PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY B BIOLOGICAL SCIENCES

Analyses of Agricultural Yield. Part IV. Water-Table Movements on a Farm in Egypt

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Phil. Trans. R. Soc. Lond. B 1932 **221**, 335-375
doi: 10.1098/rstb.1932.0005

V. *Analyses of Agricultural Yield. Part* IV.—*Water-table Movements on a Farm in Egypt.*

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(Received August 25, 1931—Read February 25th, 1932.)

[Plate 33.]

Contents.

Preliminary Note.

The purpose of this account is to place on record an exceptionally detailed set of data concerning water-table movements which have been accumulated on an area of 70 acres at Giza, near the road to the Pyramids from Cairo, and about a kilometre from the river Nile. The significance of these data is examined principally with respect to surface geology and hydrology, irrigation, and drainage; the biological aspects are purposely neglected at this stage, but will be elaborated later.

An account of earlier observations on the same site was published in 1914. These data are incorporated in the present account, being of special interest in that they were mostly taken in 1913, when the Nile flood was lower than it had been for a century.

 [Published August 16, 1932.

The summary of conclusions in this earlier account will serve to frame the situation more fully expounded in the present one :—

"1. . . . Results obtained by measurement of 17 tube-wells. . . ."

"2. The extreme complexity of the subsoil structure leads to varied conduct in the different wells, for the causes of which I have advanced most tentative explanations."

"3. Different wells were differently affected by surface irrigation, by seepage from misqas (land channels), by infiltration from a canal, by the Nile flood, and by the down-flow of water underground from Upper Egypt, this water coming from infiltration out of canals, or out of the river, or from surface irrigation, or from all these sources."

"4. The well-level in freely permeable soil rose higher during 1913 than the level of the Nile flood, which had previously been considered as the primary cause of such elevation on the site in question."

"5. The water-table, so far from being stagnant and peaceful, is continually throbbing in response to hydraulic impulses received in all directions and from unknown distances. Except in isolated clay basins it is never at rest, and even there it is slightly troubled by meteorological changes."

"6. Irrigation has raised the level of the natural water-table of Egypt."

The senior author assumes all responsibility for the actual text of this communication, and for the drawing of the diagrams other than figs. 14 to 26, for which we are indebted to Mr. Weinstein. On the other hand, the junior author has been responsible for the conduct of the post-1926 observations over and above routine, and for the planning of many of them, as well as for the stratometer studies from which two excerpts only have been used here. The term "in collaboration with" on the title-page is deliberately used to express this distinction between their respective responsibilities.

Introduction.

The first three Parts of 'Analyses of Agricultural Yield' were published fifteen years ago, and dealt with the effect of spacing, sowing-date and of the so-called seasonal influences upon the yield of cotton in Egypt. The fourth part had been intended to treat of manurial effects in the same way, but the senior author left the Egyptian service before this intention could be carried out. However, an account of the behaviour of the permanent manurial plot in St. Vincent by S. C. Harland, which appeared not long afterwards in the 'West Indian Bulletin,' represents in outline the kind of analysis of manurial effects which had been contemplated.

The effect of soil nutrients is, however, intimately associated with the physical properties of the soil. In Egypt, especially, these are of the first importance for cotton, on account of the water-demands of the deep-rooted plant. While it has long been known that manures seem to have surprisingly little effect on the final yield of cotton in Egypt, it is now being realised that this is explicable in terms of the soil-profile, combined with studies of the root-system, and is more apparent than real if the yield is "analysed." The author's return to the Egyptian Ministry of Agriculture after thirteen years spent on the other side of the cotton industry, again made his interest in the yield problem an active one, and the first step was evidently to search the accumulated data of the Giza farm to see how far the yield-behaviour of any given site had been consistent during the intervening years.

