THE HYDROLOGY OF LAKE MALAWI

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SYNOPSIS

THE GEOLOGY, PHYSIOGRAPHY, climate, vegetation, soils, and hydrology of Lake Malawi are described. This paper brings up to date the situation as the result of more complete data, and whilst confirming that the behaviour of Lake Malawi may be explained entirely in terms of natural phenomena, the relative proportions of rainfall, evaporation, and run-off are now found to differ from the values assigned by previous workers. The hydrology of Lake Malawi is compared with that of Lake Victoria, and arising out of this assessment of the water balance, the run-off from the land catchment is shown to have undergone a long-term increase.

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INTRODUCTION

LAKE Malawi, with its effluent, the Shire River, occupies a narrow tectonic basin elongated in a north-south direction along the course of the southern extension of the East African Rift Valley (Fig. 1. p. 544). The total area of the Lake Malawi catchment is 48,850 sq. miles, of which about 11,430 sq. miles are occupied by the waters of Lake Malawi, making it the third largest of the Central African lakes.

As the result of meteorological and hydrological variations, the environs of the lake and large areas of the lower Shire River area have been subjected to alternate periods of drought and flooding in past years, which have damaged or sterilized arable land and which have hindered navigation. The very

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flat unstable outlet, founded on alluvium, coupled with wide variations in the level of Lake Malawi, are seen to be mainly responsible for these conditions, although changes in the Shire River channel have been a contributory factor.

During the period 1951-57 an intensive investigation into the problem of stabilizing the level of Lake Malawi and the regulation of the outflow into the Shire River was undertaken under the Shire Valley Project Survey. This project envisaged imposing a partial contol on the outflow from the lake by the construction of a barrage at the first set of cataracts on the Shire River, at Matope. From this barrage, where an average continuous firm output of 16,000 kW. could be generated, a regulated flow would be released down river where additional power, an average continuous firm output of 224,000 kW. could be generated at three further sites. These dams would also act as controlling reservoirs, and hence would reduce flooding and assist reclamation in the extensive marsh areas of the lower Shire River area.

Whilst it is unlikely that such a scheme will be implemented without an industrial revolution in the country, any one of these sites offers the opportunity of generating a reduced amount of power to satisfy present estimates of future demands. The Nkula Falls site has now been re-examined for a modest undertaking where it is intended to generate 25,000 kW. on a run-of-the-river basis, with an initial capital outlay of £2.5 million

In order to ensure a minimum regulated flow of 5,000 cusec. in the Shire River, a barrage is now under construction at Liwonde, about 50 miles from the lake outlet. However, in Lake Malawi, as in Lake Victoria, the present range of variation of "free water" (the amount of water made available for flow down the Shire River or for storage in the lake), is much greater than that of the outflow and, therefore, regulation of the outflow cannot entirely stabilize the contents and level.

The hydrology of Lake Malawi has been investigated by Kanthack (1942)* and by Cochrane (1957), and this paper brings the situation up to date as the result of more complete data. Whilst confirming that the behaviour of the lake may be

*An alphabetical list of references is given on p. 46.

explained entirely in terms of natural phenomena, this paper also provides a reassessment of the relative proportions of rainfall, evaporation, and run-off in the water balance. Arising out of this assessment of the water balance, the run-off from the land catchment is shown to have undergone a long-term increase, possibly because of changes in the intensity pattern of rainfall coupled with a dense and rapidly increasing rural population.

THE CATCHMENT

Physiography and Structure

To the east of Lake Malawi the land catchment is narrow, not more than 25 miles wide, and extends from the southern limit of the lake to about latitude 11°S. Along this narrow strip of country the drainage is by short, steep, consequent type streams that fall directly to the lake, none of which individually contributes any appreciable flow. At about this latitude the catchment widens out to include the Ruhuhu River, which drains a large basin of Karoo sediments (Upper Carboniferous to Rhaetic) and the south-eastern flanks of the Livingstone Mountains. From the north-western corner of the Ruhuhu basin, near Njombe, the watershed follows the Kipengere Range in a north-westernly direction, and then turns westward along the 7,000 ft. summit ridge of the Poroto Mountains to include the high rainfall area centred upon Tukuyu; thereafter continuing across the northern part of the Bundali Range to the Mbozi plateau. From this point the watershed follows the Malawi-Zambia border to a point near Fort Jameson. From here it turns eastward along the Dzalanyama Range to the Kirk Range, and thence to the southern limit of the lake near Fort Johnston.

Throughout the catchment there is a large variation in altitude, ranging from 1,550 ft. (about mean lake level) to over 9,000 ft., and this has produced a wide range of natural conditions. The largest part of the catchment lies to the west in Malawi, and is drained in the main by the Songwe, North Rukuru, South Rukuru, Luweya, Dwangwa, Bua, Linthipe, and Livulezi Rivers. To the north, in Tanzania, short steep consequent rivers such as the Kiwira, Mbaka, Lufirio, and Rumbira drain the Poroto and Kipengere Mountains, and because of high rainfall in that area, all have a high average

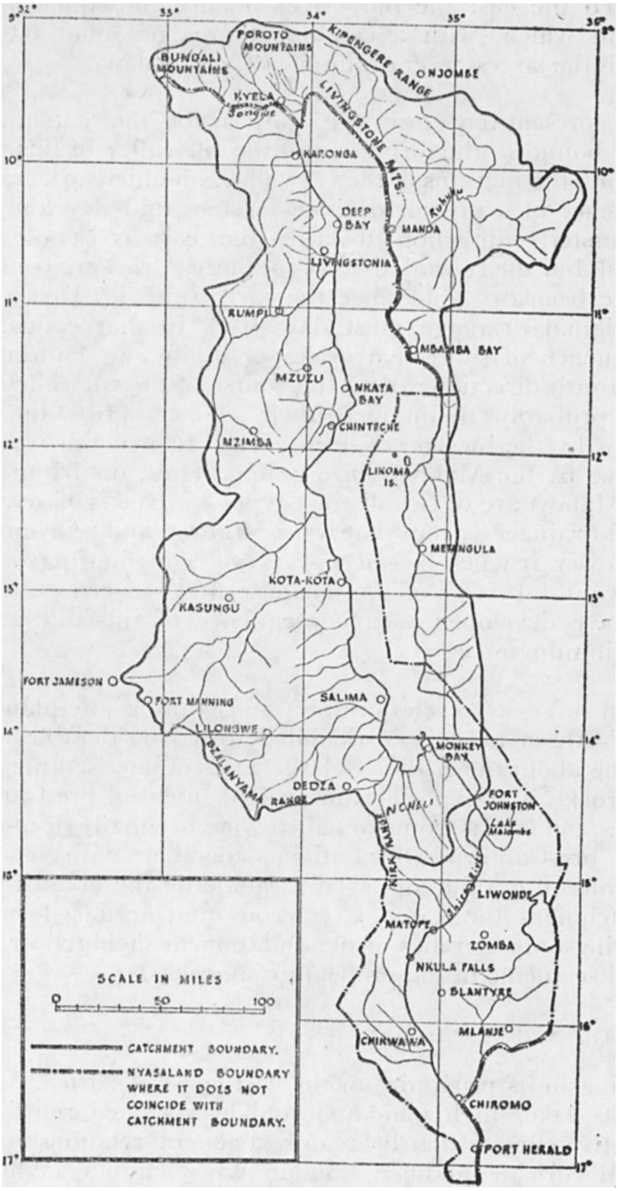

Fig. 1
Lake Malawi Shire catchment

flow. To the east the only river of any consequence is the Ruhuhu which, with a catchment area of about 6,000 sq. miles, is the largest river draining to Lake Malawi.

