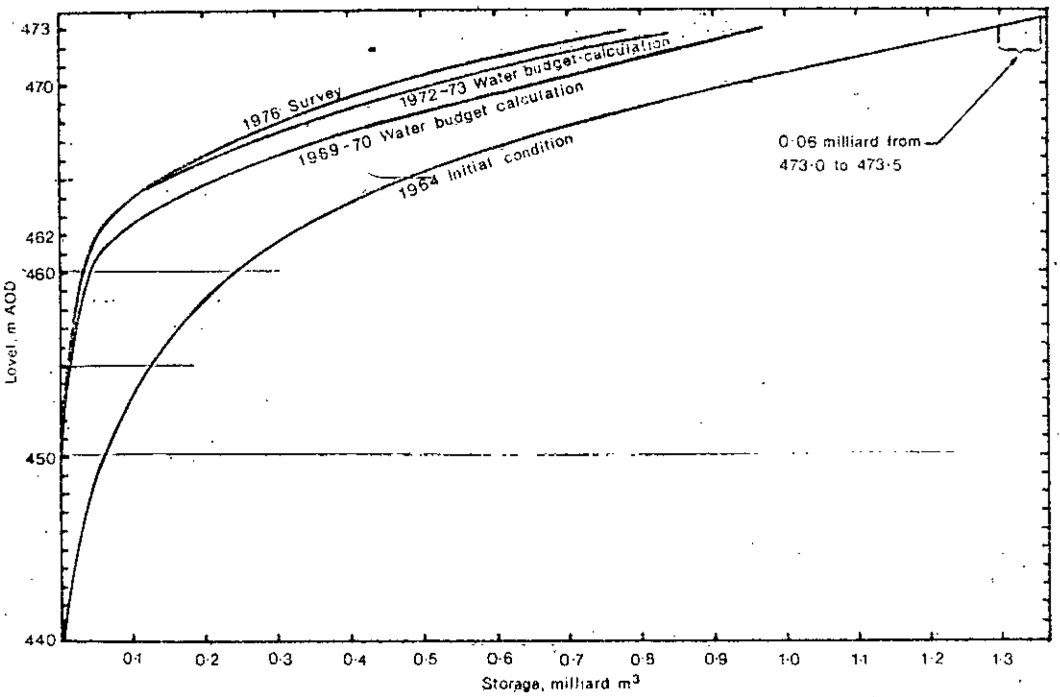
'93

.43

.24

.125

.06



deposition near the dam is avoided as is sediment entry into the power station and pump-turbine intakes. To minimise the inconvenience to those relying on canal flows, which must cease when the reservoir is emptied, flushing is done in several short duration lowerings rather than a single protracted operation.

The volume of storage remaining in the reservoir at various levels may be estimated by water budget calculations or from aerial photographs. Such estimates were made in 1969-70 and 1972-73. An echo-sounder survey was carried out in 1976 and provided the first direct measurement of storage. Figure 5 (based on data given in (2)) shows the storage/level curves at the various dates. By 1976, the original total storage of 1,300 million m^3 was 40 percent occupied by sediment, only 780 million m^3 remaining.

4.2 Sediment inflow to and deposition in the reservoir

Measurements of sediment concentration have been made on the main Atbara river in 1954 and 1959 and on the two main tributaries in 1973. These data (2) are inadequate for confident prediction of average sediment inflow, but together with measurements made on the Blue Nile (7) which has a similar type of catchment, climate, and runoff distribution, it may be estimated that concentrations in the Atbara are at a peak in July or August of about 10 kg/m^3. The aim of this section is to test whether these varied measurements and assumptions are broadly compatible with the recorded history of deposition; the calculations are listed in Table 4 for three periods each of six years.

The mean monthly inflow volumes (ie, Upper Atbara, plus Setit) for the periods 1964-69 and 1970-75 are derived from Appendix A, Table A.2; their mean is taken to apply to the period 1976-81.

The average monthly sediment concentration in kg/m^3 is assumed to reduce from 10 in July and August to 3 in September and 1 in October; this is broadly in line with observed trends.

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2) SOGREAH, op.cit. R12040, Appendix A3
7) BLUE NILE STUDY CONSULTANTS, op.cit.

Table 4

Sediment deposition calculations

	1964-69					1970-75					1976-81				
	Jul	Aug	Sep	Oct	Years	Jul	Aug	Sep	Oct	Years	Jul	Aug	Sep	Oct	Years
1.	2285	5033	2178	527		1949	5838	3263	754		2117	5435	2720	640	
2.	10	10	3	1		10	10	3	1		10	10	3	1	
3.	22850	50330	6534	527		19490	58380	9789	754		21170	54350	8160	640	
4.	30	30	30	30		30	30	30	30		30	30	30	30	
5.	6855	15099	1960	158		5487	17514	2937	226		6351	16305	2448	192	
6.	4.57	10.07	1.31	0.11		3.90	11.68	1.96	0.15		4.23	10.87	1.63	0.13	
7.	200	200	850	1100		60	60	445	830		50	50	395	740	
8.		2.4		70.0			0.64		35.0			0.56		37.0	
9.	70	70	84	98		30	30	63	96		25	25	61	96	
10.	11197	24662	3842	362		4093	12260	4317	507		3705	9511	3484	430	
11.	9.95	21.92	3.42	0.32		3.64	10.90	3.84	0.45		3.29	8.46	3.10	0.38	
12.	14.52	31.99	4.73	0.43	310	7.54	22.58	5.80	0.60	219	7.52	19.33	4.73	0.51	192
13.					-					50					60
14.					310					169					132
15.					310					479					611
16.					990					821					689
17.					980					778					...

Continued.....

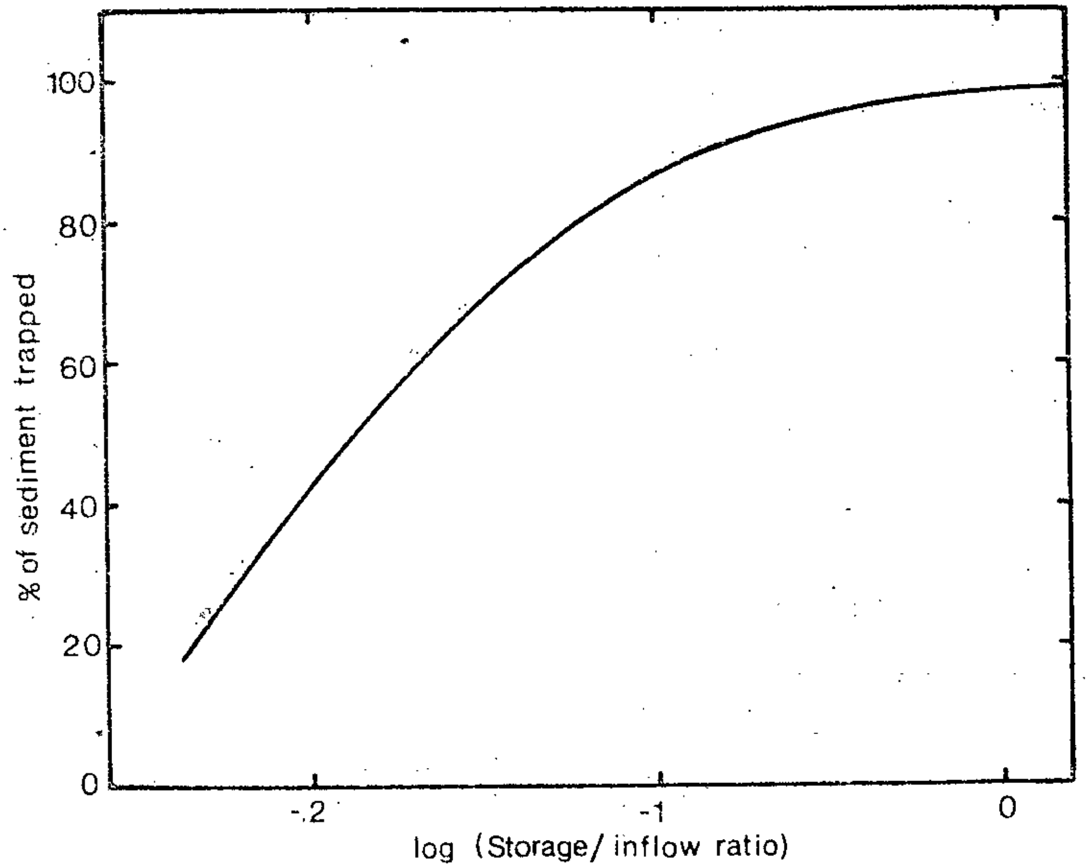
Table 4 (Continued)

Sediment deposition calculations

Row	
1.	Average monthly inflow, million m^3
2.	Sediment concentration, kg/m^3
3.	Weight of sediment, million kg
4.	Percentage sand
5.	Weight of sand, million kg
6.	Deposited volume of sand, million m^3
7.	Available storage, million m^3
8.	Storage/inflow ratio, percentage
9.	Trap efficiency, percentage
10.	Weight of fine sediment deposited, million kg
11	Volume of fine sediment deposited, million m^3
12.	Total volume deposited (Row 6 + Row 11), million m^3
13.	Volume removed by flushing in 6 years, million m^3
14.	Net sediment in 6 years, million m^3
15.	Accumulated sediment, million m^3
16.	Storage remaining at end of period, million m^3
17.	Storage remaining according to Figure 5

ANNEX 2
FIGURE 6

Assumed relationship of trap efficiency with ratio of storage to inflow, Khashm el Girba



The percentage of sand in the total sediment was estimated as 52 percent (1954), 17 percent (1959) and 30 percent on the Blue Nile in 1969 (7). An average value of 30 percent is assumed (Row 4 in Table 4) to represent a bedload on entry to the reservoir and this load is therefore retained at a density of 1,500 kg/m^3. The remaining 70 percent of the sediment is assumed to be held in suspension. The proportion which will settle out depends mainly on retention time which in turn is related to the ratio of storage volume to inflow. This proportion is known as the trap efficiency of the reservoir and its dependence on the storage/inflow ratio has been represented by empirical curves in a number of investigations. The curve shown in Figure 6 is based on the study by Brune (9). The storage/inflow ratio changes with time due to sedimentation and also varies seasonally with reservoir operating level. For this analysis, high level operation is assumed to start in mid-September. Trap efficiency estimates are shown as Row 9 of Table 4.

A density of 1,125 kg/m^3 is assumed in calculating the volume of finer sediment deposits; there will be some compaction with time but this is ignored.

The total volume deposited in each six year period is reduced by flushing. This was zero in the first period. Sogreah (3) estimated that 17.5 million m^3 was removed in 1971 and 12.5 million m^3 in 1973. It is assumed that, since 1974, 10 million m^3 is being removed each year and that this will continue. The total amount removed is therefore estimated at 50 million m^3 for 1970-75 and 60 million m^3 for 1976-81.

Table 4 finally yields (Row 16) the net encroachment on total storage in the three six year periods and the first two of these may be compared with the actual storage losses estimated directly from reservoir studies or surveys (Row 17). This comparison is encouraging and provides a realistic basis for estimates of the likely growth of sediment deposits

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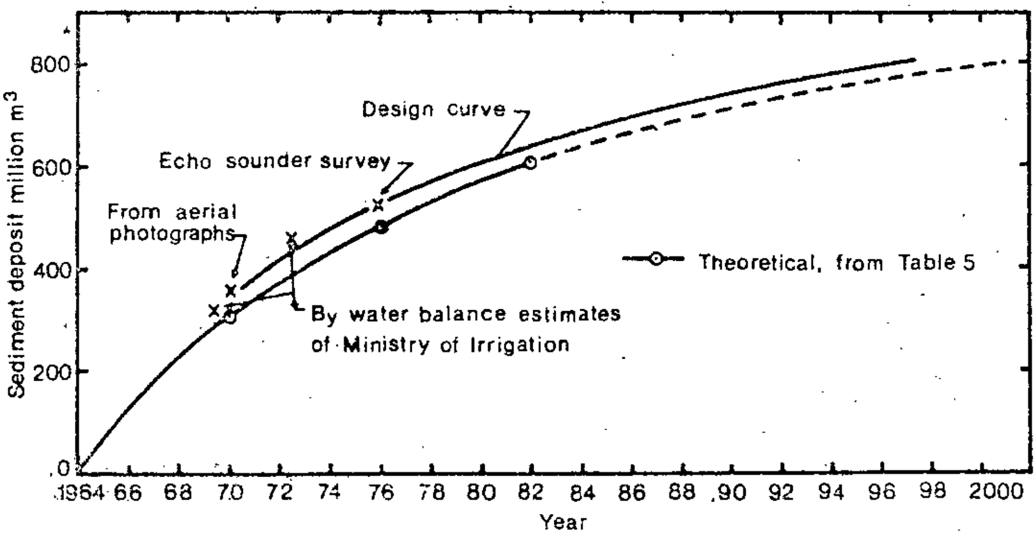
7) BLUE NILE STUDY CONSULTANTS, op.cit.
9) BRUNE G.M. 'Trap efficiency of reservoirs'. Transactions of the American Geophysical Union. Vol. 34, No. 3, Washington D.C., 1953, pp 407-418.
3) SOGREAH, op.cit.

ANNEX 2
FIGURE 7

Change in total sediment volume with time, Khashm el Girba



with time shown in Figure 7.. Beyond 1982 the extrapolation is, of course, very approximate but it is estimated that sediment volume in the reservoir will reach 800 million m^3 leaving a storage volume of 500 million m^3 between the years 1995 and 2000.

It must be emphasised that the calculations presented in Table 4 are approximate involving many assumptions and empirical results from elsewhere. While the form of the curve derived here supports the design curve in Figure 7, the forecast of the future level of sedimentation depends largely on the observed deposition during the first twelve years and such forecasts should be revised only in the light of accurate survey data. Thus it is recommended that the bathymetric survey should be repeated every two or three years.

4.3 A check on storage capacity

With Ministry of Irrigation data on inflows, outflows and reservoir levels (Appendix A, Tables A.2, A.5, and A.6) it is possible to check the storage/level curves of Figure 5. The period of emptying in the last five years was identified from the record of levels and equivalent storages were estimated by interpolation between the 1972-73 and 1976 storage curves. Evaporation losses were estimated from the evaporation rates given in Table 1 and the reservoir surface area.

Rainfall is virtually zero in the emptying period, November or December to June, and there is little possibility of any measurable inflow joining the main Atbara below the upstream gauging stations. There are a few khors joining in this reach but they have relatively small catchments and would flow only intermittently during the rainy season.