The search was attended by unexpected difficulties, due to the difficulty of locating plots of different seasons in coincident positions, which coincidence had to be unexpectedly exact in order to eliminate the alterations in sub-soil structure which may occur—and, commonly, do occur—within a few metres; nevertheless the results were gratifying. Arrangements were made to facilitate the accumulation of more data, so far as these could be fitted within the normal experimental use of the farm. The interest of our colleagues on the chemical side was easily obtained, because the intervening years of general research on Soil Science had led to an interest in these aspects of yield-causation, under the term "soil-profile."

Combining this with an old personal interest in soil-water movements, an attempt at surveying our farm was made, in order to guard against soil-variation errors in experimental work, as well as for the intrinsic interest of the puzzle. As the result of this survey we have now reached a position at which the vague "error of a plot," due to soil variation, for so long the bugbear of agricultural experiment, and only to be countered by statistical treatment (which is, in itself, a confession of ignorance of soil-variation) no longer exists. Whether it is worth while to attempt the detailed study needed to substitute knowledge of soil-variation for mere acceptance of its effects, remains to be seen, but such knowledge of our farm as we have acquired has produced one striking result in that we now use our crops as indicators of soil-structure. These show us where to search for soil-peculiarities more simply and effectively than a direct physico-chemical soil-survey could do.

The surface soil is indicated by clover; the middle soil by wheat, barley, and maize; the deep soil by cotton, flax, and beans. The last three crops indicate all depths if their development stages are watched.

At this stage it occurred to us that the soil-variations we were finding and postulating might seem almost incredible so long as there was a "biological error" concerned in their identification, and that it might be well to deal separately with our data for soil-water movements, which were themselves equally complicated, in order to remove from later expositions the necessity of repeated declarations. The movement of water in a bore-hole admits of no ambiguity in its record.

While the principal interest of the present communication is more appropriate to the irrigation engineer than to the farmer, it nevertheless became evident to us that the proper place in which to use it was in these 'Analyses of Agricultural Yield' where, as Part IV, it serves as an introduction to the actual data about the crops themselves which we hope to publish later.

A.1. *The Giza Farm.*

The site employed is now the central Experimental Farm of the Botanical Section of the Ministry of Agriculture at Giza (fig. 11, p. 350). It is also used by the Chemical and Plant Protection Sections in liaison with the Cotton Research Board. It is adjoined on the north-west by the Horticultural Section's gardens, and on the south by the farm of the Higher School of Agriculture in the same Ministry (fig. 13, Plate 33). The whole area of about 200 acres is the nearest equivalent to Rothamsted in Egypt, having been an experimental farm since 1898, when the northern half belonged to the Khedivial Agricultural Society. Portions of it, expanding from one acre to 25 acres, were under the senior author's personal control from 1904 to 1914, these being included in the 70 acres now described, to which he returned in 1927.

The site is thus well known, with data available concerning the behaviour of most parts of the land under various crops, though the earlier agricultural records are not sufficiently detailed to be of much use to-day, when we know that an error of 10 m. in locating a group of plants may bring us into a very different set of soil conditions.

The early water-table observations were discontinued in 1914, but were resumed in 1923 on the formation of the Cotton Research Board, under the control of Messrs. Bailey, Trought, Simpson, and McKenzie Taylor. Dr. Templeton continued them during 1926 until the senior author's return in 1927. Various observers and technical assistants have been responsible for them during this period, but the original observer of 1913, Shaaban Abd el Aal, still supervises them, and the data (figs. 15–24, pp. 351–6) have been recorded and plotted by the original computer, A. Weinstein, now keeper of Experimental Records to the Botanical Section.

Frame of reference.—The nomenclature of the various fields on the farm is confused and arbitrary, as also is that of the various observation points. We have substituted for this a frame of reference which, though awkward, at least has the merit of enabling the reader to visualise the approximate position of the point described. Since most of the intensive study has been conducted along the line of the central farm-road, both in 1913 and later, this has been taken as the east-west base, with its zero on the bank of the Sawahel canal (figs. 11, 12, p. 350, etc.). All points are located from this zero in metres ; thus the Old Laboratory is at 25*s*–500*e*.