The present-day drainage pattern of the catchment is closely bound to the formation of the rift valley in this region, but along the margins of the rift valley, on older surfaces, there is evidence of a pre-rift drainage system that developed in a north-easterly direction towards the east coast of Africa. Since all but the coastal areas of southern Africa are considered to have been dry land since the early Jurassic (Dixey 1938), the original drainage must date back to that epoch. As a consequence of successive cycles of uplift and faulting in a north-south direction, along the course of the rift valley, these rivers probably maintained their course across the rising margins by the incision of deep gorges at first, but were later captured by the Malawi-Shire system. Thus, the tributaries of Lake Malawi are of two distinct types; (*a*) rivers of an ancient pre-rift drainage system that were captured and rejuvenated in their lower reaches by successive cycles of faulting, and (*b*) those youthful rivers of the northern and western escarpment that have developed as a consequence of rift-faulting (Pike and Rimmington 1964).

With successive cycles of uplift and faulting, the plateaux of central Africa have been denuded to a considerable degree, bringing about the erosion of large areas of later sediments and softer rocks, and exposing the ancient shield of pre-Cambrian gneisses and schists, some of which were originally deep-seated. These pre-Cambrian formations, together with associated intrusions of granite and syenite, underlie the greater part of the catchment, the Karoo, Cretaceous, and Tertiary formations occurring only as relics of denundation in sheltered or down-faulted segments in the pre-Cambrian rocks.

Climate, Soils, and Vegetation

Owing to its proximity to the east coast of Africa, Malawi, with its lake, high plateaux, and accentuated relief, has a distinctive climate that bears only a general relationship to the Central African modified "Sudan type" climate. Whilst the plateau areas are cool, with a good to moderate rainfall, parts of the low-lying rift valley are excessively hot and, in places, are semi-arid. During the summer months the catchment lies in an inter-tropical zone, and comes under the influence of the rain-bearing inter-tropical convergence zone and the north-east monsoon, whilst during the dry season, or winter months, the south-east trade winds dominate the climate bringing about cloudless, sunny weather with occasional outbreaks of light rain on windward slopes.

Rainfall is normally confined to the period November to March, but in the northern areas the season is prolonged well into May and sometimes June. Rainfall is derived from three sets of conditions being: (1) the early rains of October and November, which consist of heat thunderstorms over high ground and the escarpment areas; (2) the inter-tropical convergence zone and the eastward encroachment of the moist Congo air boundary which, either singly or together, bring widespread rain and unstable conditions during the period December to March, with thunderstorms confined to the margins of the zone; and (3) in April and May when the south-easterly becomes re-established and brings with it rain over high ground and along the north-western shores of the lake. As the dry season progresses, these moist indraughts become less frequent and, by the end of June, the dry season is normally well established in most areas.

The mean annual rainfall over the Lake Malawi catchment (excluding the lake) is 46.4 in. (41 years), with a recorded maximum of 116 in. (Kyela) and a minimum of 27 in. (Rumpi). Less than 5 per cent of the total area of the catchment receives a rainfall below 30 in. per annum in an average year. The coefficient of variation ranges from 0.16 to 0.23, the lake shore stations showing a higher variability.

The soils of the catchment show a close resemblance to the nature of the underlying parent rocks, but the interactions of climate, topography, age, soil drift, and location have all played their part in the formation of a complex soil pattern. The most commonly encountered soils fall into the red earth category, together with soil types of different colour found in catenary association. The plateau areas are characterized by red, yellow red, and grey soils of peneplain origin that have become lighter in colour through prolonged leaching, indurated laterite in profile often being exposed on the surface wherever erosive forces have been particularly active. These soils are derived mainly from the gneisses, schist, granulites, and syenites, and because of their arrangement in catenae, heterogenous groups of soils occur in comparatively small areas, resulting in necessarily patchy cultivation. In an area that is as hilly and broken as the Lake Malawi catchment, with a long history of earth movements, colluvial soils of various types are widespread at the foot of the main rift escarpments and over the floor of the rift valley.

Very little of the vegetation with the catchment is in its natural state (Topham 1936). With a density of population exceeding that of any other country in the woodland savanna areas of central Africa, the demands for subsistence agriculture and pastoralism have repeatedly disturbed the natural vegetation. The vegetation pattern is comparable with the diversities of topography, geology, climate, and soils, and may be broadly classified into three main associations: (*a*) mixed savanna woodlands of the rift-valley areas; (*b*) the *Brachystegia-Julbernardia* woodlands of the plateaux and the wetter lake shore areas, and (*c*) the forest relics and open grassland of the highland areas. The most widespread vegetational type is more or less open *Brachystegia-Julbernardia* woodland, with a moderately dense grass cover during the summer months.

Population

The average density of population in Malawi is higher than that found in any of the adjacent territories, averaging 73 per sq. mile. Of a total of nearly 3 million, about 1.5 million are concentrated in the Southern Region and, therefore, outside the catchment area of Lake Malawi. Thus, the population of the catchment is made up of about 1.5 million to the west of the lake, with a further half a million located to the north and east in Tanzania and Mocambique, giving a density of about 54 persons to the sq. mile. These estimates are approximate only, there being no recent accurate census data.

Since 1920 the population within the catchment has increased rapidly; not only from a high natural rate of increase of about 2.5 per cent per annum, but also from substantial immigration from neighbouring Mocambique. During the years 1925-32 there was a succession of droughts and famines in that territory, causing large-scale population movements from these drier areas into the relatively better-watered and more fertile areas of Malawi. In these areas to-day the density on the fertile red soils exceeds 100 persons to the sq. mile, and locally, notably in the south-western region of the catchment, the density is as much as 400 persons to the square mile.

Whilst these population densities may appear low for other parts of the world, they are, nevertheless, high for African conditions, particulary so as almost all these people gain their subsistence from the land. Such increases in rural population in a tropical climate cannot fail to affect the natural ground cover and rate of surface run-off.

LAKE MALAWI AND THE SHIRE RIVER

The Lake Malawi basin is, as a whole, asymmetric; the eastern side had been downthrown by one main fault or series of faults, whereas the western part of the down-thrown block has been dropped in a series of westward sloping steps by parallel faults, There are, however, variations in this general easterly asymmetric shape, and near the Malawi shore, between Nkata Bay and Deep Bay, the tilt is the reverse of the general direction, the lake here attaining its greatest depth of 2,310 ft. (760 ft. below sea level). This reverse tilt was brought about by the large north-south Ruarwe fault, which is probably of Pleistocene origin (Dixey 1941). In longitudinal section the floor of the lake is of an average depth of some 1,200 ft. in the north, deepening to over 2,000 ft. toward the centre and thereafter becoming rapidly shallower to an average depth of 600 ft. in the southern section.

