THE TRAINING OF THE UPPER NILE

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PREFACE

MANY engineers have worked on the Upper Nile Problem since Sir William Garstin's day, and the Author has freely borrowed from their work, ideas, and researches. Chief among them is Sir Murdoch MacDonald, who was the first to bring down to figures Egypt's final water needs and the first to point out the urgency of meeting them. The Sennar Dam, the conception of a high dam at Gebel Aulia, and the Gezira Cross Cut are all due to him, and the idea of a Bahr el Ghazal Collector Channel is also his.

The first Inspector General of Irrigation in the Sudan was Mr. C. E. Dupuis, later Adviser to the Ministry of Public Works, Egypt, and to him is due the founding of the organization that has carried out subsequent surveys and designs. In 1904, when Mr. Dupuis founded the Service, the country was savage, unexplored, unhealthy, and largely unsettled, but he nevertheless, with unerring insight, selected the right points for the establishment of river gauging stations—none of those he selected has been abandoned, all have been found essential. He started the essential surveys and laid down lines on which Garstin's projects were to be worked out and theories for guidance, which have never led subsequent workers astray. Mr. Dupuis was succeeded by Mr. P. M. Tottenham, C.B.E., afterwards Under-Secretary of State to the Ministry of Public Works, Egypt, who was able to bring the projects for Sennar Dam, Gezira Irrigation Scheme, and Gebel Aulia Dam to an advanced state and made substantial progress with the Sudd Channel Scheme.

After the War, Mr. W. D. Roberts, Mr. G. Parker, and the Author were successive Inspectors-General. Under both the former the work of hydrological and geographical survey was greatly extended and systematized. Mr. Roberts brought the Gebel Aulia Dam Scheme to the point of calling for tenders and advanced the Bor-Zeraf Diversion Canal Project to the point of inception, while Mr. Parker opened up the unexplored region between the Bahr el Gebel and River Pibor and worked out the Veveno Project.

The Author is very specially indebted to the work of Dr. H. E. Hurst, C.M.G., Director-General of the Physical Department of the Egyptian Government, and to Mr. A. D. Butcher, C.B.E., Director-General Southern Nile. Dr. Hurst's travels in the Lake Plateau and his work on Lake Victoria and Lake Albert, on the general question of Sudd losses and on many details of this complicated question have been freely used. Mr. Butcher's critical analyses of the hydrologic data of every section of the Sudd Region, especially the Bor-Zeraf Cuts reach and his investigations of transmission and Sudd losses and of the possibilities of the Bahr el Ghazal, have killed many a false conception, while his work on the actual regulation of Sennar Dam, and the future regulation of the dams at Gebel Aulia, Lake Albert, and Lake Tsana have been of international value. The Jonglei Diversion Canal Project is also due to him.

Finally, the Author wishes to express his sincere thanks to Mohamed Saad Hawas Effendi, M.Eng., Director of the Central Hydrologic Office at Khartoum, for his constant and able assistance in digesting and controlling the masses of data now available and working them up to furnish the tables and statistics used in this book, besides preparing the maps and diagrams. It is hoped that due to his vigilance all relevant data have been taken into account and all irrelevant data excluded.

The manuscript for this book was originally prepared in April, 1937, just before the Author retired from the service of the Egyptian Government. Meanwhile the work of study of the Upper Nile problem has gone on actively. Consequently many of the points referred to in the book as being undecided or under study have in fact been settled. It is understood also that the Egyptian Government has reached a tentative decision on which the Sudd Project is to be adopted.

Despite all the foregoing acknowledgments, the Author is solely responsible for the use made of the work and theories of the engineers mentioned, as he may have used them in a context their authors did not intend and drawn from them deductions they would not support.

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THE TRAINING OF THE UPPER NILE

CHAPTER I

INTRODUCTION

Sir William Garstin's Proposals. The vital importance to Egypt of controlling the upper waters of the Nile has always been recognized by Egypt's rulers. As soon as the Sudan was reconquered from the Khalifa, Sir W. Garstin, Adviser to the Egyptian Ministry of Public Works, visited not only the Lake Plateau of Central Africa where the Nile has its source, but also traversed the whole course of the river in the Sudan. The results of his observations and his recommendations are embodied in a Blue Book, *Report on the Basin of the Nile*, published in 1904. The recommendations for control works contained in that volume have served as the basis for all subsequent work, and the experience of thirty years shows that Garstin's vision was so clear that there has been no need to change the general lines then laid down.

The works he considered to be necessary were—

1. A dam controlling Lake Albert.
2. The training of the Upper Nile through or round the marshes of the Bahr el Gebel.
3. A dam on the White Nile near its mouth.
4. A dam and barrage on the Blue Nile near Sennar to command the Gezira.
5. A dam to control Lake Tsana in Abyssinia (see map, Fig. 1).

Lake Albert was to store the water now poured uselessly into the swamps of the Upper Nile; a new channel was to be cut to allow the stored water to reach the White Nile and Egypt without undue loss; the White Nile Dam was to control and conserve the early flood waters of the White Nile and River Sobat for Egypt; the Sennar Dam and barrage were to be of local utility for the benefit of the Sudan Gezira, and Lake Tsana was to be made into a reservoir to store part of the flood water of the Blue Nile for the benefit both of Egypt and the Sudan.

In 1920 Sir M. MacDonald, K.C.M.G., C.B., at that time Adviser to the Egyptian Ministry of Public Works, put forward his proposals for the development of the Nile Basin in a work called *Nile Control.** The Sennar Dam Project, Gezira Irrigation Scheme, and the White Nile Dam Project were well advanced by then and fully described. The Sudd Channel Project was discussed in general terms and the need for more study was stressed, while a further structure, the Nag Hammadi Barrage on the Nile in Egypt, was included in the list of necessary major works.

Sir M. MacDonald dealt very fully with the questions of Egypt's future requirements of water, but his figure for the future total was increased by the International Commission on Nile Control appointed by the Egyptian and Sudan Governments to advise them on the series of works recommended. He was able to show that if these works were carried out, so as to result in the full development of all cultivable areas in Egypt, and were completed by 1955, the increase in production would only just keep pace with the increase in population. The Nile Control Commission approved the works proposed, and since then Sennar Dam, Nag Hammadi Barrage, and Gebel Aulia Dam have been completed and, in addition, a second heightening of Aswan Dam, but there is no prospect of the whole programme being completed by the year 1955.

In this book the chief concern will be with the second of Sir W. Garstin's list of works, the training of the Upper Nile, but some description and discussion of the remainder is necessary for an understanding of the present regime of the river and the changes necessary to make the best possible use of the water for the benefit of agriculture in Egypt.

General Description of the River—the Lake Plateau (Map, Fig. 1). The source of the Nile is at the head of the River Kagera, over 6 500 km. from the sea. This river enters Lake Victoria on its western shore, and the Victoria Nile flows out of this lake at the north end over the Ripon Falls, on through swampy Lake Kioga, over the Murchison Falls, and so enters Lake Albert at its northern end.

The Albert Nile. The Albert Nile issues from this lake at a distance of only 3 or 4 km. and flows in a swampy channel to Nimule, the Sudan frontier, which is the first place where the river has been regularly measured.

Nimule to Bor. Our knowledge of its hydrology above this point is based on a few scattered discharge observations and observations of rainfall and lake gauges, but from Nimule

* Egyptian Government Press, 1921.

onwards there are numerous regularly recorded gauges, and less frequent sites where discharges are regularly observed. Such discharge stations were first started on the Upper Nile in 1922, and have since been gradually increased in number, but the period during which the observations have been taken is not yet in all cases long enough to give reliable mean values, nor does it take in sufficient abnormal years.

After Nimule, the river, now known as the Bahr el Gebel, plunges over the Fola Cataract and numerous other rapids to Rejaf, whence it is navigable all the way to Khartoum.

On the reach between Lake Albert and Rejaf numerous streams join the river, all of which are torrents, being mostly quite dry in summer (though a few have a small flow at that season), but carrying a heavy discharge in flood. What proportion their contribution bears to the total flow in the river can now be estimated with fair accuracy despite the absence of exact knowledge of the discharge leaving Lake Albert, and the fact that their flow, far from being negligible, is of considerable importance, is one of the main points that has been brought to light in the last few years.

The river is regularly measured at Mongalla some distance below Rejaf, where it is considered complete, i.e. as carrying all the water that reaches the Nile from the Lake Plateau basin; as after Mongalla there are no more tributaries from this catchment, though some of the rivers of the Bahr el Ghazal basin flow into the Bahr el Gebel swamps.

The Swamps. Below Rejaf the river flows in a valley that becomes more and more swampy till beyond Bor the real swamps of the Upper Nile are entered, known as the Sudd Region. The area of these swamps varies with the level but probably averages about 6 000 to 7 000 km.^{2} They contain two fairly large islands —solid land which is dry at low water—but there are only three or four small patches of land which are dry at all stages of the river level. The main channel of the river became completely closed by *sudds* of floating vegetation during the Mahdi's rebellion and the first step taken by the Egyptian Government after the reconquest was the removal of these *sudd* blocks (hence the name of the region) which, however, are still liable to recur. The Bahr el Gebel now flows through the swamps in one main stream with many side channels leaving and rejoining it, so that its section and discharge are continually varying. In the lower 300 km. one of these side branches becomes a definite separate stream, the Bahr el Zeraf, which trends away from the Bahr el Gebel in its own valley, being for the latter part of its course a clearly defined stream running through solid land.

The White Nile and Bahr el Ghazal. The swamps end at Lake No, where the Bahr el Ghazal joins the Bahr el Gebel to form the White Nile, the Bahr el Zeraf entering the latter river about 80 km. farther on. Such water as issues from the swamps does so through the Bahr el Gebel and Bahr el Zeraf, but a very large proportion of the amount passing Mongalla has been lost, amounting on the average to about half, i.e. about fourteen thousand millions of cubic metres annually. How firstly to prevent this loss, and secondly to make the water thus saved available for irrigation in Egypt in accordance with the seasonal requirements of cultivation, is the problem of the Upper Nile.

The Bahr el Ghazal drains a very large area with a heavy rainfall, but the country is mostly flat and the swamps are extensive, so that the present contribution of this river to Egypt's water supply is negligible.

From Lake No to the River Sobat confluence the White Nile, joined by the Bahr el Zeraf, flows in a wide shallow valley with swampy berms and islands.

The River Sobat. The River Sobat is the main tributary of the White Nile, providing about half its annual discharge at this point, and, though its discharge near the mouth has been measured regularly for many years, little is known of the hydrology of its upper reaches, which are in Abyssinia. It is formed by the junction of the Rivers Baro and Pibor, the latter having many small tributaries, while both flow through extensive swamps.

The River Baro suffers in the autumn losses which, although small compared with those of the Bahr el Gebel swamps, probably amount to about two milliards* of cubic metres per annum, a valuable potential contribution to Egypt's water supply.

After the River Sobat mouth the channel of the White Nile becomes less swampy, though very wide and shallow, until it enters what may be called the desert reach near Kosti. A little above Kosti is the rocky hill, Gebelein, with rock outcrops in the river bed nearby which form a possible site for a dam to make a reservoir of about one to one and a half milliard cubic metres capacity.

The Kosti Reach to Gebel Aulia. From Kosti onwards the river is still wide and shallow, but swamp has quite disappeared and the banks are flat beaches of somewhat sandy soil. This reach

* One milliard = one thousand million.

forms a natural reservoir, as the slope of the river here is very flat. As the Blue Nile, which joins the White Nile at Khartoum to form the Main Nile, has a steep slope and rises very rapidly in flood, the effect is to dam up the water of the White Nile and form a pond of still water in the valley of this river extending for over 200 km. from the junction. At 47 km. above Khartoum on the White Nile is situated Gebel Aulia, where a dam has just been completed by the Egyptian Government to make use of some of the advantages of the features of the White Nile Valley, by turning this natural reservoir into a much larger artificial one.

The Blue Nile. The Blue Nile rises at Lake Tsana in Abyssinia, though only a small part of its water comes from the lake, most coming from large torrential tributaries of which two, the Rahad and the Dinder, join it within the Sudan frontier. The construction of a dam at Lake Tsana is included among the projects proposed for obtaining complete control of the Nile, while a dam was completed at Sennar on the Blue Nile (359 km. from Khartoum) in 1925, where water is stored in flood to irrigate cotton in the Gezira plain of the Sudan during the following spring.

The Main Nile and River Atbara. The Main Nile has only one tributary, the River Atbara, which joins it about 300 km. below Khartoum and after its confluence the river flows on to Egypt without further additions, and so through the Rosetta and Damietta branches to the sea.

Effect of Silt. The Blue Nile and Atbara are rivers whose flow varies very greatly in quantity during each year, the latter having none at all in the summer; and moreover, while the low water supply is clean and free of silt, the flood waters are heavily laden with the rich silt that has formed Egypt.

Because of this suspended silt, the velocity of the current of these rivers should not be checked in full flood by dams, for heavy deposits of silt might choke the reservoirs formed; the water of the White Nile, however, having been filtered by its long slow passage through swamps is practically free of silt and therefore a dam built on that river can operate at any season. The importance of this point is very great and constitutes the chief value of Gebel Aulia on the White Nile as a reservoir site.

The famous Aswan Dam is situated in Egyptian territory, 1 550 km. below the Atbara confluence on the Main Nile, which is practically as silt-laden as the Blue Nile and Atbara, its main tributaries in flood; hence filling operations should not normally begin at Aswan till October, when the flood is past its peak.

Tables I and II in the Appendix give the chief data concerning the flow of the Nile, namely distances of the chief points and variations of flow at salient points.

Table III in the Appendix, which is compiled from Mr. J. D. Atkinson's *Handbook of Egyptian Irrigation*, Part I,* gives the percentage of the total flow passing each salient point in the basin, both in flood and summer on the average. The river is taken to be 100 per cent at Atbara in flood, and 100 per cent at Aswan in summer.

* Egyptian Government Press, 1934.

CHAPTER II

EGYPT'S WATER REQUIREMENTS

Factors of the Problem. The first question that naturally arises is, how much water does Egypt need? with the subsidiary question of how much does she receive naturally? Egypt is almost entirely dependent on the Nile for all water, though there is a trifling amount of cultivation from rain along the Mediterranean littoral.

The water requirements have been the subject of much investigation, and estimates have been framed by many different authorities. The points that have to be decided to arrive at a final figure are—

1. Future cultivated area.
2. Water required per feddan* of cultivation.
3. Losses in canals from the head to the field.
4. Losses in the river from the point of measurement to canal head.

Each of these quantities, except the first, is largely a matter of deduction from somewhat inadequate data and could form the subject of a long paper, but it is proposed only to give the conclusion that has been officially adopted by the Egyptian Government, with a very brief indication of how the figure was reached.

Cultivable Area. About the eventual area there is very little controversy, as the cultivable area of Egypt is strictly defined, the country being an island of fertility in a sea of desert. Egypt's cultivable area consists of 7 300 000 feddans, of which at present roughly 4 300 000 feddans are under perennial cultivation, 1 000 000 feddans are cultivated under the basin system (one flooding annually), and 2 000 000 feddans are swamp and lakes in the Northern Delta. Eventually the whole of this area will be subject to perennial cultivation, except some 200 000 feddans in the north, which will be left as lakes for fishery purposes, thus giving a final perennially cultivated area of 7 100 000 feddans, of which 4 700 000 feddans will be in Lower Egypt and 2 400 000 in Upper Egypt.

Present Duty of the Water. The water actually used at main canal heads for the present perennially cultivated area in Lower Egypt is known with some accuracy, and it is assumed that the

* 1 feddan = about $1\frac{1}{16}$ acres.

area in Upper Egypt will require about 25 per cent more water at canal heads than that in Lower Egypt, while the losses in the river from Aswan to canal heads are taken as 15 per cent. The point of measurement of water reaching Egypt is the Aswan Dam, as the cultivated area above this point is trifling and the water used is included in the losses that occur between the Sudan and Egypt.

In January all canals are closed for annual clearance and maintenance, and no water is supplied for agriculture except such as is obtainable from wells sunk into the water-bearing sub-soil. Navigation must however be maintained on the Nile, which requires 75 million cubic metres per day, or, say, 2 300 millions during January. In times of stringency this can be reduced to about 50 millions per day, the remainder being retained in the Aswan Reservoir.

At present, a decree is issued annually forbidding the irrigation of fallow land (*sharaki*) from some date in April to some date in July; this measure is necessary to economize water, as during the summer every drop is required for the cotton and other summer crops. Fallow land requires very heavy watering and this cannot be permitted till the rising flood has reached a certain volume, some time towards the end of July usually. The fallow land thus watered is cultivated in food crops, and the earlier in the summer this cultivation can begin the better for the crop. The water requirements in the following table are based on the principle that watering of fallow shall not be prohibited for reasons of shortage of water, and thus allow for such irrigation to begin during June. It will almost certainly be prohibited for some period of the summer, as the existence of fallow is beneficial to the prevention of various cotton pests.

Many competent authorities consider that a very high proportion of the water used in summer is wasted by unnecessarily heavy watering and in other ways. The figure of wastage has been put as high as 30 per cent of the water passing canal heads. It is possible that this wastage may be reduced in the future, as the cultivator becomes better educated and more skilful, but it is not safe to reckon on any such economy occurring within foreseeable time.

The Sudan's Requirements. The Sudan also draws water from the Nile for irrigation, and it is estimated that by the time Egypt is fully developed the former's requirements may amount to about 6 000 million cubic metres annually, say 10 per cent of Egypt's requirements. It will be convenient to consider these requirements as occurring at Aswan (i.e. to neglect the transmission losses from Khartoum), and the figures in Table I below are given on this basis.

The totals in column 3 are rounded and adjusted to bring the total annual requirements up to a figure of 68 000 million cubic metres at Aswan. The summer requirements, February to July, are 31·7 milliards.

TABLE I

FINAL WATER REQUIREMENTS OF EGYPT AND THE SUDAN AT ASWAN FOR FULL DEVELOPMENT OF EGYPT

Millions of cubic metres
(Rounded Totals)

	Egypt	Sudan	Total
Jan.	2 300	590	2 900
Feb.	4 400	430	4 900
Mar.	4 100	470	4 600
Apr.	4 100	300	4 400
May	4 400	110	4 500
June	6 400	100	6 500
July	6 400	340	6 800
Aug.	7 300	750	8 100
Sept.	7 000	720	7 700
Oct.	7 000	750	7 800
Nov.	4 400	720	5 200
Dec.	3 700	720	4 400
	62 000	6 000	68 000

Water Available Annually. In discussing the water available to meet the above requirements we are on firmer ground, as the Nile at Aswan has been measured for many years with great accuracy and it has been possible to deduce from earlier gauge records, with fair accuracy, the discharges that occurred prior to the beginning of precise measurements. Drs. Hurst and Phillips in Vol. IV (and supplement) of *The Nile Basin** give ten-day mean discharges for the Nile (natural river) at Aswan from 1871 to 1932. Corresponding discharges for subsequent years are of course also known.

Table II (below) and Table IV (appendix) are taken from their figures, but whereas the data in *The Nile Basin* are given per calendar year, the figures in Table II are per irrigation year from August to July.

* Egyptian Government Press, 1933.

The term "natural river" indicates that the actual observed discharges have been corrected to allow for the water abstracted for storage at Sennar and Aswan; these corrected discharges show what the river would have been had there been no control works upstream the point of measurement.

TABLE II

ANNUAL DISCHARGE OF THE NILE AT ASWAN (AUGUST TO JULY) IN SIGNIFICANT YEARS
Millions of cubic metres
(Natural river)

	Period	Discharge
Average	1912–32	82 000
Lowest year	1913–14	42 000
Very low or standard year	1925–26	70 000
Good year	1914–15	90 000
Maximum year	1878–79	155 000

Table II shows that in an average year there appears to be ample water for all requirements, while even in a "very low year" there appears to be just enough. A year such as 1913–14 is of very exceptional occurrence—records indicate that its frequency is about once in every two hundred years. Table IV (Appendix), however, shows the crux of the whole difficulty of utilizing the water of the Nile, for it will be seen that even in the highest year there is a deficiency of water in some months, while in the average year there is deficiency in six months out of the eleven important ones (excluding January). On the other hand, even in the exceptionally low year, 1913–14, there was too much water in September but a deficit in the other flood months, as well as all during the summer.

Timely and Untimely Water. The following terms are useful in all discussions of water supply in Egypt—

Timely. The timely period is that during which the discharge of the natural river at Aswan is below Egypt's requirements. In an average year when Egypt is fully developed the timely period at Aswan will be from 1st February to 31st July. It is shorter at present, as Egypt is not fully developed—about March to July. Any water flowing at any point in the Nile system at such a time as to reach Aswan during this period is "timely."

Untimely. The untimely period is that part of the year that is not timely, i.e. all the rest.

The untimely period is divided into two parts, according as to whether the water in the river could be stored, if storage reservoirs were available, or not. The water of the Main Nile is too full of silt in August and September (Aswan dates) to be safe for storage, hence any excess over day-to-day requirements in those rivers in this period is truly untimely—i.e. useless. Any excess over requirements in October to January could probably be safely held in reservoirs and is therefore storable.

On the White Nile system, owing to the absence of silt, all untimely water is storable, if it can be stored before entering the Main Nile.

Hence we have—

Timely: Water immediately usable for irrigation.
Untimely: Water in excess of immediate requirements of irrigation.
Storable: Untimely water that is fit for storage.

Table III below gives the dates for these periods at salient points in the Nile basin.

TABLE III

TIME TABLE OF UTILITY OF NILE WATER

Site	Timely		Storable	
	From	To	From	To
Aswan	Feb. 1st	July 31st	Oct. 1st	Jan. 31st
Khartoum	Jan. 10th	July 15th	Sept. 11th	Jan. 12th
Malakal	Dec. 25th	June 30th		
Mongalla at present	Sept. 10th	Mar. 15th	Always storable if adequate reservoirs exist on the White Nile.	
Mongalla in future *via* Sudd Channel	Dec. 15th	June 20th		
Lake Albert in future	Dec. 10th	June 15th		
Lake Tsana	Dec. 15th	July 1st	All storable at Lake Tsana. Sept. 1st—Dec. 31st, also storable at Aswan.	

Necessity for Storage. The situation as regards supplies and requirements shown by the curves of Fig. 2 reveals the first problem of Nile control, namely, to devise means of storing the excess in late flood, where the "supply" curves of storable water are higher than the "requirements" curve, for use when the position is reversed in the following summer. From these curves and Table IV (Appendix) the amount of required storage can easily be calculated and is shown in Table IV on the next page.