Three of the observation points are mentioned repeatedly, and for these we have retained their arbitrary titles, viz. :—

Pit III	Located at 8*n*–580*e*.
Pit IV	Located at 22*n*–580*e*.
Pit XVI	Located at 5*s*–65*e*.

Levelling.—All levels are tied to Survey Department benchmarks on the farm, and nearly all have been independently determined for us by that Department, to whose staff we are much indebted, in 1913 as at the present time. The employment in the diagrams of the lettering "A.S.L." signifies conventionally "above sea-level," being the mean sea-level at Alexandria.

A.2. *The General Water-Table Problem in Egypt.*

The great improvements in Egyptian Irrigation after 1882 were in part due to the adoption of free-flow canals which run above country-level, being fed by barrages across the river. The fact that this improvement of supply was being purchased at the cost of a sur-elevation of the water-table, with a reciprocal diminution of the soil available for root-run, was noted fairly soon, at first by local outcrops of salt due to infiltration, and then by direct measurements of water-table level begun by LUCAS in 1894 in the Cairo district and developed intensively at certain Delta localities by AUDEBEAU and GIBSON. The latter workers developed the thesis in 1906 that the water-table had risen, and that there was a consequent fall in agricultural yield per acre. Both these conclusions were unpopular, as tending to disparage the remarkable work which had been done on irrigation, and a "water-table controversy" flourished from 1909 till the Great War.

The outstanding work during this period was that of FERRAR, who outlined the general situation throughout the length of Egypt, besides making what were then considered to be very detailed studies of certain localities, thereby framing the broad outlines upon which all subsequent work can be fitted. In various degrees of collaboration with FERRAR were AUDEBEAU and the senior author; HUGHES, HURST, POLLARD, BECKETT, DE LOTBINIÈRE and KEELING. By 1914* it was definitely established, though not entirely admitted, that the water-table had been raised, that cotton yields were inversely proportional to water-table heights if these latter were within 3 m. of ground level, and that a water-table rising to immerse established cotton roots was often deleterious.

The invasion of Egypt by the *Gelechia* boll-worm, which was completed by 1914, has obscured the water-table problem, since the cotton crop cannot now continue to ripen long enough to have its yield seriously affected by the flood-rise of water-table. Conditions of cultivation have been altered, and the direct effect of rising water on the cotton crop is not easily noticeable, but the other half of the problem still remains.

The continued maintenance of the water-table at higher levels than in the 'eighties seems to have brought about locally certain chemical and physical deteriorations in the soil, and with the study of these the problem enters on a fourth phase. The practical consequence will no doubt be some form of drainage, but the form must undergo local variations, and one purpose of this account is to direct attention to the vast heterogeneity of soil which may be found within a few acres, so that an admirable drainage project on one side of a road may be useless on the other side.

* (1913). For a summary to that date *see* WILLCOCKS & CRAIG.

Although the Giza site is rich in soil-structure variations, it is by no means peculiar, and very similar variations have been found after similar detailed study in other places originally believed to be homogeneous. In that the present account demonstrates these minute details it advances sufficiently beyond FERRAR's work to warrant its publication; apart from that, it merely confirms and utilises the pioneer efforts of AUDEBEAU and FERRAR.

A.3. *The Relation of Water-Table Phenomena to Soil-Structure.*

The study of the water-table is essentially geology, rather than hydrology. The geological training and experience of FERRAR was a great advantage in studying water-tables, but possibly a hindrance in presenting results for criticism by people principally interested in the hydraulic aspects. Soil heterogeneity is ever with the geologist, but to postulate a band of clay to account for a peculiar water-condition comes very near to begging the question in a controversial discussion.

Relatively little is known of the deep Nile Valley deposits, but essentially they consist of coarse detritus from lateral valleys with a skin of Abyssinian alluvium on the top, this skin growing at a rate of about a millimetre a year. For some four thousand years this skin has been almost entirely under artificial control in varying degree, following the state of government of the country; the west bank in Upper Egypt, and the Southern Delta, have been controlled still longer. The deposits laid down by the river range from sand to clay in the usual way, following current velocity. Lastly, the river and its branches have altered their courses during the six thousand years of Egyptian history, as well as before, so that a tolerably complicated sub-soil structure can be found in many places.