The outlet of the lake to the Shire River is across a submerged sand bar in a depressed, swampy area near Mponda's, some 2½ miles north of Fort Johnston. Five miles south of Fort Johnston the Shire River enters Lake Malombe, which is about 18 miles in length and 9 miles wide. This lake is shallow, its bed is remarkably level and in recent times probably formed part of Lake Nyasa (Dixey 1926).

The Shire River may be divided into three main sections in accordance with the physiography of the valley it occupies, previously described in detail by Dixey (1926), Kanthack (1942), and Cochrane (1957). Briefly, the upper section covers a distance of 82 miles from the outlet to Matope, at an average gradient of 0.28 ft. per mile, the valley floor being made up of alluvial and colluvial deposits; the middle section, where the river plunges througn the cataracts of a total fall of 1,260 ft. in 50 miles; and finally, the lower river section that comprises a wide alluvial valley extending from the foot of the cataracts to the Zambezi River over a distance of 174 miles, at an average gradient of 1.06 ft. per mile.

The seasonal variation in the level of Lake Malawi averages 3 or 4 ft., but this has been as much as 6 ft. in a single year. Over long periods of years, however, the cumulative rise or fall may be much greater, and since accurate records were commenced in 1896 the level of the lake has fluctuated from 1,538 ft, to over 1,556 ft., a range of over 18 ft.

Prior to 1896 there is considerable evidence, in the form of observations made by earlier travellers on the lake and river, to show that this fluctuation in level is a phenomenon that has persisted for a considerable time. From this evidence it has been suggested by Dixey (1924) that the lake level was very low in 1830, very high in 1857-63, high in 1873, falling in 1875-78, high in 1882, very low in 1890, but rising rapidly in 1892-95. Since records began in 1896 the level declined, reaching a minimum recorded level of 1,537.8 ft. in 1915.

Almost all flow down the Shire River had ceased by this time, the upper reaches of the river channel having become blocked by reed covered sand bars, formed by the Shire River tributaries in flood. From 1915 the level rose gradually, and in 1937 it reached a maximum level of 1,556.4 ft. at Fort Johnston, although there is some evidence to show that this level was slightly higher on the lake itself during this year. Some three years prior to this, the rising lake waters over-topped the various sandbars in the river, and a channel was again formed, although this is still partially obstructed by the remains of these old bars. After 1937 the lake level fell slightly, but in 1948 it reached a high level that was but half a foot below the 1937 level.

From 1948 there was an overall gradual decline in level, but once again in 1962 the level began to rise rapidly, and as the result of further heavy rains in 1962-63, the level reached 1,556.6 ft., some 0.2 ft. higher than the previous 1937 maximum. Present indications are that the 1964 level will exceed all drevious known levels by at least 1 ft.

Fig. 2, p. 30, shows actual lake levels recorded from 1896, to 1963 with probable levels between 1860 and 1896, compiled from a number of historical sources by Latham (1960). Arising out of this examination of historical sources, Latham has also shown that the level of the outlet has risen, having probably been built up in shallow waters when the lake level was low. Recent soundings on the bar show that there has been no accretion or erosion of the bar during the past 25 years, during which period the lake level has been high.

In September 1956, a bund was constructed across the Shire River at Liwonde, and all flow from Lake Malawi ceased. This bund was breached in August 1957, and during the period of closure an additional 12 in. was stored in the lake, although now depleted. The construction of the Liwonde bund was undertaken on the probability that the lake level was declining, but during the wet season of 1956-57 the level rose rapidly, and it was found necessary to breach the bund to prevent flooding of certain lake shore areas.

HYDROLOGY

The long-term changes in the level of Lake Malawi, and the variable regime of the Shire River, have given rise to many speculations on their possible cause, but it was Kanthack (1942) who first drew attention to the delicate balance that exists between rainfall, run-off, evaporation, and outflow from the lake, and that these long-term changes could be attributed to purely natural phenomena.

The amount of water contributed by run-off and reduced by evaporation during the period of rise is the surplus amount or *freewater* (Cochrane 1957) made available for storage or for flow down the Shire River. Thus, with a ratio of land catchment to lake area of 3.3 to 1, and with high fixed losses from the lake area, the effect upon the amount of free-water in the lake in any one year would be a magnification of the variation of annual rainfall and run-off over the catchment.

On the basis of more complete data Cochrane (1957) later confirmed this delicate balance, and put forward a tentative quantitative water balance and furthermore sought to extend the existing record by a qualitative analogy between sunspot activity and the amount of free-water in the lake. Whilst

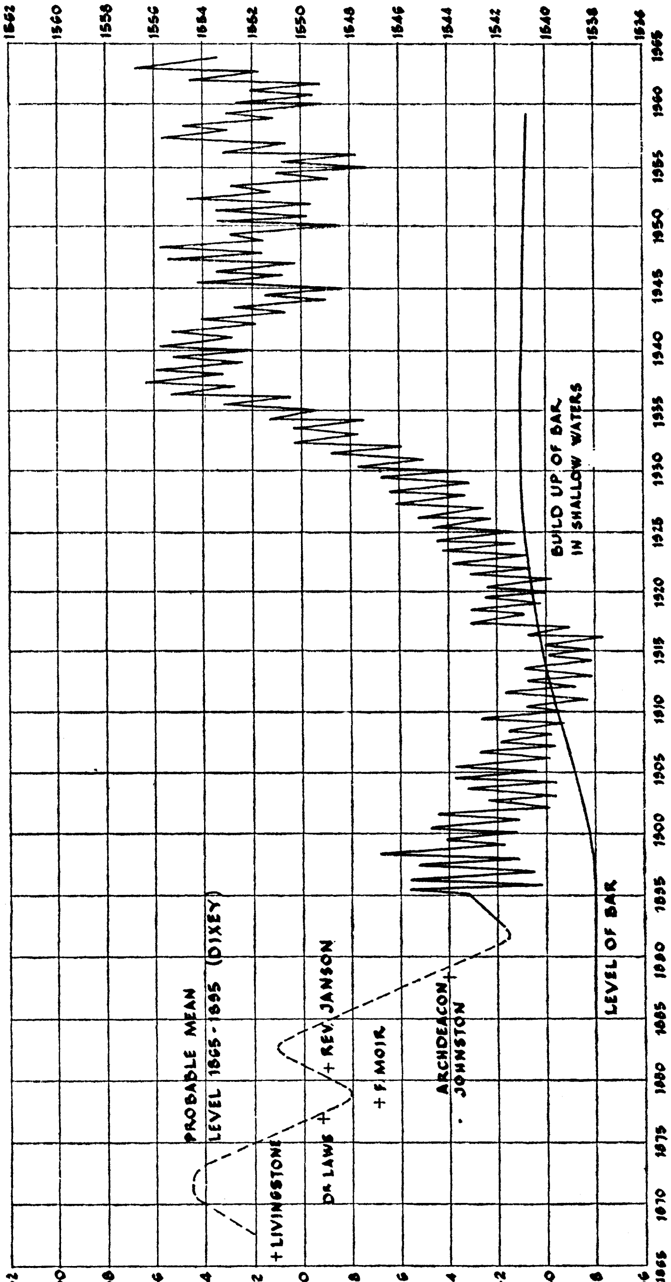

Fig. 2
Level of Lake Malawi 1895–1963

changes in storage from one year to the next, together with changes in outflow and rainfall, are known from measurement, the proportions contributed by (*a*) run-off from the catchment, (*b*) direct rainfall on the lake and (*c*) the amount lost by evaporation are now found to differ from the values calculated by Cochrane. The following paragraphs outline the data available and the methods employed in calculating the various components in the water balance.