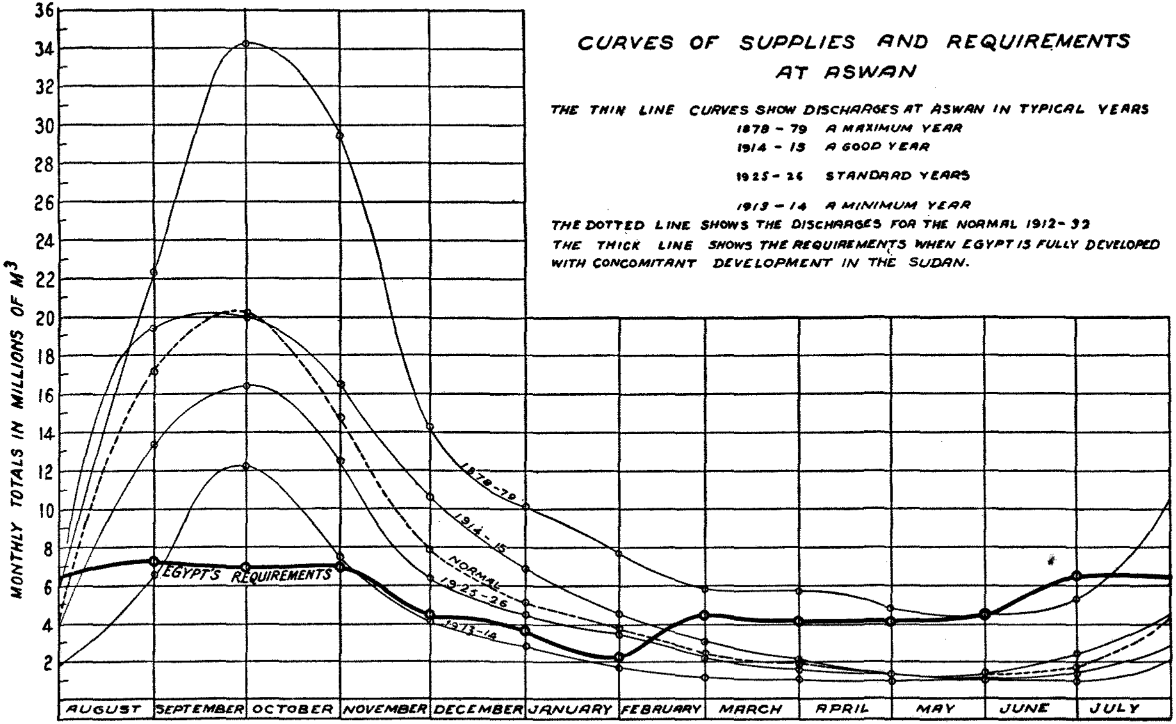

CURVES OF SUPPLIES AND REQUIREMENTS AT ASWAN
THE THIN LINE CURVES SHOW DISCHARGES AT ASWAN IN TYPICAL YEARS
1878 - 79 A MAXIMUM YEAR
1914 - 15 A GOOD YEAR
1925 - 26 STANDARD YEARS
1913 - 14 A MINIMUM YEAR
THE DOTTED LINE SHOWS THE DISCHARGES FOR THE NORMAL 1912- 32
THE THICK LINE SHOWS THE REQUIREMENTS WHEN EGYPT IS FULLY DEVELOPED WITH CONCOMITANT DEVELOPMENT IN THE SUDAN.
MONTHLY TOTALS IN MILLIONS OF M3
36
34
32
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
AUGUST
SEPTEMBER
OCTOBER
NOVEMBER
DECEMBER
JANUARY
FEBRUARY
MARCH
APRIL
MAY
JUNE
JULY
1878-79
1914-15
NORMAL
1925-26
1913-14
EGYPT'S REQUIREMENTS

FIG. 2

TABLE IV

STORAGE REQUIRED AS AT ASWAN TO GIVE FULL REQUIREMENTS IN SIGNIFICANT YEARS WHEN EGYPT IS FULLY DEVELOPED
Milliards of cubic metres

Year	Storage Required	Water Available for Storage
Average: 1912–32	18·5	11·1
Lowest year: 1913–14	30·2*	Nil
Very low year (Standard): 1925–26	18·5	6·6
Good year: 1914–15	19·6	18·3
Maximum year: 1878–79	1·3	47·6

* Includes deficit in flood months.

The interesting point that emerges from this Table is that the deficiency of supply to requirements in summer (storage required) is practically the same in all years (except the abnormal ones 1878–9 and 1913–14), the difference in the "quality" of the years, from the Irrigation point of view, being due to the amount of "storable" water, i.e. what makes a year "good" or "bad" is the amount of excess in late flood.

It is not possible to predict the late flood, so regulation must begin on a date fixed beforehand on whatever assumption as regards supplies and requirements is decided at the time by the competent authorities to be safe. At present filling the Aswan Reservoir begins in October, and all calculations in this paper are based on the assumption that all the surplus water after 1st October will be stored. The amount of this surplus is shown in the last column of Table IV above, and it will be seen to be always less than the amount of storage required (except in a maximum year). Hence the second problem of Nile Control emerges: namely, how to increase the amount of storable water. This could be done either by increasing the supply in late flood in the Main Nile or by storing the water of the White Nile before it mixes with the Blue Nile.

More Flood Water Required. The point that more flood water is required needs stressing, as there has been a tendency cavalierly to turn down any projects that only increase the amount of water in the flood months.

It should be noted that projects to increase supplies in late flood would do no harm in years of high flood, for the peak has passed Aswan before the end of September. If a project, however, would increase the supplies in early as well as late flood, it must be handled with caution, as any increase at such a time might aggravate the disaster that is bound to occur sooner or later in Lower Egypt from an overwhelming flood unless very large and expensive flood protection works are built.

Reverting to the consideration of Table IV.

Storage Capacity Required. It is obviously uneconomical to provide storage to meet a year of such infrequent occurrence as 1913–14, even if it could be done, but on the other hand a year with a total supply such as 1925–6 has occurred five times in the period 1871–1934, and it would therefore seem that this should be regarded as the "standard" year for which provision has to be made. The corollary is that in many years there will be too much water available in late flood, and hence great care must be taken in its distribution at this season to avoid the danger of over-watering and thus waterlogging the soil.

To provide adequate irrigation in a standard year it appears that Egypt needs to increase the natural flow of the river at Aswan by about 19 milliards of cubic metres of water during the period February to July from storage reservoirs, and to find an additional 12 milliards during the late flood.

We can now proceed to a consideration of the training works that are possible, reach by reach, and attempt to estimate whether their combined effect will provide the foregoing reservoirs and quantities of water.

CHAPTER III

SOURCES OF SUPPLY

IT should be stated at once that there is no known source of water in the Nile basin, below Lake Albert, which flows in the summer months and is not already feeding the Nile during those months.

The capacities of the existing reservoirs, as at Aswan, total about 8 milliard cubic metres as follows—

Aswan	5	milliards
Gebel Aulia	2	,,
Sennar	0·8	,,
Total	7·8	say 8 milliards

Lake Victoria. The source of the Nile is the River Kagera, flowing into Lake Victoria. Our hydrological knowledge of both the river and the lake is very small, but it has been suggested that the lake forms a source from which a large addition to Egypt's water supply could be obtained.

There would, in theory, appear to be two methods of controlling Lake Victoria, and so increasing Egypt's water supply, the first being to build a dam at the Ripon Falls and regulate the discharge so that it is steady every year, thus using the excess over the mean in high years to make good the deficit in low years. This is the same as is proposed for Lake Albert, to be discussed below.

It is not possible at present to say whether such a work is feasible, what it would cost, or what benefits it would produce.

The second project is to combine regulation as above with a permanent lowering of lake levels, which would produce a double effect: (*a*) the arrival in Egypt of the water taken out of the lake by lowering the level, and (*b*) an increase in the run-off tending to produce a permanent increase in the lake discharge.

Taking the latter effect first, its amount depends on the fact that on the lake there is an annual excess of evaporation over rainfall amounting to about 40 mm., and therefore a permanent decrease of the lake area should increase the discharge of the lake, by decreasing evaporation losses and by the additional run-off from the newly exposed area.

An investigation of the problem has shown that if the run-off

K (proportion of total rainfall that reaches the lake) exceeds about 7 per cent, there will be a gain by decreasing the lake area. The best available figures show the value of K to be 8, and using this, a reduction of about 17 per cent in lake area would give an increased lake discharge of about 400×10^6 m^3. per annum, or, say, 200 million at Aswan, after the Sudd Channel is complete; for even when this is the case the transmission losses from Lake Victoria to Aswan are not likely to be less than 50 per cent, even if the Victoria Nile were remodelled. The reduction of lake area by 17 per cent would involve considerable unfavourable effects on the Lake Victoria ports and riparian interests, with no compensating advantages to them; would have practically no effect at all on Egypt's water supply till the Sudd Channel is made; and would even then be trifling.

The water Egypt would gain by decreasing the lake area and contents as above is a draft on capital, a one-time lowering of the lake. It is stated that a decrease of 17 per cent in lake area would involve the release of about 14 milliard cubic metres of water. Even if the whole of this volume were discharged in one year its effect on the discharge from the swamps of the Bahr el Gebel, 1 600 km. distant, would in all probability be negligible, until the river had been trained through or round the swamps. Large quantities would be lost between the Victoria and Albert Lakes, and practically all the remainder in the Bahr el Gebel swamps. It is doubtful if as much as 1 milliard would reach Egypt—and the operation could not be repeated.

In view of the ephemeral nature of the gain due to the draft on capital and the trifling amount to be obtained as a permanent revenue, it does not seem that projects to increase Egypt's water supply by a permanent lowering of Lake Victoria levels require more study at present.

The control of the lake to secure a steady average discharge —the first proposition—might however lead to a lasting benefit, but no opinion can be given on the proposal without a great deal more study.

The chief data required for the purpose would be discharges of the Victoria Nile at the head, below Ripon Falls, and at the mouth, below Murchison Falls. A few years' observations at each site should enable these falls, which are more or less clear-overfall weirs, to be calibrated, so that river gauge readings would give discharges. As Jinja gauge, which is upstream Ripon Falls, has been observed for a great number of years, calibration of these falls would give a long period knowledge of the discharge here. The same remarks do not apply to Murchison Falls, but if observations here were started soon, an adequate series would be available for determining the value of a project by the time it became necessary from the point of view of Egypt's needs to contemplate its construction.

The Victoria Nile. This is the name given to the river joining Lake Victoria to Lake Albert, whose length is about 400 km.

Our knowledge of its hydrology is again negligible. It is known to flow through extensive swamps (Lake Kioga), but the magnitude of the losses thus caused is not known. There is an interval of four to five months between peak levels on Lake Victoria and Lake Albert. In so far as the Lake Albert levels depend on the Victoria Nile, it would seem that the effect of the swamps in this river is to introduce this long lag. Any project for controlling Lake Victoria would involve as a necessary corollary the survey, geographical and hydrological, of its effluent to ascertain what training might be necessary here.

It is not improbable that adequate training works on this river might diminish losses and thus increase Egypt's water supply, but the present state of our knowledge does not permit us to say whether such a project would be economically sound.

Lake Albert. Lake Albert may be considered as the source of the Nile from the point of view of the irrigation engineer. It has an area of about 5 300 $km.^2$ and is fed by the Victoria Nile, the Semliki river, and numbers of small streams. Its only outlet is the Bahr el Gebel, the reach of this river from Lake Albert to Nimule (the Sudan frontier and the site of rapids and the Fola Cataract) being known as the Albert Nile. The lake would form an admirable and economical reservoir, as the shores are mostly very steep, so that an increase in level does not much increase the area, and hence evaporation losses. Its waters are slightly saline and there are salt pans on the southern shores, but it has been shown that in all probability turning the lake into a reservoir would decrease the salinity.

A survey carried out by the Egyptian Government in 1932 showed that a suitable site could be found for building a dam some 80 km. from the lake, though the heavy overburden and the indifferent quality of the rock might make it a very expensive structure.

The purpose of the reservoir would be of course to store water in flood for release at subsequent periods of low supply, but not in the same way as the reservoirs at Aswan and elsewhere. These are filled every flood and emptied every summer, but Lake Albert might go on filling for years and then emptying for years; it would provide over-year storage. It is obvious that in the long run only as much water could be let out of the lake as had run in, but the lake could serve two functions: it could store excess over the average in high years for use in subsequent low years, and it could also concentrate the discharge during any year so as to release it at the time most suitable for agriculture in Egypt.

At present the usefulness of Lake Albert is limited to the two above functions, owing to our inability to forecast the size of the flood and subsequent summer supply either on the White Nile or Blue Nile system. If ever it becomes possible to make such predictions with reasonable certainty, then obviously when a good supply is coming on the Blue Nile the discharge of Lake Albert could be decreased below the average and extra water stored for use in subsequent years when the forecast showed low supply on the Blue Nile. The possibility of making such forecasts depends on an increased knowledge of the meteorology of practically the whole of Central Africa, and awaits the arrival of a genius to make a generalization from the data. The importance of meteorological study is appreciated by the Egyptian Government, who maintained meteorological observations over the whole of the Sudan, till the responsibility was assumed by the Sudan Government in 1936, and Egypt subscribes funds to assist meteorological study in the other territories concerned.

The lake discharge is calculated by indirect means. The outlet, the head of the Albert Nile, is in a desolate swampy region, infected with sleeping sickness, in which it is not feasible, even if it were useful, to establish a permanent river gauge station, though discharges have been measured there on a few occasions. At present the first gauging station on the Nile is at Mongalla, 419 km. from Lake Albert, where gauges have been regularly recorded since 1904 and discharges since 1922; occasional discharges were observed in the period 1904–22, by which, with the aid of gauge discharge curves, the Mongalla discharges for the earlier period can be computed with fair accuracy. During the months December to March there is practically no rainfall in this region, and therefore the Mongalla discharge must be practically the same as the lake discharge. The nature of the Lake Albert to Mongalla reach is such that at this period transmission losses and tributary gains must both be small. A relation can therefore be established between the lake gauge at Butiaba and the discharge at Mongalla, using the observations of the rainless months only. There is a certain amount of extrapolation at high levels beyond the range of the period of precise measurements, but the range of these months in the years 1922–34 very nearly covers the annual range in any one year.

It was found in 1932 that even if a permanent discharge station had been established near the outlet of the lake, the observations would have been quite useless. The Egyptian Government expedition that was surveying this reach to find a site for the dam also observed discharges regularly for a period of weeks. It was at once discovered that seiches were of almost daily occurrence and of such a magnitude as to cause irreconcilable differences between discharges observed in the morning and afternoon of the same day. Near the mouth the river appeared to vary greatly in discharge from hour to hour, while 216 km. farther down at Nimule, the discharge was quite steady. The discovery of this fact elucidated the mystery as to why some of the few discharges observed in earlier years at the mouth differed so widely from those computed from the Butiaba-Mongalla relation.

A gauge station also exists at Nimule, where discharges were regularly observed from February, 1923, to June, 1930, and a reliable gauge discharge relationship established, which is checked once or twice annually. A correlation of Nimule discharges with Butiaba gauge confirms the results of the Mongalla–Butiaba correlation. It may be taken that this relation gives a reliable figure for the lake discharge; its probable error has not been computed, but there seems to be no reason to consider it larger than that of an ordinary river gauging station, i.e. about 5 per cent.

Careful scrutiny of all available data has established the fact that there was a considerable change in the relation Mongalla discharge to Butiaba gauge somewhere between 1914 and 1921. From the two relations obtained the annual discharges of the lake have been calculated with the results given in Table V (Appendix). The figures for some of the earlier years are not as reliable as figures of later years, but are the best obtainable.

It is most important to determine, before the dam is built, what the normal discharge of the lake is, because it will not be possible to measure it afterwards. When the reservoir is made, it will in all probability operate on a sliding scale of discharges, which will increase the annual discharge as reservoir levels approach the upper designed limit and vice versa. If the normal discharge on which the reservoir is operating is not correct, then over a long period of years the levels will be continually approaching either the higher or lower limit, and the responsible authorities will then have to decide whether it is safe to alter the adopted figure. If they increase it, the Sudd Channel leading the reservoir waters to the White Nile may have to be enlarged; if they decide to decrease it, it means that Egypt will get less water than was calculated when the project was sanctioned, that the Sudd Channel has been made too large, and much money wasted. It is obvious, therefore, that the utmost caution must be exercised in determining the figure to adopt as the normal annual discharge of the lake; it is better to make it too low than too high.

The actual levels of the lake from 1904 to 1934 are plotted in Fig. 3, and show a very high peak in the years 1917 and 1918, which is quite out of proportion to the rest of the curve. From the scientific point of view, this peak must be included in the data for calculating the normal, but from the constructional point of view, a factor of safety must be introduced to safeguard against the damages described above that would arise from overestimating the normal.

It has been proposed to cut out these two years 1917 and 1918 altogether from the calculation of the mean, but this would appear too drastic. These two high years occurred during a period of high levels, which was followed by a period of very low levels. To maintain the relative lengths of the two periods as they were, it is suggested that a fair mean would be obtained by cutting off the peak as at 1st January, 1917, assuming the levels rose steadily but slightly for two years to the level in January, 1919, and then followed their actual course. The effect on the mean of the above two assumptions is shown in Table V below—

TABLE V

MEAN ANNUAL DISCHARGE OF LAKE ALBERT IN MILLIARDS OF CUBIC METRES FOR VARIOUS PERIODS ON VARIOUS ASSUMPTIONS

Assumption	Period	Mean
Using all data	1904–34	24·0
,, ,, ,, ...	1904–21	26·9
,, ,, ,, ...	1922–34	20·0
Cutting out 1917 and 1918	1904–34	22·5
,, ,, ,, ,, ...	1904–21	24·6
Reducing 1917 and 1918 to level of January, 1917. (These discharges would then be 29·8 and 30·9 respectively.) . .	1904–34 1904–21	23·0 25·2

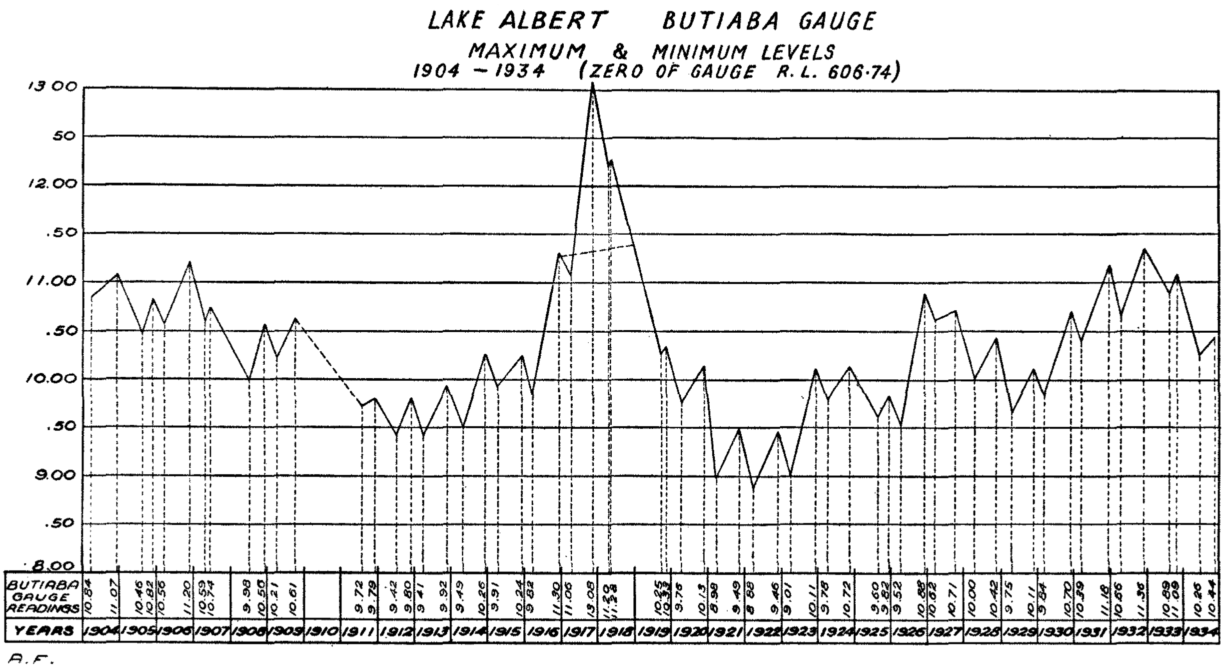

LAKE ALBERT BUTIABA GAUGE
MAXIMUM & MINIMUM LEVELS
1904 – 1934 (ZERO OF GAUGE R.L. 606·74)
13.00
50
12.00
.50
11.00
.50
10.00
.50
9.00
.50
8.00
BUTIABA GAUGE READINGS
10.84 11.07 10.46 10.82 10.56 11.20 10.59 10.74 9.98 10.56 10.21 10.61 9.72 9.79 9.42 9.80 9.41 9.92 9.49 10.26 9.91 10.24 9.82 11.30 11.06 13.08 10.25 9.76 10.13 8.98 9.49 8.88 9.46 9.01 10.11 9.78 10.72 9.60 9.82 9.52 10.88 10.62 10.71 10.00 10.42 9.75 10.11 9.84 10.70 10.39 11.18 10.66 11.36 10.89 11.09 10.26 10.44
YEARS
1904 1905 1906 1907 1908 1909 1910 1911 1912 1913 1914 1915 1916 1917 1918 1919 1920 1921 1922 1923 1924 1925 1926 1927 1928 1929 1930 1931 1932 1933 1934
A.F.

Fig. 3

The above figures show that the mean for the last period is very much lower than that for the earlier or the whole period. This does not appear to be due to the more accurate discharge measurements since 1922, but to the fact that since then the Upper Nile system has been experiencing a cycle of low levels. After various trials, the figure of 23 milliards has been adopted as the working annual normal and on this basis Table VI (Appendix) has been worked out showing the volume that would have been taken out of, or put into, the lake annually, had regulation begun on 1st January, 1904.

The volume of 23 milliards per annum cannot be discharged only with an eye to use in Egypt for irrigation, as navigation must be maintained all the year round in the Bahr el Gebel. It is believed that a discharge of 300 $m.^3$ per sec. at the lake, or, say, $\frac{3}{4}$ milliard per month, will suffice for this purpose; hence $4\frac{1}{2}$ milliards of the 23 must be discharged during the six untimely months and wasted as far as irrigation is concerned, unless a place can be found to store them on the White Nile.

Table VI shows that the accumulated storage would have been as much as 48·3 milliards, which, translated into metres, taking the lake area as 5 300 $km.^2$ would necessitate a range of 9·0 metres.

The general features of the future Lake Albert Dam could be worked out from the above data. The dam will have to have an escape at the level of the top of the effective range, and the actual range will go a little above this; similarly, to allow for a series of very low years, which may empty the reservoir despite the operation of the sliding scale, some latitude must be allowed at the lower limit. Hence with an effective storage range of 9 metres, an actual range of 10 metres is required.

In the past, levels on the gauge at Butiaba have ranged through 4·20 metres from 8·88 to 13·08; in the future they will range from 10 to 20 on this gauge and the latter contour has recently been demarcated on the ground by the Survey Departments of Uganda and the Belgian Congo, at the request and expense of the Egyptian Government.

It is important to note, from the point of view of the regime of the river below the dam, that provision must be made for discharges somewhat larger than have occurred in the past for the following reason. If the reservoir is full to its effective range, 19·5 metres, and a year of heavy precipitation occurs, the discharge through the dam must be such as to limit the rise during the year to $\frac{1}{2}$ metre, i.e. it must equal the discharge that would have occurred had there been no dam plus the amount represented by the maximum recorded rise in lake levels in a year, less half a metre; it has been calculated that this might exceed 3 000 $m.^3$ per sec. for a period of weeks.

The effect of such a discharge on the design and regime of the Sudd Channel will be considered later in this note (p. 76).