The burial of the old "basin-systems" under modern perennial systems of irrigation during the last century must also tend to elaborate the structure of the upper sub-soil, since an established basin is traversed by an arborescent network of run-off depressions which are levelled over during conversion. On the Giza farm there are traces of this, as well as of the extensive making-up of the surface which preceded its use as the garden of Giza Palace.

With erosion and re-deposition it is possible to produce slopes of one-in-one at unconformable junctions of sand and clay; two such cases are known on the farm. At 0*n*/510*e* (see fig. 12, p. 350) there is clay to more than 3 m. depth before permeable strata are struck at 6 m.; moving only 10 m. south from this point there was no connection with these permeable strata at 13 m. depth, being a slope of not less than 7 in 10. Another similar junction was actually exposed in a cutting at 15 *s*/750 *e*, where loam lay horizontally over a sand-clay junction which sloped at 45° for a metre to the foot of the excavation, and possibly much further. Fossil basin-deposit laminæ were found near by.

In yet another part of the same excavation we found "fossil cracks" from a longpast summer's fallow, sand having sifted downwards into cracks in clay, about a metre below the present land surface; such cracks run deep, and such a bed might be almost impermeable horizontally, yet easily permeable vertically. Such considerations must not be forgotten when using the junior author's Stratometer to map these underground structures; we have freely used this instrument (*e.g.*, figs. 6 and 29, pp. 346 and 362), though its limit is reached at present before four metres depth. But it is clear that details of structure at much greater depths may be important in fixing the position of underground water-conduits and water-barriers, so it is quite possible that the future may show a useful application of miniature geophysical methods to the irrigation and drainage problems of alluvial soil. Meanwhile the examination of air-photographs taken repeatedly over the same area at different stages of crop development has proved very useful at Giza (fig. 13, Plate 33); we are indebted to the British Royal Air Force for this assistance, in the shape of six photographs at monthly intervals. Ideally, the series should be continued until the full rotation of crops has been covered; failing this, a single photograph taken during the maximum rise of the water-table in a year of abnormally high flood should be most valuable. A map illustrating the kind of result which would be obtained is shown in fig. 28, p. 362.

The deep-lying detritus termed the "sakia gravels" is the most important water-channel; encountered at a depth of some 10 metres, it yields water to the indigenous cattle-power water-lifting wheels known as "sakias." The rate of propagation of the flood wave through it down the Delta has been observed by AUDEBEAU and by FERRAR. Its importance consists in the fact that it offers practically no obstacle to transmission of pressure changes, and relatively little to bulk movement of water. This importance is often overlooked through the inevitable use of distorted vertical scales (*cf.* figs. 6, p. 346, and 43, p. 373). The resistance to lateral flow through a distance of a hundred metres in ordinary soil must often be prohibitive in comparison with the resistance in a vertical direction for the same distance; the longer way round must usually be the quicker for sub-soil water, so that the addition of fresh water in one place may cause the emergence of stale water in another.

For convenience in description, we shall classify water-tables into four types, conditioned by the soil structure:—Free, Isolated, Perched, and Backwater. They are illustrated in fig. 1, which we are fortunately able to superimpose upon a drawing of an

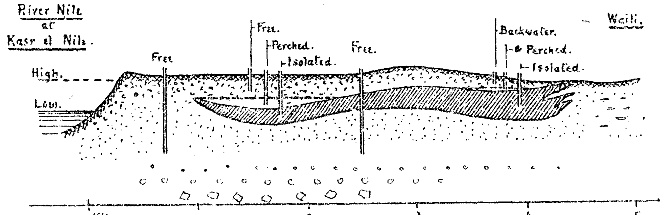

FIG. 1.—Types of water-table. Illustrated upon an actual section under Cairo. Copied from E. C. Bowden-Smith.