The calculations are shown in Table 5 and the results summarised in Figure 8. Agreement is fair in the earlier years but this is not so surprising as the storage curve for 1972-73 was based on a similar study. In 1976-77 however, the storage change calculated from outflow minus inflow is 30 percent greater than that calculated from change of level according to the 1976, survey-based, storage curve. There seems to be either more inflow, less outflow or more available storage than indicated by present measurements and/or assumptions. As indicated in 2.4, it was not possible to study the details of flow computations so no opinion can be offered on the cause of the discrepancy. It remains a serious cause for concern that, in the year in which the first actual survey of sediment was conducted,

ANNEX 2
FIGURE 8

Change in storage during drawdown period, Khashm el Girba, 1972-77. milliards m^3

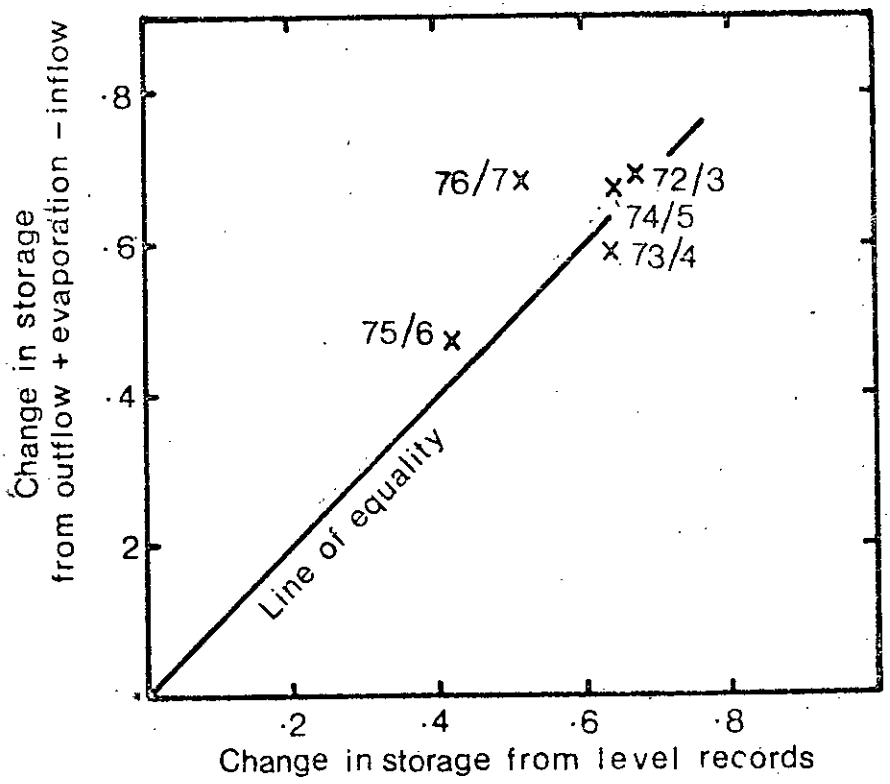


Table 5

Storage calculations
(All flows are volume totals in million m^3)

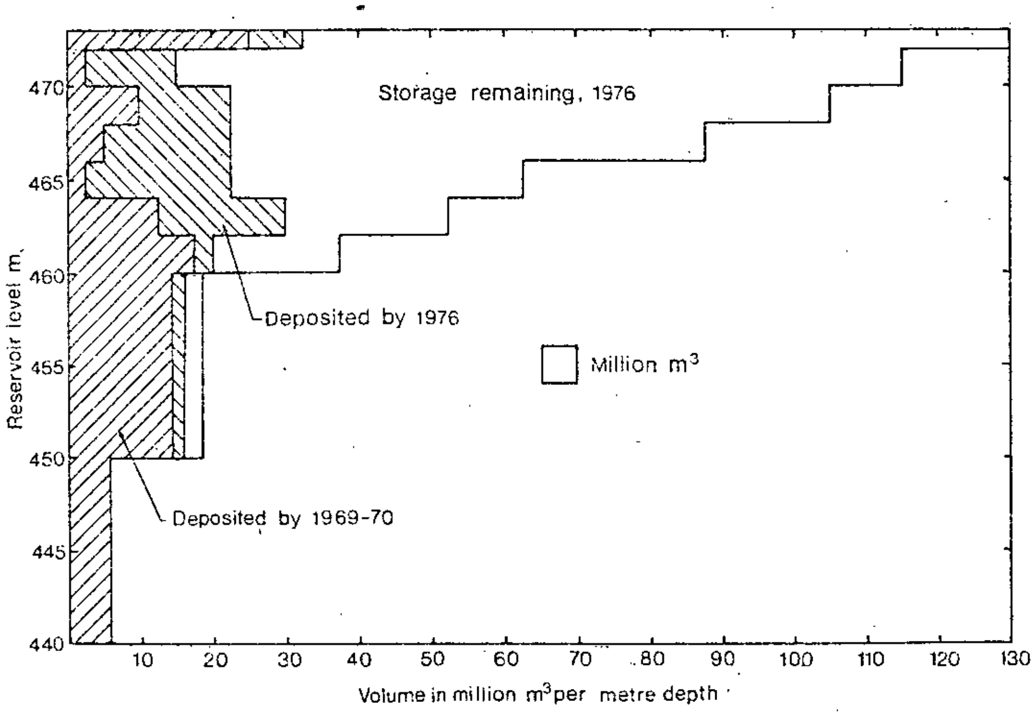
	From 473 m on:	To 1 June level:	Initial storage:	Final storage:	Difference:
1972/73	Nov 1	465.1	830	160	670
1973/74	Nov 11	465.7	813	180	633
1974/75	Nov 1	465.1	796	150	646
1975/76	Dec 1	468.5	778	360	418
1976/77	Dec 1	466.8	750	230	520

		Outflows:			
	Inflow*	Canal	Evaporation	Downstream	Apparent storage change
1972/73	87	621	117	42	693
1973/74	288	762	114	8	596
1974/75	284	835	120	8	679
1975/76	377	671	127	53	474
1976/77	103	643	112	33	685

* Calculated from Table A.2 from date of level 473 m given above until 1 June

ANNEX 2
FIGURE 9

Distribution of sediment and storage by level



there should be such a large error in the water balance.

4.4 Sediment distribution and forecast storage curves

Figure 9 shows the changes in sediment distribution with level. This is a convenient way of illustrating where the sediment is being deposited and it also demonstrates the success of the flushing operations in preserving a limited amount of storage below 462 m. For distributing the future sediment, however, it is probably more useful to plot the smoothed curves showing the percentage deposited below a given level as in Figure 10.

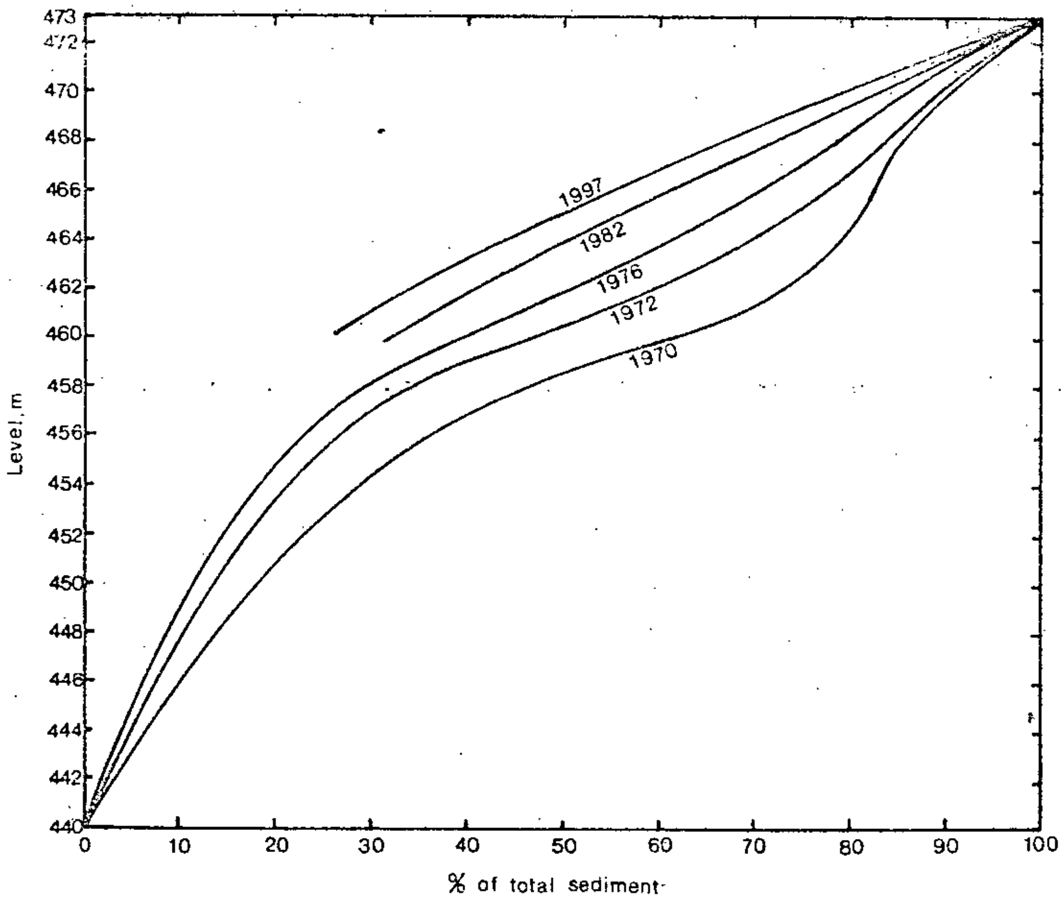
In constructing Figure 10 it was assumed that flushing will maintain a constant storage of 35 million m^3 at 460 m and that storage at 462 m will decrease to 50 million m^3 by 1997. By following the general trend of the previous curves, it was possible to construct two curves for the 1982 and 1997 conditions where, from Figure 7, total sediment volumes of 640 and 800 million m^3 are expected. These lead finally to the forecast storage level curves shown in Figure 11 and Table 6.

Table 6
Storage and Area curves, Khashm el Girba

Level	Surface area (km^2)	Storage million m^3 1976	1982	1997
450	-	-	-	-
455	7	12	12	12
460	20	35	35	35
462	26	60	55	50
463	30	75	70	60
464	35	100	90	70
465	41	135	120	85
466	49	185	150	105
468	62	320	260	190
470	80	475	410	300
473	130	778	660	500

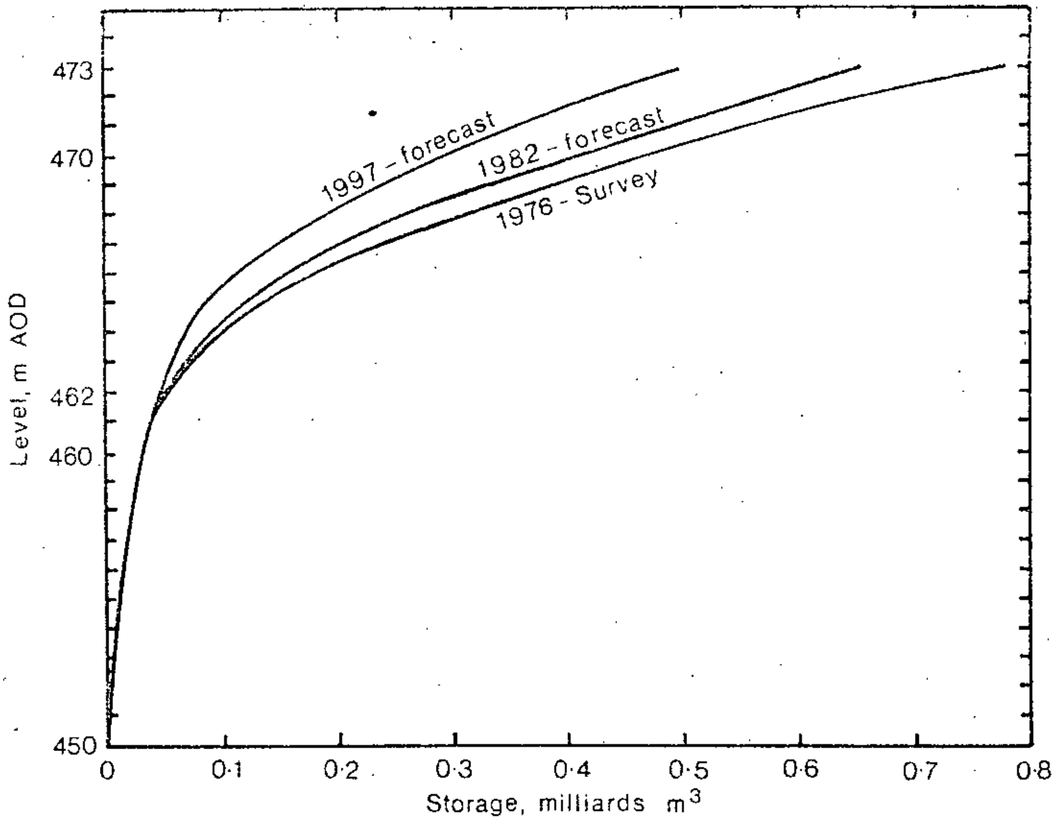
ANNEX 2
FIGURE 10

Percentage of sediment deposited below given level



ANNEX 2
FIGURE 11

Storage level curves, 1976 to 1997



4.5 Surface area changes

Table 6 also shows the area of the surface of the reservoir at various levels, as this information is needed to calculate evaporation losses from the water surface. The area at a given elevation will decrease with time due to sediment deposition but this effect has been ignored in the calculations because it would otherwise be necessary to assess the increase in evaporation through the vegetation which becomes established on the reservoir margins and delta deposits.

5. Power generation

This chapter briefly outlines the capacity of existing plant and the demand requirements. There are currently a number of problems with the maintenance and operation of the installed plant but in these studies it is assumed that all such equipment is working to design specifications. Further details are given in Annex 3, Chapter 3.

5.1 Installed capacity

Power may be generated at Khashm el Girba in one of three ways:

a. When the reservoir level is at least 2.0 metres above the level in the main canal, the releases into the canal may be passed through up to three pump-turbines each of 2 MW capacity. From characteristic curves supplied by the Public Electricity and Water Corporation (PEWC), power generation may be approximated by:

$$P(\mathrm{kw}) = 10.2\ HQ$$

where H is the head in metres
and Q is the discharge in million m^3/10 days.

In the simulation studies, it is presumed that all canal discharge is used to generate power whenever possible. Water level on the canal side is calculated as:

$$\text{Level (m)} = 463.3 + (Q/9.5)^{0.53}.$$

b. Water may be released downstream through one or two Kaplan turbines in the base of the dam. Each turbine can produce up to 3.3 MW, and the power generated is given by:

$$P = 9.8\ HQ$$

Downstream water level is calculated as:

$$\text{Level (m)} = 432.0 + ((Q + \text{Spill})/27.1)^{0.36}.$$

It is assumed that an average discharge of 8 million m^3/ 10 days (9.3 m^3/s) is run through each Kaplan thus giving maximum power at top water level. In the simulation studies it is further assumed that both Kaplans are run 24 hours per day (total of 16 million m^3 in 10 days) if the reservoir is being operated at 462 m and that one is running 24 hours and the other 16 hours per day (13 million m^3 in 10 days) at all other times when water is not required for irrigation.

c. There are currently three diesel generators at the dam but two are out of commission and replacements have been ordered. Installed capacity (the single generator) is now 1.1 MW but should reach 5 MW by 1979 according to PEWC (10).

The generating capacity at Khashm el Girba is linked to the Eastern Grid (Halfa, Gedaref, Showak). The only other sources of power are generators at the Sugar Factory in Halfa. Spare capacity available from these is currently 1.4 MW but is soon to be 1.7 MW and may eventually reach 3 MW.

There are plans to connect the Eastern Grid to Kassala in 1979-80. In Kassala there is a surplus of energy but, in most months, a shortage of generating capacity (expected to be 4.5 MW in 1979) to meet peak loads. There are also plans, still being evolved at PEWC and elsewhere, to connect with the Blue Nile grid and these control the development of hydropower on the Upper Atbara. The current proposal there is that 30 MW should be initially installed at Rumela dam.