Lake Albert to Mongalla. The general nature of the river below Lake Albert has already been described. A graphic and more detailed description can be found in Garstin's book, and many travellers have also painted the scenery in eloquent language. In general terms, from the engineer's point of view, a large volume of water pours out of Lake Albert in increasing quantity throughout the year, and is augmented during the rainy season by torrents in about the first 400 km. of its course. The river flows, at low levels, between wide berms that will become swamps, and then through large areas of swamp, in a state of greater or less dryness. As the flow increases, the berms are covered and the swamps increase in size, absorbing large quantities of water first in filling and then in evaporation from the large water and swamp surfaces formed.

The first reach below Lake Albert, as far as Nimule (km. 216) is swampy in nature; there is a good channel with swampy berms, and increasing the water level here will cause additional evaporation losses, which are, however, not likely to be heavy. A survey may one day be required here to ascertain whether it would be worth while embanking this reach to reduce these future losses. There are two tributaries, the Achwa and Unyama, much direct drainage and numerous smaller streams. The Achwa has never been measured, but the Unyama was regularly observed from October, 1923, to June, 1930. Its mean annual discharge is 166 million cubic metres, the maximum month in the mean year being May at 18 $m.^3$ per sec. and the minimum being January and February when it is dry.

From Nimule to Rejaf (km. 365), the river falls over a succession of rapids, the biggest and finest being the Fola Rapids just below Nimule; the losses on this reach cannot be of any importance at any stage. Three important tributaries join the main river here: the Asswa, the Kaia, and the Kit.

The Asswa was regularly measured from September, 1923, to June, 1930, and the mean annual discharge is found to be 1 450 millions cubic metres. The Kaia has never been measured, while the Kit has only been estimated now and then, when an observer happened to pass while it was in spate. The Asswa is believed to have discharged as much as 400 m.^{3} per sec. in May, 1928, and the Kit over 200 m.^{3} per sec. in June, 1922.

The short reach from Rejaf to Mongalla (km. 431) is mostly within banks, with swampy patches. Losses are believed to be small and there are one or two inconsiderable tributaries.

Torrents. The above tributaries, with numerous smaller torrents and direct drainage, constitute at some periods of the year a large proportion of the total water passing Mongalla. As they cannot be controlled by damming Lake Albert, it is of importance to know their amount, which of course must be calculated indirectly by subtracting the lake discharge as at Mongalla from the actual Mongalla discharge, thus giving the torrents as at Mongalla.

Confining ourselves to the period of continuous observations 1922–34, it is found that the average, the maximum and the minimum monthly torrents are as shown in Table VII (Appendix), which gives also the same data for the lake discharge as at Mongalla. For the period 1922–34, the average annual discharge at Mongalla was 24·1 milliards, of which 20 milliards came from the lake and 4·1 milliards from torrents. For the long period 1905–35, the average Mongalla discharge was 28·5 milliards per annum. (Tables IX and X, Appendix.)

The proper utilization of these torrents presents a problem which must be combined with the question of the navigation water necessarily to be released from Lake Albert during the untimely period. It is estimated that the time of travel along the future Sudd Channel from Mongalla to Aswan will be about a month and a half, hence the torrents arriving at Mongalla from about July to December will be untimely, if they are diverted down this channel. The timely torrents (January to June) are exceedingly variable, and may be nil in every month except May, when they may be of negligible amount; for purposes of design they should be neglected.

The matter is further discussed on p. 74, where the future regime of the Upper Nile is being considered.

The Losses in the Swamps. At Mongalla, then, the river is complete. Below this point the swamps begin, though they are not serious for the next 128 km. to Bor, where the real Sudd Region—the Upper Nile swamp—starts and borders the river on both sides for the next 619 km. of its course to its junction with the Bahr el Ghazal. On the west of this long stretch there are many streams, coming from the Nile–Congo divide, which carry a considerable volume in flood and pour it into the swamps of the Bahr el Gebel and Bahr el Ghazal, which seem to be continuous. It is believed that no water from these streams enters the Bahr el Gebel, but in the absence of detailed topographical knowledge of this vast and inaccessible area, no certain judgment on this point is at present possible.

Before considering in detail the hydrology of the lower reaches of the Bahr el Gebel, it will be well to discuss the general problem of the losses.

Table IX (Appendix) gives the annual discharge of the Bahr el Gebel at Mongalla and the amount that escapes at the lower end of the swamps into the White Nile. From this it appears that the average Mongalla annual discharge is 28·5 milliards, of which a little less than half, 14·0 milliards, is lost *en route* to the White Nile (Malakal).

To determine this loss it would appear to be necessary first to determine the time of travel of water from Mongalla to the White Nile, and the whole question of "time of travel" needs discussion. Owing, however, to the fact that the variation in swamps discharge from month to month is very small compared with the Mongalla discharge, the difference between loss allowing for lag and loss without allowing for lag is small, as will be seen from Tables IX and X (Appendix).

Objection has been taken to the use of the term "time of travel" on the ground that the swamps form a lake, with water pouring in at one end and out at the other, thus rendering the term meaningless; but recent investigations, begun in 1935, tend to confirm the opinion long held that, though the swamps form a continuous sheet of water, they are not a lake in the hydrologic sense.

These investigations were carried out by erecting duckboard tracks on piles from the river's edge into the swamps and recording water levels on fixed gauges along these tracks. These gauges consisted of the outer casings (4 in.) of boring sets, which were driven 30 ft. into the ground and filled with liquid cement mortar. They have not moved, and the levels recorded on them can be considered reliable.

A typical cross-section of the Bahr el Gebel and swamp is shown in Fig. 4.

The water of the swamps falls very steeply immediately on leaving the river's edge, as much as 25 cm. in the first 50 metres, or a slope of 1 in 200. Thereafter the slope decreases until at about one kilometre from the river it is very flat. It must be understood that the swamp is a dense tangle of vegetation,

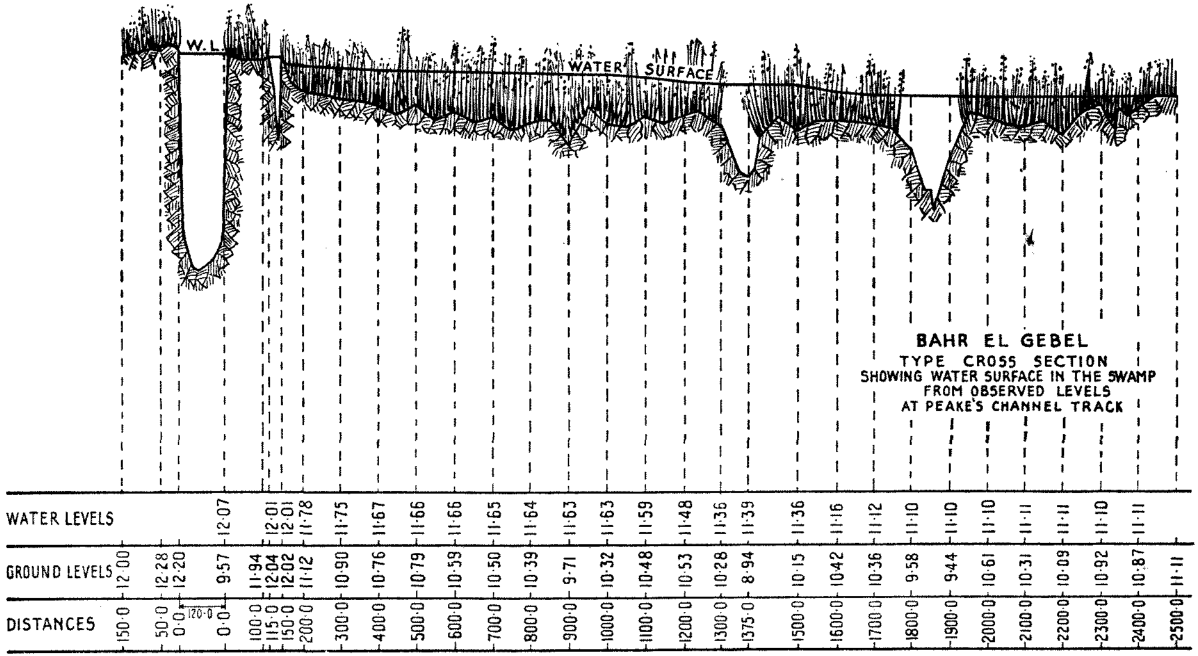

W.L.
WATER SURFACE
BAHR EL GEBEL
TYPE CROSS SECTION
SHOWING WATER SURFACE IN THE SWAMP
FROM OBSERVED LEVELS
AT PEAKE'S CHANNEL TRACK
WATER LEVELS
12·07 12·01 12·01 11·78 11·75 11·67 11·66 11·66 11·65 11·64 11·63 11·63 11·59 11·48 11·36 11·39 11·36 11·16 11·12 11·10 11·10 11·10 11·11 11·11 11·10 11·11
GROUND LEVELS
12·00 12·28 12·20 9·57 11·94 12·04 12·02 11·12 10·90 10·76 10·79 10·59 10·50 10·39 9·71 10·32 10·48 10·53 10·28 8·94 10·15 10·42 10·36 9·58 9·44 10·61 10·31 10·09 10·92 10·87 11·11
DISTANCES
150·0 50·0 0·0 120·0 0·0 100·0 115·0 150·0 200·0 300·0 400·0 500·0 600·0 700·0 800·0 900·0 1000·0 1100·0 1200·0 1300·0 1375·0 1500·0 1600·0 1700·0 1800·0 1900·0 2000·0 2100·0 2200·0 2300·0 2400·0 2500·0

Fig. 4.

practically impenetrable without clearance. This vegetation very soon grew up as thickly as ever under and round the clearing made to erect the track, so that observations along the track are truly representative of sudd conditions. On approaching a channel through the swamps, the water level rises again a few centimetres to the level of the water in this channel, whether the latter is open water or overgrown, which is related to the level in the main river according to relative slopes. The swamp consists of a network of interlacing streams, some of them open water, some of them thickly overgrown. These streams enclose islands of swamp in which the water is at a lower level than in the streams. The "islands" frequently contain lagoons of open water, into which the swamp water trickles, and sometimes they are not islands, but peninsulas, the enclosed lagoon having an open water connection with the main stream. The relations of level and flow are extraordinarily complicated and not yet elucidated, but it seems clear that the water pouring into the swamps from the main river either flows in defined but unknown and overgrown channels, that may either dissipate themselves entirely or return to the main river, or pours out of these channels into the swamp proper, the "islands," and is definitely lost.

When an increase of discharge occurs at Mongalla, levels rise as the extra water flows along the main and side channels, and with the rise of levels there is an increase of the water lost into the swamps, hence the change of discharge travels like a wave and much slower than the actual particles of water flowing in the channels, while only a fraction of the increase reaches the tail end of the swamps. The "time of travel" is defined as the time interval between the occurrence of the maximum and minimum discharges of each year at Mongalla and their occurrence respectively at Malakal, the gauging station on the White Nile where the swamps discharge is determined. There are other factors that affect the swamps discharge—rainfall on the swamps, tributaries from other river systems and the ponding effect of the Sobat River on the White Nile—which are small compared with the Mongalla discharge, but may nevertheless be of importance.

The method of determining the swamps discharge at Malakal must be described. Malakal is situated on the White Nile, 146 km. from the head. The river here consists of the water contributed by the Bahr el Gebel, Bahr el Ghazal, Bahr el Zeraf, and River Sobat. Of late years all these rivers have been regularly measured, so that the White Nile discharge is completely analysed. In earlier years, more reliance was placed on gauge discharge curves and measurements were less frequent; the Ghazal was not measured at all, being taken as a uniform 20 m.^{3} per sec., while the Zeraf was only measured at infrequent intervals. For these earlier years, the swamps discharge at Malakal is taken as White Nile minus Sobat minus Ghazal. Since 1923, both the Gebel and Zeraf have been regularly measured at their mouths, and moreover a tie bank was made in 1923 right across the berms of the White Nile valley at Abu Tong, just upstream of the confluence of the Bahr el Zeraf and the White Nile, which concentrates all the flow in the Bahr el Gebel and White Nile valleys in the river channel, where it is regularly measured. As the flow here consists not only of the Bahr el Gebel water but of any water coming down the Bahr el Ghazal, the latter's discharge has to be deducted in calculations of the amount of water from Mongalla that reaches Malakal. It is possible, probable even, that at certain times of the year the Bahr el Ghazal discharge at the mouth includes Bahr el Gebel water that has overflowed through swamp channels into the Bahr el Ghazal. It is not measurable but neither is it of importance. The value for swamp discharge at Malakal from 1923 onwards is therefore the sum of the discharges of the White Nile at Abu Tong and the Bahr el Zeraf at the mouth, less the Bahr el Ghazal discharge. It differs little from the sum of the discharges of Zeraf and Gebel at their mouths, which is easier to calculate, and perhaps more accurate, owing to the somewhat unreliable character of the Bahr el Ghazal discharges.

It has already been mentioned that all through the Nile Basin the records for the early period to 1922 are not so accurate as those since that date, hence wherever it seems useful normals have been worked out for the whole period (1904 or 1905 to 1934), for the early period (1904 to 1922) and for the later period (1923 to 1934). It is surprising how frequently the three normals practically agree.

Table VIII (Appendix) gives the actual intervals in ten-day periods between peaks at Mongalla and Malakal for the years 1905 to 1934, while Table VI, p. 39, gives a summary of the average lag for the three above periods. The differences in the average lags are slight, the over-all average being 9·6 ten-day periods, say 96 days, with a very large variation. This is partly due to the difficulty of determining with sufficient accuracy the occurrence of the peaks at the downstream end, where they are not very marked, so that they are easily displaced by any slight experimental error, and partly to the fact that the lag varies with the state of the river and swamp levels when the flush at the upstream end occurs. From these data the time of travel has been taken at a round figure of 3½ months, which has been used to determine the losses between Mongalla and Malakal shown in Table IX (Appendix), while the losses calculated without any allowance for lag do not differ significantly from those of Table IX and are shown in Table X (Appendix).

No useful deductions as to lag can be made from a consideration of annual discharges, but the tables seem to refute the statement sometimes advanced that in fact the swamps discharge is constant, for it has varied from 10·4 to 19·6 milliard cubic metres per annum if calculated with lag (Table IX), and from 10·4 to 20·7 milliards if without lag (Table X).

In general terms then it is true to say that the highest swamp discharges at the tail occur about 3 to 3½ months later than the discharges that caused them at Mongalla. While this fact is not significant in the calculation of annual losses, it is of importance in the study of the regime of the river, with a view to its future modification to economize water.

It is obviously essential to be able to predict the swamps discharge resulting from any given Mongalla discharge that may be obtained by regulation at Lake Albert. Owing to the variability in the time of travel, no relation between individual discharge measurements at Mongalla and Malakal can be established, but it is possible to establish a fair relation between total volume passing Mongalla during a given fairly long period and the volume passing Malakal during the corresponding period, however much later. A curve has been drawn between the total Mongalla discharge and the total swamps discharges at Malakal during the two lowest months in every year. The data for this curve are shown on Table XI (Appendix) and the curve in Fig. 5. It forms the basis for the hydrological design of all training projects, as it demonstrates that up to a discharge of about 500 $m.^3$ per sec. at Mongalla the losses to Malakal are of the order of 20 per cent., and thereafter increase very rapidly. The distance from Mongalla to the White Nile by a diversion channel would be about 400 to 450 km., and it is not likely that any artificial canal of this length would be subject to smaller losses than 20 per cent. Hence no useful purpose would be gained in any training works by reducing the discharge carried by the Bahr el Gebel as at Mongalla to less than about 500 $m.^3$ per sec.

There exists also another relationship between Mongalla discharge and swamps discharge at Malakal, which is not in accord

RELATION BETWEEN MONGALLA DISCHARGE AND SWAMP DISCHARGE

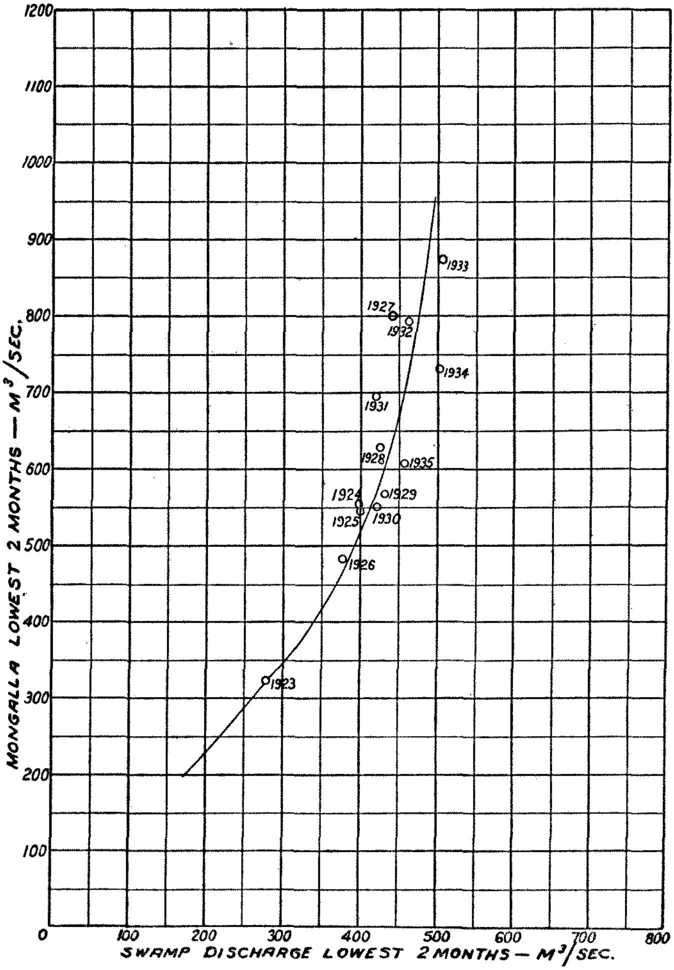


FIG. 5.

with the $3\frac{1}{2}$ months lag, namely, a close correlation of the Mongalla discharge for September, October, and November, with the swamps discharge for the following March, April, May, i.e. a six months lag.

TABLE VI

AVERAGE INTERVALS IN TEN-DAY PERIODS BETWEEN OCCURRENCES OF MAXIMA AND MINIMA, RESPECTIVELY, AT MONGALLA AND MALAKAL FOR VARIOUS PERIODS

Period	No. of Intervals between		Mean of Maxima and Minima
	Maxima	Minima	
1905–34 . .	9·8	9·4	9·6
1905–22 . .	9·6	9·4	9·5
1923–34 . .	10·2	9·2	9·7
Mean . . .	9·9	9·3	9·6

This relation can be expressed in the form of an equation and makes it possible to foretell with reasonable accuracy the swamps discharge in March, April, and May, of any year from the flood discharge at Mongalla of the previous September, October, and November.

Let Y = mean swamps discharge for March, April, May, in m.^{3} per sec.;

and X = mean Mongalla discharge for previous September, October, November, in m.^{3} per sec.

The three equations for the usual three periods are given in Table VII below—

TABLE VII

RELATION BETWEEN MONGALLA FLOOD DISCHARGES AND MALAKAL SWAMP DISCHARGES IN FOLLOWING SPRING IN MEAN CUBIC METRES PER SECOND

Period	Equation	Coefficient of Correlation	Probable Error of One Observation m^3 per sec.
All years, 1905–34 . .	$Y = 0{\cdot}159\,X + 267$	0·85	25
Early years, 1905–21 .	$Y = 0{\cdot}168\,X + 244$	0·90	23
Later years, 1922–34 .	$Y = 0{\cdot}249\,X + 205$	0·85	21

These relations are empirical facts; their rational explanation has yet to be found. They would seem to make it worth while investigating whether losses are related to water levels in the swamps.

Evaporation. How can the huge losses shown in Appendix Tables IX and X, which have ranged from 5 to 39 thousand million cubic metres in a year, be accounted for?

The water must be either evaporated, or disappear into the sub-soil or flow out of the basin.

All water that disappears into the sub-soil must either flow away under ground or eventually be evaporated from the surface. Few investigations into the sub-soil flow have been made, but there are no obvious signs of such flow and it is believed to be practically non-existent.

It can be stated quite definitely that the only exit from the swamps is the White Nile, formed by the Bahr el Gebel, Bahr el Ghazal and Bahr el Zeraf.

Evaporation is believed to be the chief source of loss, and to ascertain its amount with exactitude, the area and rate of evaporation should be known from month to month. To obtain this information is a matter of great difficulty and expense owing to the terrible nature of the country, for during the rainy season, which is also the flood season, and for months thereafter, the country bordering the swamps is impassable for man and beast, as it is too muddy and the grass too high to make movement possible. During the dry season, the land and the pools dry up, and it is only possible to trek along the edge of the swamp, owing to lack of water elsewhere. The swamp water is stagnant and foul, and the difficulties of maintaining an expedition in such regions, even for a short time, are so great as to be in practice insuperable. The only way to delineate the edge of the swamp is by air photography, and in fact the whole of the Bahr el Gebel swamps have been mapped in this way by the Air Survey Company Limited under contract with the Egyptian Government. This photography took several seasons, so that the water conditions revealed cannot be correlated with definite gauges and discharges.

Air photography here is accompanied by great difficulties owing to the atmospheric conditions. During the dry months the huge grass fires fill the atmosphere with smoke, and during the rainy months clouds and storms are of continuous occurrence. Both conditions reduce periods of visibility suitable for air photography to a minimum, so that a proposal to photograph the whole area every month is not a practical proposition. A whole fleet of aeroplanes would be required, whose aerodromes would of necessity be some distance from the sites to be photographed, so that it would never be possible to foretell from visibility conditions at the aerodromes at any moment what the conditions would be at the sites of work. These difficulties make the expense prohibitive.

Hence as far as evaporating area is concerned, estimates based on existing maps must be used, and it is considered fair to allow an average width of 10 km. on the true swamps, Bor to Lake No, 619 km. long, and, say, 2 to 3 km. on the short reach Mongalla to Bor of 128 km. By average is meant the average width during the year of the whole swamp, not the average width at high levels.

The above figure for average width is based on an assumption as to the divide of the Bahr el Gebel and Bahr el Ghazal swamps, whereas in fact we do not know that there is such a divide. The two systems of swamps may be continuous and the Gebel water be spilt at high levels, westward, into the Bahr el Ghazal basin. There is some ground for thinking this may be the case, for it has been shown from the extremely sketchy information available that the total swamp areas of the Bahr el Gebel plus Bahr el Ghazal basins might account for the loss by evaporation of the quantities of water lost from the Bahr el Gebel discharge at Mongalla and the total precipitation on the Bahr el Ghazal catchment combined.

A survey has recently been completed from Mongalla northwards along the western side of the Bahr el Gebel to demarcate the extreme western limit to which the highest flood waters could spread; it should show that the water spreads into the Bahr el Ghazal at high levels.

Evaporation has been observed for many years on Piché evaporimeters at either end of the Sudd region, and at Shambe and the Zeraf Cuts, both the latter being in the heart of the sudd.

At the last two places an attempt has been made to determine the relation between evaporation from an open water surface and evaporation from the swamps, i.e. from a water surface covered with vegetation. A tank 10 metres by 10 metres was made in the heart of the swamps, partly filled with earth, on which swamp vegetation was then cultivated. The evaporation loss was regularly observed at the Zeraf Cuts for five years, 1927 to 1931, but then administrative difficulties supervened and eventually made it advisable to abandon this tank and build another similar one at Shambe, where observations were begun in 1932. The results of these experiments are not entirely satisfactory as the vegetation in the tanks is not as luxuriant as that in the swamps, but reliable data were obtained at the Cuts. At Shambe great difficulty was experienced both in getting the vegetation to grow in the tank and to get a reliable local observer; the readings here had to be discarded as unreliable till August, 1934.