Change in Storage

A record of lake level is available from 1896 to date, although the earlier record up to 1916 may have been subjected to a slight error owing to the transfer of gauge datums between Nkata Bay, Monkey Bay, and Fort Johnston during the years 1914-16. Over the past decade lake level has been observed at a further six gauges sited at various points on the periphery of the lake, but all calculations involving changes in storage are taken from the record of the Fort Johnston gauge. The annual change in storage has been taken as the difference between minimum levels recorded each year, normally reached during late November to early December.

In 1958, Young (unpublished report) carried out a statistical evaluation of all lake gauge datums from existing records, and showed that during the first half of the wet season there existed a hydraulic gradient from south to north and that during the latter part of the wet season the gradient reversed itself, the lake then being higher in the north. The difference was found to be of the order of 3 in., and as it appears to be an annual occurrence, no account has been taken of it in these calculations. It would appear possible that this may be caused by set-up due to the swing of the main wind direction from north to south during the latter part of the wet season.

Expansion of the water body amounts to about 3 in. over an annual cycle, but as the change in water temperature over the same period is effectively zero, this effect has been neglected. Surface seiche movements caused either by rapid changes in barometric pressure, heavy rain or, more commonly, strong winds, have been recorded on three automatic limnographs situated at Monkey Bay, Nkata Bay, and Deep Bay. The maximum seiche observed has been 4 in. with a period of 6 hr. This effect has also been neglected in these calculations.

Outflow

Owing to the very low velocity of the Shire River at its outlet from the lake, coupled with the presence of Lake Malombe, all outflow measurements have been made at Liwonde where the wide alluvial plain narrows and the channel bed is composed of reasonably stable gravel. Seepage past the gauging station is unknown, but on the left bank crystalline rocks outcrop close to the river, and it is only on the right bank that any seepage can occur. In percentage of the total flow, however, this is likely to be small.

The gauging station, now equipped with a 450 ft. span boat-cable and automatic water-level recorder, has been maintained at this point since 1948, but regular current meter measurements were not initiated until 1951. Discharge measurements, using floats, were made by Kanthack in 1939, and by Berchevaise in November 1947. The first current meter discharge was made by the author in November 1948. Because of a continuous slight movement of bed shape at this point, discharge measurements continue to be taken at intervals of at least once a month.

As all outflow from Lake Malawi is subject to evaporation loss in Lake Malombe, the flow measured at Liwonde has been adjusted positively to include this loss, calculated from evaporation pan data at Fort Johnston. Prior to 1948, outflow has been determined from stage discharge curves constructed from discharge measurements at Liwonde against equivalent gauge heights at Fort Johnston in a manner similar to that employed in Cochrane (1957)

Rainfall over the Catchment

Rainfall over the land catchment is recorded at 109 stations, fairly well distributed through the catchment, but the greater number of these stations show a record for less than 20 years. Twenty-nine stations have a record extending back for more than 20 years, of which only 14 show a record of more than 30 years. At one station, Chinteche, there is a continuous record for 56 years. The data available in published reports cover different periods of the year, the Tanganyika and Portuguese records referring to the period January/December, whilst the Malawi records refer to the period July/June. All records have been recalculated on the basis of November/ October, to coincide with the local hydrological year.

From these data isohyetal maps for each year were drawn by the same hand, and the average rainfall over the catchment was calculated. Prior to 1928-29 data were too scanty to permit the accurate delineation of isohyets, but it was found possible to extend the record back to 1920-21 by utilizing 12 long-term stations. The annual totals at these stations (marked by a circle in Fig. 3, opposite), for the period 1942-62 were compared to catchment rainfall computed from all stations for the same period, and the relationships were found to be:—

$$R_c = 0.717\ R_{12} + 9.90 \text{ in.} \qquad \ldots\ldots \qquad \ldots\ldots \qquad \ldots\ldots \qquad (1)$$

where R_c is the annual catchment rainfall and R_{12} is the mean of the annual rainfall at 12 representative stations.

The correlation coefficient is 0.91, and the probable error of estimate is $\pm$ 2.45 in. Therefore, whilst the annual catchment rainfall covering the period 1928-62 is considered to be as accurate as the data and the method will allow, the estimate based on equation (1) prior to this period may be in error from 5 to 10 per cent. The main rainfall over the land catchment for the period 1921-62 was found to be 46.4 in.

Direct Rainfail on the Lake

In past studies of the water balance of Lake Malawi, no distinction has been made between rainfall over the land and that over the lake, mainly because no data were available. In temperate climates observations have shown (Hunt 1959) that rainfall is often lower over lake areas than over adjacent land, thus supporting a similar belief held in respect of Lake Malawi.

In tropical climates, however, where a considerable proportion of the rainfall occurs in the form of convectional thunderstorms, as opposed to frontal systems in temperate climates, it is possible that rainfall over the lake may exceed that over the adjacent land for the following reasons. At night the cool air from the surrounding land blows towards the lake where, the water being warmer, it rises and forms towering cumulo-nimbus and thunder with heavy downpours during the night, often continuing until about 9 a.m. the following morning. These storms may drift slowly in either a north-westerly or south-westerly direction with the overall prevailing