5.2 Power requirements

Table 7 lists the requirements for energy and power in 1979-80. Two sets of figures are given: one for the Eastern Grid alone and one including the net effect of connection with Kassala.

In calculating the extent to which power from Khashm el Girba can meet these demands, it is necessary to deduct the requirements of the pump-turbines when operating as pumps; this occurs whenever the level in the reservoir is less than 4.5 m below the level in the canal. Below that level four high lift pumps are used but they have limited capacity capable of supplying little more than essential services. In any case, there is now so little storage available at low levels that severe rationing would already be in force should these pumps be needed.

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10) PUBLIC ELECTRICITY AND WATER CORPORATION. Development Plan for Electricity - Technical supplement. 1977.

The power required to drive the pump turbines as pumps is approximated by:

$$P = 16.7\ HQ$$

At or near the maximum lift, the discharge through the pumps may be less than the canal release target. For simplicity, it is assumed that the extra water is supplied by the high lift pumps using the same equation.

Table 7
Forecast energy and power demands
1979-80

	Eastern Grid		Eastern Grid + net Kassala	
	Gwh	MW	Gwh	MW
Jul	2.10	7.06	0.69	6.92
Aug	2.82	8.61	0.97	8.11
Sep	1.97	5.36	0.14	5.60
Oct	2.26	4.90	0.90	5.34
Nov	2.26	4.98	0.85	5.07
Dec	2.26	4.98	0.79	4.85
Jan	2.40	5.66	0.95	5.50
Feb	2.12	5.00	0.65	5.08
Mar	2.12	5.18	0.84	5.45
Apr	2.12	6.41	1.14	6.64
May	2.4	4.73	1.31	4.95
Jun	2.4	6.41	1.20	6.77

Source: Public Electricity Water Corporation. Development Plan for Electricity - Technical Supplement, 1977.

6. Irrigation demand pattern

This chapter is concerned with the selection of target releases at the head of the main canal. While these are governed largely by irrigation demands, industrial and domestic requirements, and evaporation from the canal system have also been included. The aim is to choose a realistic sequence of 36 values which reflects the average scheme requirements and which can be used in the reservoir simulation study.

6.1 Annual variation in crop water requirement for irrigation

The irrigation requirement of a crop depends on rainfall and evaporation and so naturally varies from year to year. In the Blue Nile Study (7), the annual requirement, deduced from climate data, was found to vary within ± 15 percent of the mean and Appendix A, Table A.5 illustrates a similar variation in actual releases from Khashm el Girba. The greatest variations occur in the rainfall months of July, August and September. Figure 12 shows that the canal release in a given month is broadly related to rainfall in the same month, plus half the rainfall in the previous month. There is a clear tendency for irrigation requirements to be less in periods of high rainfall. While this would be interesting and relevant in most studies, it is not so important here because there is usually more than adequate inflow to the reservoirs throughout the rainy season. Thus the development of a method of adjusting irrigation releases according to rainfall would not benefit the study directly since its only effect would be to improve the accuracy of prediction of spillage from the reservoir. It is therefore considered that the use of average crop water requirements is a justifiable simplification for the purposes of the reservoir simulation study.

6.2 Total requirements from Khashm el Girba

A series of reports by Sogreah (1), (2), (3), (4), the Ministry's account of February 1975 (11), and other papers derived from these contain the same values of expected monthly canal releases which are described as 'experienced' releases. The figures are, however, almost the same as recorded in Table 6 of the Ministry's report of April 1973 (6) where it is noted that they originate from the

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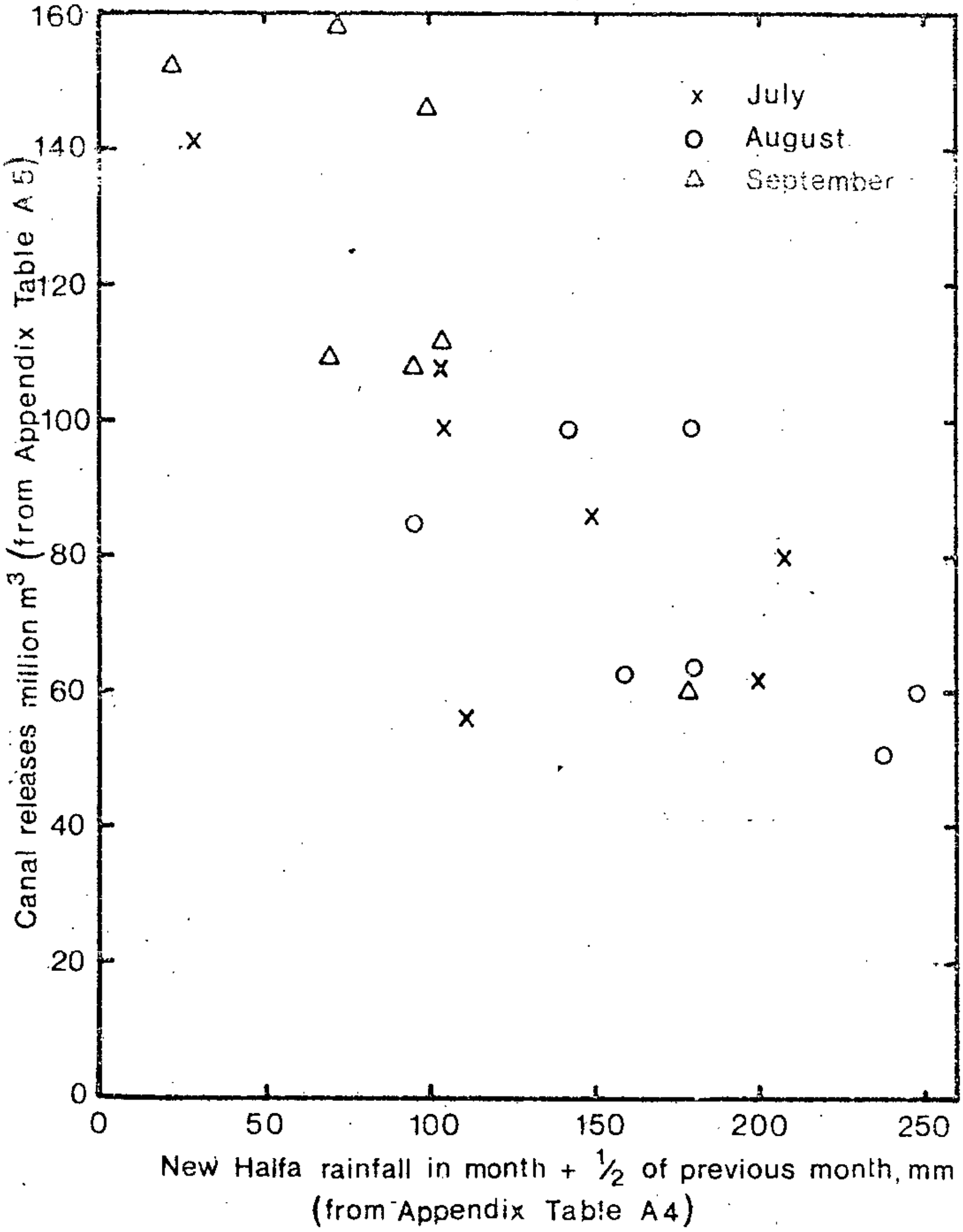
7) BLUE NILE STUDY CONSULTANTS, op.cit
1) SOGREAH, op.cit. R11728
2) SOGREAH, op.cit. R12040
3) SOGREAH, op.cit. R12534
4) SOGREAH, op.cit. R11835
11) MINISTRY OF IRRIGATION. 'Upper Atbara Project". February, 1975.
6) MINISTRY OF IRRIGATION. op.cit.

ANNEX 2
FIGURE 12

Variation of main canal releases
with rainfall



'agreement' between Government departments of March 1972. The only difference in the figures is that the pre-watering of wheat, groundnuts and cotton has been omitted from the later tabulations.

In Table 8, the first column lists the 10-day releases derived from (6) with the omission of pre-watering; the average of actual releases over the period 1972-77, calculated as shown in Appendix A, Table A.5, are listed in the second column. From July to November, abstractions have been less than expected. This reduced demand may be due partly to local rainfall but there has also been under-utilisation of the land and usually some delay in agricultural operations. The other explanation of unexpectedly low releases is inability to meet demand. This is not because of rationing when resources are low but because of difficulty in pumping to the canal when the reservoir is being operated at low level (462 m) to avoid sedimentation in the live storage. The effects of agricultural delay are also seen in the increased demand from February to May although inefficient distribution at field level could be the cause. The increased demand in June is probably due to an early start being made with groundnut pre-watering once the flood is clearly on its way. The efficiency of past water use is discussed in more detail in Annex 3.

The demand pattern expected to satisfy the proposed new crop rotation (Annex 3, Table 10) is shown in the third column of Table 8. Note that, despite using 17 percent more water than at present, the requirement during the critical period from October to June is actually reduced.

7. Reservoir simulation studies

This section describes the computer program used in assessment of Khashm el Girba reservoir operation.

7.1 Purpose of reservoir simulation

The traditional approach to reservoir operation is to define a given inflow sequence as the 'mean' year or the '80 percent reliable' year and then to assign similar probabilities to

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6) MINISTRY OF IRRIGATION. op.cit.

Table 8

Main canal requirements, Khashm el Girba
million m^3

		'Agreement' of March 1972		Average 1972-77		Proposed new requirements	
Jul	1	30	146	33	96	68	185
	2	57		35		72	
	3	59		28		45	
Aug	1	40	140	23	79	40	151
	2	45		25		51	
	3	55		31		60	
Sep	1	61	195	37	125	67	219
	2	65		40		76	
	3	69		48		76	
Oct	1	74	224	59	195	74	229
	2	73		65		81	
	3	77		71		74	
Nov	1	87	231	69	206	70	180
	2	77		69		55	
	3	67		68		55	
Dec	1	64	194	64	194	48	127
	2	64		63		41	
	3	66		67		38	
Jan	1	44	140	54	150	37	101
	2	46		46		34	
	3	50		50		30	
Feb	1	27	74	43	106	28	67
	2	27		37		22	
	3	20		26		17	
Mar	1	9	27	25	65	14	44
	2	9		24		15	
	3	9		16		15	
Apr	1	10	30	13	40	15	45
	2	10		14		15	
	3	10		13		15	
May	1	12	36	15	46	17	84
	2	12		15		17	
	3	12		16		50	
Jun	1	12	36	19	81	56	183
	2	12		29		61	
	3	12		33		66	
Annual total:		1478 (902) (1)		1383 (1083)		1615 (1060)	

(1) Figure in brackets after annual total is the total requirement, Oct-Jun inclusive.

the resulting irrigation and power output. This was the method used by Sogreah (2). Usually, however, it leads to difficulties in specifying exactly what constitutes a 'mean' year; this is particularly true when the investigation is concerned with maximising the use of water in every year by allocating priorities and rationing based on forecasts which are in turn based on the sequence of inflows. It is then necessary to examine many possible inflow sequences.

An alternative and more powerful technique is to test the reservoir operation with a number of possible inflow sequences and then to study the statistics of the output directly. With the increasing use of computers, this is a straightforward and extremely flexible procedure. Many combinations of irrigation targets, power targets, inflow sequences, storage assumptions, gate operating rules and rationing procedures can be examined and tested at a relatively small cost.

7.2 The computer program

The computer program keeps an account of inflows to, outflows and losses from, and storage in the reservoir. The inflows are 10-day total flows and are the sum of the tributary flows of the Setit and Upper Atbara. There is one sequence of 21 years of recorded data and there can be any number of sequences of 50 years based on the Lower Atbara record (1922-73) as described in 2.8 and Appendix B. In these studies, the historic period has been analysed separately from the four synthetic sequences which have been generated. There are therefore five data sequences in all. Because there is no over-year storage, the order of years within the sequence is irrelevant.

Three storage states have been considered (Table 6):

- the storage as surveyed in 1976
- the forecast storage in 1982
- the forecast storage in 1997.

Three irrigation demand patterns have been studied (Table 8):

- the planned pattern of March 1972
- the average of actual patterns 1972-77
- the cropping pattern proposed in this Report (Annex 3).

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2) SOGREAH, op.cit. R12040

The program operates by rules, described later in this chapter, that determine the allocation of water to evaporation, storage, spillage and Kaplan turbine or canal releases. In each 10 day period, the actual allocation of water to each of these components is calculated, together with the amount of energy generated by the turbines or needed by the pumps. At the end of each run, both a summary of the key statistics for each year of simulation as well as histograms of irrigation supply efficiency are given. The results of the simulation are discussed in Chapter 8.

7.3 Evaporation from the reservoir surface

Evaporation in each 10-day period is determined from the figures given in Table 3 (mm per month) and the area/level curve of Table 6. The use of average figures for net evaporation (evaporation - rainfall) rates, rather than a representative range of figures, is discussed in 3.1. In calculating future evaporation requirements where levels and areas are unknown, an average relationship of changing level with time is used.

7.4 Power targets

The power targets are based on the wish to avoid using diesel power to drive the pump turbines. The required Kaplan flows are set at 13 million m^3/10 days from 1 July until the end of September. This is the period when the reservoir level is likely to be below the canal level so that pumping will be needed. In general, however, power generation is a secondary consideration and priority is given to irrigation needs at all times.

7.5 Operating level

The program simulates the change of operating level between 473 m and 462 m according to the inflow sequence. Representing the reservoir control as a set of gates, these are closed through the recession until sometime in June. At any time after 1 June, if the 10-day inflow is greater than the one before and there is enough water in store to meet current demands, the gates are opened and the operating level is changed to 462 m. This is done to confine sedimentation near to the central channel in the reservoir.

The gates are closed and the operating level restored to 473 m after the peak of the flood has passed. Many trials have been made in search of a foolproof operating rule which would balance the need to close late for sediment control against the risk of not filling the reservoir. It was found that there was very little flexibility in the choice of dates. Closure need never take place before 1 September and should never be delayed beyond 21 September. As the program works in 10 day periods, it can choose one of only three dates, namely 1 September, 11 September or 21 September. It does so by comparing expectations (inflow to come + storage) with total remaining requirements (evaporation, irrigation and power targets).

The computer program also allows for an alternative filling strategy, for which the date for gate closure is fixed at 11 September.

A study of all the 21 years of actual data suggested that, once the annual peak has passed, a simple recession curve, given by the equation:

$$Q_t = 0.6\ Q_{t-1}$$

could be used to estimate a lower limit for the remaining 10 day inflows. Then, for the current period T (after the annual flood has passed) with a flow Q_T, the sum of the remaining inflows from the start of the period T to the end of the year (30 June) is given by:

$$\sum_{t=T}^{36} Q_t = 2.5Q_T.$$

This equation neglects any inflows during June and may therefore be considered conservative. The shape of the recession curve for discrete 10 day intervals is shown in Figure 13.

The gate closure rule looks ahead one period and compares expectations with requirements in 10 days' time. If requirements are greater, the gates are closed and the reservoir filled to 473 m.

Both the normal operating level of 473 m and the drawdown level of 462 m can easily be changed in the simulation and the performance of the reservoir examined under alternative assumptions.

7.6 Rationing procedures

As soon as the gates are closed, the possible need for rationing is examined. The comparison is again of expectations with requirements. Thus, if the sum of the expected inflow from the start of period T (ie, $2.5Q_T$ or $1.5Q_{T-1}$) and the actual storage is less than the total remaining requirements, then rationing may be required.