The results obtained are of importance, though inconsistent, for at the Cuts the annual evaporation off a swamp surface works out at about 2·7 times that off an open water surface, whereas at Shambe this ratio, for one year's observations, is only 1·5. The open water evaporation was determined at each site from a Piché evaporimeter; the vagaries of these instruments are well known and too much reliance must not be given them. To obtain a better figure, a large tank, also 10 metres square, was made and floated in a lagoon near the Cuts for measuring open water evaporation, but no figures of any value have yet been obtained, owing to the difficulty of making a wave-breaker that would prevent splashing into the tank, and owing to the tank and wave-breaker being wrecked by storms, floating islands and hippopotami. An attempt is being made to erect the tank in the Shambe lagoon in a more sheltered position, but meanwhile the only figures available for open water evaporation are those of the Piché evaporimeters. The readings of this instrument must, in the Sudan, be multiplied by 0·50 to give evaporation off an open surface, and this has been done for all Piché data quoted below.

Table XII (Appendix) gives the rainfall, open water evaporation, swamp evaporation, the ratio of the two, and the net evaporation off a swamp area at the Zeraf Cuts, which is here 590 mm. per annum.

By net evaporation is meant total evaporation minus total rainfall.

Evaporation and rainfall data have been regularly observed at Mongalla and Juba, south of the swamps, and at Malakal, north of them, for many years and reliable normals are available, which must be taken into consideration in discussing this question.

Table XIII (Appendix) gives the mean of Mongalla and Malakal evaporation and rainfall data. The Mongalla normals are for the period 1906–30 combined with those for Juba from 1931–35, as Mongalla was abandoned in 1930 and Juba is only 42 km. away. The Malakal normals are for the period 1915–35.

The evaporation figures are for open water surfaces, deduced from Piché evaporimeter readings, and the net annual evaporation off an open water surface is found to be 471 mm.

The area of the swamps varies throughout the year with the river level, so that maximum evaporation rate cannot be applied to maximum area and so on, and an attempt has therefore been made to weight the evaporation data in accordance with the swamp areas to which they may apply. No actual figures for swamp areas at various levels are available or ever likely to be, as has been explained above, so that weighting has had to be done on the basis of the best opinion available regarding the variation of swamp areas during any one year.

It has been assumed that on the average the minimum area in any year is 70 per cent of the maximum in that year, and the year has been divided into four periods according to levels, i.e. periods during which the levels and therefore swamp areas may be considered more or less steady. The following weighting table (Table VIII) is thus produced—

TABLE VIII

WEIGHT OF EVAPORATION AND RAINFALL DATA FOR THE SUDD REGION

Period			Weight (per cent)
September	October	November	100
August	December	January	90
July	February	March	80
April	May	June	70

Mean area is therefore assumed 85 per cent of maximum area. When these weights are applied to the monthly net evaporation in Tables XII and XIII it is found that the annual net swamp evaporation, deduced from the Cuts tank, falls from 590 mm. to 501 mm., and the annual evaporation off an open water surface as deduced from Mongalla and Malakal falls from 471 mm. to 399 mm.; i.e. the result is the same as using the mean area.

There is a difficulty about using the Mongalla, Zeraf Cuts, Shambe, and Malakal data together as the normals are for different periods, as follows—

Mongalla—Juba	1906–35
Shambe	1931–35
Zeraf Cuts	1927–31
Malakal	1915–35

As there is no systematic variation of the normals at the various stations for the differing periods it is difficult to say what is the best figure to take for evaporation off the Sudd; the mean of Mongalla plus Malakal is too high, while the mean of Shambe plus Zeraf Cuts is too low. It is therefore assumed that a fair representation will be obtained by combining the mean of Juba and Shambe for the period 1931–5 with the mean for Malakal and the Cuts for the periods 1927–31, and the composite Table XIV (Appendix) of evaporation and rainfall has been worked out on this basis, showing the weighted net evaporation off an open water surface to be 259 mm. per annum.

The last question to be settled in this connection is the ratio of swamp evaporation to open water evaporation which, according to present knowledge, is about 2·7 at the Cuts and 1·5 at Shambe. Allowance must also be made for the fact that about 10 per cent of the swamp area is open water lagoons. Applying these figures to the weighted net evaporation for the year, 259 mm. (Table XIV), it seems that the annual evaporation off the swamps lies between 380 and 660 mm. One would not be far out in taking the net evaporation at half a metre per annum off the whole area of swamps.

This implies a mean evaporating area of 28 000 km.^{2} to account for a mean annual loss of 14 milliard cubic metres of water, and no such area can be found within what are usually considered the limits of the Bahr el Gebel valley. Hence it would appear that survey must show the possibility of water escaping into the Bahr el Ghazal basin.

Summary. Briefly summarized, the state of our knowledge as regards losses in the swamps is as follows—

(*a*) The amount lost is known with fair accuracy and has varied from about 5 to about 39 milliards of cubic metres per annum, and is directly proportional to the discharge of the Bahr el Gebel at Mongalla, being on the average about one half, say 14 milliards, per annum. The swamps discharge is not constant, but has varied between 10 and 20 milliards per annum.

(*b*) Up to a discharge of about 500 m.^{3} per sec. at Mongalla, the losses through the swamps are 20 per cent under the present regime of the river.

(*c*) The maxima and minima of the swamps discharge curve at Malakal occur on the average three to three and a half months later than the maxima and minima at Mongalla, with a considerable variation, but nevertheless the flood discharge at Mongalla is fairly closely correlated to the following spring discharge of the swamps, a lag of six months.

(*d*) The losses cannot be accounted for by evaporation on the Bahr el Gebel swamps, and it is assumed that a large part of the water escapes into the Bahr el Ghazal basin. This point is under investigation.

(*e*) Some of the Bahr el Ghazal rivers flow into the lower swamps of the Bahr el Gebel directly and their volume is not known.

CHAPTER IV

HYDROLOGY IN DETAIL

THE broad facts regarding the losses on the Bahr el Gebel and its hydrology as a whole have now been fully discussed, but before passing to a consideration of the possible training projects, a brief account of some details of the hydrology must be given. For this purpose the river divides itself naturally into three reaches with geographical boundaries surprisingly definite in their correspondence to changes in the hydrological nature of the river. The three reaches of the Bahr el Gebel are—

(*a*) Mongalla to Bor	km.747 to km.619
(*b*) Bor to the Zeraf Cuts . . .	km.619 to km.289
(*c*) Zeraf Cuts to the Mouth . .	km.289 to km.0

The head reach of the White Nile from Lake No to Zera Mouth (79 km.) is also best considered as part of the swamps.

Mongalla to Bor (Fig. 6). The important feature of this reach is that it forms a natural self-regulating escape, for the discharge at Bor seldom exceeds about 800 m.^{3} per sec. Even in the exceptional year 1917, when the Mongalla discharge reached 2 700 m.^{3} per sec., Bor did not exceed about 900 m.^{3} per sec., as estimated from a not very reliable gauge discharge curve. Topographically, the Mongalla–Bor reach has a high bank on the east which is never topped by the flood. On the west the bank is of the same nature, though lower, for about 45 km. and then the high ground gradually recedes from the river leaving a berm that is swamp at high water level with low swampy islands in the river.

On the lower part of this reach on the west bank there is the Aliab system of swamps and channels which extends to below Bor. Some proportion of the water that escapes out of the river upstream of Bor returns at times below Bor through the lagoons that end the Aliab system. The Air Survey maps show no continuous channel past Bor on the western side, but there seem to be some overgrown channels which might nevertheless carry a discharge. A little above Bor on the western side there is a well-defined channel called the Khor Unyam Koji, which short-circuits the Bor discharge site, so that its discharge is added to the Bor discharge of the Bahr el Gebel, to determine total water passing Bor.

Gauges on this reach are regularly observed at Mongalla, Terrakeka, Malek, and Bor.

The discharge of the river at Mongalla is known with fair accuracy for the period 1905–21 from a gauge-discharge curve, and much more accurately for the period 1922–35.

Very much less is known about the Bor discharge. Very few observations were taken there till 1925, the gauge discharge curve is of a bad shape, and the points have a big scatter, so that the computed discharges prior to this date are not very reliable. From April, 1925, to February, 1928, regular observations were taken at frequent intervals, and since then a fair number of discharges have been observed, so that the annual gauge discharge curves are fairly reliable. The data, such as they are, show that there is an average loss of 6·2 milliard cubic metres per annum between Mongalla and Bor; but if we take the latter period of accurate observations from 1925 and include Khor Unyam Koji in the Bor discharge an annual loss of only 2·8 milliards.

TABLE IX

Loss between Mongalla and Bor
(Quantities in milliards of cubic metres per annum)

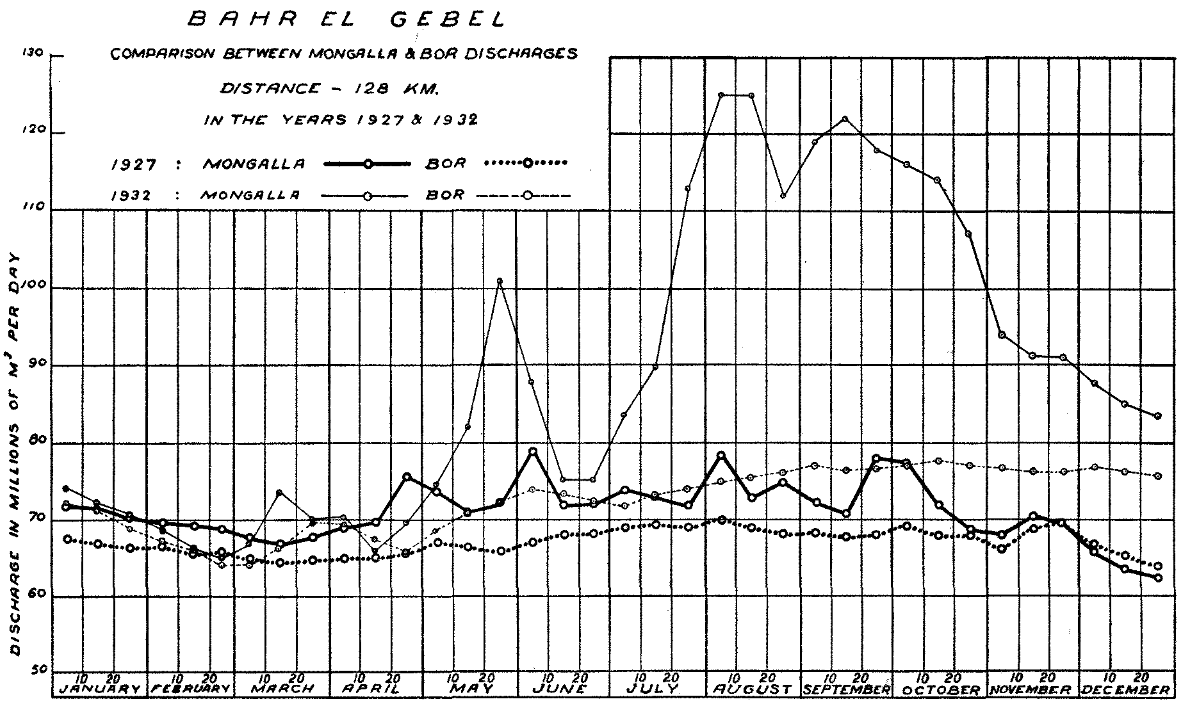
	Annual Discharges		Loss
	Mongalla	Bor	
1905–34	28·5	22·3	6·2
1925–34	25·9	23·1 *	2·8

* Khor Unyam Koji included.

The river channel at low levels is then a good carrying channel with only normal transmission losses, but, as stated, when the Mongalla discharge rises above about 800 $m.^3$ per sec. practically all the excess above this figure is lost. This phenomenon is shown very clearly in the curves in Fig. 7, in which are plotted on a time basis the discharges at Mongalla and Bor for the two years 1927 and 1932. The former was a low year during which Mongalla varied very little and Bor less. In 1932, there was quite a high flood at Mongalla, but the effect on Bor was small (Khor Unyam Koji is added to Bor in the diagram).

The losses at low levels are mostly true transmission losses, but at high levels the greater part of the loss is due to spilling out of the channel.

The data show that the low stage average loss is about 6 per



BAHR EL GEBEL
COMPARISON BETWEEN MONGALLA & BOR DISCHARGES
DISTANCE – 128 KM.
IN THE YEARS 1927 & 1932
1927 : MONGALLA BOR
1932 : MONGALLA BOR
DISCHARGE IN MILLIONS OF M³ PER DAY
130
120
110
100
90
80
70
60
50
JANUARY
FEBRUARY
MARCH
APRIL
MAY
JUNE
JULY
AUGUST
SEPTEMBER
OCTOBER
NOVEMBER
DECEMBER
10
20

FIG. 7

cent of Mongalla, with a variation from nil to 13 per cent, where the high stage average loss is 25 per cent, with a variation from 10 per cent to 40 per cent. No allowance for lag has been made in calculating these losses.

A somewhat similar effect on a smaller scale occurs in the first 45 km. of this reach from Mongalla to Gemeiza. The channel at Gemeiza will not carry more than about 1 100 m.^{3} per sec., and any excess over this quantity at Mongalla is spilt into high-lying swamps and pools on the west bank. When the river falls most of this water returns, so that the total annual loss between Mongalla and Gemeiza is small. On the average of the years 1931 to 1934, while Mongalla was 29·6 milliards per annum, Gemeiza was 28·6 milliards.

The characteristics of the river at Gemeiza were investigated, as this was the proposed site for a barrage in connection with the Veveno Diversion Project to be described later.

Bor to Zeraf Cuts (Fig. 8). The next reach stretches from Bor (km. 619) to the Zeraf Cuts (km. 289), a distance of 330 km. and embraces the worst swamps. The most important engineering feature is the varying size of the main river channel, which in some reaches can carry about 600 m.^{3} per sec., and in others only about 170 m.^{3} per sec. The channel is lined with walls of swamp vegetation, mostly papyrus, and the water normally flows above ground level, there being a constant loss, as already explained, due to water escaping sideways through the papyrus walls.

Both this reach and the lower one were badly blocked by floating vegetation (*sudds*) during the Mahdi's time, and blocks occasionally occur now, but despite these *sudds*, the main channel of the river is very little affected by time, but seems to be quite stable in section and position. On the other hand, the side channels seem to be much more subject to variation, spills that are open one year becoming closed the next and vice versa.

The main swamp area lies on the east of the main channel, and is divided into three systems, which, however, have no definite boundaries; starting from the south they are called the Atem, the Awai, and the Upper Zeraf systems.

The Atem and Awai systems are marked by each having a series of "heads" where water flows from the Gebel into the channels and the Awai system by a series of "tails" where water flows back into the Gebel. Going downstream from Bor we have first Atem heads Nos. 1 to 3; these are followed by Awai Head No. 1, Awai Tails 1 and 2; Awai Heads 2 and 3, and then Awai Tail 3, about 30 km. below Shambe. Then comes the Upper

Zeraf system which has no defined heads, except Baker's channel which is completely blocked, but gets its water from the Awai system and discharges into the Zeraf at the latitude of the Cuts. The channels of the Awai and Upper Zeraf system have been mapped but change frequently, and these eastern swamps get narrower towards the north of this reach.

The edge of the swamps is very clearly defined on the Air Survey map, but this limit is only the edge of the permanent swamp; in flood and during the greater part of the year in high years the land outside it is flooded. Within it, however, is the true river bed and permanent swamp with a permanent main channel and many variable side channels.

The Atem system concentrates most of its water in the River Atem, which flows on the extreme east of the swamps for some small distance past a place called Jonglei, which is fairly high and mostly dry. (The River Atem was once known as the "Gertrude Nile," so named by its discoverer.) This place is of importance in the consideration of training works, as it is the site for the head works of the first stage of a diversion project, which seems to offer many advantages.

On the west bank, starting from the south, the tail of the Aliab system borders the main channel opposite the Atem system on the east bank. The former system is very largely fed from great numbers of spills below Bor, though probably some of its water comes from above Bor. It ends in two big lagoons, Lakes Fajarial and Papiu, the former being 29 km. upstream the latter. Lake Papiu sometimes discharges as much as 600 m.^{3} per sec. into the main river; it has an independent tributary, the River Gell, whose discharge is not known but is inconsiderable, even in flood. Below Lake Papiu, the bordering of swamp narrows down and a spit of fairly high land touches the river at Kenisa (km. 493) and Abu Kuka (km. 476). It is this high land (nevertheless flooded at high levels) that forces the water and the swamps over to the east. From Abu Kuka to Shambe on the west (opposite the Awai system) there is just swamp, with no distinctive name or channels, fed direct from the main stream, and of unknown extent.

Shambe is a spot of dry land from which a road runs inland, westwards, to Wau, the capital of what was once the Bahr el Ghazal Province, now part of the Equatorial Province. West of Shambe there is swamp for about 10 km. traversed by a causeway; there are a few small channels overgrown with vegetation but no flowing open water. Below Shambe the swamps get wider but have no distinctive name, though there are two well-known channels: Fell's and Peake's. Fell's is of little importance; it bypasses the main river for some length. Peake's Channel is bigger, and by-passes the heads of the Zeraf Cuts, joining the river again a few kilometres below them.

Between Shambe and the Cuts there is one very small patch of high land on the east bank, dry at all stages of the river, known as Ghabat Inderab, where there is a gauge, astronomical point, and precise bench mark.

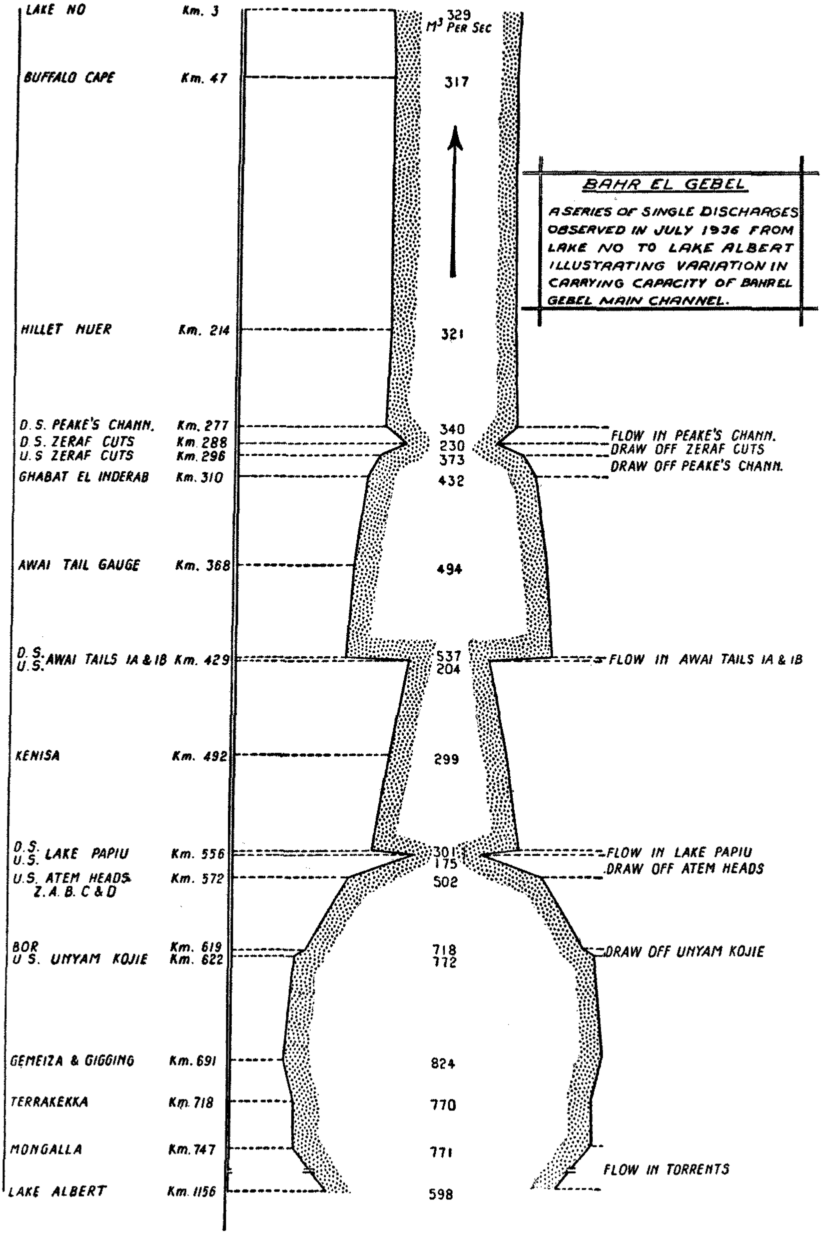
As regards the hydrology of this reach we have Bor discharges, as previously described, and for a period of five years, 1927–31, a complete analysis of the water leaving the reach below the Zeraf Cuts, as well as the discharges of the Upper Zeraf.

Discharges were regularly observed for long enough at Jonglei on the River Atem to be able to establish a gauge discharge curve for this station.

A considerable number of discharges have been taken at points scattered in time and space along the main channel and the spills in and out, and in addition series of discharges have been taken along the main channel.

These series are taken by the observer steaming along the river and stopping at selected sites for his observations, the idea being to get a picture of the actual flow along the river at a given time. Such a picture is shown by diagram in Fig. 9, where the intercepts are simultaneous, or practically simultaneous; discharges in the main steam and the abscissae are distances along the stream. While this diagram gives a profile of the river showing most graphically the variation in discharge almost from kilometre to kilometre, it seems doubtful whether valid deductions as regards losses can be made owing to the indubitable fact of lag, as defined and described previously. Steaming along the river, upstream, in the winter one encounters flood levels as far as Shambe, say—the gauges are high and the country, to the naked eye, is obviously flooded. Two days later, getting to Bor, one quite obviously is in low, though not the lowest, levels, and the country likewise is drying up. It would seem misleading, therefore, to deduct an individual Shambe discharge from an individual Bor discharge of approximately the same date, and say the difference is the loss, though of course if the discharges at each of these sites are summed over periods, the difference of the sums is the loss.

It became possible in 1936 to organize discharge observations so that they were taken regularly throughout the year at selected



BAHR EL GEBEL
A SERIES OF SINGLE DISCHARGES OBSERVED IN JULY 1936 FROM LAKE NO TO LAKE ALBERT ILLUSTRATING VARIATION IN CARRYING CAPACITY OF BAHREL GEBEL MAIN CHANNEL.
LAKE NO Km. 3
329 M³ PER SEC
BUFFALO CAPE Km. 47
317
HILLET NUER Km. 214
321
D. S. PEAKE'S CHANN. Km. 277
340
FLOW IN PEAKE'S CHANN.
D. S. ZERAF CUTS Km. 288
230
DRAW OFF ZERAF CUTS
U. S. ZERAF CUTS Km. 296
373
DRAW OFF PEAKE'S CHANN.
GHABAT EL INDERAB Km. 310
432
AWAI TAIL GAUGE Km. 368
494
D. S. U. S. AWAI TAILS IA & IB Km. 429
537
204
FLOW IN AWAI TAILS IA & IB
KENISA Km. 492
299
D. S. U. S. LAKE PAPIU Km. 556
301
175
FLOW IN LAKE PAPIU
U. S. ATEM HEADS Z. A. B. C & D Km. 572
502
DRAW OFF ATEM HEADS
BOR Km. 619
718
U. S. UNYAM KOJIE Km. 622
772
DRAW OFF UNYAM KOJIE
GEMEIZA & GIGGING Km. 691
824
TERRAKEKKA Km. 718
770
MONGALLA Km. 747
771
FLOW IN TORRENTS
LAKE ALBERT Km. 1156
598

FIG. 9

sites along the river. From these observations date-discharge curves will be plotted which should illustrate and illuminate the flow along the channel, the lag from point to point, and the losses in each reach.