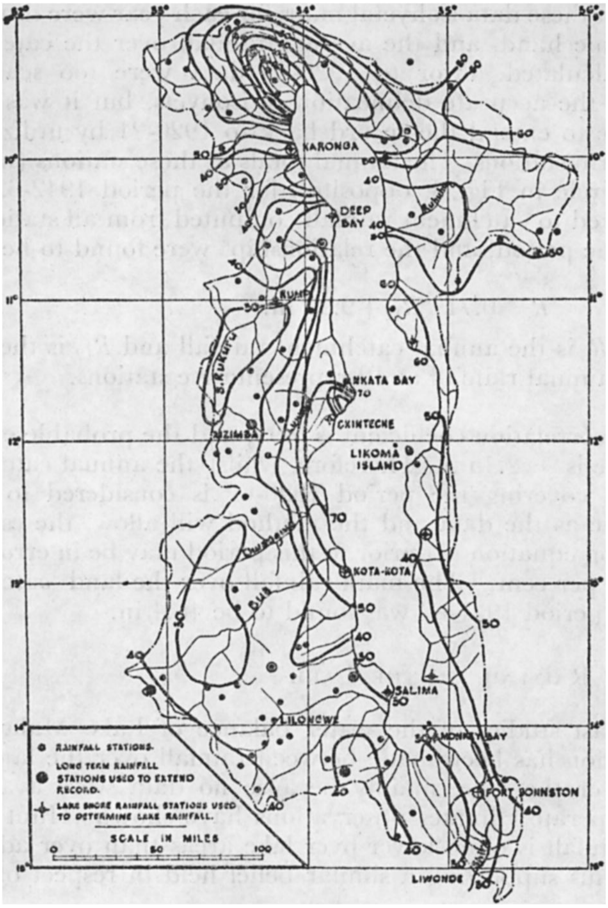

Fig. 3
Average annual rainfall, 1921–1962

wind at that time, and give rise to early morning thunderstorms along the western shores of Lake Malawi. During the day the circulation is reversed, and the shallow lake breeze, charged with vapour, sets steadily on to the shores, the lake now being the focus for descending air. By the afternoon masses of cloud build up over the lake shore which may result in further rain in the late afternoon. A similar sequence of events has been observed over Lake Victoria (Kendrew 1949), where the average lake rainfall is considered to be about the same as that over the land.

From personal observation, heavy night thunderstorms over Lake Malawi are a feature of the weather during the summer months, except during those periods when the inter-tropical convergence zone dominates the catchment with thick-layer cloud. An anlysis of the rainfall record from Nkata Bay and Karonga for the past five years shows that, on the average, 56 per cent of the total annual rainfall occurred in the form of early morning thunderstorms drifting in from the lake. Furthermore, the rainfall record from stations situated on the northern and western shores of the lake show a higher rainfall than stations situated only a few miles inland. Despite the above explanation, the determination of the actual amount of rainfall falling on the lake remains intractable. If it is assumed, however, that rainfall measured at various points on the periphery of the lake represents rainfall over an adjacent area of lake, an approximation may be arrived at.

Fourteen rainfall stations so situated were selected, and a series of half-polygons over the lake area were constructed around each station, after the method suggested by Thiessen. The areas of these half-polygons were then used to weight the annual fall recorded at each of the 14 stations. Lake rainfall calculated from these weighted values shows that this is, on the average, some 13 per cent higher than that over the land, or 53.5 in. To extend the record back beyond 1928-29, the mean of the annual totals of rainfall at Fort Johnston, Kota Kota, and Karonga was correlated with lake rainfall for the period 1942-62, and the following relationship was found:—

$$R_1 = 0.35 \ R_3 + 32.6 \text{ in} \qquad \ldots\ldots \quad \ldots\ldots \quad \ldots\ldots \quad (2)$$

where R_1 is the annual lake rainfall, and R_3 is the mean of the annual rainfall observed at Fort Johnston, Kota Kota, and Karonga. The correlation coefficient is 0.70, and the probable error of estimate is $\pm$ 4.8 in.

Evaporation

Sunshine duration, or Gunn Bellani radiation integrator, dew point, temperature, and wind run data are available from 1958 to date at three stations situated on the lake shore (Fort Johnston, Salima, and Karonga) and temperature, dew point and wind data are available at a further three stations (Kota Kota, Nkata Bay, and Likoma Island). Evaporation pan data are available for Karonga, Deep Bay, Nkata Bay, Kota Kota, Salima, and Monkey Bay, for the period 1952-62.

Monthly averages of meteorological data were taken and evaporation calculated from a modified form of Penman's (1948) approximation of the energy balance. The modifications consist of a different wind term, suggested by Penman (1956) and by the substitution of the Glover and McCulloch (1958) form of the empirical relation between sunshine hours and radiation, a relation developed from mainly African data and one that takes latitude into account. For the 4 years since 1958, the following annual totals were calculated to have been:—

		in
1958–59	......	77.5
1959–60	......	79.3
1960–61	......	80.3
1961–62	......	74.9
Mean	......	78.0

Monthly totals so calculated assume that there is no change in heat storage, and require adjustment. However, as the change in lake temperature over an annual cycle has been found by observation to be effectively zero, the annual totals require no adjustment.

These estimates are supported by observational data from the six evaporation pans ("Kenya" type)* from which the mean annual evaporation over the same period was 82.35 in. This gives an E_o/E_{pan} coefficient of 0.95, equivalent to 0.86 for the American class A pan. Experience elsewhere has shown that the class A pan has an average annual coefficient of 0.70, but coefficients of 0.6 and 0.8 and greater have been recorded, the higher coefficients being from humid areas (Linsley, Kohler, and Paulhus 1958).

In a previous paper the author (Pike 1962) has shown that pan coefficients in Malawi are negatively correlated with the range in mean air temperature, the coefficient approaching unity as the range in temperature decreases. A small range in mean air temperature is characteristic of humid areas.

Kanthack (1942) estimated the average annual lake evaporation to be 84 in., which he compared almost exactly with 18

*The "Kenya" type evaporation pan is 48 in. in diameter, and 17 in. deep, with 2 in. freeboard, raised above the ground with a protective 1 in. wire mesh screen. Comparative measurements made in Malawi against the American class A pan show that the "Kenya" pan evaporates, on the average, 10 per cent less.

years of water balance observations on the Mulungushi Dam near Broken Hill, Northern Rhodesia. Cochrane (1957), however, estimates the annual evaporation from Lake Malawi to be less, about 61 in., which he calculates from an empirical evaporation formula presented in an earlier work (Cochrane 1956). He proposed:—

$$E = \frac{T^2}{100} X \sqrt{\frac{u+3}{20\ H_r}} \times \left(\frac{60}{H_r\ T}\right)^{0.8} \text{ in. per annum.}$$

where T is the mean annual temperature (° F.), H_r is the mean annual relative humidity, and u is the mean annual wind speed in miles per hr. This formula is based on an analysis of evaporation pan data from 77 world-wide sites and four water-budget studies, including Lake Hefner. As written the formula contains eight exponents, which have been established from a large number of observations, allowing considerable latitude for curve fitting. Naylor (1958) has also drawn attention to the fact that E is proportional to $^3\sqrt{u}+3$ instead of $u^{0.7}$. E is also seen to be proportional $\frac{1}{H_r\ 1.13}$ instead of the vapour pressure differential.

This formula does not conform to either the mass transfer or energy balance theories of evaporation, both of which were exhaustively tested at Lake Hefner and Lake Mead and their validity was confirmed, even if the methods employed were perhaps too elaborate for everyday use. Penman's (1956) approximation of the energy balance is based on the sound physical principle of the energy balance, and is ideally suited for routine evaporation determinations because it relies only on meteorological data obtained at first-order stations. Because all these data are not always available, statistical correlation techniques have been employed to extend the record.