ANNEX 2
FIGURE 13

Assumed recession curve of successive average 10-day inflows

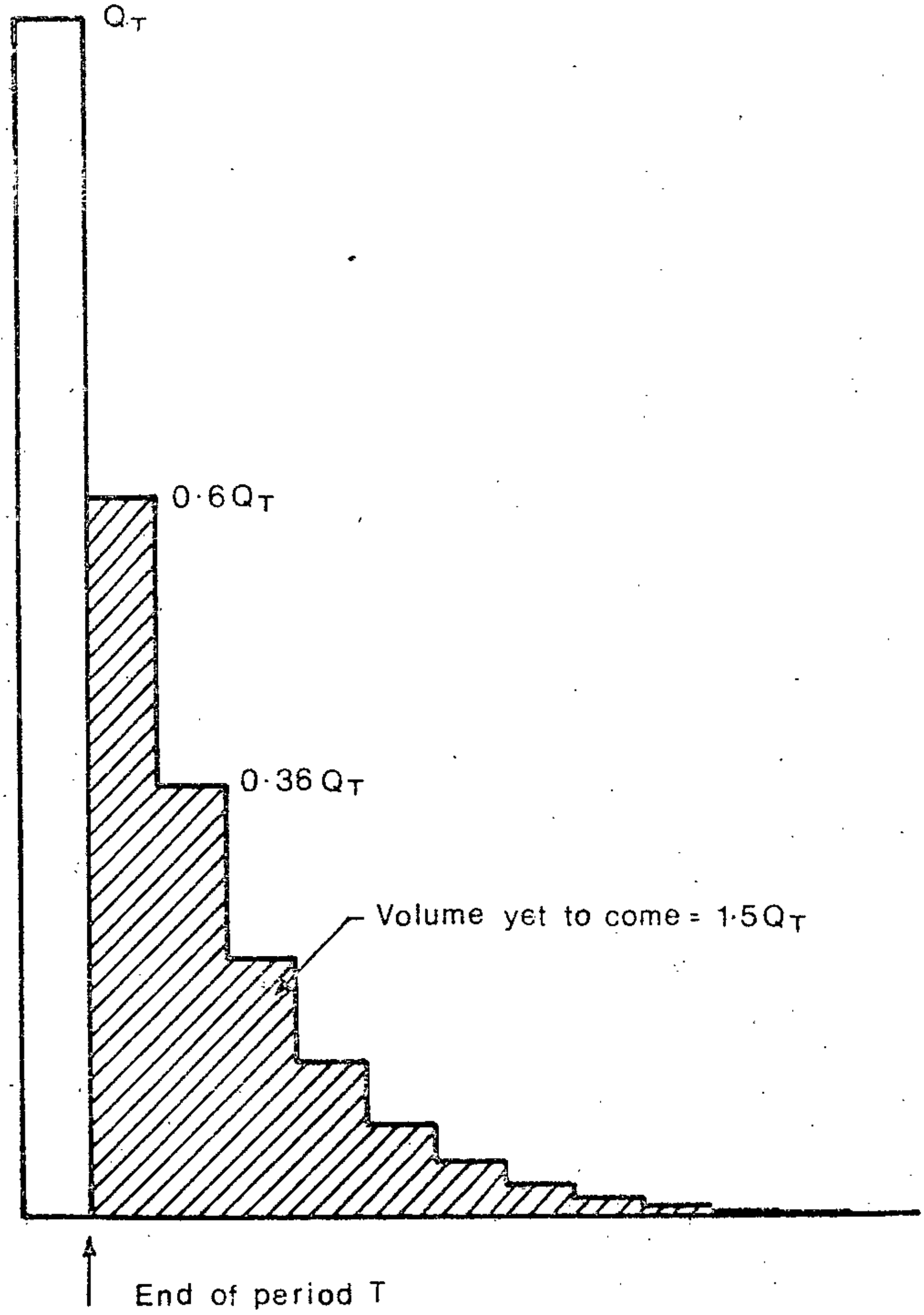


Figure 14 illustrates a typical pattern of requirements and expectations. It shows that the period of most uncertainty is in October when the reservoir is full but starting to empty and the total inflow yet to come is least predictable.

The program calculates the deficiency (requirements - expectations) as a percentage of the requirements and applies it pro-rata to the requirements in the current period up to a maximum of 25 percent. It is recognised that this may be unrealistic in that sufficient warning is available to adjust the irrigation requirements later in the year and rationing might be unnecessary if future inflows are in excess of the lower limit recession curve (Figure 13). Consequently, the program's calculation of irrigation supply efficiency (the ratio of irrigation water supplied to the target) is slightly conservative and its use of any surplus water later in the season to generate power with the Kaplan turbine is correspondingly a little optimistic.

If the inflows do not rise above the predicted recession curve, rationing requirements in excess of the maximum 25 percent can continue through to the end of the season and in theory the reservoir becomes empty. In practice, when the worst case arises, more severe rationing would obviously be applied to safeguard the essential supplies.

If future expectations exceed remaining requirements, the surplus water is used in the following ways:

- If the reservoir is spilling while operating at 462 m more water is put out through the Kaplan turbine up to a maximum of 16 million m^3 in 10 days assuming 24 hour operation for both turbines.
- The current surplus is divided by the number of remaining periods and used to generate power with the Kaplan turbines.

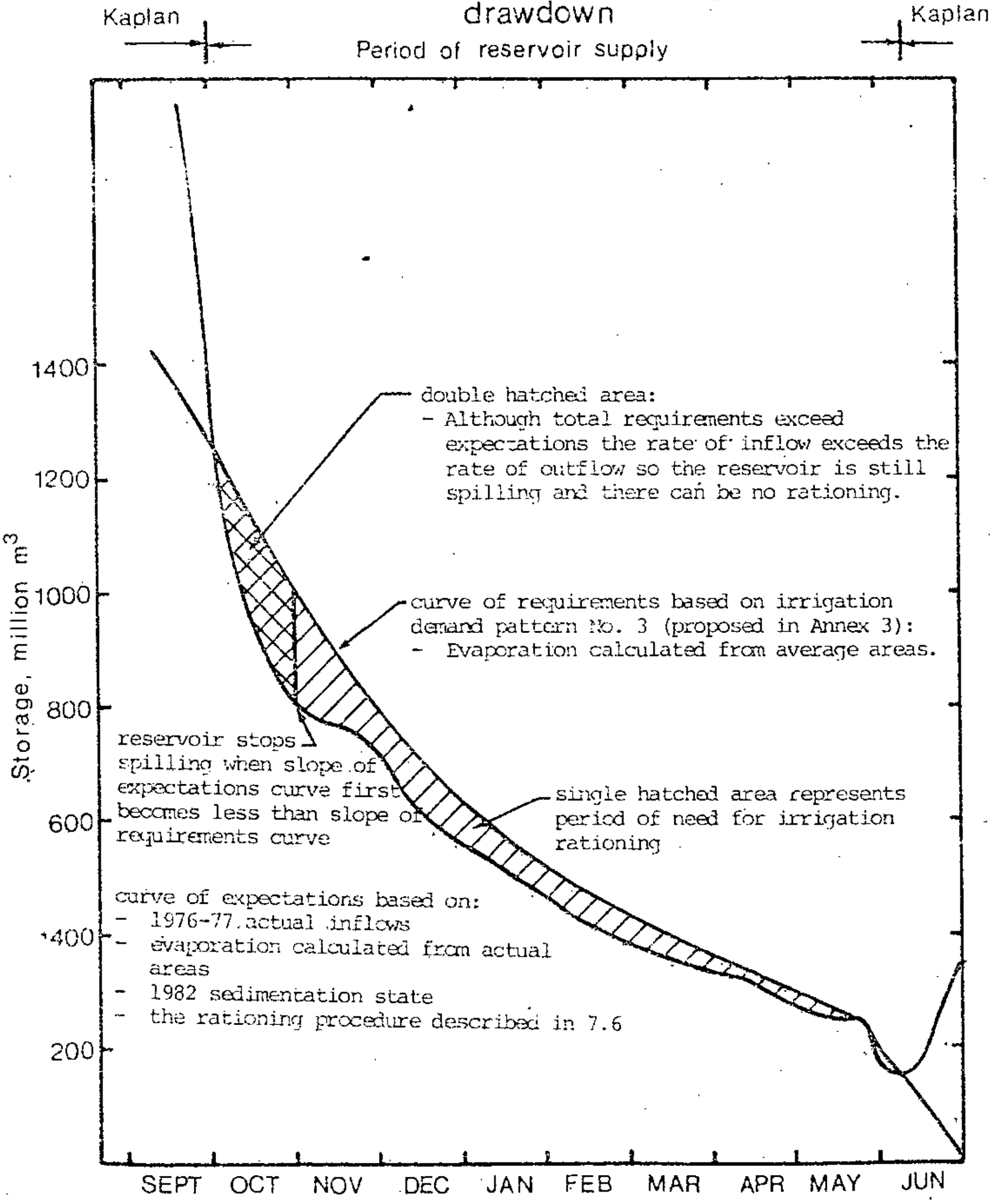
8. Results and discussion of reservoir simulation studies

8.1 The five data sets

Although it had been established (Appendix B) that the historic and synthetic data sets were statistically compatible in terms of monthly flows, it was decided to explore the sensitivity of the reservoir simulation model to the inflow data by running the model with four synthetic data sets of 50 years' duration as well as the

ANNEX 2
FIGURE 14

Example of changing expectation and remaining requirements during reservoir drawdown



double hatched area:
- Although total requirements exceed expectations the rate of inflow exceeds the rate of outflow so the reservoir is still spilling and there can be no rationing.

curve of requirements based on irrigation demand pattern No. 3 (proposed in Annex 3):
- Evaporation calculated from average areas.

reservoir stops spilling when slope of expectations curve first becomes less than slope of requirements curve

single hatched area represents period of need for irrigation rationing

curve of expectations based on:
- 1976-77 actual inflows
- evaporation calculated from actual areas
- 1982 sedimentation state
- the rationing procedure described in 7.6

historical 21 years' record. As shown in Table 9, there was little variation in model output between the data sets and subsequent analysis was restricted to a single set (No. 2).

Table 9

Comparison of model output between data sets.

(1976 storage, average observed irrigation pattern)

Mean annual values of:	Data set: Historic (21 yrs)	Synthetic (50 yrs) 1	2	3	4
inflow, milliard m^3	12.73	13.34	13.05	12.52	12.61
evaporation, milliard m^3	.16	.17	.17	.17	.17
spillage, milliard m^3	10.84	11.39	11.15	10.57	10.69
irrigation releases, milliard m^3	1.42	1.45	1.45	1.45	1.45
Kaplan output, Gwh	23.67	25.75	24.12	25.21	23.47
pump-turbine output, Gwh	11.49	12.21	12.18	12.14	11.88
pump-turbine requirement, Gwh	6.83	6.69	6.65	6.62	6.54

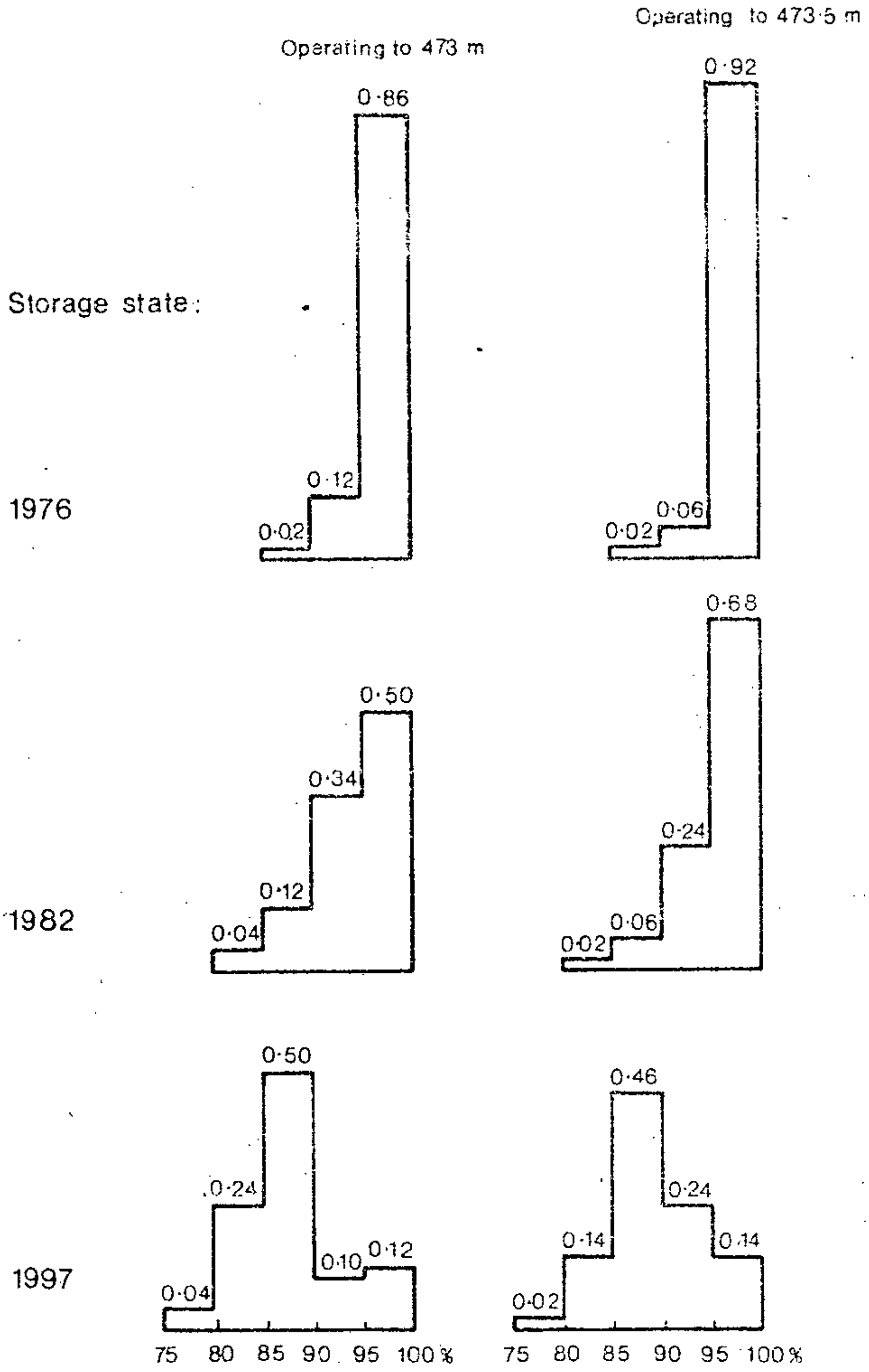
8.2 Irrigation supply efficiency

The performance of the reservoir in supplying irrigation can be reported in a number of ways. The most succinct is to express the total water supplied as a percentage of the requirement. Table 10 gives these figures for three states of sedimentation and the three demand patterns which were studied.

It can be seen that the highest irrigation supply efficiency is achieved for the demand pattern planned originally. The proposed pattern however, which requires much more water, is almost as efficient. For each of the demand patterns, the effect of the successive reductions in storage volume is clear. For example, for the proposed cropping pattern the expected average irrigation shortfall would be 192 million m^3 for the 1997 storage state, compared with only 31 million m^3 for 1976.