Gauges along this reach have existed for sometime at Bor, Jonglei, Kenisa, Shambe, Awai Tail 3, Ghabat Inderab and the heads of Cuts 1 and 2 Zeraf. The co-ordination with discharges is bad, except at Jonglei, where the gauge dsicharge relation during the years 1930 to 1936 has altered very little.

Some years ago it was found that the relative resistance to water flow of the main channel and the swamp channels was constant, as was shown by the fact that Jonglei gauge (in the swamps) can always be predicted from Bor and Shambe gauges, or Bor and Kenisa gauges. As this can be done with a high degree of accuracy, discharges at Kenisa and Jonglei can be calculated for the whole period for which Bor and Shambe gauges are known, provided a reliable gauge discharge curve is available. The curves now in course of being established at various sites along the river, especially Kenisa, will give an idea of discharges carried in previous years, but great caution will be necessary in using these results, as gauge discharge curves have a habit of changing suddenly and without warning.

The Zeraf Cuts 1 and 2 are two canals, each about 4 km. long, connecting the Bahr el Gebel with the Bahr el Zeraf. They were made in 1910 and 1913, with the object of increasing the discharge leaving the swamps. They have been fully discussed previously by the author* and the conclusion reached that they seem to have failed in their object.

From these Cuts, northwards, the Bahr el Zeraf flows parallel to the Bahr el Gebel and carries from 30 per cent to 40 per cent of the total discharge, being fed to a small extent from the Upper Zeraf Swamps, but chiefly from the Cuts. The heads of the Cuts are short-circuited by Peake's Channel, as already explained, so that the total discharge in this latitude is the Zeraf downstream of the Cuts plus the Gebel downstream Peake's Channel. The results of these discharges summarized for five years, are shown in Table X below, which also gives the annual discharges for the same period at Mongalla, Bor, and the downstream end of the swamps. It will be noted that on the average over half the swamp loss occurs in this reach. It may be more, and the loss in the Mongalla–Bor reach correspondingly less, if it is eventually

* *Problem of the Upper Nile*, Egyptian Government Press, 1929.

shown that the Bor site is short-circuited by a substantial amount of water.

TABLE X

BAHR EL GEBEL DISCHARGES IN REACHES SHOWING LOSSES
(Milliards of cubic metres per annum)

Site	1927		1928		1929		1930		1931		Mean 1927–31
	Dis-ch'ge	Loss	Dis-ch'ge	Loss	Dis-ch'ge	Loss	Dis-ch'ge	Loss	Dis-ch'ge	Loss	
Mongalla . .	26·0		26·6		21·3		22·7		29·0		25·1
		2·6		4·0		0·9		1·9		5·6	3·0
Bor . . .	23·4		22·6		20·4		20·8		23·4		22·1
		7·4		6·0		4·6		5·9		7·1	6·2
Cuts* . . .	16·0		16·6		15·8		14·9		16·3		15·9
		2·5		3·1		2·1		1·2		2·9	2·4
Mouth† (Swamp Discharge)	13·5		13·5		13·7		13·7		13·4		13·5
Total Loss		12·5		13·1		7·6		9·0		15·6	11·6

* Cuts discharge is taken as Zeraf downstream tail Cut 2 plus Gebel downstream Peake's channel.

† Swamp discharge is taken as Zeraf Mouth plus White Nile at Abu Tong minus Ghazal.

Zeraf Cuts to Mouth (Fig. 10). This last reach is parallelled on the east the whole way to the White Nile by the Bahr el Zeraf. For the first 100 km. approximately from the Cuts, swamp is continuous from the Gebel to the Zeraf and beyond, with a certain number of islands covered with Doleib palms. From about 170 kilometres (from its mouth) on the Zeraf, this river runs in a well-defined channel with swampy berms, getting narrower, and during the lower part of its course the land through which it runs is distinctly higher than the Bahr el Gebel some 80 km. to the west.

The Bahr el Gebel is bordered by swamp on both sides. On the east there is one place where high land reaches the river, Buffalo Cape, 50 km. from the mouth. During the greater part of every year there is dry land from here across to the Zeraf and a line of precise levels has been run here, which show the banks of the Zeraf to be about two metres higher than Buffalo Cape. During flood, Buffalo Cape is an island, and in high floods is entirely submerged. There are various side channels in these eastern swamps, and from them issue some defined channels which appear to join the White Nile between Gebel Mouth and Zeraf Mouth, though it is not definitely known whether the channels are continuous from the Gebel to the White Nile.

On the west bank there is continuous heavy swamp the whole way, with only one dry spot, Hillet Nuer, 214 kilometres from the mouth, from which by aid of a causeway it is possible to journey westwards. All through the swamp, from Shambe to the Bahr el Ghazal, there is a long narrow "island," i.e. land on which cattle can graze during the low periods in low years. Near Hillet Nuer, Gage's Channel takes off and runs north west. It was discovered by the late Captain Ferguson to be continuous with the Khor Doleib which joins the Bahr el Ghazal about 30 km. from the mouth; it is practically all densely overgrown and has no perceptible flow near the head.

There are indications that some of the Gebel water, escaping westwards, flows into Lake No at some levels and thus rejoins the Bahr el Gebel via the Bahr el Ghazal.

Hydrologically, this reach is known through gauges at the Cuts, Hillet Nuer, Buffalo Cape, and the Mouth, and by the regular discharges at the Cuts from 1927 to 1931 and regular discharges at the Mouth since 1923. Series of discharges have been taken along this reach at various times, without revealing any striking peculiarities; the carrying capacity is fairly uniform and the relation between level and discharge is now being systematically investigated. The losses and the percentage losses have been plotted against the mean levels of the reach and show a big scatter; both increase fast with the mean levels. As nothing is known about water levels in the swamps themselves, it has not been possible to find out whether losses are dependent on such levels in any way.

Table X (above) gives the losses on this reach for the period 1927–31, and shows them to be of the same order, but somewhat smaller, as the losses on the Mongalla–Bor reach.

White Nile—Lake No to Sobat Mouth (Fig. 11). This reach of the White Nile, about 124 km. long, is really part of the Sudd Region as far as the Zeraf mouth, at least (km. 79). The swamps are narrower and high land is always visible along the left bank and very soon on the right. On the right bank two *khors* (channels) join the river: the Maya Sinyora, first discovered and explored by Miss Tinné nearly eighty years ago, and the Khor Yergol. Both these *khors* have discharges during the flood, but it is not known to what extent the water is spill water from the Bahr el Gebel above the mouth, or from the White Nile or from both. On the left bank there is an important parallel channel called the Khor Lolle, which also carries a discharge in flood. This river has its source northwards towards the Nuba Mountains, and it is probable that some at least of its discharge is new water; the rest may be spill from the White Nile. Investigations are being undertaken to try and clear up these uncertainties as to the source of the discharges of the White Nile tributaries, as the matter is of some importance in connection with the losses on the reach Lake No to Zeraf mouth.

The Bahr el Gebel and Bahr el Ghazal are measured regularly at their mouths, and the White Nile at the head as a check; a comparison of White Nile at Lake No with the White Nile at Abu Tong (see p. 36) therefore gives the losses on the Lake No–Zeraf reach. From the Zeraf junction to the Sobat junction, about 45 km., the White Nile valley becomes less swampy. The whole of this reach, from Lake No, runs very nearly in an east-west direction, across the main slope of the country, and its own slope is very flat indeed, being about 2½ cm. per km. in the low season and falling to less than 1 cm. per km. in flood.

The Sobat River is an important stream in flood, with an average maximum discharge of about 900 $m.^3$ per sec. The discharge increases very quickly from about May, with the consequence that there is heavy ponding in the White Nile upstream of the Sobat junction. At the highest levels this ponding effect spreads back to Lake No and beyond, and an appreciable loss is caused in the White Nile discharge due to its having to fill this pond, which seems to stretch back up to about Buffalo Cape on the Bahr el Gebel, a distance of 175 km., and beyond Yoynyang on the Bahr el Ghazal, a distance of over 200 km. (These distances are from Sobat mouth.)

This loss occurs at present during the untimely period and is not of importance, but similar action may be caused in the future, by the training projects to be described below, during the timely period, and it is therefore essential to form some estimate of the limiting amount of these losses. The evidence at present available (comparison of the White Nile discharges at Lake No and Abu Tong) tends to show that these losses as far upstream as Lake No are not large, even including the whole of the flow of the tributaries as new water. An important point to remember here is that training projects increasing the White Nile discharge would produce high levels and large evaporating areas during the hot dry months, January to June, when evaporation rate is high and rainfall small, whereas high levels at present occur during the flood months, when the meteorological conditions are exactly the reverse. The available figures are given in Table XI on the next page.

It should be noted that whereas the White Nile has been regularly measured since 1923, the tributaries have only been observed since 1933, and the means are therefore not strictly comparable. Table XI shows that the loss in the untimely period of high levels is 3 per cent on the assumption that the tributaries are entirely caused by spill water from the White Nile, i.e. water already included in the Lake No measurement.

TABLE XI

LOSSES ON THE WHITE NILE FROM LAKE NO TO ABU TONG
(Totals in millions of cubic metres.)

	1923–35			
	Jan.–June		July-Dec.	
Discharges at—				
Lake No	4 956		4 992	
Abu Tong	4 908		4 855	
Loss	48		137	
,, per cent		1		3
Tributaries	53		50	
Total loss	101		187	
Total loss per cent including tributaries		2		4

Tributaries observed only for 1933 to 1935.
All 1933 observations omitted as unreliable.

If the tributaries on the contrary are all new water, the true loss is increased by the amount of their flow, and would be 4 per cent, so there is little difference between the two figures. It is believed, however, that the average flow of the tributaries is higher than that indicated by the only two years, 1934 and 1935, for which the measurements are reliable.

The loss on the lower reach, from Zeraf mouth to Sobat mouth, has been worked out from the available published data and found to be 3 per cent, hence the total loss at present at high levels from Lake No to Sobat mouth may be taken as 7 per cent within the limits of discharges actually carried. The higher discharges which will be necessitated by the later stages of any Sudd Channel Project should not increase the percentage losses, up to Lake No, if they occurred at the same season of the year as at present. As this will not be the case, it would seem to be unsafe to assume these losses as being less than 7 per cent. With regard to the ponding to be caused by future high levels upstream of Lake

No in the Gebel and Ghazal swamps proper, data are being collected, which may make it possible to fix a limiting figure for the losses.

River Sobat (Fig. 1). The River Sobat is the most important tributary of the White Nile and its discharge near the mouth has been measured regularly for many years. It is formed by the junction of the Rivers Baro and Pibor, the former being entirely in Abyssinian territory, while the latter forms the boundary between Abyssinia and the Sudan. Round the Baro-Pibor junction there are swamps only second in extent to the Sudd Region, and as they are in foreign and unsettled territory they have not been investigated. At Gambeila on the Baro some 200 km. upstream the Baro-Pibor junction there is a Sudan Government enclave, leased from the Abyssinian Government, where discharges were observed for a number of years and a river gauge has been regularly observed since 1905. The total discharge of the Baro can therefore be established from gauge-discharge curves, with reasonable accuracy. The group of discharges, Baro mouth, Pibor mouth, Sobat head is also regularly observed; hence the loss between Gambeila and the Sobat should be calculable. Unfortunately, owing to our ignorance of the topography of this region, it is not possible to ascertain definitely how much of the Pibor water is new water and how much has come by spills from the Baro below Gambeila. It is not worth while going into all the intricacies of the network of channels here, as very little of our knowledge is definitive, so that the position, as known at present, can only be stated in broad and tentative terms.

About 12 km. above the junction with the Baro, there is a tributary on the right bank of the Pibor called the Makwai, which is believed to derive the majority of its water by spills from the Baro below Gambeila; it is thought that little of the Baro spill water spreads beyond this, and that all other water flowing in the Pibor is therefore new water. Hence Baro at Gambeila plus Pibor above Makwai form the Sobat at the head; knowing these three measurements, the real loss on the Baro between Gambeila and the Sobat head can be estimated and this is done in Table XII on the next page.

The Baro–Pibor swamps round their junction are unexplored, and there may be all sorts of short-circuiting of the discharge sites at high levels which militate against the accuracy of the figures. They are, however, the only ones available to give some idea of the order of magnitude of the losses, which are seen to average about 2 000 million cubic metres per annum in the untimely (flood) period and about 300 million per annum in the summer. Now the Baro is the river closest to Egypt on which there is any substantial loss of water annually from sheer spilling and evaporation; hence from the strictly engineering point of view this is the first area that should have been investigated. Partly owing to the fact that it is isolated, the Sobat only being navigable from about June to November, but chiefly owing to the river being in a foreign country, Abyssinia, very little attention has been paid to the possibility of conservation works here.

It is probable that all that would be required to prevent the flood waste is the embankment of the river on both sides for a distance of about 200 km., with some dredging in the Sobat to permit of river access to the works the whole year round. A great deal of the water saved would be untimely and unstorable on the Main Nile, but all would be storable on the White Nile if the necessary reservoirs existed.

TABLE XII

LOSSES ON THE RIVER BARO 1929–33
(Average Annual Totals in millions of cubic metres)

Site	Jan.–June 1931–33	July–Dec.	
		1929–33	1931–33
(1) River Baro at Gambeila	1 900	10 400	10 500
(2) River Pibor upstream Makwai	600	1 600	1 600
(3) River Sobat at Head	2 200	9 800	10 100
(4) Loss on River Baro (1) + (2) − (3)	300	2 200	2 000

The losses from Sobat head to Egypt must be taken as about 30 to 35 per cent, and hence the average untimely water to be obtained as at Aswan would be about $1\frac{1}{4}$ milliard cubic metres per annum.

The bank required might be 3 to $3\frac{1}{2}$ metres high, with 10 metres crest width, thus involving the excavation of some 30 million cubic metres of earth costing something of the order of two million pounds.

Bahr el Ghazal (Fig. 1). The Ghazal is a dead river, sluggish, overgrown with weeds, and carrying a negligible discharge, which has been known to fall to nil at the mouth, while the maximum ever observed is 91 m.^{3} per sec. The only available discharge site at the mouth is a bad one, much affected by wind, so that great reliance cannot be placed on any individual figure, though the mean of a large number of observations is probably not far wrong. The yearly average is only 18 m.^{3} per sec., and this despite the fact that this river is the sole drain of an area of about half a million square kilometres subject to the heavy rains of Central Africa. The reason is that the water all gets evaporated in the huge swamps lying in the angle between the Bahr el Gebel and the Bahr el Ghazal, known as the "Great Bog."

Neglecting the small and unexplored *khors*, mostly overgrown, the tributaries are first the Khor Doleib, at kilometre 30 from the mouth on the right bank. It has already been mentioned above that this is continuous with Gage's Channel taking off the Bahr el Gebel at Hillet Nuer, where it is completely overgrown; for the last 25 to 30 km. before it joins the Bahr el Ghazal it is, however, a broad sheet of water about 100 metres wide and 2 to 2½ metres deep, but despite this it carries practically no discharge. Next comes the Bahr el Arab at kilometre 146 from the mouth on the left bank, draining a large area in Kordofan and Darfur, also an important looking channel in which also only very trifling discharges have ever been observed. The third tributary is the River Jur, which is really the upper reach of the Bahr el Ghazal and is navigable in flood to Wau, the capital of the old Province. It has occasionally been measured in winter near its junction with the Ghazal, and then has a discharge of only about 30 m.^{3} per sec., falling rapidly, despite the fact that it has the Lol as a tributary, a fairly important stream in flood.

The north limit of the Great Bog is on the line from Shambe to Wau, and at this latitude the rivers Lau or Yirrol, Meridi, Tonj, and Jur run well above the Bahr el Gebel level at Shambe. River gauges exist on the Lau, Tonj, and Jur, and have been levelled; there is also a gauge on the Lol, but its reduced level has not yet been determined. Discharges of the Lau and Meridi Rivers have never been measured, but some observations were taken on the Tonj and Jur in 1930. The Jur had a discharge in October of 600 m.^{3} per sec., and was, judging from the Wau gauges, probably higher in September. The Tonj had a discharge of over 100 m.^{3} per sec. in August, and was also probably higher later in the year, but there was then no gauge there to give evidence on this point. It seems certain from the shape and nature of the beds of all these rivers that they carry a large quantity of water from August to October annually. They sometimes overflow their banks and turn even the high country into a shallow lake for weeks at a time. The average discharge in flood can only be guessed within wide limits, which might be, as a sum of the four, between 800 m.^{3} per sec., and 1 600 m.^{3} per sec., i.e. from two to four milliard cubic metres per month for about three to four months.

Owing to our profound ignorance of the hydrology and even geography of this country, only tentative ideas as to possible conservation works have ever been suggested.

One proposal was to remodel the Bahr el Ghazal to be a big drain, increase the discharge to a figure not stated, and pump it into the White Nile at Lake No. As it is barely worth while considering a scheme which would produce less than one milliard cubic metres annually at Aswan, and assuming transmission losses from Lake No to Aswan to be about 30 per cent, this means provision would have to be made for pumping about 1·5 milliards in six months, or, say, 100 m.^{3} per sec. To make this possible the Bahr el Ghazal would have to be dredged to run at a slope of not less than 5 cm. per km., which would mean a six metres lift at Lake No at least and very deep excavation. It would probably have to be dug even lower than this for the branch drains through the Bog to be effective, so that the total cube of excavation on over 200 km. of the Bahr el Ghazal, plus an unknown number of branches of unknown length, might easily be many hundreds of millions of cubic metres.

Further, if the scheme were meant to work during the timely period it is by no means certain that the water would not have evaporated from the Bog, and the system would therefore not furnish the discharge required. It does not seem worth while investigating this proposal to the point of making a preliminary project.

A second suggestion is to catch the waters of the above rivers in a collector channel in the latitude of Shambe–Wau before they fall into the Bog and lead them to the Bahr el Gebel, below Shambe and thus to Egypt. This scheme of course presupposes that the Bahr el Gebel has been remodelled, and is possible because there is a fall of about 20 metres from Wau to Shambe; the required canal would be about 300 km. long. Now as these rivers cease flowing in November, all water that reached Egypt would be untimely, but would nevertheless be needed in the future to fill reservoirs, though as the time of travel from Shambe to Aswan would be about five weeks through the Sudd Channel, only the waters of September and October would be storable. By providing for a maximum discharge of 800 m.^{3} per sec. in the last reach, and 300 in the first, it might be possible to add about three milliards to the river, of which half might reach Aswan. The cube of excavation required would be of the order of 150 million cubic metres and might, with modern machinery, cost about seven to eight million pounds, which is more than twice as much as Egypt has hitherto paid for water, but what she must expect to pay for the last few milliards required.

There are two small lakes near Yirrol, some 80 km. from the Bahr el Gebel, which might be turned into storage reservoirs, filled in flood by the Lau River, with water that would otherwise be wasted. The capacity of these lakes is not large and in all probability the canal required to lead the water to the Bahr el Gebel would be prohibitive in cost.

No other suggestions seem to have been made for attempting to derive some benefit from the enormous quantities of water wasted in the Bahr el Ghazal. None of the three is very promising, but the Collector Channel proposal is worth study. If Egypt in the future really wants the last milliard, this may be as cheap a source as any.

CHAPTER V

TRAINING PROJECTS IN GENERAL

In order to prevent the huge waste of water that occurs in the swamps of the Bahr el Gebel, training works must be undertaken. Though the study of the Upper Nile has been carried out for many years, the hydrology and geography of the region are so complicated that no project has yet been finally adopted, but the number of *prima facie* projects that were at one time worth consideration has, by the work of the last few years, been narrowed down from nine to three, namely—

The Veveno Project.
The Bor-White Nile Project.
The Remodelling of the Bahr el Gebel Project.

The two former are diversions projects—water would be taken from the Bahr el Gebel and diverted by canals either through the River Sobat to the White Nile or direct to this river.

It has already been pointed out that there is no useful object in reducing the Bahr el Gebel discharge below 500 $m.^3$ per sec. at Mongalla or, say, 470 $m.^3$ per sec. at Bor, and hence any project need only provide for the diversion of the excess over this quantity at Bor. This moreover secures the essential condition of maintaining the Bahr el Gebel as a navigable river.

The discharge of Lake Albert has been taken as 23 milliards per annum of which 4·5 milliards are needed in the six untimely months to maintain navigation. Thus during the remaining six months the discharge would be 18·5 milliards as at Mongalla, or about 1 200 $m.^3$ per sec. This would be reduced to about 1 130 $m.^3$ per sec. at Bor near where any training project begins, of which 470 $m.^3$ per sec. would go down the Bahr el Gebel, leaving 660 $m.^3$ per sec. to be diverted. Any project should be so designed as to be capable of being gradually enlarged from a first stage, yielding about one-third of the ultimate benefit. During the early stages, regulation on Lake Albert would furnish the requisite timely discharge and allow the remainder of the annual discharge to be dissipated in the untimely period, though possibly some might be retained in Lake Albert to build up a reserve. It is therefore not till the later stages that the discharge required at Mongalla would exceed 800 $m.^3$ per sec. in the timely period. When this stage is reached, the river from Mongalla to Bor may have to be embanked on the west side for the greater part of its length to prevent the waste that now occurs at high discharges.

Egypt will eventually require every drop of water that can be made available, and hence it seems certain that construction once begun will be pushed on continuously till the above discharges are reached. Two dangers therefore have to be avoided if the project is designed in stages; the first stage may be made along a line cheap for that stage but very expensive for the final stages, and on the other hand the reverse position may arise, where the first stage is expensive, but the final stages cheaper. The final project should be kept in view the whole time and if, as assumed above, construction is continuous an expensive first stage may be worth while, but if there are likely to be long halts between successive stages a cheap first stage at the cost of an expensive final stage may nevertheless be economically sound. A decision on this point involves considerations of national development and financial capacity, but would seem to be necessary before any project can be finally approved for construction.