In the energy balance equation, the heat term is shared principally by evaporation, E, and sensible heat transfer to the atmosphere, H. Since neither E nor H can be evaluated directly, it is necessary to employ a ratio of these two quantities, Bowen's ratio. This ratio has been shown to vary under certain conditions, but over water surfaces it remains effectively constant (Anderson 1954), and under such conditions any observational technique that will give a measure of H will automatically give a measure of the corresponding changes in E. As the principal effect of H is to lower or raise the air temperature, the measurement of this quantity provides a useful index by which evaporation may be estimated. This principle has been exploited by a number of workers (Thornthwaite 1948; Blaney *et al* 1942), and the same principle was initially adopted to extend the evaporation record for Lake Malawi.

Monthly values of E_o for the four-year period 1958-62 were calculated from Penman's method, and these monthly values were then correlated with mean monthly air temperature for the same period, and the relationship

$$E_o = 0.397\ T_a - 21.5 \text{ in. per month} \quad \ldots\ldots \quad (3)$$

was determined. The correlation coefficient is 0.933, and the probable error of estimate is $\pm$ 0.39 in. An improvement in this estimate was obtained by considering dew point data as an additional variable affecting evaporation, and a multiple regression of evaporation on temperature and dew point shows

$$E_o = 0.3925\ T_a - 0.1350\ e_d - 14.02 \text{ in. per month} \quad (4)$$

with a probable error of estimate of $\pm$ 0.20 in., where Ta is the mean air temperature in °F., and *ed* is the mean dew point in °F. Temperature and dew point data are the average of monthly means observed at Fort Johnston, Kota Kota, and Karonga.

Equation (4) was used to calculate annual evaporation from monthly temperature and dew point records for the period 1921-58. Official meteorological records at lake shore stations cover the period 1935-62, but earlier records for four lake shore stations are contained in the Nyasaland Protectorate Blue Books (1907-1935).

The mean annual evaporation for the period 1921-62 is calculated to have been 76.6 in., with a minimum of 72.6 in. and a maximum of 84.1 in.

Run-off

Over the four-year period 1955-59, run-off from 65 per cent of the catchment area of Lake Malawi was measured at gauging stations operated by the Nyasaland and Tanganyika Governments. The location of these gauging stations and the contributing area are shown in Fig. 4.

After 1959 it was found impracticable to continue the operation of the gauging station on the Ruhuhu River, and the area effectively covered by gauging stations was reduced to 49 per cent. Only one of these stations was equipped with an automatic stage recorder during the period.

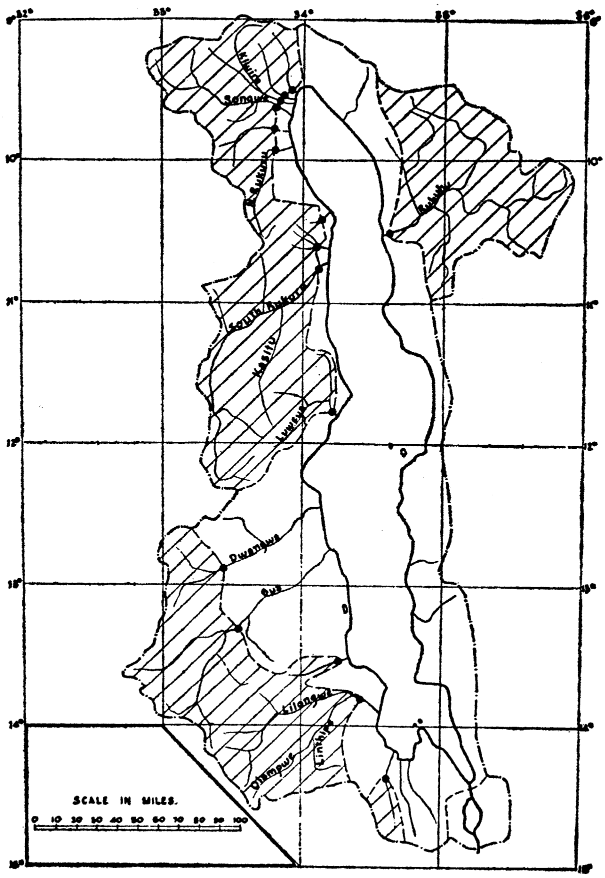

Fig. 4
Rated river gauging stations

The surface and underground run-off volume, therefore, presents an unknown in the water balance, but as it is the only unknown, the residual in the equation may theoretically be assigned to it. As all errors in the estimation or measurement of the other components will be accumulated directly in this residual, it was felt necessary to obtain some qualitative confirmation. The total run-off volume measured from 65 per cent of the catchment was assumed to be proportional to the volume from the whole catchment, and the measured volumes were adjusted, as set out in Table I.

TABLE 1

SURFACE RUN-OFF IN MILLIONS OF ACRE-FT.—LAKE MALAWI

	1955–56	1956–57	1957–58	1958–59
Measured	18.3	17.9	12.6	7.5
+35 per cent "Adjustment"	9.9	9.6	6.7	4.1
Total	28.2	27.5	19.3	11.6
Water balance	30.8	29.6	19.0	15.8
Difference, per cent	9.2	7.6	1.5	36.0

Agreement is close in only one year out of the four, but the adjusted volumes do indicate the order of magnitude of run-off. In order to confirm the above estimates, a relationship between rainfall, evapotranspiration, and run-off was employed. The author has previously shown (Pike 1964) that annual catchment yield may be approximated to within a probable error of 10 per cent from rainfall and potential evaporation data. Rainfall, open-water potential evaporation (E_o), and run-off data for four catchments of widely differing physical characteristics in Malawi were analysed to obtain values of actual evapo-transpiration. Two of the catchments are situated within the Lake Malawi catchment. The difference between annual rainfall (R) and run-off (Q) from any catchment is made up principally of evapotranspiration (E_t), seepage past the gauging station (G), and the change in ground-water storage ($\triangle S$). Thus

$$R—Q=E_t+G+\pm \triangle S$$

and $$E_t=R—Q—G\pm \triangle S.$$

From these catchments R, Q, and $\triangle S$ were determined, and G was neglected as almost all outflow was considered, from geological evidence, to pass as surface flow at the gauging station. From this data it was shown that E_t is mainly a function of potential open-water evaporation and moisture availability. This, in turn, depends principally on the intensity and time distribution of R. Under Malawi conditions rainfall occurs at much the same intensity and over the same period each year and, therefore, E_t is mainly a function of the size of R. It was found that E_t could be expressed as

$$E_t = \frac{R\,E_o}{\sqrt{R^2+E_o{}^2}} \quad \ldots\ldots \quad \ldots\ldots \qquad (5)$$

This equation also presents a method by which run-off may be estimated from data for R and E_o data alone, by the equation $Q = R - E_t$ without consideration of ground-water storage.