ANNEX 2
FIGURE 15

Histograms of irrigation efficiency for proposed cropping pattern - probability of annual efficiency being in range shown



It is understood (2) that there is a possibility of operating this reservoir at 473.5 m. As can be seen from Figure 5, this would provide an extra 60 million m^3 of silt-free storage. Table 10 shows the improvement in irrigation supply efficiency which would result. As expected, the improvement becomes more marked in later years. If the level could be varied by more than 0.5 m, the date by which the mean irrigation supply efficiency reduces to a particular value would naturally be further deferred. Accurate survey data extending to the higher levels would be needed before more precise figures could be given

Table 10
Mean irrigation supply efficiencies, percent

Storage state	Irrigation pattern (total volume)			
Year (volumes)	originally planned (1473)	average 1972-73 (1383)	proposed (1615)	proposed - operating to 473.5 m
1976 (778)	99.0	96.4	98.1	98.9
1982 (660)	96.7	91.5	94.4	96.3
1997 (500)	90.3	85.1	88.1	89.7

Although the mean irrigation supply efficiency is a useful statistic for comparative purposes, it is perhaps more important to examine the range of annual values about the mean. Therefore, in Figure 15, the probability that the supply efficiency lies within a given range has been plotted. These histograms have been drawn for three storage states and for two maximum operating levels and illustrate the effect of changes in storage both through sedimentation and raising the top water level. For each operating level, the histograms have a definite shift towards the left with time, as storage is progressively lost through sedimentation. This indicates that the reliability of being able to achieve a given, high level of efficiency decreases significantly with time. In 1982, for example, an efficiency of 90 percent would be achieved with a reliability of 84 percent (ie, in 84 years out of 100) by operating at 473 m. By 1997 the same efficiency could only be achived at the same operating level with a 22 percent reliability. This reliability could, however, be increased to 36 percent by raising the operating level to 473.5 m.

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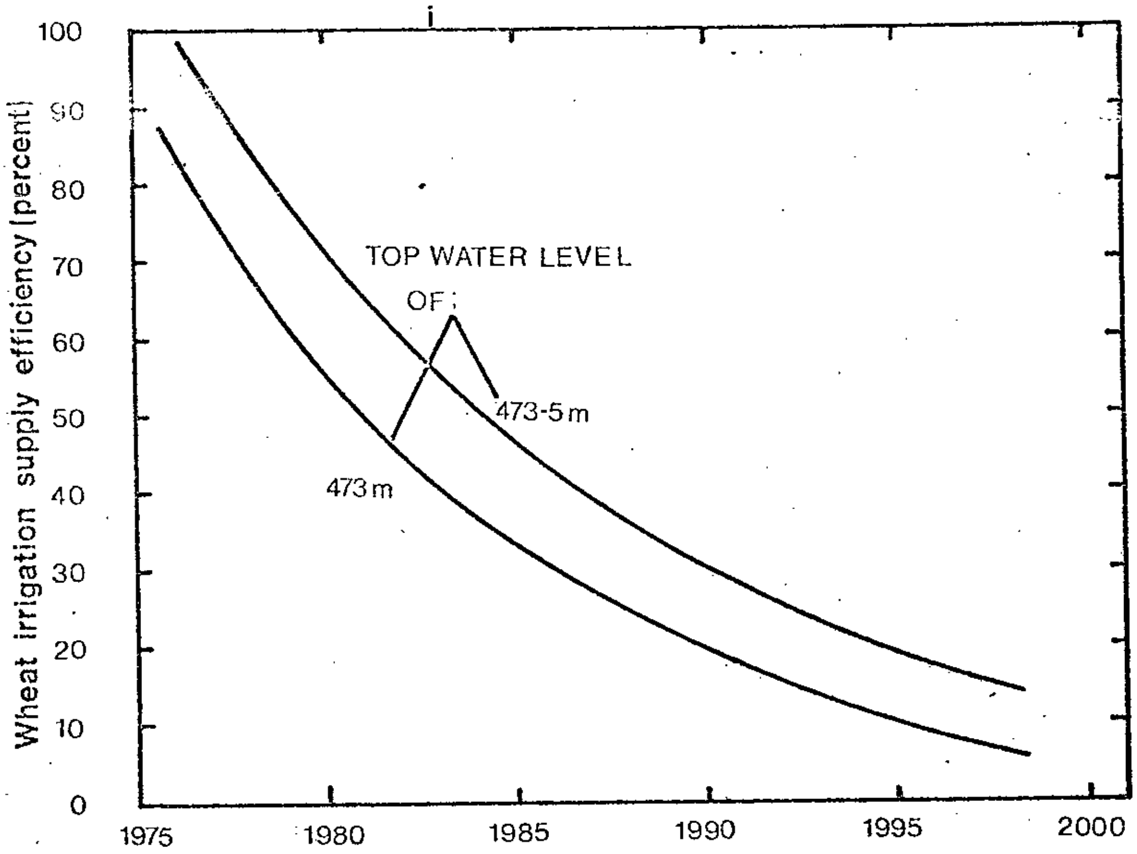
2) SOGREAH, op.cit. R12040

ANNEX 2
FIGURE 16

Reduction of wheat irrigation supply efficiecy with time



If the irrigation shortfall is presumed to fall entirely on the wheat area, on the grounds that the groundnut and cotton irrigation will have finished and the demands for sugarcane, freehold land and forest, and for domestic use are fixed, then the fraction of the wheat requirement which can be met may be deduced from the annual irrigation supply efficiency. They are related by:

$$ISE_{wheat} = \frac{276.6 - 1615(1-ISE_a)}{276.6}$$

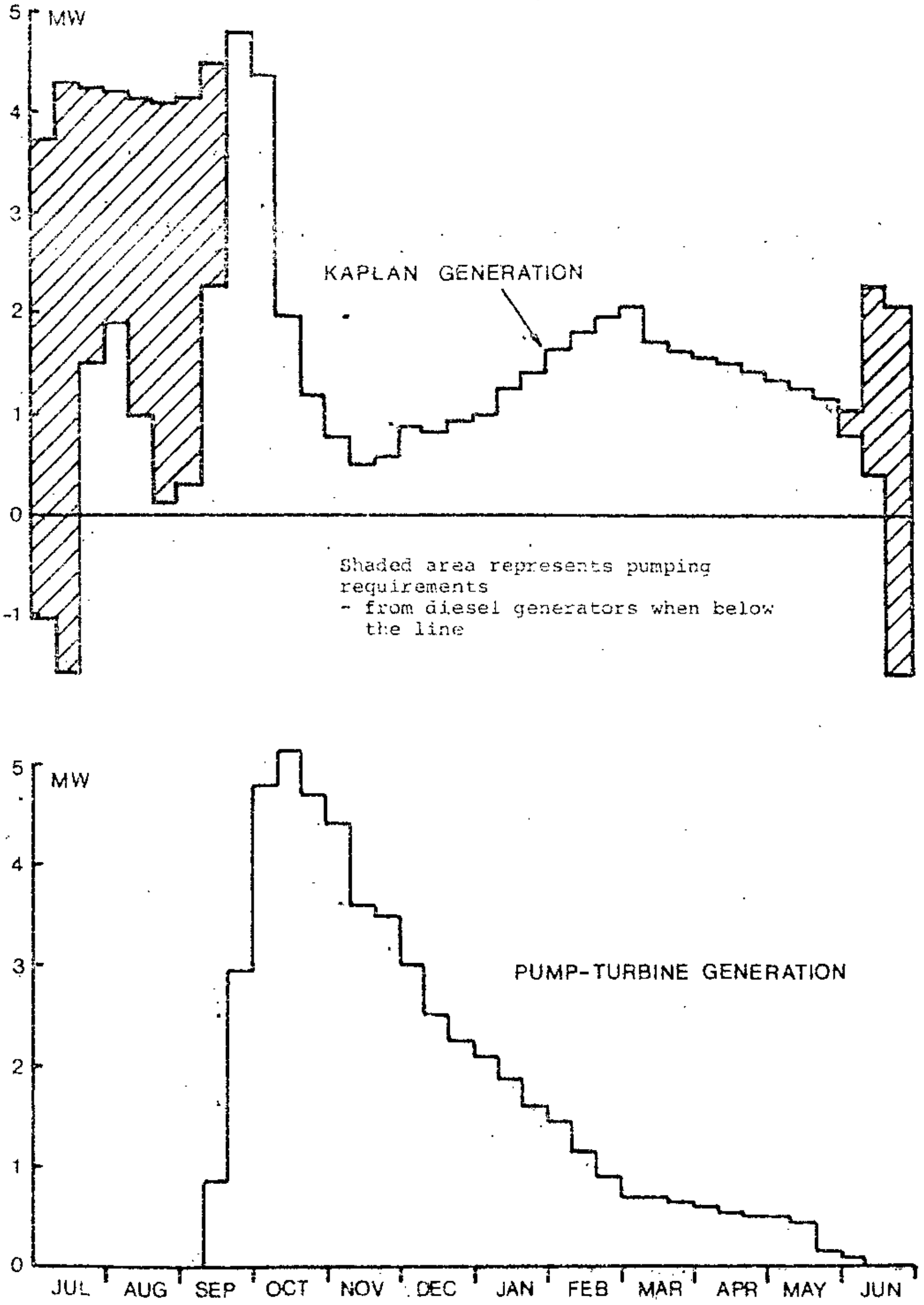
because the wheat irrigation requirement is 276.6 million m^3 out of a total requirement of 1615 million m^3. Thus, values of annual irrigation supply efficiences of 95, 90 and 85 percent (or overall shortages of 5, 10 and 15 percent) are equivalent to supplying 71, 42 and 12 percent of the wheat irrigation need as well as meeting the other needs in full. Lower supply efficiencies cannot be met by the wheat irrigation alone. The probabilities of various overall irrigation supply efficiencies of Figure 15 may be reinterpreted in terms of wheat supply efficiencies; for instance, the probability of meeting 90 percent of the total demand or 42 percent of the wheat demand would be 98 years out of 100 in the 1976 storage state, 84 out of 100 in 1982 and 22 years out of 100 in 1997. By interpolation, the percentage of the wheat irrigation demand which could be met 4 years out of 5, with all the shortage loaded onto the wheat, would be 85 percent in 1976, 44 percent in 1982 and 7 percent in 1997. This trend is illustrated in Figure 16 for top water levels of 473 m and 473.5 m. Use of the alternative, fixed date, filling strategy has an insignificant effect on these results.

8.3 Power production

The summary of the annual energy generation and pumping requirements given in Table 11 gives an indication of the range of values to be expected and also illustrates the effect of a decrease in storage or a change in the maximum operating level. To show the likely variations in these values throughout the year, we have included in Table 12 average 10 day figures for the 1976 storage state, the proposed irrigation demand pattern and an operating level of 473 m; Figure 17 shows this information in graphical form. The actual power generated or required in a given year, is highly dependent on the rationing and filling strategies selected for the simulation. The average values mentioned above are used solely to illustrate seasonal variations. Note that on average, there is a requirement for the diesel generators for some of June and July simply to supply water to the main canal.

ANNEX 2
FIGURE 17

Average power generation and canal pumping requirements
MW



Shaded area represents pumping requirements
- from diesel generators when below the line

Table 11
Summary of annual energy generation and requirements (Gwh) - 50 year sample (Proposed irrigation demand pattern)

	1976 storage 473 m	1976 storage 473.5 m	1982 storage 473 m
Pump turbine generation:			
- minimum	9.7	9.7	9.7
- mean	12.4	13.3	12.0
- maximum	15.8	17.3	15.3
Kaplan turbine generation:			
- minimum	9.5	9.5	8.6
- mean	18.8	22.3	14.1
- maximum	38.5	41.0	34.0
Pump turbine energy requirement when pumping:			
- minimum	5.2	5.1	4.7
- mean	8.4	8.4	8.2
- maximum	14.2	14.2	13.6

Comparing the distribution of surplus power with the forecast demands of Table 7, it is clear that hydropower makes a very limited contribution of about 7 MW in October, 4 MW in November, 3 MW in December and an average of 2 MW until May. This is an average year and such figures do not represent firm power which would be approximately two thirds of the pump-turbine generation only. Kaplan generation can never be considered part of firm power available outside the dam site because, in a dry year, it would cease as soon as the reservoir level was raised to 473 m.

Considering the figures in Table 7, it would seem that all the plans for increasing the diesel capacity at Khashm el Girba and the New Halfa sugar factory will need to be realised. Even then, there appears to be a potential shortage in August whether or not the connection to Kassala is made. Connecting to the Blue Nile grid as soon as possible would clearly ease these difficulties.

8.4 Practical instructions for reservoir operation

As the sediment load of the inflows to the Khashm el Girba reservoir is high, and the available storage is only a small proportion of the annual river discharge, the actual operation of the reservoir is critical for minimising

Table 12
Average power generation and pumping requirements (MW)

		Pump-turbine		Kaplan
		Generating	Pumping	
Jul	1	...	4.76	3.75
	2	...	5.92	4.33
	3	...	2.71	4.26
Aug	1	...	2.30	4.20
	2	...	3.17	4.14
	3	...	3.96	4.11
Sep	1	...	3.78	4.15
	2	.85	2.19	4.49
	3	2.93	...	4.83
Oct	1	4.79	...	4.36
	2	5.14	...	1.96
	3	4.69	...	1.19
Nov	1	4.39	...	.77
	2	3.58	...	.52
	3	3.50	...	.60
Dec	1	3.02	...	.87
	2	2.51	...	.81
	3	2.25	...	.42
Jan	1	2.10	...	.98
	2	1.87	...	1.24
	3	1.61	...	1.41
Feb	1	1.46	...	1.65
	2	1.14	...	1.65
	3	.88	...	1.97
Mar	1	.70	...	2.07
	2	.70	...	1.70
	3	.65	...	1.64
Apr	1	.61	...	1.57
	2	.56	...	1.50
	3	.51	...	1.43
May	1	.51	...	1.36
	2	.44	...	1.27
	3	.15	...	1.17
Jun	1	.09	0.20	1.06
	2	...	1.84	2.28
	3	...	4.17	2.10

the loss in storage through sedimentation. Simply, the need to avoid sedimentation whenever possible must be balanced against the risk of water shortages from failing to fill the reservoir and must also take account of the need for irrigation rationing should the inflow recession continue steeply.

It is therefore desirable for those responsible for the reservoir operation to be able to determine objectively not only when the reservoir level should be raised, but also the extent of any irrigation rationing and consequent adjustment of agricultural plans, should this be required. Although clearly limited by the use of 10 day data, and the simplified approach to rationing, the operating rules developed for the reservoir simulation program suggested that a simple graphical procedure could be used. The procedure described is included in this report in the hope that its development may be useful in the formulation of an operating strategy.