The Veveno Project. It was believed for some years that during the extraordinarily high flood of 1917–18 a direct water connection was established between the Bahr el Gebel on the Mongalla–Bor reach and the upper waters of the River Pibor, through its tributary the Veveno. During the War hydrological work on the Upper Nile was at a minimum, and no definite evidence of this belief was obtained. Mr. O. L. Prowde, C.M.G., at that time Inspector of Irrigation, Upper Nile, saw however that if there were such a high level connection, it might be improved to give connection at all seasons from the Bahr el Gebel to the River Sobat. As the latter carries only a very small discharge in the summer, its wide empty bed might be used at that time to carry water diverted by a comparatively short and possibly cheap channel from the Gebel to the Veveno and down the Veveno through the Pibor and Sobat Rivers to the White Nile. This proposal could only be tested by survey, which presented for many years unsurmountable difficulties owing to the waterless and impassable nature of the country. A small military patrol crossed this country in five days on camels in 1912, carrying their own water, but no one else had ever been known to get across in the dry weather. Schemes for carrying out the survey with donkey transport were found impracticable, and the work could not be undertaken till six-wheel lorries were introduced. Even these lorries could not get over the ground, broken up with closely spaced hummocks formed by the roots of burnt-out grass, till road-graders had smoothed the surface and made dry-weather roads. The survey was then carried out in the 1929 and following seasons, and it was found that there could not have been a water connection between the Gebel and Veveno Rivers in 1918 as there was a plain about 80 km. wide separating the two, whose level was about 1·25 metres above the highest water levels recorded in 1918. Nevertheless, the main difficulties of the exploration having been overcome, it was decided to carry on the field work to a point where a project could be worked out. The whole matter was then carefully considered by a Departmental Committee of the Egyptian Irrigation Service, and the results published in 1932 in an Egyptian Government Departmental Paper, *The Veveno-Pibor Scheme.* Only a brief résumé of the matter need therefore be given here.

Owing to the great depth of cutting otherwise required for the canal, a barrage would be necessary before the work on the canal could begin; it was found that the Veveno was negligible in its upper reaches and so winding in the lower ones that no benefit would be gained by following its course rather than cutting a new canal, 220 km. long, from Gemeiza on the Gebel to Pibor Post on the Pibor; the lower reaches of the Pibor were found so small that they could not carry the required discharge and a further canal or relief channel capable of carrying about 145 $m.^3$ per sec. at the head and about 130 km. long was necessary; the average time during which the bed of the Sobat could be used for the diverted water was only about four months per annum; an increase in the size of the Project would involve very heavy works along the whole 330 km. of the River Pibor, whose magnitude could not be estimated, besides the enlargement of the Veveno Cut.

The project therefore comprised a barrage on the Bahr el Gebel at Gemeiza, a canal from there to the River Pibor capable of conveying 350 $m.^3$ per sec., and a relief channel from Akobo on the River Pibor to Nyanding on the Sobat to assist the lower reaches of the River Pibor. The whole would have cost about £E. 8 000 000, not including Lake Albert Dam, and would have provided about two milliard cubic metres of water per annum at Malakal in the timely season.

In consequence of the above considerations, the Egyptian Government decided not to proceed with the preparation of the

Veveno Project, till the two other projects mentioned above had been worked up to the same state.

The Bor-White Nile Project. The late Mr. J. S. Beresford, C.I.E., formerly Inspector General of Irrigation in India, first suggested to Sir William Garstin a direct cut from Bor on the Bahr el Gebel to the mouth of the Sobat on the White Nile, and this idea was incorporated by the latter in his proposals for dealing with the Upper Nile.

One of the first surveys carried out was to do the necessary levelling from Bor to the White Nile by the most convenient, not the shortest, route which established the feasibility of the Project. No very intensive study was given to it for many years, because at the time the only method of construction would have been by dredgers working from the two ends, and the time taken before the first water flowed through the canal would have been long indeed.

An alternative to the straight line cut was a proposal made in 1923 called the Bor–Zeraf Project, to run a canal along the eastern edge of the swamps from Bor to about kilometre 170 on the Zeraf, and remodel the Zeraf from this point. Now the Zeraf is a very winding stream, the straight line from kilometre 170 along the channel to the mouth being only about 100 km. long, and moreover in any scheme where the discharge of the Bahr el Gebel at Bor is kept at about 470 $m.^3$ per sec., the discharge of the Zeraf would only be about 80 to 100 $m.^3$ per sec., whereas its carrying capacity would be nearly double this figure. Hence this project was further modified by abandoning the remodelling of the Zeraf and continuing the new canal in a straight line but reduced section from kilometre 170 to the White Nile, with a short connecting link to the Zeraf through which the latter's discharge could be brought up to the maximum safe figure. The advantage of running the canal close to the swamps is that access for dredgers can be obtained at several points by short cuts from the Bahr el Gebel, and the number of working faces correspondingly increased and the time for construction reduced.

A further modification called the Jonglei Canal Project was to start the canal at Jonglei below Bor instead of above Bor. This place has already been described (see p. 50). It has been discovered that the Atem River at this point always carries a sufficient proportion of the water passing Bor to feed a diversion canal for the first stage of the Project. The increased discharge required for later stages would either be obtained by prolonging the canal southwards, east of the swamps, to a point above Bor, or by improving the Atem southwards in its course through the swamps. In any case, Jonglei is the nearest point to the White Nile where an adequate body of water flows close to hard land, and hence a canal from here is shorter than from anywhere else and offers a considerable economy in construction of the first stage at any rate. The line adopted follows the eastern edge of the Atem swamps to the Zeraf and thence in straight lines, close to the Zeraf, to the White Nile near the Zeraf mouth. This line can be constructed throughout by dredgers, but before adopting it, another and shorter line direct from Jonglei to the nearest point on the White Nile was investigated, the proposal being to construct it by land machines—drag lines—of the largest size, served by a railway to be constructed *ad hoc* along the canal line. Despite the great economy in unit rates of excavation to be obtained from drag lines, the construction by this method was considered less favourable for two reasons. First, owing to the heavy annual rains turning the whole area into a swamp from about mid June to end September, land machines could only operate for about 8½ months of the year anywhere on the line; secondly, the southern end of the line goes through land that lies low compared to the river levels and might be below such levels for years at a time, and hence be under water for an unknown length and not capable of excavation by land machines.

The direct Beresford line from Bor to the Sobat mouth has not been surveyed. It is, of course, longer than the line Jonglei to White Nile, but shorter than the line Bor–Jonglei–White Nile. There are indications of some sort of a ridge along here, and a possibility that it is not subject to flooding from the river. If this were so it could be constructed by drag-lines, probably at a cheaper rate per cubic metre than seems possible with dredgers. It would seem advisable therefore to survey this line before a final decision is reached on the Bor–White Nile Diversion Canal.

The water and land levels at Jonglei are such that no barrage is necessary here to divert water into the canal, thus giving a considerable economy in cost compared with the Veveno Project.

Owing to the fact that above a discharge of about 500 m.^{3} per sec. the Sudd losses are very variable, it is at present impossible, and will perhaps remain so, to predict with much accuracy the effect on the Gebel mouth discharge of a Sudd Channel from Jonglei when the Bor discharge is maintained, say, at 700 m.^{3} per sec., and 220 m.^{3} per sec. are drawn off down the channel. This is not, however, very serious; it only means the Sudd

Channel may be too big in the first stage, but the extra capacity would be of use as soon as the second stage is reached and the head of the channel taken to Bor, either by improving the Atem or extending the canal.

With the Gebel taking 470 m.^{3} per sec. at Bor, and without the Lake Albert Reservoir to supplement the supply, such a Sudd Channel would very seldom be able to work at full capacity. In the standard year there would be a mere trickle averaging 17 m.^{3} per sec. at the head during the months February and March, while the average discharge in the whole timely period would only be about 37 per cent of capacity. In an average year, which is in fact a good year, there would be a better showing—the canal could run at full capacity for two months and would average 89 per cent for the whole timely period. Hence if the Channel were constructed and Lake Albert Reservoir not formed, Egypt would get an increased supply in good years, and little or none in bad, when it is most wanted. Agricultural development would be made unnecessarily hazardous and it would therefore seem that the Lake Albert Dam is an essential element of any Bor–White Nile Diversion Project.

The cube of excavation of the Jonglei Canal or first stage of the Bor–White Nile Project is estimated at about 65 million metres cube and the cost at £E. 4 500 000 including head works, locks, etc., but not including the cost of Lake Albert Dam. It will provide about two milliards per annum at Malakal in the timely period and is therefore very much cheaper than the Veveno Project. Future stages and costs have not been worked out in detail.

In the first stage the question of losses caused by adding large volumes to the White Nile is not important, though the amount is difficult to estimate. In the later stages ponding is sure to be caused, which will stretch back beyond Lake No and affect the Bahr el Gebel and Bahr el Ghazal and thus cause flooding of unknown extent and concomitant losses in the swamps. Data are accumulating which will make it possible to make an estimate of the extent of such swamping; it is not likely to be as large as once feared and could be prevented either by remodelling (deepening) the White Nile, or embanking the lower reaches of the Bahr el Gebel and Bahr el Ghazal. Whether the cost of such works would be a sound expenditure, economically speaking, relative to the amount of water to be saved, remains to be seen. The total final cube, including such embankment of the Gebel at the mouth and above Bor, is not likely to be less than about

200 million cubic metres, and the cost including all subsidiary works except Lake Albert Dam about £E. 12 000 000.

Remodelling the Bahr el Gebel. The length along the stream from Bor to the mouth is 619 km., whereas the length along straight lines following the general line is only about 450 km. The slope is good and the stream is fast and deep between papyrus walls. The channel is stable, which indicates that it has taken up a course suitable to the soil. Hence it is to be expected that any increase in general velocity caused by cutting off bends and thus increasing the slope would cause erosion and fresh bends, which could only be prevented by heavy expenditure on protection.

It seems, therefore, that if this river is to be made to carry 1 130 m.^{3} per sec. instead of 470 m.^{3} per sec. the existing channel must be enlarged with all or nearly all its bends, and the increase in section is more or less equivalent to making a Sudd Channel 619 km. long instead of a diversion channel of the same carrying capacity about 350 to 400 km. long. It is true there are advantages in using the existing river, the principal ones being ease of access and multiplicity of working faces. The cubes of excavation have not yet been worked out, but will probably be of the order of 500 million cubic metres, and therefore so much in excess of those of any diversion channel as could probably not be balanced by any cheapening of excavation rates, despite the fact that neither headworks nor locks would be required.

Double Embankment Project. As the remodelling of the actual channel seems such a hopeless proposition, the study of an alternative method of utilizing the Bahr el Gebel is being undertaken, namely, to leave the channel itself untouched but to throw up banks from salient to salient on each bank and let the water find its own way down the waterway thus formed, which would have an average width of about 1·7 km.

The water level falls rapidly from the river through the papyrus, as already described, to the level of the swamp water through a height of about one metre, and the depth of water in the swamps may be about the same. Hence the present maximum water level in the Gebel may be about two metres above the ground level under the proposed banks, and a bigger head might be involved by the project.

The first step in considering the scheme was to ascertain under what conditions banks could be made in the Sudd Region to withstand a head. Small tanks were therefore thrown up by dredgers at regular unselected intervals along the Bahr el Gebel, on the principle of fair sampling, and tested for leakage. The tanks at each site were of two sizes: a small size of about four metres by four metres internally, and a larger size of about eight metres by eight metres. The object of having tanks of two sizes was to ascertain whether there was any leakage through the bed as well as through the banks forming the tanks. If there had been such leakage, the larger tanks would have shown a bigger leakage per metre length of bank than the small ones. As this was not the case, it was proved that the surface on which the tanks were built was impermeable.

Owing to the limitations of the machinery available and the cost, the banks were made with the crest a little above the water level in the swamps, the inside of the tanks was pumped out to form 0·50 cm. head and occasionally 1 metre head, and the leakage measured through the banks from the high water level in the swamps to the low water level in the tanks. This was done by measuring the increase of level per 24 hours in the tanks, the gauges having been calibrated from a measuring tank. Due allowance was made for evaporation. The banks were of 2 metres crest width and about 3 to 1 side slope; the sections were irregular and the head could not always be applied at the same point, as this depended on the natural level of the water in the swamps. For practical purposes and ease of comparison, a bank was deemed to be 100 per cent watertight when the leakage per metre length in 24 hours under 1 metre head was 0·1 m.^{3}, and it was assumed that the leakage varied directly as the head. This figure was taken because this amount of leakage on two banks each 450 km. long would be absolutely negligible.

When the experiments were begun it was expected that to obtain a watertight bank all the papyrus, growing and decaying, would have to be cleared from under the site for the bank and from the borrow-pit, but this was found to be quite unnecessary. One such tank was made (i.e. site and borrow-pit cleared) and was found to be actually watertight, i.e. the leakage was barely measurable and, on the above definition of watertightness, it became several thousands per cent watertight. Subsequently therefore the tanks were constructed of spoil as it came, full of vegetation and detritus, which was dumped on the site of the bank, without clearing the site. Experiments were carried out on seventeen tanks at eight sites between Lake No and Bor in the years 1934 to 1936; while the results varied from site to site, at only one was there any difficulty in forming a good bank, through which the leakage was very small, in this way. At this site, a good sound bank was formed by cleaning the site of the bank and the borrow-pit. The "watertightness" varied from 272 per cent to 13 per cent, and it follows therefore that there need be no fear of heavy leakage losses through the banks of a Sudd Channel, which would have a crest width of ten metres as against the two metres of the test banks, provided there is no breakdown of the assumed law that leakage is proportional to head.

The nature of the soil was found to vary very much, both from site to site and at the same site, in proportions of clay and sand and decaying vegetation. A test tank will be maintained and tested annually for signs of deterioration, and there appears to be only one more hypothesis to be tested, namely that leakage is proportional to head. There are indications amongst the tests made that the leakage increases faster than the head, but it has not yet been possible to carry out tests at heads exceeding about one metre. As the banks might have to stand a head of two metres or more, it is hoped that experiments at such heads will be carried out when machinery and funds are available, to give assurance that any remodelling scheme, which involves such heads, is structurally sound.

If this scheme were carried out, there would be a discharge of 1 130 m.^{3} per sec. flowing between these two banks, 1·7 km. apart, from Bor to Lake No. The banks would be about 450 km. long, and the channel between them would be 619 km. long, varying frequently in section from a present carrying capacity of about 170 m.^{3} per sec. to one of about 600 m.^{3} per sec. between the papyrus walls. It seems difficult to predict convincingly what would happen hydraulically in such a channel.

The losses from Bor to Lake No up to about 500 m.^{3} per sec. are about 15 per cent; they are hardly likely to be less for this embanking project.

Pharaonic Project. A third method of dealing with the Bahr el Gebel has been proposed, based on the historic method said to have been employed by the Pharaoh Menes when dealing with the Nile in Egypt, and hence known as the Pharaonic Project. Menes is supposed to have concentrated on the west bank of the Nile by embanking it and leaving the east bank as an escape. The same method is proposed for the Bahr el Gebel, namely, to construct a bank from Mongalla to Lake No and thus prevent any escape of water westwards while leaving the east a swamp. There would also be a bank along the right (south) bank of the Bahr el Ghazal for about 100 km. upstream from Lake No, to prevent swamping from the ponding caused in this river.

The greater part of the swamps fed by the Bahr el Gebel appear to lie to the west. This is not yet proved definitely, but is almost certain. Cutting off these westward swamps will raise water levels in the eastward ones, and thus increase their area. The ground, however, rises faster to the east than to the west, and hence the increase in the east should be much less than the decrease in the west i.e. on balance the losses should be reduced. The Gebel-Ghazal divide survey, previously referred to and now in progress, should establish a relationship between swamp areas on the east and west of the Gebel and thus enable an estimate to be made of the probable reduction in losses due to shutting off the western swamps.

When this project was first proposed in 1928 it was thought that the bank need be only about two metres high, but the recent discoveries of the relation of river, swamp and land levels make it probable the bank might have to be over three metres high. On the other hand, it is not unreasonable at this stage to assume that the losses may be reduced by half instead of a quarter, as assumed in 1928. The project is therefore worth investigation, even if only as the first stage of the Double Embankment Project.

Both the Double Embankment Project and the Pharaonic Project would, before Lake Albert Dam is built, produce their major effect in the untimely period, and therefore be of little assistance to Egypt's water supply unless reservoirs existed downstream, which could be filled by the extra untimely water. There is a danger that these projects, without Lake Albert Dam, might increase high floods in Egypt by the early untimely water. Whether this danger is important or not would depend on the change in the time of travel (as previously defined) from Mongalla to Malakal. At present, high discharges at Mongalla in July and August do not affect the river in Egypt till about October and November. If the time of travel is so shortened as to produce an effect in August and September, an ordinary high flood might be turned into a dangerous one. This is more likely to occur with the Double Embankment Project than the Pharaonic Project, hence the latter would be the safer, pending the construction of Lake Albert Dam. When that is built, the basic Mongalla untimely discharge will be reduced to 300 $m.^3$ per sec. and hence the torrents on top of this are never likely to be dangerous.

Thus it would appear that the order of construction of a Bahr el Gebel Embankment Project should be—

1. Pharaonic Project—left bank only.
2. Lake Albert Dam.
3. Double Embankment Project—right bank.

A good deal more survey and research is required before this project as a whole and in its successive stages can be compared with the whole and the stages of any Bor–White Nile Diversion Project, but a rough estimate of the cube is as follows—

Pharaonic Project—		
Mongalla-Bor, left bank . . .	130 km.	4×10^6 m³
Bor-Lake No, left bank . . .	450 km.	43×10^6 m³
Bahr el Ghazal, right bank . .	100 km.	5×10^6 m³
		52 million m³
Double Embankment Project—		
Right bank along Bahr el Gebel, Mongalla to Lake No . . .		47 million m³
Total (say) .		100 million m³

No headworks or regulators appear necessary in this project except a head sluice at the Zeraf Cuts and a lock to the Bahr el Ghazal at Lake No. Access is easy, the work would give a progressive beneficial effect from its beginning, and the cost should not exceed about £E. 7 000 000 not including Lake Albert Dam.

If the relative areas of swamp to east and west of the Bahr el Gebel are as they are thought to be, this Project appears to have many advantages.

Regime and Water Available from any Sudd Project. The benefit to Egypt of any project in terms of water is the difference between the swamp discharge at Malakal at present and that to be produced by whatever project is adopted, which depends on the transmission losses to be incurred between Mongalla and Malakal, and on the losses from Malakal to Aswan.

The Departmental Committee on the Veveno-Pibor Scheme decided after full investigation of the few relevant data available to adopt a figure of 30 per cent as the losses from the head at Gemeiza on the Bahr el Gebel to the mouth of the River Sobat. Losses upstream of Gemeiza and losses caused by ponding on the White Nile upstream Sobat mouth, were not considered. This was to some extent based on the losses in the Gezira Canal, the main canal of the Gezira Irrigation Scheme and the only canal in the Sudan of any size, and on the assumption that the losses along the Veveno Cut from the Gebel to Pibor Post would be of the same order, length for length. Thus the losses on 220 km. length were taken as 10 per cent.

It should be noted that the Gezira Canal is a high level canal cut entirely through heavy impermeable loess; the Sudd Channel, however, will penetrate through the similar but much thinner coating of the Zeraf plain into sands and, occasionally, fine gravel. To adopt on the Zeraf a figure for losses derived from Gezira conditions may therefore perhaps be considered optimistic.

However, using this figure as a basis, the losses along a canal on the line Bor-Jonglei-Zeraf km. 170–White Nile, total length 390 km. would be 18 per cent. To this has to be added 6 per cent for losses from Mongalla to Bor and not less than 7 per cent for losses on the White Nile between Malakal and Lake No, making a total of 31 or, say, 30 per cent, for any Bor–White Nile Diversion Project.

For the Bahr el Gebel Remodelling (embanking) Project, the estimate for losses must be even more of the nature of guess-work. Under present conditions, the losses at low levels when there is practically no spilling are about 20 per cent from Mongalla to the White Nile, and they are not likely to be less than this for the Double Embankment Project. Add to this 7 per cent for losses in the White Nile to Sobat mouth and the total is a minimum of 27 per cent.

It is proposed provisionally to adopt the figure of 30 per cent for the losses between Mongalla and Malakal as a minimum, whatever the route. They may be more than this, but should always be a little less on the Bahr el Gebel route than the Diversion Canal route.

The proposed regime of Lake Albert Dam in the future would be full supply of 1 200 m.^{3} per sec. for six months, and then low supply (navigation water) of 300 m.^{3} per sec. for the other six months. There would be transition periods at each end, but this detail need not be considered now.

The regime at Mongalla would be as above plus torrents entering the river below Lake Albert. A small amount of torrent discharge mostly occurs in the latter months of the timely period (Table VII, Appendix), but no dependence can be placed on its arrival and whatever there is can only be treated by Egypt as a bonus; the discharges are small compared with the final discharge of a Sudd Channel and can easily be passed either down the Channel or the Gebel. The total as at Mongalla in a mean year is about one milliard cubic metres, of which about half would reach Aswan—in some years it may be less than a fifth of this amount.

During the untimely period the torrents vary according to the month and year from about 50 m.^{3} per sec. to about 600 m.^{3} per sec. (these are monthly averages—individual spates may be much larger), and will come down on top of the 300 m.^{3} per sec., steady navigation water from Lake Albert, which has to go down the Gebel, leaving only the torrents available for the Sudd Channel, if a Diversion Project is adopted.

In a year of minimum supply in the untimely period there will be a torrent discharge varying from nil to about 130 $m.^3$ per sec., in a mean year it will vary from a trickle to about 320 $m.^3$ per sec. and in a maximum year from about 100 $m.^3$ per sec. to 600 $m.^3$ per sec.

It is obvious that even in a maximum year, there will be some months when the Sudd Channel would be running at about one metre depth and in other years, for months at a time during the rainy season, this wide deep artificial channel would have only a foot or two of water in it, and would almost certainly therefore get overgrown with papyrus, ambatch, elephant grass, etc. It is expected that during the first stages of a Diversion Project, when the water from Lake Albert would suffice to keep a steady flow down the channel the whole year, the berms would get covered with vegetation and also the side slope to a depth of, say, two metres below water level, and in fact, in calculating discharges of a diversion canal, such areas of the cross-section are omitted.

In the final stage a problem arises, owing to the lack of water in the untimely or rainy period, which would appear to be most serious and has not yet received any study, for, scientifically speaking, nothing is known of the habits and ecology of the swamp vegetation. It is, however, a matter of common knowledge and observation that growth is exceedingly rapid and luxuriant in the rainy season, so that vegetation will be established on the berms and upper part of the side slopes, which would in all probability spread downwards and all over the bed, so that the channel might be choked and unable to carry the discharge when it was reopened at the beginning of the timely period. This spread of vegetation happened in most, but not all, of the experimental tanks above mentioned, made for testing seepage, so though it is not certain that such action would take place all along the canal, it would almost certainly occur on long reaches. The unsolved problem is how to deal with this danger, which might be so serious that the only way to cope with it would be to keep the discharge much more uniform throughout the year, i.e. reduce the timely discharge from 1 200 $m.^3$ per sec. to 900, and increase the untimely from 300 to 600 $m.^3$ per sec. plus torrents. The untimely water might then be largely wasted in the absence of reservoirs lower down in which it could be stored, and thus reduce the benefits of the Lake Albert Dam and Sudd Channel Scheme very considerably.

If the Double Embankment Project were adopted it would seem impossible to predict what would happen in this respect to the long-established Bahr el Gebel taking a course of 619 km. between banks 450 km. long when the discharge fell from 1 200 $m.^3$ per sec. to 300 $m.^3$ per sec. plus torrents, but at any rate the untimely discharge along a remodelled Bahr el Gebel would be a higher proportion of its full (timely) discharge than in the case of a Diversion Project, so the bed should keep cleaner.