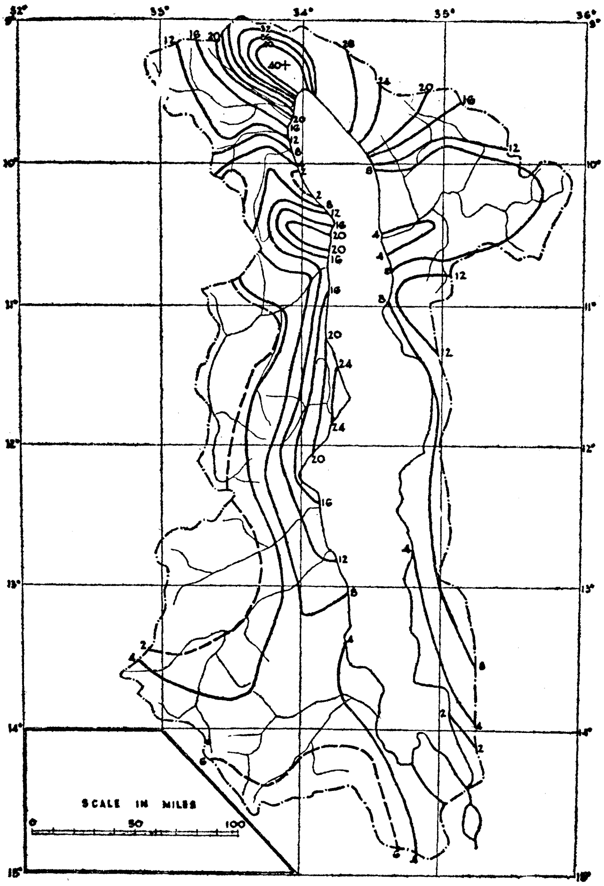

Fig. 5
Average annual run-off (in.)

To estimate E_t for the Lake Malawi catchment and hence Q, isohyets of average rainfall were superimposed over a similar map showing iso-evaporation (E_o) lines taken from an earlier work (Pike 1962). At the intersections of these two series of lines E_t was computed by equation (5), and Q was obtained by simple subtraction. These computed values of Q were then plotted separately, and lines of equal values of Q were drawn for the whole catchment (Fig. 5, p. 559); hence the average value of Q for the entire catchment was found to be 9.02 in. The computed water balance average Q is shown to be 10.22 in., a difference of 12 per cent. Both this estimate and that made by adjusting measured run-off confirm that the run-off factor for the Lake Nyasa catchment is of the order of 20 per cent.

Table II sets out the complete water balance calculated by the methods outlined above.

TABLE II
LAKE MALAWI—WATER BALANCE

Years	Minimum Lake Level, ft.	△ H ft.	Q, in.	Free Water		Rainfall, in.		Eo	Run-off		
				ft.	in.	Land	Lake		million acre-ft.	in.	per cent
1921–22	1,540.79	Nil	Nil	Nil	Nil	42.6	48.3	72.6	14.8	7.14	16.7
1922–23	1,541.45	+0.66	Nil	+0.66	+7.92	47.8	57.1	75.7	16.1	7.78	16.7
1923–24	1,541.62	+0.17	Nil	+0.17	+2.04	35.1	52.6	84.1	20.4	9.99	28.4
1924–25	1,542.69	+0.62	Nil	+0.62	+ 7.44	49.0	58.0	77.9	16.6	8.03	16.3
1925–26	1,542.54	+0.25	Nil	+0.25	+ 300	49.1	50.8	75.7	17.0	8.50	17.3
1926–27	1,543.29	+0.75	Nil	+0.75	+ 9.00	45.4	51.0	72.6	18.6	9.000	19.8
1927–28	1,543.04	—0.25	Nil	—3.25	—3.00	45.3	53.9	72.5	9.5	4.59	10.1
1928–29	1,543.79	+0.75	Nil	+0.75	+9.00	42.2	52.6	80.1	11.3	5.45	12.9
1929–30	1,545.45	+1.66	Nil	+1.66	+19.92	45.0	51.6	77.9	28.2	13.62	30.2
1930–31	1,546.04	+0.59	Nil	+0.59	+7.08	48.0	59.5	74.2	13.2	6.40	13.3
1931–32	1,548.21	+2.17	Nil	+2.17	+26.04	59.7	52.1	75.2	30.0	14.75	24.7
1932–33	1,547.79	—0.42	Nil	—0.42	—5.04	43.1	51.2	76.0	12.1	5.84	13.5
1933–34	1,549.45	+1.66	Nil	+1.66	+19.92	54.0	55.0	79.3	26.4	12.76	23.6
1934–35	1,550.70	+1.25	1.0	+1.33	+15.96	46.5	62.0	77.2	19.1	9.55	20.6
1935–36	1,552.87	+2.17	5.0	+2.59	+31.08	52.0	63.8	76.3	26.6	13.30	25.5
1936–37	1,553.62	—0.75	9.0	+1.50	+18.00	44.8	49.3	75.8	27.2	13.60	30.4
1937–38	1,552.69	—1.00	8.0	—0.33	—3.96	41.0	54.8	75.2	10.0	5.02	12.3
1938–39	1,552.29	—0.33	10.0	+0.50	+6.00	46.5	52.0	76.2	18.4	9.25	19.8
1939–40	1,552.79	+0.50	14.0	+1.67	+20.00	49.0	56.2	77.2	25.0	12.58	25.6
1940–41	1,552.79	Nil	14.0	+1.17	+14.00	41.0	48.0	78.8	27.3	13.70	33.4
1941–42	1,551.79	—1.00	16.0	+0.33	+3.96	46.8	53.2	75.5	16.1	7.80	16.6
1942–43	1,550.04	—1.75	15.0	—0.50	—6.00	46.8	48.2	75.5	13.0	6.52	14.0
1943–44	1,548.54	—1.50	11.0	—0.58	— 6.96	40.6	45.7	77.4	15.1	7.59	18.6
1944–45	1,551.29	+2.75	17.0	+4.17	+50.04	62.3	64.3	73.7	36.2	18.15	29.0
1945–46	1,550.62	—067.	14.0	+0.50	— 6.00	42.6	45.0	74.8	14.6	7.31	17.2
1946–47	1,552.24	+1.92	17.0	+3.34	+40.08	57.7	63.2	74.1	31.1	15.57	26.9
1947–48	1,552.62	+0.08	19.0	=1.16	+13.92	45.0	54.3	75.9	21.6	10.81	24.0
1948–49	1,549.45	—3.17	13.9	—2.01	—24.12	36.2	44.6	78.8	6.5	3.26	9.0
1949–50	1,550.45	+1.00	13.7	+2.14	+25.68	50.2	55.3	75.9	28.2	14.10	28.0
1950–51	1,549.96	—0.49	13.8	+0.66	+7.92	43.0	44.0	77.6	24.5	12.27	28.5
1951–52	1,551.62	+1.66	15.8	+2.97	+35.64	53.8	64.0	78.1	30.3	15.17	28.2
1952–53	1,549.37	—2.25	13.8	—1.10	—13.20	37.4	43.7	77.4	13.0	6.52	17.4
1953–54	1,548.01	—1.36	10.8	0.46	— 5.52	37.5	43.4	78.1	18.5	9.25	24.7
1954–55	1,548.26	+0.25	10.0	+1.08	+12.96	42.2	54.8	76.3	21.1	10.57	25.0
1955–56	1,550.84	10.9	10.9	+3.49	+41.88	49.0	65.5	74.5	30.8	15.43	31.4
1956–57	1,553.06	+2.22	4.4	+2.58	+30.96	50.9	58.9	75.9	29.6	14.14	27.7
1957–58	1,551.30	—1.76	17.9	—0.26	—3.12	38.5	44.9	79.2	19.0	9.53	24.8
1958–59	1,549.66	—1.64	14.8	—0.40	—4.80	39.6	46.8	77.5	15.8	7.91	20.0
1959–60	1,549.53	—0.13	13.2	+0.97	+11.64	47.7	52.6	79.3	23.3	11.69	24.5
1960–61	1.549.27	—0.26	12.3	+0.77	+9.24	54.4	59.7	80.3	18.1	9.08	16.5
1961–62	1,551.84	+2.57	16.4	+3.93	+47.16	52.1	61.5	74.9	36.9	15.42	29.5
Average			13.5	+0.97	**+11.64**	**46.4**	53.4	**76.6**		10.22	22.0