The method is based on the recession equation, given in Section 7.5, from which the total expected volume of the inflows from a given instant to the end of the year can be deduced. For example, at the end of a 10 day period, T, during which the total inflow was Q_T, then the total inflows to be expected are:

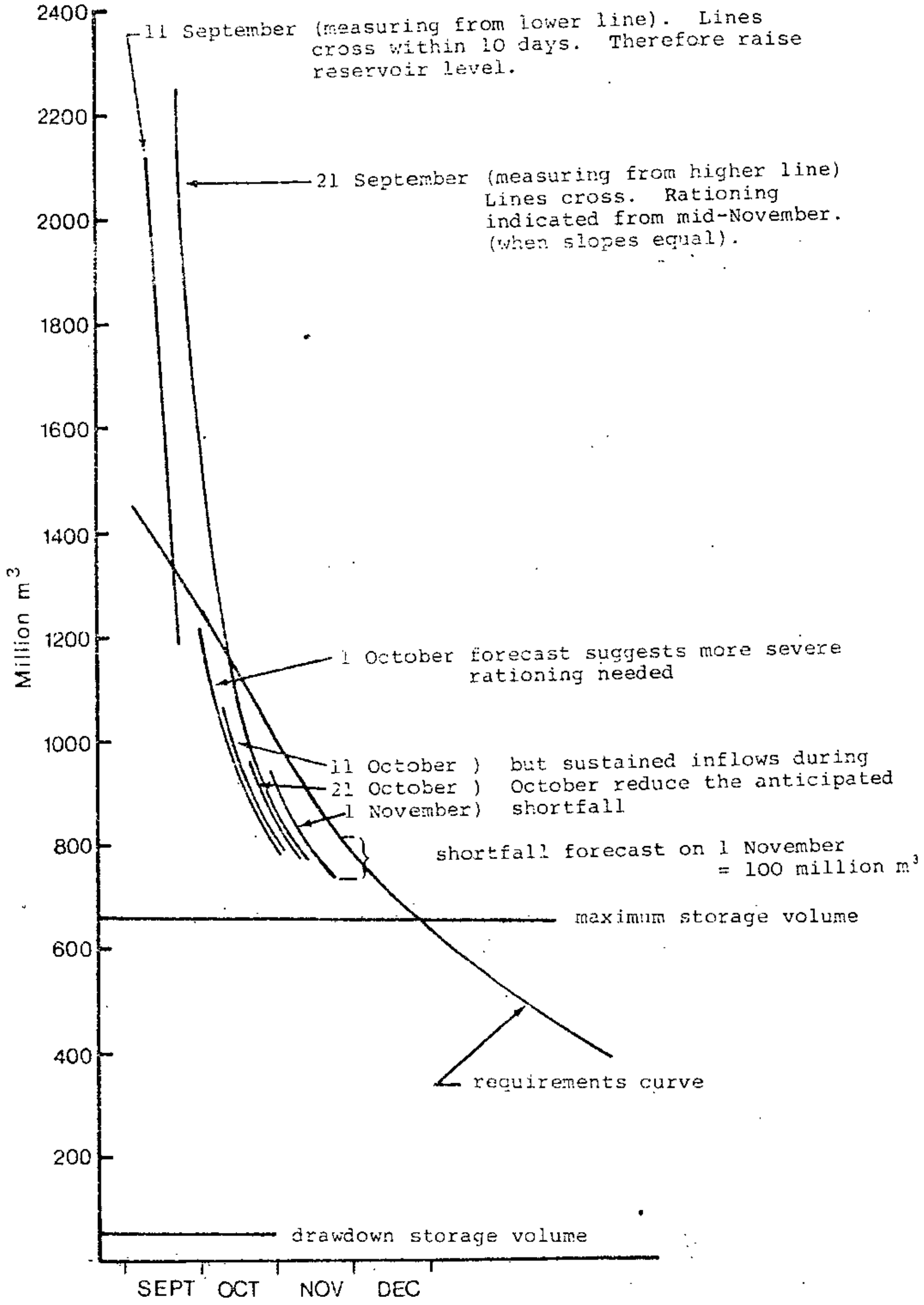
$1.5\ Q_T$	from the end of period T
$0.9\ Q_T$	from the end of the period in 10 days' time
$0.54Q_T$	from the end of the period in 20 days' time
$0.32Q_T$	from the end of the period in 30 days' time
$0.19Q_T$	from the end of the period in 40 days' time
$0.11Q_T$	from the end of the period in 50 days' time

The curve of expected total inflows thus derived at the end of any 10 day interval can then be superimposed on the curve of total requirements. Gate closing or rationing decisions can then be made from the configuration of the two curves. As discussed in Section 7.5, the gates are invariably closed sometime in September; a decision therefore has to be made whether to close the gates on 1, 11 or 21 September. Any remaining decisions will concern rationing alone.

A worked example using the 1970/71 inflow data and the 1982 storage state, for which the drawdown storage volume is 55 million m^3, is given below and illustrated in Figure 18.

ANNEX 2
FIGURE 18

A procedure for reservoir operation



At the beginning of a new 10 day period and measuring from the drawdown storage volume, the diminishing curve of future expected inflows is plotted. Should this curve and the requirements curve cross within the period, then the gates should be closed and the reservoir allowed to fill to its maximum operating level.

In this example, the gates should be closed on 11 September. The curve of expected inflows is then drawn using the flow of the first 10 day period and measured from the maximum storage volume of 660 million m^3. As the curves cross, indicating that the sum of the expected inflows and the present storage is insufficient to meet requirements, rationing must be anticipated and can be estimated at the time when the slopes of the two lines are equal and spilling stops.

From the expected inflows estimated on the 21 September, rationing should be anticipated from the middle of November. Successive forecasts are then made at the end of each period and the anticipated degree of rationing is slowly reduced as inflows are sustained through October at a higher level than had been anticipated.

The strategy for choosing the date for gate closure described above has been used in deriving the results presented in this section. The alternative, fixed date strategy has also been tested. While the effects of this alternative strategy on irrigation supply efficiency and on power is negligible, in most years it leads to gate closure earlier than would be necessary. Thus the variable date strategy should give an overall benefit in time as it will tend to reduce the loss of storage through sedimentation.

9. Requirements for further work

9.1 Hydrological data

According to flow records from the Setit catchment, average annual runoff is only 9 percent of rainfall. As discussed in Section 2.6, this is considerably less than the proportion for the Upper Atbara and is also less than for the similar catchments of the Rahad and Dinder to the south.

As reported in Section 4.3, there is an imbalance when the known reservoir storage curve of 1976 is compared with the records of inflow and outflow; underestimation of inflow volumes is one explanation.

Although there are many possible explanations for the above observations, it is suggested that a further review of all available flow data and computation should be undertaken. This should include checks on the calibration of current meters used to establish stage-discharge relations. It is estimated that the review would require two man-months, plus a further three man-months (maximum) if it should be necessary to reprocess the basic data.

9.2 Sedimentation

Although further measurement of suspended sediment would be useful in confirming or otherwise some of the assumptions made in Section 4.2, a further survey of actual deposition is considered more important. It is the current annual rate of deposition in the reservoir which largely controls the forecasts of future states and, as we have seen, storage estimates based on a water balance are insufficiently accurate.

It is therefore recommended that the bathymetric survey of 1976 should be repeated in 1979. This should give a much better estimate than can be made now of the siltation rate for the present system of reservoir operation with seasonal drawdown and regular flushing.

9.3 Extension of reservoir operation studies to the three reservoir case

Synthetic data generation was done for the Setit and Upper Atbara separately in anticipation of simulating the upstream reservoirs. For this report, we have considered only Khashm el Girba reservoir in detail. An extension to the more complicated problem of optimising the three reservoir system could be undertaken but is probably not justified until the doubts raised in 9.1 above have been resolved.

9.4 Reservoir evaporation

As discussed in Section 3.2, estimates of average annual evaporation from the water surface of the reservoir have ranged from 2,000 to 2,900 mm. This is a significant area of uncertainty which involves as much storage as might be gained by raising the reservoir level by 0.5 m. Further comparisons of pan measurements and Penman estimates should be made at all available sites in the region.

SUDAN

New Halfa rehabilitation scheme

ANNEX 2

APPENDIX A

Hydrological and meteorological data

Table A.1

Atbara at mouth (K3), 10-day flows
(million m^3/day)

Year	Period	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1968	1	0.30	0.15	0.10	0.08	3.21	3.50	41.00	144.00	56.00	23.60	0.58	0.18
	2	0.30	0.14	0.09	0.04	6.90	5.98	65.50	111.00	8.80	17.90	0.49	0.16
	3	0.20	0.13	0.09	-	4.09	20.20	111.00	125.00	7.30	4.25	0.26	0.09
1969	1	0.10	0.10	0.05	0.05	0.05	3.40	34.00	106.00	14.40	3.10	0.46	0.20
	2	0.10	0.10	0.05	0.05	0.70	2.50	55.00	170.00	4.40	2.80	0.36	0.15
	3	0.10	0.10	0.05	0.05	5.00	7.10	49.00	151.00	1.56	1.00	0.21	0.10
1970	1	0.10	-	-	0.25	0.20	-	-	142.00	128.00	8.40	6.90	0.35
	2	0.10	-	0.30	0.15	-	-	9.90	224.00	114.00	14.60	1.90	0.20
	3	-	-	0.35	0.10	-	-	66.00	242.00	49.00	12.30	0.50	0.10
1971	1	0.10	0.04	-	-	-	-	28.00	85.00	130.00	21.00	0.75	0.20
	2	0.10	-	-	-	-	-	44.00	153.00	61.00	9.30	0.60	0.10
	3	0.10	-	-	-	-	4.10	44.00	145.00	39.00	3.10	0.30	0.03
1972	1	0.01	-	-	-	-	-	6.00	36.00	14.00	8.90	1.00	-
	2	-	-	-	-	-	-	57.00	93.00	19.00	1.90	0.30	-
	3	-	-	-	-	-	-	79.00	111.00	16.00	1.50	-	-
1973	1	-	-	-	-	-	-	-	225.00	33.00	23.00	2.50	0.30
	2	-	-	-	-	-	-	55.00	222.00	71.00	15.00	0.90	0.10
	3	-	-	-	-	-	-	146.00	135.00	46.00	7.90	0.50	0.10

Table A.2

Setit, 10-day flows
(million m^3/day)

Year	Period	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1956	1	...	...	...	...	...	...	28.55	75.53	77.57	10.1	3.74	1.34
	2	...	...	...	...	...	...	38.84	192.70	47.97	9.14	2.29	1.05
	3	...	...	...	...	...	...	44.30	137.34	18.07	10.16	1.72	0.75
1957	1	0.73	0.44	...	...	...	-	5.71	98.75	98.75	3.44	1.56	0.65
	2	0.63	0.35	...	...	...	-	15.92	162.24	76.45	3.13	1.01	0.51
	3	0.49	0.34	...	...	...	-	31.72	187.16	9.28	2.78	0.81	0.36
1958	1	0.33	0.16	...	...	...	3.44	15.48	190.10	130.45	10.21	5.27	1.03
	2	0.27	0.10	...	...	...	2.41	38.45	199.62	100.29	4.34	2.17	0.81
	3	0.19	-	...	...	...	1.56	128.63	271.93	76.55	3.44	1.31	0.59
1959	1	0.56	0.33	...	...	...	3.44	21.18	123.38	169.28	46.30	4.04	0.92
	2	0.48	0.26	...	...	...	2.23	56.40	189.37	220.00	5.27	1.88	0.73
	3	0.37	0.25	...	...	...	7.04	67.42	172.82	140.49	4.14	1.17	0.53
1960	1	0.50	0.28	...	...	...	-	25.46	67.42	110.30	20.58	1.56	0.68
	2	0.42	0.22	...	...	...	-	33.89	46.30	84.70	5.60	1.06	0.54
	3	0.32	0.18	...	...	...	-	145.53	82.62	57.30	3.54	0.86	0.39
1961	1	0.36	0.21	...	...	...	-	27.50	57.30	118.31	18.07	3.64	2.92
	2	0.30	0.21	...	...	...	-	47.97	120.44	52.22	8.61	3.13	1.94
	3	0.23	0.21	...	...	...	3.54	67.98	164.88	35.13	4.34	2.12	1.51
1962	1	1.31	0.69	...	...	...	0.28	8.74	114.30	145.53	40.77	4.24	2.65
	2	1.14	0.52	...	...	...	0.25	14.90	181.66	51.26	11.90	3.64	2.12
	3	0.94	0.44	...	...	...	0.36	40.00	148.92	41.94	6.04	3.36	1.71

Continued.....

Table A.2 (continued)

Year	Period	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1963	1	1.56	0.81	...	...	...	-	16.36	123.28	87.60	10.31	3.20	3.20
	2	1.41	0.66	...	...	...	-	25.46	95.75	36.13	5.82	4.64	2.41
	3	1.14	0.58	...	...	...	-	69.11	75.03	17.80	3.94	3.44	1.79
1964	1	1.26	0.75	...	...	...	0.69	19.70	182.00	...	16.14	6.04	3.28
	2	1.31	0.62	...	...	...	0.62	47.50	203.20	...	13.12	4.84	3.06
	3	1.41	0.48	...	...	...	4.54	211.80	280.50	27.50	8.61	3.84	2.85
1965	1	2.35	1.94	...	...	...	0.51	10.16	90.96	71.96	7.48	2.17	1.46
	2	2.12	1.94	...	...	...	1.31	16.14	111.09	21.18	6.37	2.00	1.10
	3	1.88	1.51	...	...	...	2.65	41.55	84.00	9.56	2.71	1.66	0.81
1966	1	0.66	0.52	...	...	...	0.52	17.26	77.06	47.97	4.64	1.66	0.66
	2	0.60	0.84	...	...	...	1.31	15.26	63.28	29.91	2.99	1.36	0.52
	3	0.54	0.46	...	...	...	2.65	47.97	60.98	10.46	3.28	0.98	0.42
1967	1	0.34	0.16	...	...	...	0.58	19.98	214.96	90.45	22.59	5.23	3.44
	2	0.27	0.11	...	...	...	9.42	37.70	168.40	52.81	12.98	4.70	2.44
	3	0.21	0.08	...	...	...	10.46	157.25	148.75	31.90	7.40	4.83	2.04
1968	1	1.68	1.10	...	...	...	-	30.38	66.14	21.83	6.60	1.50	1.23
	2	1.44	1.00	...	...	...	-	45.00	53.90	15.04	3.44	1.05	0.80
	3	1.27	0.76	...	...	...	-	80.72	56.40	9.00	2.12	1.44	0.61
1969	1	0.52	0.61	...	...	...	2.52	15.40	100.74	36.53	4.31	1.22	0.58
	2	0.40	0.38	...	...	...	6.14	28.44	84.50	23.76	2.36	0.90	0.52
	3	0.70	0.24	...	...	...	13.34	36.14	75.05	8.68	1.88	0.67	0.43

Continued.....

Table A.2 (continued)

Year	Period	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1970	1	0.38	0.21	...	...	...	0.90	1.68	117.42	75.62	12.28	4.31	1.88
	2	0.30	0.12	...	...	...	1.16	27.27	145.56	54.90	8.84	2.91	1.62
	3	0.26	0.06	...	...	...	12.80	78.20	136.11	17.57	6.44	2.36	1.38
1971	1	1.22	0.75	...	...	...	–	15.71	51.04	51.63	6.01	2.12	0.90
	2	1.16	0.58	...	...	...	–	24.15	100.74	61.90	3.44	1.44	0.75
	3	0.90	0.46	...	...	...	2.20	34.58	76.94	13.52	2.61	1.16	0.64
1972	1	0.58	0.36	...	...	...	0.42	22.98	47.00	18.19	3.44	1.05	0.70
	2	0.52	0.30	...	...	...	0.90	36.92	45.00	16.13	2.04	1.16	0.49
	3	0.43	0.21	...	...	...	8.04	24.93	34.58	7.40	1.62	1.16	0.40
1973	1	0.34	0.11	...	...	...	0.40	14.68	203.22	46.36	18.16	6.97	4.06
	2	0.28	0.05	...	...	...	0.70	35.07	170.25	46.52	18.81	5.84	3.40
	3	0.21	–	...	...	...	10.46	65.63	77.99	28.27	9.40	4.83	2.93
1974	1	1.55	–	...	...	...	2.18	56.98	95.96	79.38	22.13	3.63	1.48
	2	0.33	–	0.05	...	0.58	0.86	61.11	220.20	63.73	10.71	2.55	1.22
	3	–	–	...	...	0.72	16.53	81.95	97.33	36.17	7.09	1.94	0.93
1975	1	0.89	0.74	0.35	0.45	1.25	1.86	23.97	181.30	164.65	38.64	9.98	4.25
	2	0.69	0.71	0.23	0.29	0.19	3.94	37.31	184.35	122.80	28.67	7.57	4.42
	3	0.59	0.64	0.07	0.33	0.10	13.36	52.75	205.07	71.26	14.67	5.54	3.13
1976	1	2.48	1.24	0.73	0.67	2.75	0.66	28.09	113.95	79.46	10.83	4.47	1.52
	2	2.04	1.12	1.56	0.42	1.16	3.18	34.63	105.80	43.90	7.09	4.41	1.15
	3	1.42	0.72	0.80	0.28	2.59	13.62	55.66	100.10	22.55	4.07	2.69	0.86

Continued.....