The time of travel along a Sudd Channel from Mongalla to Malakal is taken as ten days, whether through a diversion canal or a Gebel embankment. In the case of a Diversion Project there is also water flowing down the Gebel, which is steady at about 470 $m.^3$ per sec. for six months, and then 300 $m.^3$ per sec. for six months, so the question of time of travel of this water does not arise.

The losses during the untimely period might be a little less than during the timely, but no account is taken of this in Tables XV and XVI (Appendix) which show the effect of a Sudd Channel, whether a diversion canal or Gebel remodelling, on the swamps discharge at Malakal in a standard and a mean year, calculated on the above basis.

From these tables it appears that while there is a gain in the timely period, there is a loss in the untimely period. The whole of this loss is a true loss, as the untimely water is all storable, and hence the net gain to Egypt is the difference between the timely gain and the untimely loss. Deducting 20 per cent as the transmission losses from Malakal to Aswan, the value of the Lake Albert Dam and Sudd Channel as at Aswan is 4·7 milliards of cubic metres in a standard year, and 3·6 milliards in the mean year. It should be noted that this quantity is on the credit side both when considering the deficiency in the summer supply and the deficiency in storable water in the flood. It seems then that training the Nile through these swamps will not produce the unlimited supply once supposed available.

One difficulty remains to be considered: how to deal with the maximum flood escape discharge from Lake Albert of a possible 3 000 $m.^3$ per sec. Such a quantity of water could not be allowed to flow through to Egypt as it might cause a very dangerous flood, if the Blue Nile happened to be high. There are several ways of dealing with this, each expensive, as is to be expected.

The first and simplest is to make Lake Albert Dam higher. It is already proposed that with a maximum storage level of 19·50 on the Butiaba gauge, spill ways should be so large that the level could never rise about R.L.20. It is possible that this maximum level could be increased to R.L.22 or more without increasing very much the effect on riparian rights that is contemplated by holding the level R.L.20. This would mean an extra ten milliards of storage capacity available in the lake, and in such condtions the maximum flood escape discharge could probably be kept down to a manageable quantity.

If such a proposal is found not to be practicable, the flood escape water must be dissipated in the Sudan or stored there till it can pass through Egypt with safety, after the Blue Nile flood is over. There are two areas in the Sudan where this could be done, the Sudd Region and the high-lying plains of the White Nile Province above Gebel Aulia Dam.

Whether the Sudd Channel is a Diversion or an Embankment Project, its effect will be to stop the annual swamping of the Sudd Region. With the Diversion Project, the Gebel discharge will be so heavily reduced that although there may be some swamp it will be very much less than now, while the Embankment Project would prevent all swamping but that due to local rain. The soil in the Sudd Region appears to be good fertile clay and silt, there is a heavy rainfall, and round the borders there is a thriving and rapidly increasing population; hence there is little doubt but that as flooding becomes permanently reduced the Sudd Region will be populated. It is therefore difficult to contemplate using this area as a flood escape.

The case as regards the White Nile Province seems different—the area is arid, semi-desert, sparsely populated and only a trifling proportion is cultivated from rain. It can be commanded by a high dam at Gebel Aulia, as will be described below, and if any damage is done here, it would be small and in any case far less than would be caused in Lower Egypt by a disastrous flood. It would therefore seem possible to make provision for passing the flood escape water from Lake Albert right through the Sudd Channel to the White Nile, where it would be held up by the Gebel Aulia Dam, flood the high levels of the reservoir (and be largely dissipated by evaporation), and be passed on to the sea in winter.

If the proposal to heighten Lake Albert Dam were found acceptable, any contemplated discharge not exceeding about 1 500 $m.^3$ per sec. could be passed down the Sudd Channel, designed for 1 200 $m.^3$ per sec., without difficulty or extra expense, whether the channel is a diversion or an embankment channel. If, however, 3 000 m.^{3} per sec. is to be passed on, the necessary enlargement of the diversion canal would obviously be absolutely prohibitive, as the whole bed would have to be increased in size. The Embankment Project could be more easily adapted to cope with the contemplated maximum, as only the banks need be heightened.

If the maximum Lake Albert discharge is 3 000 m.^{3} per sec. provision must be made for preventing this reaching Egypt till the winter, and it would therefore seem that a high dam at Gebel Aulia may be a necessary corollary of a low dam at Lake Albert.

Any estimates of cost for heightening Lake Albert Dam or the banks of the embanked Bahr el Gebel must be very tentative. Perhaps £E. 1 000 000 may be considered a safe figure to add to all other costs of the Sudd Channel Scheme to meet the high flood discharge danger, not counting the cost of heightening the Gebel Aulia Dam, which appears to be necessary for other reasons.

If such a high flood occurs in the interim period, before the completion of the final stage of the Project, it would be dissipated, as at present, in the Sudd Region.

It appears then, first, that a Diversion Project would cost more than an Embankment Project, and it would be longer after the beginning of construction before any benefit accrued to Egypt; secondly, though the estimate of transmission losses from Mongalla to Malakal has been taken the same for both types of project, there is more danger of serious underestimation in the Diversion Project; thirdly, the vegetation difficulty is likely to be more serious in the Diversion Project; and fourthly, high floods on Lake Albert can be handled more cheaply by an Embankment Project. On all these counts therefore the balance of advantage seems to tilt in favour of an Embankment Project. Such a project would cost about £E. 8 000 000 (including the heightening to cope with a Lake Albert discharge of 3 000 m.^{3} per sec.) plus about £E. 5 000 000 for Lake Albert Dam.

A Dam at Gebelein. The next place of possible future importance in the control of the Nile is Gebelein, about midway between Malakal and Gebel Aulia on the White Nile. Preliminary borings and survey show that a dam could probably be built here without difficulty to form a reservoir of about 1½ milliard cubic metres capacity, or say one milliard as at Aswan. The country that would be drowned out is wild, with practically no cultivation or important villages, and very few inhabitants, so that the compensation problem is not likely to be of importance. The total cost might be about £ E. 2 000 000.

Hydrologically, it must be considered in connection with Gebel Aulia Dam, 350 km. downstream. If the latter is raised to its full useful height there will be no water available under present conditions to fill a reservoir at Gebelein. On the other hand the compensation required, if Gebel Aulia Dam is raised, may be so great that the extra storage will be cheaper if made at Gebelein. For the final development of the Upper Nile and Egypt, it will appear that both Gebelein Dam and a Higher Gebel Aulia Dam will be required with training works on the Ghazal basin rivers, or on the River Baro to supply the water to fill them.

The White Nile Dam at Gebel Aulia. A dam across the White Nile at Gebel Aulia, 47 km. from the mouth at Khartoum, was completed in 1937 by the Egyptian Government to the design of Messrs. Coode, Wilson, Mitchell and Vaughan-Lee, consulting engineers. The dam is 5 km. long, of which 1·693 km. are in masonry, and the rest is an embankment with a core wall. The maximum head is 7·75 metres and it forms a reservoir 314 km. long with a maximum area of 1 318 km.^{2}. The storage level is R.L.377·20 and the contents at this level are just over three milliards of cubic metres of water, but owing to evaporation losses when standing full and losses en route to Aswan, its capacity as at Aswan is only about two milliards. No doubt in due course the engineers responsible for its construction will give a full and detailed description of the work, so nothing more need be said about that now.

The dam was originally designed in 1913 as a means of holding up the flood and thus reducing the period of high levels and improving the drainage of Lower Egypt. It however became obvious that the possibilities of the site would enable a dam here to fulfil much wider functions, and in 1920 a design was accepted by the Egyptian Government for a dam 2·8 metres higher than the present one, which would hold over 50 per cent more water (say 5·3 milliards) in every year and in years of high flood could hold up to ten milliards of water and thus act as a flood escape of considerable utility. Construction of the High Dam was begun in 1920, but owing to the financial and political crises that then occurred work was suspended in 1921. There were several abortive re-beginnings in the next ten years, and finally the Egyptian Government decided in 1932 to build the present low dam now completed. This dam is, however, designed on a wide base so that when the heightening has to be done it will not be necessary to thicken it as well. Moreover, the extra sluices which would be necessary when it is heightened have been provided, but they are at present without gates, etc., and blinded, i.e. filled with masonry.

The general function of this work in the control of the Nile is to store the flood waters of the River Sobat. It will begin to fill annually in the early flood as soon as this has reached a height to supply the current needs of agriculture in Egypt. The criterion for this is the gauge on the Main Nile at Atbara, where the river is complete. Some time early in July the volume flowing is shown by this gauge to be sufficient, and the sluice gates of Gebel Aulia Dam will be shut tight. The regulation is a little intricate, as there has to be a pause of about a month in the filling operation in most years, but in general the reservoir will be full by about the end of September. All the water that is thus used to fill Gebel Aulia Reservoir would otherwise have been wasted to sea, a waste which at present goes on till about the end of December. The water available in the White Nile at Gebel Aulia from 15th July to 15th September, which corresponds roughly to the untimely non-storable period at Aswan, will be about 3·9 milliards in a mean year, so that to fill a high reservoir here another 1·4 milliards would have to be taken from water that could be stored at Aswan, corresponding to about 1·2 milliards at Aswan. For the standard year, the position is practically the same. A higher dam at Gebel Aulia could be filled under present conditions, firstly because the pause of about a month from about 20th August would not be necessary and this untimely water could be stored, secondly because filling could go on later.

The 1920 design of the High Dam provided for a maximum level of 380·00 with a normal storage level of 378·50 as against the present 377·20. The normal storage would be something over five milliard cubic metres of which about 3·2 milliards would reach Aswan, while the extra 1·5 metres depth of capacity up to R.L.380 was to be used only in years of high flood as a flood escape. This possibility is due to the configuration of the valley in which the reservoir lies, as above R.L.378·50 there is a very wide flat plain which forms a shallow evaporating pan, and the total content of the reservoir at this level of 380 has been put at ten milliards of cubic metres, which is probably a conservative figure. A year of very high flood on the Blue Nile (and therefore also the Main Nile) is not necessarily very high on the White Nile; hence it would only be possible to use the flood escape function of the Reservoir to the full in years when the White

Nile and the Blue Nile were both very high, unless a cross connection were made between the two above Gebel Aulia Dam.

Gezira Cross Cut. It was proposed in 1918 to construct a huge canal across the Gezira to take off upstream the Sennar Dam on the Blue Nile, and lead the top of the high flood waters of the river into the Gebel Aulia Reservoir in the neighbourhood of Kosti. These waters would be stored there during August to October annually and then, as the Blue Nile flood fell, released to Egypt and the sea till the reservoir was reduced to the summer storage level. It is obvious that such a cut, controlled by the Sennar Dam and its own head sluice, would give the irrigation engineer absolute mastery of the Nile at all seasons, but the work is of the largest size and could not be usefully undertaken without a high dam at Gebel Aulia. Owing to the delays in building this, nothing much more has been done about the Gezira Cross Cut.

An alternative suggestion to the take-off being upstream Sennar Dam was to make the head works at some spot lower down the Blue Nile and nearer the White Nile, such that the top levels of the Blue Nile could flow into the Gebel Aulia Reservoir. The advantages would be the shortening of the canal line from about 100 km. to about 80 km., and a considerable reduction in the depth of cutting. The disadvantages are, first, that it would cut across that part of the Gezira plain that is cultivable under the Irrigation System depending on the Sennar Dam instead of the unprotected and comparatively undeveloped country south of Sennar, and, secondly, the control would not be nearly so effective.

In addition to the above flood protection function, which would only be used very occasionally, a Gezira cross cut could also be used for switching over some of the Blue Nile untimely water into the Gebel Aulia Reservoir in any year when the White Nile supply would be insufficient to fill it.

The difficulty about dealing with the Blue Nile is that no forecasts can be made of the beginning of the flood, its rise, its length, or its fall. It is not till November when the river is low and still falling that any forecasting is possible. During the rest of the year the Roseires gauge (about 650 km. south of Khartoum on the Blue Nile) gives the first notice of what is happening. The time of travel from here to Khartoum is only five to twelve days, according to the season, and from thirteen to thirty-three days to Aswan, the shortest time being at high flood. Hence at present the only method of regulation would be to decide beforehand the worst conditions against which provision is to be made and to assume that those conditions are going to occur.

On the White Nile, however, forecasts of limiting conditions can be made, i.e. it is possible to tell by the end of July, the discharge below which the river will not fall in the following two months and so on, and hence whether water must be taken from the Blue Nile into Gebel Aulia Reservoir in August, or not.

On this basis the hydraulics of the proposed cut, had it existed, have been worked out for every year from 1904 to 1934, and a system of regulation devised that would have enabled both a high Gebel Aulia Reservoir and the Aswan Reservoir to have been filled in every year except the extraordinarily low year 1913, when nothing could have given Egypt complete protection.

Regulation would have begun according to the White Nile forecast, and enough water taken out of the Blue Nile to fill Gebel Aulia Reservoir to R.L.379 instead of R.L.378·50.

By end of October it was possible to forecast whether the supplies flowing in the Blue and White Niles would be sufficient to fill Aswan Reservoir. If they were sufficient the excess in Gebel Aulia Reservoir (above 378·50) could be escaped to the sea. If insufficient, it could then be passed down to Aswan where it would be stored with less evaporation loss than it would incur at Gebel Aulia.

The average amount of water taken from the Blue Nile for this purpose would be 1·1 milliard cubic metres per annum.

To enable the Cross Cut to protect Egypt efficiently against the highest known flood it would have to be capable of carrying about 3 000 m.^{3} per sec. A cut of this size with a high level reservoir at Gebel Aulia would have been capable of reducing every known high flood at Aswan to a level below the "danger level" at Aswan, namely R.L.93 on the Aswan gauge. It would, of course, also be large enough to fulfil its annual duty of ensuring the filling of Gebel Aulia Reservoir (High Level).

The Blue Nile in flood has a velocity of 2 m. per sec. and there seems no reason why the Cut excavated through the same soil as that through which the Blue Nile flows should not be designed to the same velocity. On this basis the total cost of the Cut (and heightening of Gebel Aulia Dam) might be of the order of £E.7 000 000. This is a large sum of money, but Egypt is already making provision for an expenditure of at least £E.5 000 000 on flood *protection* measures in Egypt, whereas for the expenditure of about £E.7 000 000 flood *prevention* could be assured and over one milliard cubic metres of summer water be provided. As such water is worth to Egypt about £E.2 500 000 the cost of the flood prevention may be taken as about £E.5 000 000, the difference between total cost of the scheme and the value of the summer water it produces. The prevention of floods by works in the Sudan would therefore appear to cost no more than protection by works in Egypt when the flood has come. The works in Egypt would only provide a fire-escape, while those in the Sudan would prevent a fire occurring.

The one danger of the Gezira Cross Cut Project is that of silting up the Gebel Aulia Reservoir. Under the proposed regulation (not including the flood protection function), if the maximum amount of the suspended silt were deposited and none swept out again as the reservoir emptied, the reduction in the capacity of the reservoir would be about one-fiftieth of 1 per cent per annum. The flood protection function would be used only a few times per century and would add a small amount to the silt.

Sennar Dam. The discussion of works on the White Nile and its branches is now complete and there remain only the Sennar Dam and Tsana Dam.

The Sennar Dam and the Gezira Irrigation Scheme have been fully described in papers read before the Institution of Civil Engineers. The dam was completed in 1925 and by its means some 900 000 feddans of cotton land are now protected in the Gezira.

The dam acts partly as a barrage and partly as a dam to form a reservoir, holding about 780 million cubic metres which, without raising the structure, could be increased to about 900 millions. The reservoir is small compared with the others on the Nile.

The reservoir is brought up to canal supply level in July annually, taking about 250 to 300 million cubic metres of untimely water. Its filling with the remaining 500 million cubic metres takes place during November with untimely water, which is, however, storable on the Main Nile at Aswan. After the irrigation of the Gezira is completed in April every year, about 200 million cubic metres of stored water are at present released as an addition to Egypt's summer supply.

A Dam at Lake Tsana. Lake Tsana is a lake of about 3 000 $km.^2$ in area, forming the source of the Blue Nile, and is situated in Abyssinia, 1 611 km. along the river from Khartoum. An Egyptian Government Expedition from 1920 to 1926 measured its discharge regularly at the outlet and was able to establish a reliable gauge discharge curve. With occasional intermissions the gauge at the outlet has been regularly observed since then, so that the discharge is known for a long period and is found to be less than 5 per cent of the total natural river at Aswan, so that its contribution is not of great importance in the regime of the Nile Basin.

The time of travel from the outlet to Roseires is taken as about fifteen days, so to Aswan it would be about one month in flood and 1½ months in summer. The losses are taken as 30 per cent to Aswan. The timely period at Lake Tsana is therefore from 15th December to 1st July, during which its total mean discharge as at Aswan is only 470 millions, or about 3 per cent of the total flow (natural river) at the latter place during the corresponding period. The flow in a standard year is not known. The total untimely flow at Lake Tsana is, of course, all storable there, while the latter part, after 1st September at Tsana (1st October at Aswan) is also storable at Aswan and would in the future be actually stored there.

The following Table XIII shows the figures from which the effective value of Lake Tsana to Egypt can be deduced—

TABLE XIII

Lake Tsana Discharges: Standard Year and Mean 1921–32
Values as at Aswan, i.e. reduced by 30 per cent, in millions of cubic metres

Nature of Discharge	Mean Year	Standard Year
Timely	470	—
Untimely storable only in Lake Tsana . .	440	280
Untimely storable in Lake Tsana or at Aswan	1790	1200
Total	2700	—

In the future, the only benefit that would accrue to Egypt's summer supply is the amount only storable at Lake Tsana, i.e. which would otherwise have to flow to sea as it would arrive at Aswan before 1st October, the date when it is assumed storage can begin there. This amounts to 440 millions in a mean year and only 280 millions in the standard year. If the remainder of the untimely flow were stored at Lake Tsana, its effect would be to leave Aswan partly unfilled, i.e. it would increase the reservoir capacity available in the Lower Nile, which has been shown to be an essential condition for the development of water supplies from the Upper Nile. The amount of this increase is not large, being only 1 790 millions in a mean year and 1 200 millions in the standard year, and until possible supplies from the River Baro or Bahr el Ghazal Basin had been developed the additional capacity could not be filled.

Under existing conditions there is still storable water available at Aswan to fill this extra capacity.

The conditions at Lake Tsana are such that the water level cannot be raised much owing to the existence of churches and holy places just above present high water levels. The outflow, however, is over a rocky cataract, whose crest could be lowered to the desired amount to give any required range on the lake. To make the lowering of the crest effective the outlet channel would have to be deepened for many miles by rock-cutting, which would be very expensive.

If Lake Tsana is eventually used in a similar manner to Lake Albert to give its whole annual average flow during the 5½ timely months, the maximum accumulation of water, from the known records since 1921, would have been of the order of two milliard cubic metres, which corresponds to about two-thirds of a metre over the area of the lake; hence the range required to provide over-year storage here would not be large.

It is estimated that the cost of the dam and outlet channel with the required subsidiary works, such as roads, would not cost more than £E.4 000 000.

Additional Storage at Aswan. The total reservoir capacity available if all the foregoing works are carried out would be about 16 milliard cubic metres (as below) against a required capacity of about 19 milliards.

Reservoir	Capacity as at Aswan in Milliards of Cubic Metres
Aswan	5·0
Heightened Gebel Aulia	3·2
Gebelein	1·0
Lake Albert	3·6
Sennar	0·8
Lake Tsana	2·2
Total (say)	16·0

As Egypt's requirements of summer water are about 32 milliards annually, if no more reservoirs are found there must eventually be a shortage of about three milliard cubic metres, or 10 per cent, in her summer supply in average years.

There may be further reservoir sites on the Blue Nile in

Abyssinia between Lake Tsana and the Sudan frontier or on the River Sobat above Gambeila, but the valleys have not been explored. Reservoirs here could relieve Aswan.

On the White Nile and its branches no feasible reservoir sites are known other than those described.

The Main Nile between Khartoum and Aswan was examined before Aswan was built, and before its first heightening, and no good sites other than Aswan were found.

There is a possible dam site at Khashm el Girba on the River Atbara, where a reservoir could be formed having, it is said, a capacity of about two milliard cubic metres. A reservoir here would also relieve Aswan, but no project has ever been worked out; though it will have to be done some day, as otherwise it would seem that, to provide the extra three milliards, a new dam may become necessary at Aswan.

The latter idea has occasionally been the subject of conversation, but has never been investigated. The present Aswan Dam cannot be heightened again, so to increase the storage would involve scrapping it and building a new one to form a reservoir holding about eight milliards of cubic metres. Such a structure would be very expensive and the compensation would also be heavy, so that the total cost of the project might be about ten million pounds. It would be no use undertaking it till works have been begun in the Upper Nile to supply extra water in late flood.

CHAPTER VI

SUMMARY AND CONCLUSION

Future Reservoir Capacity. When Egypt is fully developed, with a concomitant development in the Sudan, about nineteen milliard cubic metres of timely summer water will be required in an average or standard year over and above that flowing in the natural river, while only from about six to eleven milliards of untimely water, over and above day to day requirements, will be flowing in the Nile at Aswan during the period when it can be stored, October to January.

If the developments which have been discussed were carried out the available reservoir capacity as at Aswan, including a new dam at Aswan to hold eight milliard cubic metres, would be about nineteen milliards, i.e. the necessary reservoir capacity can be found.

The total water available in a mean year as at Aswan from filled reservoirs would be—

Site	Milliards of Cubic Metres as at Aswan in a Mean Year
Main Nile at Aswan, October to January .	11·1
River Baro Development	1·2
Bahr el Ghazal Basin Development . .	1·5
Lake Tsana, filled 1st July to 1st September .	0·4
White Nile, filled 15th July to 15th September	2·0
Sennar, filled July	0·2
Lake Albert and Sudd Channel . . .	3·6
	20·5

In a standard year, the available storable natural supply at Aswan may be reduced to 6·6 milliards, but the effect of Lake Albert and the Sudd Channel may be increased to 4·7 milliards, making the total about 19 milliards instead of 20·5. Hence if the developments foreshadowed give the quantity of water estimated, there would be enough to provide Egypt's requirements even in a standard year.

Cost. The cost of these works can only be estimated in a very rough way to give some idea of the order of magnitude—

Work	Possible Cost in Millions of Pounds
A new dam at Aswan	10
Lake Albert Dam	5
Gebelein Dam	2
Sudd Channel	8
Bahr el Ghazal Basin Development	8
River Baro Development	2
Lake Tsana Dam, with roads and outlet channel	4
Heightening Gebel Aulia Dam and Gezira Cross Cut	7
	46

Before Egypt can benefit from these works, the land to be reclaimed and the basin irrigated land to be converted to perennial irrigation must be provided with canals and drains at a cost of about £E.15 per feddan for about three million feddans or a total of £E.45 million.

The total cost of the major and conversion works would therefore be of the order of £E.90 million, which would include effective flood protection worth not less than £E.5 million. It is believed conservative to put the increase of capital value on the lands affected at £E.30 per feddan, which also gives a total of £E.90 million. In addition to this increase, the State as a whole would benefit by the maintained prosperity of the people and the increase in indirect returns, while the extra direct revenue from the converted and reclaimed land should pay for the maintenance of the new works.