Secular Changes in Rainfall

An analysis of a number of long-term rainfall stations in Malawi (Tetley 1959) has shown apparent cycles of high or low rainfall. A similar analysis was made for the Lake Malawi catchment for the 41 years of record, where 10-year moving averages have shown two periods of above average rainfall, but from the period ended 1954 there has been a general decline. A similar analysis of the run-off data for the same period, however, shows (Fig. 6) that run-off has been increasing, particularly from 1950 onwards, from which time the rainfall is seen to have decreased.

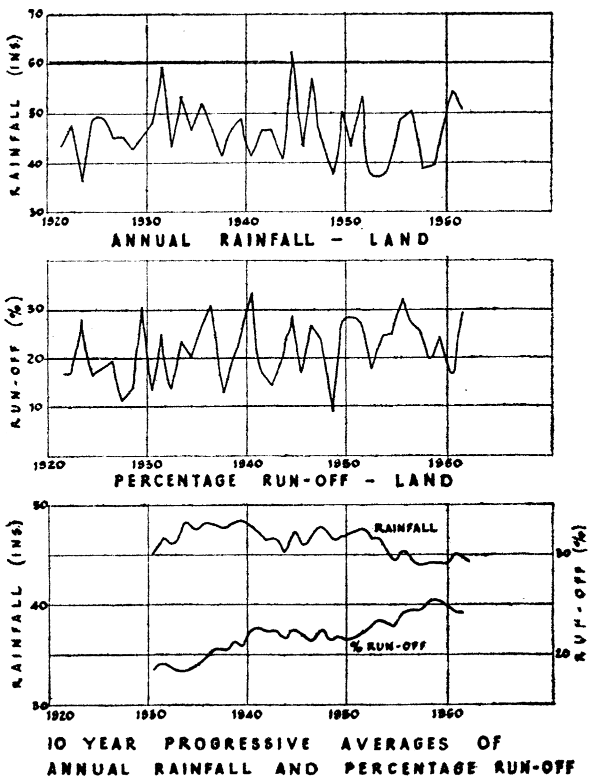

Fig. 6
Variation in annual rainfall and run-off.

During the late 1920s and early 1930s there was a considerable influx of population from neighbouring Mocambique, and from 1948 onwards agriculture in the country has steadily undergone transition from a purely subsistence toward a subsistence and cash-crop economy. This has necessitated greater areas of woodland being cleared for cultivation, coupled with additional subsistence gardens being opened for the increasing population on the land. These population increases and increasing agricultural tempo have undoubtedly had an effect on the natural rates of run-off, but to what extent it is difficult to ascertain. Experience elsewhere in central Africa has shown that run-off is increasing, particularly in the Zambezi and Kafue River catchments, where there have been no large influxes of population.

It is thought that, in the case of the Zambezi (Dr. D. T. Edmonds, private communication) this increase may well be due to marginal changes in the intensity or distribution of rainfall. An investigation on these lines for rainfall data in the Lake Malawi catchment shows that the average daily rainfall for each year, obtained by dividing the annual total rainfall by the number of rain-days, has increased in some areas and yet decreased in others, but no firm conclusions may be drawn from the data.

Whether or not the increase in run-off revealed by this investigation is due to land-use changes or changes in rainfall intensity patterns alone or a complex combination of these two factors, it has an important consequence in any hydrological analysis of Lake Malawi. Any forecast of future behaviour on the basis of past records will be largely nullified by this changing catchment regime.

THE WATER BALANCE OF LAKES MALAWI AND VICTORIA

In the foregoing paragraphs the methods used to obtain the relative proportions of the water balance have been given. The relevant figures are shown in Table III. It is of interest to compare the hydrological conditions of these two lakes,

TABLE III

WATER BALANCE—LAKES MALAWI AND VICTORIA

	Lake Malawi	Lake Victoria
1. Lake Area, sq. miles	11,430	26,500
2. Catchment Area, sq. miles	37,420	76,700
3. Ratio item 2 to item 1	3.3	2.9
4. Rainfall, land, in.	46.4	48.6
5. Rainfall, lake, in.	53.5	49.0
6. Mean Air Temperature,°F.	74.6	69.0
7. Evaporation, in.	76.6	49.0
8. Outflow, in.	13.5	12.0
9. Run-off,in.	10.2	6.7
10. Run-off, per cent rain	22.0	13.8
11. Mean free water, in.	+11.6	+12.0

Despite the differences between the two lakes in latitude (about 10°), size, and shape of the water bodies, the hydrology of both lakes is strikingly similar. The main differences in the water balance, however, lie in the proportions assigned to run-off and evaporation. Lake Victoria, with a mean surface elevation of 3,600 ft., is situated astride the equator and experiences rain throughout the year, with consequent cloudiness. Lake Malawi, on the other hand, has a mean surface elevation of 1,550 ft., some 2,000 ft. lower, and experiences rain for six months of the year only. From May to October the weather over Lake Malawi is dominated by the S.E. Trade Winds, which are generally dry and strong. The difference in mean air temperature is 5.6°F., that over Lake Malawi being higher. In terms of air temperature alone this increased air temperature, being high on the temperature scale, would increase evaporation by 26 in., if the Bowen ratio over both lakes is assumed to be constant. The difference in evaporation rates may, therefore, be explained in terms of prevailing climate over the two lakes.

Lake Victoria occupies a comparatively shallow, broad, and downwarped depression, and the slope of the surrounding catchment is comparatively gentle and in some parts, particularly in the north west, is depressed. Steeper country is confined to the north-east and on a smaller scale to the south-west Lake Malawi, however, occupies a narrow tectonic basin with short steep rivers draining to it for almost the whole of its length, and the overall slope is considered to be much greater.

The greater difference in slope, the absence of depressed topography along the shore line, and the underlying geology being made up of hard crystalline rocks, are considered to be sufficient reasons for this increased amount of run-off.

CONCLUSION

As it would be clearly impracticable to measure all items in the water balance of a catchment so large, the main task in this case has been to apply various techniques of approximation, to provide a reasonable estimate of the various proportions of the water balance. This analysis, notwithstanding the errors contained in measurement and approximation has, however shown an important result. The run-off over the land is increasing, and because of this the problems of stabilization and regulation are rendered even more complex.

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