Table A.2 (continued)

Year	Period	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
	1	0.85	0.43	0.23	0.72	0.20	0.73	21.18	83.05	74.81	15.13	11.49	3.20
1977	2	0.68	0.34	0.21	0.22	0.82	3.72	39.16	221.40	49.87	15.25	5.32	3.02
	3	0.55	0.30	0.18	0.08	0.24	11.32	84.21	172.39	25.18	12.56	3.93	2.49

Table A.2

Upper Atbara, 10-day flows
(million m^3/day)

Year	Period	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1956	1	...	...	...	...	...	...	33.50	67.00	96.80	38.00	5.62	1.30
	2	...	...	...	...	...	...	37.20	82.10	63.00	19.90	3.90	1.00
	3	...	...	...	...	...	...	55.30	90.70	44.10	15.60	2.16	0.78
1957	1	0.35	–	...	...	...	–	6.50	34.60	66.50	6.05	0.86	0.26
	2	0.26	–	...	...	...	–	14.70	63.10	29.40	3.02	0.52	–
	3	–	–	...	...	...	–	21.60	89.00	11.20	1.30	0.35	–
1958	1	–	–	...	...	...	0.78	18.14	77.86	66.96	10.37	2.16	0.26
	2	–	–	...	...	...	3.02	30.67	104.04	31.54	3.46	1.30	–
	3	–	–	...	...	...	2.16	57.51	123.33	30.24	1.73	0.26	–
1959	1	0.13	–	...	...	...	–	10.40	70.90	76.90	9.50	11.70	4.30
	2	–	–	...	...	...	6.05	19.00	90.70	80.40	11.70	8.20	1.30
	3	–	–	...	...	...	17.71	58.80	177.00	29.40	13.00	4.30	0.39
1960	1	0.35	–	...	...	...	–	43.90	43.90	77.70	19.90	2.16	0.26
	2	0.17	–	...	...	...	–	30.20	38.00	48.80	6.50	0.43	0.43
	3	–	–	...	...	...	5.00	51.20	44.10	43.20	4.30	0.26	0.39
1961	1	–	–	...	...	...	–	40.60	103.70	118.00	18.10	4.32	1.70
	2	–	–	...	...	...	–	48.80	104.00	69.10	13.40	3.00	2.10
	3	–	–	...	...	...	14.70	57.90	106.00	31.00	6.10	1.70	0.78
1962	1	–	–	...	...	...	–	7.78	61.30	99.80	22.46	2.59	1.04
	2	–	–	...	...	...	–	23.33	85.54	63.90	9.50	1.73	0.43
	3	–	–	...	...	...	12.96	31.54	88.50	56.16	5.01	1.04	0.24
1963	1	–	–	...	...	...	–	9.50	64.50	74.60	16.90	2.60	1.70
	2	–	–	...	...	...	3.46	21.10	83.80	29.40	7.80	2.20	0.85
	3	–	–	...	...	...	1.73	51.71	92.40	35.40	3.90	1.70	0.47

Continued......

Table A.2 (continued)

Year	Period	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1964	1	0.26	–	...	...	...	–	8.21	...	...	21.17	6.05	2.07
	2	–	–	...	...	...	1.70	17.28	...	...	15.98	3.46	1.73
	3	–	–	...	...	...	5.62	59.20	...	...	12.27	2.59	1.73
1965	1	1.73	–	...	...	...	–	10.90	44.60	51.00	14.69	2.59	0.78
	2	0.86	–	...	...	...	1.73	16.85	63.90	28.10	11.23	2.42	0.52
	3	0.43	–	...	...	...	6.05	33.70	63.10	16.85	4.50	1.50	0.26
1966	1	–	–	...	...	...	–	7.10	24.36	30.54	7.13	4.19	0.97
	2	–	–	...	...	...	1.73	8.06	28.63	23.88	7.34	2.48	0.71
	3	–	–	...	...	...	6.05	18.14	44.93	13.31	7.95	1.49	0.48
1967	1	0.20	–	...	...	...	–	13.14	49.43	106.50	25.92	3.18	1.34
	2	0.26	–	...	...	...	–	19.18	55.04	61.78	15.55	2.03	0.91
	3	0.12	–	...	...	...	–	33.04	86.00	32.40	6.05	1.60	0.63
1968	1	0.48	0.13	...	...	...	–	19.01	51.84	24.11	16.02	2.27	0.76
	2	0.30	0.11	...	...	...	–	30.10	30.35	18.38	7.24	1.38	0.69
	3	0.19	0.08	...	...	...	8.55	47.43	54.86	16.20	4.15	1.04	0.35
1969	1	0.26	0.08	...	...	...	1.60	17.28	47.09	34.56	7.02	1.28	0.35
	2	0.17	0.07	...	...	...	9.07	36.29	79.50	40.90	4.06	1.96	0.24
	3	0.12	–	...	...	...	11.60	23.75	71.27	26.30	2.20	0.52	1.00
1970	1	0.10	0.04	...	...	...	–	2.55	41.60	62.64	13.17	4.19	0.52
	2	0.08	0.01	...	...	...	–	9.00	84.67	50.98	10.85	2.20	0.50
	3	0.05	–	...	...	...	13.00	25.90	84.67	22.98	8.90	1.33	0.42
1971	1	0.30	0.08	...	...	...	2.63	19.70	38.88	76.44	10.97	3.37	0.76
	2	0.17	0.04	...	...	...	2.12	21.60	79.49	65.66	6.26	1.84	0.48
	3	0.12	–	...	...	...	3.80	26.10	84.24	22.03	4.73	1.17	0.32
1972	1	0.24	0.08	...	...	...	–	14.77	20.10	20.30	7.02	1.08	0.30
	2	0.17	–	...	...	...	–	22.20	31.97	14.77	2.96	0.63	1.30
	3	0.11	–	...	...	...	6.37	17.06	28.12	13.60	2.00	0.43	0.08

Continued......

Table A.2 (continued)

Year	Period	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1973	1	–	–	...	...	...	–	6.90	42.98	30.72	19.18	3.28	0.91
	2	–	–	...	...	...	–	27.09	85.20	48.33	16.56	2.65	0.59
	3	–	–	...	...	...	8.90	22.25	45.08	33.19	6.13	1.54	0.25
1974	1	0.18	–	...	...	...	2.32	39.30	50.75	86.78	28.20	3.57	0.69
	2	0.14	–	...	...	...	4.49	34.95	110.75	58.00	9.29	2.29	0.39
	3	0.09	–	...	...	...	13.30	48.50	68.86	50.25	4.91	1.56	0.28
1975	1	0.18	0.02	...	...	...	0.26	14.26	70.19	154.42	37.37	5.06	1.50
	2	0.09	...	...	...	...	3.14	20.09	117.53	93.25	21.05	2.97	1.21
	3	0.05	...	...	...	...	8.57	48.49	132.05	67.34	9.09	2.13	1.03
1976	1	0.47	0.19	...	...	...	0.59	28.00	74.70	54.00	12.40	3.45	0.41
	2	0.38	0.10	...	...	...	2.25	31.40	59.70	35.70	8.00	2.40	0.19
	3	0.33	0.05	...	...	...	13.75	39.45	76.09	21.00	4.75	1.13	0.05
1977	1	...	...	...	...	...	–	16.30	42.40	55.60	18.05	6.05	0.75
	2	...	...	...	...	...	6.56	22.80	124.40	41.60	21.20	2.90	0.37
	3	...	...	...	...	...	10.90	57.36	65.36	24.65	12.68	1.45	...

Table A.3

Meteorological data for Halfa, 1976-77

		Mean max temp	Mean min temp	Rel. humid. @ 0800	Wind speed knots	Sunshine hours	%	Evap. Penman mm	Class A Pan, mm
1976	Jan	33.4	15.1	65	7.4	10.4	92	179	279
	Feb	34.5	15.0	65	7.7	10.1	87	197	313
	Mar	39.3	19.5	43	6.8	9.7	80	274	440
	Apr	40.7	21.9	33	6.1	10.4	84	290	486
	May	42.3	26.3	35	5.3	10.7	84	311	505
	Jun	40.9	25.7	39	7.5	9.8	75	311	543
	Jul	35.8	22.7	69	7.1	7.5	58	236	344
	Aug	37.2	22.8	66	7.6	9.3	72	267	384
	Sep	37.3	22.9	57	6.3	8.6	70	246	297
	Oct	39.1	23.0	55	5.4	9.1	80	244	344
	Nov	36.8	20.3	58	4.9	10.2	90	204	306
	Dec	35.5	18.5	63	5.7	9.7	87	189	310
1977	Jan	32.3	13.3	52	6.8	10.2	90	193	301
	Feb	35.1	16.4	53	7.4	10.1	86	192	319
	Mar	38.3	19.3	20	7.9	9.7	81	302	422
	Apr	40.3	19.4	23	6.4	10.5	84	289	468
	May	41.4	24.8	31	6.1	9.3	73	303	546
	Jun	40.2	25.7	46	9.4	8.8	67	315	492

Continued......

Table A.3 (continued)

	Mean max temp	Mean min temp	Rel. humid. @ 0800	Wind speed knots	Sunshine		Evap. Penman mm	Class A Pan, mm
					hours	%		
Jul	37.3	23.9	64	10.7	7.6	59	277	372
Aug	34.9	22.5	75	8.1	7.7	62	232	242
Sep	38.8	23.9	61	6.0	9.8	80	262	348
Oct	37.4	21.6	49	5.5	9.4	80	231	344

Notes:

The average dry bulb temperature at 0800 is assumed to be mean of the average daily maxima and minima. The proportion of incoming radiation received at surface is estimated from recorded sunshine and latitude:

$$RC/RA = 0.29 \cos. \text{latitude} + 0.52\, N/NN$$

The latitude of Halfa is 15°19' N. N/NN is the ratio of recorded hours of sunshine to the maximum possible.

Table A.4

Monthly rainfall totals (May-Oct) at Showak and Khashm el Girba/New Halfa

	Showak						Khashm el Girba/New Halfa					
	May	Jun	Jul	Aug	Sep	Oct	May	Jun	Jul	Aug	Sep	Oct
1941	...	...	19	70	8	...	80	89	79	221	94	7
1942	3	17	81	–	98	10	89	1	209	87	159	6
1943	...	...	91	–	196	21	15	...	166	79	53	30
1944	...	21	137	207	15	9	...	11	103	68	...	...
1945	29	42	63	343	114	32	59	14	109	272	24	5
1946	...	88	205	200	100	3	4	59	112	271	171	6
1947	...	59	85	241	55	...	...	12	167	160	63	...
1948	...	60	163	236	122	3	14	48	17	129	42	12
1949	32	94	160	115	83	49	3	18	140	162	21	16
1950	...	80	164	202	135	...	...	41	333	140	71	...
1951	66	4	196	152	76	1	13	...	55	113	47	17
1952	9	45	244	197	119	...	9	24	87	113	43	11
1953	100	253	246	214	72	4	26	32	176	157	82	...
1954	...	...	359	190	88	...	41	94	285	59	119	1
1955	...	35	160	140	105	...	...	9	110	132	46	...
1956	...	56	118	243	31	14	...	18	162	113	70	6
1957	...	...	206	145	50	...	...	41	59	181	52	...
1958	...	105	204	75	39	9	...	53	161	107	76	...
1959	18	40	161	326	63	9	...	16	63	115	56	...
1960	–	115	169	203	–	–	11	12	96	84	97	...
1961	193	69	238	247	...	...	...	...	179	163	18	...
1962	...	–	170	135	118	...	...	1	106	113	69	...
1963	...	–	199	97	–	...	21	1	33	126	38	1
1964	...	41	105	296	85	...	–	–	78	102	47	...
1965	62	72	150	174	67	20	1	3	58	99	41	39
1966	21	2	104	172	8	27	2	21	36	97	36	25
1967	...	95	39	170	74	32	2	36	61	87	112	46
1968	19	156	85	63	...	...	...	101	84	180	...	...
1969	41	102	65	157	56	20	1	38	59	169	24	...
1970	2	35	65	338	...	37	6	...	149	75	32	35
1971	17	46	78	213	62	...	10	28	186	87	61	7
1972	9	86	151	191	13	...	5	117	52	116	14	31
1973	42	32	105	201	137	...	16	16	95	49	27	2
1974	8	112	85	123	32	18	31	61	177	160	19	7
1975	...	73	77	104	119	...	...	33	12	232	62	...
1976	4	51	342	128	68	20	...	22	93	133	29	3
1977	5	58	200	163	15	28	...	6	78	57	...	...

Table A.5

Khashm el Girba main canal releases 1970-77
(million m^3)

	Jul				Aug				Sep			
	1	2	3	Σ	1	2	3	Σ	1	2	3	Σ
1970	...	...	...	86	...	...	...	63	...	...	...	109
1971	...	...	...	62	...	...	...	64	...	...	...	112
1972	14	26	16	56	34	26	39	99	47	50	62	159
1973	51	38	19	108	24	25	36	85	52	52	48	152
1974	28	30	22	80	14	21	25	60	43	50	53	146
1975	44	49	48	141	23	21	7	51	10	18	32	60
1976	30	32	37	99	20	33	46	99	35	30	43	108
mean	33	35	28	90.	23	25	31	74	37	40	48	121
s.d.	13	8	12	27	7	4	14	18	15	14	10	32

	Oct				Nov				Dec			
	1	2	3	Σ	1	2	3	Σ	1	2	3	Σ
1970	...	...	...	164	...	...	...	197	...	...	...	203
1971	...	...	...	161	...	...	...	189	...	...	...	187
1972	74	73	60	207	59	58	59	176	55	58	55	168
1973	54	63	73	190	71	72	68	211	64	62	69	195
1974	65	59	75	199	80	69	72	221	67	63	69	199
1975	40	63	70	173	65	74	72	211	67	63	72	202
1976	64	67	77	208	71	71	69	211	68	69	70	207
mean	59	65	71	186	69	69	68	202	64	63	67	194
s.d.	12	5	6	18	7	6	5	14	5	4	6	12

	Jan				Feb				Mar			
	1	2	3	Σ	1	2	3	Σ	1	2	3	Σ
1971	...	...	...	171	...	...	...	128	...	...	...	75
1972	...	...	...	152	...	...	...	139	...	...	...	63
1973	41	24	33	98	35	22	17	74	11	10	12	33
1974	48	50	56	154	41	37	26	104	32	50	13	95
1975	62	56	56	174	47	41	27	115	20	12	14	46
1976	62	54	55	171	50	45	37	132	32	24	20	76
1977	55	47	48	150	44	41	31	116	32	22	23	77
mean	54	46	50	153	43	37	26	115	25	24	16	66
s.d.	8	12	9	24	5	8	7	20	8	14	4	19

Continued......