Time Table. Hussein Sirry Pasha, now Minister of Public Works, has shown in his work *Irrigation Policy** that to convert or reclaim about 40 000 feddans per annum is about the capacity of Egypt, hence the works need not be done in a shorter time than about seventy-five years from 1935. Not much more than about one million pounds per annum is therefore required on the average, an amount which Egypt is accustomed to spend on capital irrigation works.

A possible time table and order of preference for the major works might be as shown on page 89.

* Egyptian Government Press, 1935.

Works	Years
Heightening Gebel Aulia Dam . .	1945–50
Gezira Cross Cut	1950–60
Sudd Channel	1960–80
Lake Albert Dam.	1965–70
Gebelein Dam	1980–85
New Aswan Dam	1985–90
Bahr el Ghazal Basin Development .	1990–2000
River Baro Development . . .	2000–2010

It seems, therefore, that Egypt can be developed to the full from waters flowing in the Basin of the Nile in accordance with the proposals of Sir William Garstin and Sir Murdoch MacDonald, with some additional works; that the cost will not be excessive and the return adequate, but that always the population will be pressing on its means of subsistence, for to avoid this these works should have been completed by 1955 and not sixty years later.

APPENDIX

TABULATED DATA

TABLE I

DISTANCES ALONG THE NILE FROM THE SEA TO THE SOURCE
(Kilometres)

Place	Inter-mediate	From Sea	From Aswan	From Khartoum	From Lake No
Damietta Mouth . .	0	0	—	—	—
Delta Barrage . .	242	242	—	—	—
Cairo	23	265	—	—	—
Aswan	942	1 207	0	—	—
Halfa	345	1 552	345	—	—
River Atbara Mouth .	1 205	2 757	1 550	—	—
Khartoum . . .	325	3 082	1 875	0	—
Gebel Aulia . . .	45	3 127	1 920	45	—
Kosti Bridge . . .	279	3 406	2 199	324	—
Malakal . . .	494	3 900	2 693	818	—
River Sobat Mouth .	23	3 923	2 716	841	—
Bahr el Zeraf Mouth .	45	3 968	2 761	886	—
Lake No Junction Bahr el Ghazal and Bahr el Gebel	78	4 046	2 839	964	0
Head of Zeraf Cut 1 .	295	4 341	3 134	1 259	295
Ghaba Shambe . .	112	4 453	3 246	1 371	407
Kenisa	86	4 539	3 332	1 457	493
Bor	126	4 665	3 458	1 583	619
Mongalla . . .	128	4 793	3 586	1 711	747
Rejaf	58	4 851	3 644	1 769	805
Nimule	216	5 067	3 860	1 985	1 021
Lake Albert, Head of Albert Nile . .	160	5 227	4 020	2 145	1 181
Lake Albert Mouth of Victoria Nile . .	3	5 230	4 023	2 148	1 184
Murchison Falls . .	35	5 265	4 058	2 183	1 219
Lake Kioga . . .	220	5 485	4 278	2 403	1 439
Ripon Falls, Lake Victoria . . .	125	5 610	4 403	2 528	1 564
Mouth of River Kagera, Lake Victoria . .	220	5 830	4 623	2 748	1 784
Source of River Kagera .	670	6 500	5 293	3 418	2 454

TABLE II

Discharges of the Nile and its Branches at Salient Points

Site	Period	Annual Totals in Milliards of Cubic Metres			Millions of cubic metres per day (from 10-day means)			
					Mean		Absolute	
		Min.	Mean	Max.	Min.	Max.	Min.	Max.
Lake Albert . .	1908–34	12·0	23·0	45·4	54·7	75·1	27·8	163·8
Bahr el Gebel at Mongalla . .	1905–34	15·3	28·5	55·8	58·6	115·0	26·8	245·0
Bahr el Gebel at Mouth . .	1924–34	8·6	9·4	10·1	23·0	28·0	19·5	29·2
Bahr el Ghazal at Mouth . .	1923–34	0·5	0·6	1·0	0·05	4·3	−1·3	7·8
Bahr el Zeraf at Mouth . .	1908–34	2·8	4·5	9·1	9·4	16·0	4·7	29·2
Swamps Discharge	1905–34	10·4	14·1	20·7	32·7	47·1	20·9	68·1
Sobat River at Mouth . .	1905–34	9·5	13·9	23·1	5·3	73·4	2·2	108·0
White Nile at Malakal . .	1905–34	22·6	28·4	44·4	43·6	114·0	28·3	168·0
Blue Nile at Khartoum. .	1900–34	25·7	53·2	79·2	8·8	607·0	3·7	934.0
Main Nile at Tamaniat . .	1911–34	46·2	77·4	107·0	50·5	649·0	28·7	880·0
River Atbara at Mouth . .	1903–34	4·9	12·4	27·0	Dry	241·0	Dry	547·0
Aswan Natural River . .	1871–1932	45·5	96·2	139·0	47·5	861·0	23·9	124·0

TABLE III

Percentage of Total Flow Passing Salient Points on the Nile

Site	Percentage of Maximum Supply normally passing Site	
	Summer	Flood
Mongalla.	77	12
Bahr el Ghazal at Mouth . . .	3	1
River Sobat at Mouth . . .	14	7
Malakal	73	12
White Nile at Mogren . . .	63	10
Blue Nile at Khartoum . . .	17	70
River Atbara at Mouth . . .	0	20
Main Nile at Atbara	80	100
,, ,, Wadi Halfa . . .	78	95
,, ,, Aswan	100	91
,, ,, Delta Barrage . .	69	63
Rosetta Branch at Sea . . .	0	40
Damietta Branch at Sea . . .	0	19

TABLE IV

MONTHLY DISCHARGES OF THE NILE AT ASWAN IN SIGNIFICANT YEARS (AUGUST TO JULY) COMPARED WITH FINAL REQUIREMENTS

(Natural River) Millions of Cubic Metres

Month	Eventual Requirements (Egypt and Sudan)	Actual Discharges				
		Average Year, 1912–32	Lowest Year, 1913–14	Very Low or Standard Year, 1925–6	Good Year, 1914–15	Maximum Year, 1878–9
Aug.	8 100	17 200	6 500	13 400	19 400	22 300
Sept.	7 700	20 200	12 200	16 600	20 000	34 200
Oct.	7 800	14 700	7 540	12 500	16 500	29 500
Nov.	5 200	7 900	4 120	6 450	10 700	14 300
Dec.	4 400	5 110	2 830	4 480	6 930	10 100
Jan.	2 900	3 700	1 720	3 440	4 510	7 690
Feb.	4 800	2 450	1 150	2 150	3 090	5 830
Mar.	4 600	1 910	1 070	1 640	2 130	5 740
Apr.	4 400	1 480	947	1 340	1 360	4 850
May	4 500	1 390	998	1 330	1 170	4 540
June	6 500	1 710	975	2 390	1 460	5 210
July	6 800	4 220	2 010	4 360	2 850	10 500

TABLE V

ANNUAL DISCHARGE OF LAKE ALBERT AS AT MONGALLA

Milliards of cubic metres per annum

Year	Annual Discharge	Year	Annual Discharge
1904	32·6	1918	45·4
1905	29·7	1919	27·2
1906	32·0	1920	21·9
1907	31·0	1921	16·5
1908	25·1	1922	12·0
1909	27·0	1923	13·8
1910	24·8	1924	17·5
1911	20·4	1925	15·6
1912	17·8	1926	18·4
1913	19·3	1927	24·0
1914	19·8	1928	20·2
1915	22·8	1929	17·9
1916	26·1	1930	19·7
1917	44·9	1931	24·4
		1932	27·1
		1933	27·3
		1934	21·8
		Mean 1904–34	24·0

TABLE VI

REGULATION OF LAKE ALBERT AS A RESERVOIR SINCE JANUARY, 1904, ON THE BASIS OF A NORMAL ANNUAL DISCHARGE OF 23 MILLIARDS OF CUBIC METRES

Year	Actual Discharge during Year	Quantity taken from or added to Storage during Year	Quantity in Reservoir at end of Year
1904	32·6	+ 9·6	9·6
1905	29·7	+ 6·7	16·3
1906	32·0	+ 9·0	25·3
1907	31·0	+ 8·0	33·3
1908	25·1	+ 2·1	35·4
1909	27·0	+ 4·0	39·4
1910	24·8	+ 1·8	41·2
1911	20·4	− 2·6	38·6
1912	17·8	− 5·2	33·4
1913	19·3	− 3·7	29·7
1914	19·8	− 3·2	26·5
1915	22·8	− 0·2	26·3
1916	26·1	+ 3·1	29·4
1917	(29·8)	+ 6·8	36·2
1918	(30·9)	+ 7·9	44·1
1919	27·2	+ 4·2	48·3
1920	21·9	− 1·1	47·2
1921	16·5	− 6·5	40·7
1922	12·0	− 11·0	29·7
1923	13·8	− 9·2	20·5
1924	17·5	− 5·5	15·0
1925	15·6	− 7·4	7·6
1926	18·4	− 4·6	3·0
1927	24·0	+ 1·0	4·0
1928	20·2	− 2·8	1·2
1929	17·9	− 5·1	− 3·9
1930	19·7	− 3·3	− 7·2
1931	24·4	+ 1·4	− 5·8
1932	27·1	+ 4·1	− 1·7
1933	27·3	+ 4·3	2·6
1934	21·8	− 1·2	1·4

TABLE VII

Analysis of Bahr el Gebel Discharge at Mongalla into Lake and Torrents Contributions

1922–34; in Millions of cubic metres per month

Month	Average 1922–34		Maximum				Minimum			
	Lake	Torrents	Lake	Year	Torrents	Year	Lake	Year	Torrents	Year
Jan.	1 760	0	2 530	1933	0	—	1 030	1923	0	—
Feb.	1 510	0	2 190	1933	0	—	868	1923	0	—
March	1 580	0	2 350	1933	0	—	880	1922	0	—
April	1 500	190	2 200	1933	450	1928	843	1922	0	1923, 1932, 1933
May	1 590	590	2 290	1933	2 240	1928	880	1922	189	1927
June	1 560	330	2 180	1933	1 020	1928	942	1922	0	1933
July	1 630	520	2 230	1933	918	1923	1 010	1922	202	1924
Aug.	1 680	820	2 280	1932	1 600	1923	1 020	1922	285	1924
Sept.	1 690	700	2 300	1932	1 270	1932	1 020	1922	237	1927
Oct.	1 810	560	2 560	1932	1 100	1926	1 130	1922	180	1934
Nov.	1 810	320	2 530	1932	690	1923	1 110	1922	129	1927
Dec.	1 880	50	2 610	1932	257	1925	1 100	1922	0	1922, 1924, 1927, 1928, 1929, 1930, 1931, 1932, 1933 and 1934
	20 000	4 080								

Total

Jan 1760
Feb 1510
Mar 1580
Apl 1690
May 2180
June 1840
July 2150
Aug. 2500
Sept 2390
Oct 2370

TABLE VIII

Lag between Mongalla and Malakal of Occurrence of Maximum and Minimum Discharges respectively

Year	Mongalla: Total Mills m³	Maximum			Minimum		
		Date at Mongalla	Date at Malakal	Interval in 10-day Periods	Date at Mongalla	Date at Malakal	Interval in 10-day Periods
1905	36 200	Nov. 21–31	Jan. 1–10, 1906	4	Mar 21–31	June 11–20	8
1906	38 930	Sept. 11–20	Nov. 21–30	7	Mar. 11–20	May 21–31	7
1907	35 920	Nov. 1–10	Jan. 1–10, 1908	6	Apr. 1–10	July 21–31	11
1908	29 810	Aug. 21–31	Sept. 21–30	3	Apr. 11–20	June 11–20	6
1909	31 910	Sept. 21–30	Feb. 1–10, 1910	13	Mar. 11–20	June 11–20	9
1910	30 390	Sept. 11–20	Jan. 21–31, 1911	13	Apr. 1–10	June 11–20	7
1911	25 270	Sept. 11–20	Dec. 21–31	10	Mar. 1–10	May 1–10	6
1912	33 440	Sept. 11–20	Dec. 21–31	10	Mar. 11–20	June 21–30	10
1913	21 000	July 21–31	Nov. 21–30	12	Mar. 21–31	July 1–10	10
1914	25 520	Nov. 11–20	Jan. 21–31, 1915	7	Apr. 21–30	July 11–20	8
1915	27 880	Oct. 1–10	Jan. 1–10, 1916	9	Mar. 11–20	June 21–30	10
1916	37 890	Sept. 21–30	Dec. 11–20	7	Mar. 11–20 Mar. 21–31	June 11–20	8
1917	55 810	Oct. 1–10	Mar. 11–20, 1918	16	Mar. 21–31 Apr. 1–10	July 11–20	10
1918	47 130	Jan. 1–10	Apr. 1–10	9	Dec. 21–31	May 11–20, 1919	14
1919	31 200	July 21–31	Dec. 11–20	14	Mar. 21–31	Sept. 21–30	18
1920	25 800	Aug. 1–10	Dec. 21–31	14	Mar. 21–31	July 21–31	12
1921	16 620	Oct. 11–20	Dec. 21–31	7	May 1–10	July 1–10	6
1922	15 260	Sept. 1–10	Dec. 21–31	11	Feb. 21–28	June 1–10	10
1923	19 320	Aug. 1–10	Dec. 21–31	14	Mar. 11–20	June 1–10	8
1924	20 450	Nov. 1–10	Jan. 11–20, 1925	7	Mar. 21–31	July 1–10	10
1925	18 870	Nov. 21–30	Jan. 1–10, 1926	4	Mar. 11–20	June 11–30	10
1926	24 850	Aug. 11–20	Feb. 1–10, 1927	17	Mar. 21–31	July 21–31	12
1927	26 030	June 1–10	Aug. 11–20	7	Dec. 21–31	Feb. 21–29	6
1928	26 600	May 21–31	Aug. 11–20	8	Mar. 11–20	May 21–31	7
1929	21 300	May 1–10	Aug. 11–20	10	Apr. 1–10	July 1–10	9
1930	22 700	Nov. 1–10	Jan. 11–20, 1931	7	Feb. 21–28	May 11–20	8
1931	29 000	Sept. 1–10	Jan. 21–31, 1932	14	Feb. 21–28	May 21–31	9
1932	32 600	Aug. 1–10	Jan. 11–20, 1933	16	Feb. 21–29	June 1 –10	10
1933	30 600	Sept. 11–20	Dec. 21–31	10	Apr. 21–30	Aug. 1–10	10
1934	26 300	Aug. 21–31	Nov. 21–31	9	Apr. 1–10	Aug. 1–10	12
		Total		295			281
		Mean		9·8			9·4
		General Mean				9·6	

TABLE IX

Losses in the Swamps

3½ months' lag

Discharges in milliards of cubic metres per annum

(Feb. to Jan. at Mongalla; June to May at Malakal)

Year	Mongalla Discharges	Swamps Discharges	Losses
1905–06	35·9	12·8	23·1
1906–07	39·3	13·7	25·6
1907–08	35·1	13·4	21·7
1908–09	29·6	14·8	14·8
1909–10	31·9	16·3	15·6
1910–11	30·1	14·1	16·0
1911–12	24·8	13·2	11·6
1912–13	23·2	13·4	9·8
1913–14	23·2	13·4	9·8
1914–15	25·9	13·9	12·0
1915–16	27·8	13·2	14·6
1916–17	39·3	16·4	22·9
1917–18	57·7	18·4	39·3
1918–19	44·7	19·6	25·1
1919–20	30·6	16·0	14·6
1920–21	24·9	12·5	12·4
1921–22	16·1	11·1	5·0
1922–23	15·2	10·4	4·8
1923–24	20·1	11·5	8·6
1924–25	20·3	12·9	7·4
1925–26	18·7	12·1	6·6
1926–27	25·8	12·8	13·0
1927–28	25·6	13·2	12·4
1928–29	26·4	13·9	12·5
1929–30	21·1	13·5	7·6
1930–31	23·2	13·5	9·7
1931–32	29·4	14·1	15·3
1932–33	32·9	14·9	18·0
1933–34	30·2	16·2	14·0
1934–35	25·8	15·3	10·5
Mean:	28·50	14·02	14·48

1905–22: Swamp discharge = White Nile at Malakal minus Sobat minus Ghazal.

1923–35: Swamp discharge = Zeraf + White Nile at Abu Tong minus Ghazal.

TABLE X

Losses in the Swamps

No allowance for lag

Discharges in milliards of cubic metres per annum, 1st January to 31st December

Year	Mongalla Discharges	Swamps Discharges	Losses
1905	36·2	13·7	22·5
1906	38·9	13·0	25·9
1907	35·9	13·8	22·1
1908	29·8	14·2	15·6
1909	31·9	16·0	15·9
1910	30·4	14·8	15·6
1911	25·2	14·2	11·0
1912	23·4	13·1	10·3
1913	23·0	13·6	9·4
1914	25·5	13·7	11·8
1915	27·9	13·4	14·5
1916	37·9	14·9	23·0
1917	55·8	17·4	38·4
1918	47·1	20·7	26·4
1919	31·2	17·2	14·0
1920	25·8	13·3	12·5
1921	16·6	12·2	4·4
1922	15·3	10·4	4·9
1923	19·3	10·5	8·8
1924	20·4	12·9	7·5
1925	18·9	12·4	6·5
1926	24·9	12·1	12·8
1927	26·0	13·5	12·5
1928	26·6	13·5	13·1
1929	21·3	13·7	7·6
1930	22·7	13·7	9·0
1931	29·0	13·4	15·6
1932	32·6	14·4	18·2
1933	30·6	15·9	14·7
1934	26·3	16·0	10·3
1935	23·5	14·6	8·9
Mean:	28·4	14·1	14·3

N.B. See note, Table IX, *re* determination of swamps discharge.

TABLE XI

Relation between Lowest Discharges of the Bahr el Gebel at Mongalla and the Swamps at Malakal

Means of lowest two consecutive months per annum in m³ per sec., 1923–35

Year	Mongalla	Swamps
1923	325	279
1924	554	398
1925	548	400
1926	486	378
1927	802	442
1928	629	425
1929	568	432
1930	552	422
1931	696	419
1932	794	461
1933	874	505
1934	732	502
1935	608	456

TABLE XII

Evaporation and Rainfall at Zeraf Cuts

Monthly Normals in mm. per month, 1927–31

Month	Evaporation		Ratio Swamp to Open Water	Rainfall	Net Swamp Evaporation	Weight	Weighted Net Swamp Evaporation
	Open Water	Swamp					
Jan.	57	123	2·2	0	123	90	111
Feb.	59	119	2·0	1	118	80	94
March	63	135	2·1	11	124	80	99
April	53	133	2·5	33	100	70	70
May	44	117	2·7	96	21	70	15
June	33	104	3·2	148	− 44	70	− 31
July	31	105	3·4	125	− 20	80	− 16
Aug.	28	101	3·6	115	− 14	90	− 13
Sept.	30	107	3·6	144	− 37	100	− 37
Oct.	33	107	3·2	84	23	100	23
Nov.	41	98	2·4	4	94	100	94
Dec.	52	103	2·0	1	102	90	92
Totals	524	1 352	—	762	590	—	501

TABLE XIII

Evaporation and Rainfall at Mongalla, Juba (1906–35) and Malakal (1915–35)

Monthly Normals in mm. per month
(Mean of Mongalla and Malakal)

Month	Evaporation: Open Water	Rainfall	Net Evaporation	Weight	Weighted Net Evaporation
Jan.	216	1	215	90	194
Feb.	207	8	199	80	159
March	196	23	173	80	138
April	127	65	62	70	43
May	86	109	— 23	70	— 16
June	59	123	— 64	70	— 45
July	46	156	— 110	80	— 88
Aug.	42	163	— 121	90	— 109
Sept.	48	129	— 81	100	— 81
Oct.	63	89	— 26	100	— 26
Nov.	106	25	81	100	81
Dec.	172	6	166	90	149
Totals	1 368	897	471	—	399

TABLE XIV

Assumed Open Water Evaporation and Rainfall in the Sudd

Monthly Totals in mm.

Month	Mean Evaporation	Mean Rainfall	Net Evaporation	Weight	Weighted Net Evaporation
Jan.	158	0	158	90	142
Feb.	159	3	156	80	125
March	146	19	127	80	102
April	106	51	55	70	38
May	74	99	— 25	70	— 18
June	55	121	— 66	70	— 46
July	44	148	— 104	80	— 83
Aug.	41	158	— 117	90	— 105
Sept.	46	120	— 74	100	— 74
Oct.	50	77	— 19	100	— 19
Nov.	94	12	— 82	100	82
Dec.	131	3	128	90	115
	1 112	811	301	—	259

TABLE XV

Future Swamps Discharge at Malakal: Computations for Untimely Period

Mongalla Discharge is 300 m.^{3} per sec. plus Torrents
Loss to Malakal is 30 per cent

Mean Year

(Quantities in millions of cubic metres per month)

Month	Mongalla Discharge			Losses in Swamps (30%)	Malakal Swamps Discharge	Remarks
	Navigation Water	Torrents Discharge	Total			
July . .	804	520	1 326	398	928	Torrents Discharges taken as mean of years 1922–34
Aug.. .	804	820	1 624	487	1 137	
Sept. .	778	699	1 477	443	1 034	
Oct. . .	804	560	1 364	409	955	
Nov. .	778	325	1 101	330	771	
Dec. . .	804	46	850	255	595	
Total .	4 772	2 970	7 742	2 322	5 420	

Standard Year
1925

Month	Navigation Water	Torrents Discharge	Total	Losses in Swamps (30%)	Malakal Swamps Discharge	Remarks
July . .	804	285	1 089	327	762	Torrents Discharge taken for 1925
Aug.. .	804	586	1 390	417	973	
Sept. .	778	369	1 147	344	803	
Oct.. .	804	236	1 040	312	728	
Nov. .	778	447	1 225	368	857	
Dec. . .	804	257	1 061	318	743	
Total .	4 772	2 180	6 952	2 086	4 866	

TABLE XVI

SWAMPS DISCHARGE AT MALAKAL: PRESENT AND FUTURE

The timely discharge at Mongalla is 1 200 m.³ and the loss at Malakal is 30 per cent. Torrents are neglected

The untimely discharge is as calculated in Table XVI

(Quantities in millions of cubic metres per month)

UNTIMELY PERIOD

Month	Standard Year, 1925–26			Mean Year		
	Present	Future	Difference	Present	Future	Difference
1925 July	1 010	760	− 250	1 090	930	− 160
Aug.	1 020	970	− 50	1 150	1 140	− 10
Sept.	970	800	− 170	1 170	1 030	− 140
Oct.	1 080	730	− 350	1 240	960	− 280
Nov.	1 010	860	− 150	1 170	770	− 400
Dec.	1 030	740	− 290	1 240	600	− 640
Untimely Total	6 120	4 860	− 1 260	7 060	5 430	− 1 630

TIMELY PERIOD

Month	Standard Year, 1925–26			Mean Year		
	Present	Future	Difference	Present	Future	Difference
1926 Jan.	1 090	2 250	1 160	1 320	2 250	930
Feb.	930	2 030	1 100	1 160	2 030	870
March	1 030	2 250	1 220	1 220	2 250	1 030
April	960	2 180	1 220	1 130	2 180	1 050
May	970	2 250	1 280	1 110	2 250	1 140
June	990	2 180	1 190	1 050	2 180	1 130
Timely Total	5 970	13 140	7 170	6 990	13 140	6 150

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