Table A.5 (continued)

	Apr				May				Jun			
	1	2	3	Σ	1	2	3	Σ	1	2	3	Σ
1971	...	...	...	44	...	...	...	42	...	...	...	41
1972	...	...	...	52	23	21	24	68	23	23	16	62
1973	11	12	13	36	13	11	12	36	13	27	41	81
1974	12	12	11	35	13	13	14	40	19	33	33	85
1975	12	12	13	37	13	14	15	42	17	27	36	80
1976	17	16	15	48	15	13	15	43	19	26	32	77
1977	15	16	15	46	15	15	17	47	24	35	39	98
mean	13	14	13	43	15	15	16	45	19	29	33	75
s.d.	2	2	1	6	4	3	4	10	4	4	8	17

	Year (Jul-Jun)
	1323
	1311
	1223
	1454
	1399
	1385
	1466
mean:	1366
s.d:	80

Table A.6

Average reservoir levels (L, metres AOD) and downstream releases (Q, million m^3) by 10-day periods for Khashm el Girba, 1972-77

		1972		1973		1974		1975		1976		1977	
		L	Q	L	Q	L	Q	L	Q	L	Q	L	Q
Jan	1	465.6	-	469.8	2.9	470.5	-	470.4	...	...	...	471.4	1.7
	2	465.5	-	469.4	2.7	470.0	-	469.8	...	...	...	471.0	1.7
	3	...	-	478.9	3.0	469.4	-	469.9	...	...	...	470.5	1.9
Feb	1	...	...	478.4	3.3	468.6	-	468.6	...	471.2	1.6	470.1	1.6
	2	...	...	462.9	3.7	468.5	-	468.1	...	470.8	1.6	469.7	1.6
	3	...	...	467.6	2.9	468.0	-	467.7	...	470.4	1.4	469.3	1.3
Mar	1	...	...	467.2	3.4	467.6	-	467.3	1.1	470.1	2.0	468.9	1.5
	2	464.0	...	467.0	0.9	467.3	0.9	467.0	0.2	469.8	3.8	468.5	1.5
	3	...	...	466.7	0.3	467.0	-	466.8	2.2	469.6	5.0	468.2	1.7
Apr	1	...	...	466.5	0.2	466.8	-	466.5	0.9	469.4	4.2	468.1	1.4
	2	...	...	466.1	0.3	466.5	-	466.2	2.8	469.2	4.1	467.9	1.4
	3	...	...	466.6	0.3	466.3	-	465.9	-	468.9	4.0	467.6	1.4
May	1	465.4	4.7	465.5	2.2	...	-	465.8	-	468.8	4.5	467.3	1.3
	2	462.6	5.1	465.4	0.3	465.6	0.9	465.6	-	468.7	6.0	467.2	1.3
	3	464.4	5.7	465.2	1.1	465.6	4.8	465.2	1.3	468.6	7.0	467.0	1.4
Jun	1	463.7	6.4	...	...	465.8	5.3	464.9	7.8	478.0	6.1	466.7	1.2
	2	462.5	7.8	465.5	4.2	465.9	4.8	464.9	19.4	476.1	100.3	466.7	1.2
	3	463.5	242.8	465.1	7.3	466.6	1177.5	466.1	114.8	476.1	268.7	468.5	93.6
Jul	1	462.4	5.9	465.7	37.4	463.1	1065.7	464.7	377.6	463.2	570.7	...	...
	2	461.8	7.9	463.4	810.9	462.3	1486.4	465.0	600.3	463.3	623.1	...	...
	3	462.4	2.4	457.5	1120.7	464.9	1904.5	463.2	1126.5	463.2	1061.3	...	...
Aug	1	462.6	8.9	462.1	2145.0	457.2	3303.5	463.6	224.8	458.8	1750.8	455.8	1360.0
	2	462.8	1067.8	465.9	2336.7	465.6	1858.4	462.3	12.1	462.9	1605.3	464.8	3297.9
	3	464.7	540.8	466.8	1037.1	460.7	1285.0	462.0	3873.3	463.0	1400.4	460.9	2549.2

Continued.....

Table A.6 continued....

	1972		1973		1974		1975		1976		1977	
	L	Q	L	Q	L	Q	L	Q	L	Q	L	Q
Sep 1	470.5	3.7	471.5	324.7	469.8	976.0	462.0	8.3	473.8	1133.3	467.7	677.2
2	472.8	232.3	472.8	793.6	472.1	647.6	465.5	1793.9	471.1	282.2	472.0	470.6
3	473.1	175.7	473.0	431.1	472.8	341.2	471.1	920.1	473.0	245.1	473.1	294.8
Oct 1	468.2	40.7	473.1	186.0	463.1	75.5	472.9	565.1	473.3	103.1	473.3	166.0
2	473.2	3.3	473.3	169.3	463.1	5.5	473.1	284.8	473.4	46.0	473.4	206.8
3	473.2	2.0	473.3	23.5	473.2	0.7	473.3	88.9	432.4	6.8	473.4	135.3
Nov 1	472.9	2.8	473.2	4.5	473.1	-	473.4	41.0	473.3	1.4	473.4	60.4
2	472.7	2.8	472.9	1.2	472.8	-	473.4	24.0	473.3	1.4	473.3	6.1
3	472.7	-	472.5	-	472.4	-	473.3	1.4	473.1	1.4	473.2	4.7
Dec 1	471.4	2.8	472.1	-	472.5	-	473.1	1.7	472.8	3.8	...	...
2	470.8	2.8	471.6	-	471.5	-	472.9	1.7	472.3	3.2	...	...
3	470.2	3.1	471.1	-	470.9	-	472.6	1.9	471.8	2.4	...	...

SUDAN

New Halfa rehabilitation scheme

ANNEX 2

APPENDIX B

Extension of Setit and Upper Atbara records

Records of the natural flow of the River Atbara near its confluence with the Nile have been collected during the period 1903 to 1977. Examination of the available streamflow measurements and water level data for the period 1974 to 1977 showed them to be inadequate to produce reliable flow estimates during this period. As a result, reliable flow records exist only for the period 1903 to 1973. Records for the gauging stations of particular interest during this study on the Upper Atbara and the Setit, only exist for the period 1957 to 1977. For operational studies it was decided that an extended, 50 year record at these upper gauging stations would be desirable, to be produced by correlation with the existing long-term record near the mouth of the Atbara.

The model used in this data extension exercise is a multivariate lag-one Markov model, and enables cross-correlations between concurrent flows at the three gauging stations (ie, lag-zero cross-correlations) as well as lag-one serial correlations within the individual station records to be preserved in the extended flow sequences. The model takes the general matrix form:

$$\underline{x}_t = \underline{A}\,\underline{x}_{t-1} + \underline{B}\,\underline{\varepsilon}_t \qquad (1)$$

where $\underline{x}_t$ is an (nx1) vector of standardized values at time t, with

$$x_t^i = \frac{(z_t^i - \mu_i)}{\sigma_i}$$

$\underline{A}$, $\underline{B}$ are (nxn) matrices containing the parameters of the model and $\underline{\varepsilon}_t$ is an (nx1) vector of independent random elements; n is the number of stations.

For the present exercise it is assumed that the matrix $\underline{A}$ is diagonal, and that the matrix $\underline{B}$ has a lower triangular form; with three gauging stations equation (1) can be written in full as:

$$x_t^A = a_{11}x_{t-1}^A + b_{11}\varepsilon_t^A$$

$$x_t^S = a_{22}x_{t-1}^S + b_{21}\varepsilon_t^A + b_{22}\varepsilon_t^S$$

$$x_t^U = a_{33}x_{t-1}^U + b_{31}\varepsilon_t^A + b_{32}\varepsilon_t^S + b_{33}\varepsilon_t^U$$

where x_t^A is the flow in the Atbara near the mouth at time t

x_t^S is the flow in the Setit at time t

x_t^U is the flow in the Upper Atbara at time t.

The lag-one serial correlation for each flow series is preserved by the elements of the $\underline{A}$ matrix, and the lag-zero cross correlations between the series are maintained through the elements of the $\underline{B}$ matrix.

This method of analysis can only be applied to what is known as a stationary series, that is one with seasonal effects removed. Before doing this a logarithmic transformation was applied to the basic flow data (q_t) to give a series which was assumed to be normally distributed:

$$z_t = \log_e q_t$$

This series was then standardised by removing the mean (μ_j) and standard deviation (σ_j) of the transformed flows for the month (j) in which the transformed flow Z_t occurs, giving:

$$x_t = \frac{Z_t - \mu_j}{\sigma_j}$$

As formulated in (1) the model is unable to cope with periods of zero flow and so a method of lumping together the months of the dry season was adopted to produce a seven season year. The seasons were:

- April-June
- July
- August
- September
- October
- November
- December-March.

This successfully eliminated all periods of zero flow.

Lag-zero cross correlations and lag-one serial correlations were calculated for each season for the period of common record of the three stations 1957 to 1973, (Tables B1 and B2).

Tables B1 and B2 illustrate that it would be unrealistic to assume that both the cross-correlation and serial correlation remained constant throughout the year. As a result, for record extension purposes, the year was finally split into four periods during which the correlations remained fairly constant. The periods selected were:

- August to November
- December to March
- April to June
- July.

Table B1

Lag Zero Cross Correlations

Stations	Apr-Jun	July	Aug	Sep	Oct	Nov	Dec-Mar
Upper Atbara and Atbara	-0.3636	0.7941	0.8768	0.7749	0.6116	0.3588	0.0794
Setit and Atbara	-0.1653	0.5607	0.9243	0.8449	0.7629	0.5356	0.2596
Setit and Upper Atbara	0.2264	0.5966	0.7764	0.8313	0.8465	0.5523	0.5313

Table B2

Lag One Serial Correlations

Stations	Apr-Jun to July	Jul to Aug	Aug to Sep	Sep to Oct	Oct to Nov	Nov to Dec-Mar	Dec-Mar to Apr-June
Setit	0.1214	0.3429	0.7582	0.7135	0.7902	0.9084	-0.5092
Upper Atbara	0.2418	0.4353	0.7073	0.5825	0.7298	0.8015	-0.1840
Atbara	-0.1435	0.2605	0.6578	0.8830	0.8529	0.8765	-0.0272

The matrices $\underline{A}$ and $\underline{B}$ had then to be calculated separately for each period. The $\underline{A}$ matrix contains the lag-one serial correlation coefficients as its diagonal terms. This is to preserve the serial correlation in the resulting series. The calculation of the elements of the $\underline{B}$ matrix is more involved. It can be shown that the equation to be solved is:

$$\underline{BB}^T = \underline{M}_o - \underline{AM}_o{}^T\underline{A}$$

where $\underline{M}_o$ is the lag-zero cross correlation matrix and the superscript T denotes the transpose of the matrix. From knowledge of the elements of the (BB^T) matrix, the elements of the assumed lower triangular matrix $\underline{B}$ can be calculated.

When generating the extended flow records the equations quoted earlier can be rearranged slightly to give:

$$\varepsilon_t^A = (x_t^A - a_{11}x_{t-1}^A)/b_{11}$$

$$x_t^S = a_{22}x_{t-1}^S + b_{21}\varepsilon_t^A + b_{22}\varepsilon_t^S$$
$$s_t^U = a_{33}x_{t-1}^U + b_{31}\varepsilon_t^A + b_{32}\varepsilon_t^S + b_{33}\varepsilon_t^U$$

to make use of the knowledge of the Lower Atbara record.

The elements ε_t^S and ε_t^U were generated as pseudo-random numbers from a normal distribution of zero mean and unit variance, to account for the unexplained variance in the extended records.

Having generated the flows for each season of the extended record, the flows had to be broken down into monthly values when seasons contain a number of months. This was done in two main steps, firstly by deciding whether or not a monthly flow should be zero and secondly what its magnitude should be.

The first step was achieved by examining the historical record for occurrences of zero flow in each month. For the April to June season the records indicated that both the Setit and Upper Atbara always remain dry during April and May. The December to March season was handled by calculating for each month the probability (P_O) of the flow in that month being zero, given that the flow in the previous month was non-zero. Within this season, a month of zero flow was always followed by another month of zero flow. Thus, for any month, the probability of non-zero flow is zero if the previous month had zero flow and $(1-P_O)$ if the previous month had non-zero flow.

When generating a 'dry season' monthly value, a uniformly distributed random number in the range (0,1) was generated. If this was less than the probability of a zero value, a zero value was generated, otherwise a non-zero value was generated as follows. For each dry season month a logarithmic transformation was applied to the non-zero flows and the mean and variance deduced on a monthly basis. A non-zero flow in that month was then generated by sampling a pseudo-random number from a normal distribution of mean zero and unit variance; this was then transformed to have the historic mean and variance. The generated monthly flows for the season are then adjusted by a common factor to ensure that the sum of the monthly flows equals the generated season total.

The monthly flow generation model was tested by generating 50 sequences of flow data for the most recent seventeen years of reliable data for the Lower Atbara gauging station. The historical data available for the upper gauging stations were then tested statistically to see if they could reasonably have come from the population of 50 generated sequences. The most important results of this comparison are summarised in Table B3.

Table B3
Comparison of historical and synthetic data
Monthly inflow, million m^3

Month	Generated Data		Historical Data
	Mean	Standard Deviation	Mean
Jan	30.4	4.1	30.3
Feb	14.0	2.0	14.5
Mar	–	–	–
Apr	–	–	–
May	–	–	–
Jun	248.2	108.9	191.2
Jul	2130.7	134.4	2209.0
Aug	5924.6	450.6	5889.0
Sep	3179.2	296.0	3289.0
Oct	569.3	58.7	619.0
Nov	151.2	15.0	161.0
Dec	67.9	7.3	70.2
Oct-May	827.8	74.5	889.6

Examination of the total flow during the months October to May was included as this proved to be the critical flow period for the reservoir simulation study. Statistical tests show that the hypothesis that the historical data come from the population of generated sequences cannot be rejected (at the 10% level) in any of the comparisons made, which included comparison of the maximum annual and minimum annual flows in each sequence.

The generated monthly totals were then broken down into 10-day flows. It was assumed that generally the flows will be distributed within the month in the same proportions as the flow at the Lower Atbara gauging station. This assumption, however, proved to be too general and had to be refined in months where the smallest 10-day flow recorded at the lower gauging station was less than 15% of the total monthly flow.

The refinement adopted was to assume that the 10-day flows varied geometrically (ie, by a common factor) throughout the month. If the final 10-day flow of the previous month is denoted by p, and the total flow in the current month by M, then the common factor assumed, r, can be found using:

$$r = \sqrt{\frac{M}{3p}}$$

The first approximation to the three 10-day flows are then (Pxr), (Pxr^2) and (Pxr^3). These estimates are revised by a common factor to ensure that the sum of the 10-day flows equals the calculated total monthly flow.

A number of sequences of 10-day flows for the Upper Atbara and Setit gauging stations were generated by sampling different series of values of ε_t^S and ε_t^U in order to explore the sensitivity of the reservoir simulations to the variance of these terms.