actual section made by E. C. BOWDEN SMITH on the other bank of the Nile opposite Giza, thus indicating that our postulated variations of soil structure are not unreasonable. Free Water-tables are those found in AUDEBEAU'S "terres permeables," typified by sands. Isolated Water-tables are those found in AUDEBEAU'S "terres impermeables," such as clays. Perched Water-table is an accepted description (*vide* STEWART) which is self-explanatory. The Backwater Water-table is a new expression which we have introduced to cover a number of cases where land can be emptied and filled with infiltration water quite easily, and yet the water is sluggish in its response to minor causes of movement.

These terms are merely type-descriptions, without any sharp demarcation. Thus curves I and J in fig. 31, p. 365, begin as free water-tables, but become perched when they have fallen below a certain level. The broad distinction between free and isolated types can be seen by comparing figs. 25, p. 357, and 26, p. 361.

A.4. *Methods for Observing Water-Tables.*

It is not easy to establish the exact connection between soil-water-content and water-table level. The existence of these difficulties has led to some waste of criticism concerning the simple reading of water-level in tubes, wells, and pits. But the latter are consistent in themselves, as we shall show, and our definition of "water-table" in this account is simply the level at which water stands at temporary equilibrium in a hole of specified depth, not less than 2 cm. in diameter.

Some of these difficulties doubtless arise from the instability of the water-table, and the marked local variations which can be found over very short distances (fig. 7, p. 346). In the present account we neglect any readings taken at intervals of less than a day, but we are also obtaining continuous records, which show many features of interest; for the present it suffices to repeat that a stagnant water-table is rarely to be found.

1. *Sakia pits.*—These tap the deep gravels, and are of importance in mapping the broad hydrological features of the Nile valley; they are fully free, and provide the secondary base-line to which the behaviour of local soils can be related. The original base-line is, of course, the height of the river itself, as shown on the Nile gauges.

2. *Tube wells.*—Two-inch iron pipes are provided with a perforated end-section 20 cm. long, covered with gauze, and ending in a point. They can be driven into soft soil or dropped into a hole bored with an auger, the sides being rammed and the surface raised to prevent surface water working down their sides. A certain liability to choke up can be tested by pouring water into them, and though convenient, they need regular supervision. Passing through an impermeable layer they may form a line of leakage and so record water coming really from higher levels than the one in which the perforated point is located.

3. *Bore-holes.*—The utility of the simple bore-hole without any lining, for temporary observations, was noted by HUGHES, who sounded the water in such holes by blowing

down a rubber pipe, reinforced against stretching, and calibrated. Such holes are conveniently left in using the stratometer, and can often be observed for several months; in soft soils they can be lined with cheap thin metal tubing.

4. We are examining the possibilities of a cheap permanent bore-hole made by leaving a square rod always inside the thin lining, and projecting below its lower end into the soil. The rod is removed to read on it the water-depth, and then replaced. Since the displacement of the rod is a large fraction of the volume of the tube, any water which has entered during the reading is lifted above the equilibrium level when the rod is replaced, and escape of this water washes the unprotected exit clear of silt.

5. *Pits.*—The Cotton Research Board decided to install special Pits at the Giza farm to meet some of the criticisms of the usual tube-well. A section of one of these is given in fig. 2. The tubes were forced horizontally by a jack through holes in flanges bedded in the concrete sides; thus the soil above their points was not disturbed, and leakage down the side of one tube could not affect it or its neighbours, avoiding a definite risk in the usual grouping of 1-, 2- and 3-metre tube-wells together. Six such pits were installed, whose locations are shown on the map (fig. 12, p. 350). Unfortunately three of them found impermeable localities and were not very interesting, but a remarkable chance led to the placing of two of them in typical permeable and impermeable sites respectively, although they were only 15 m. apart. The data obtained from the reading of water-levels in these large open pits form the backbone of our present account.

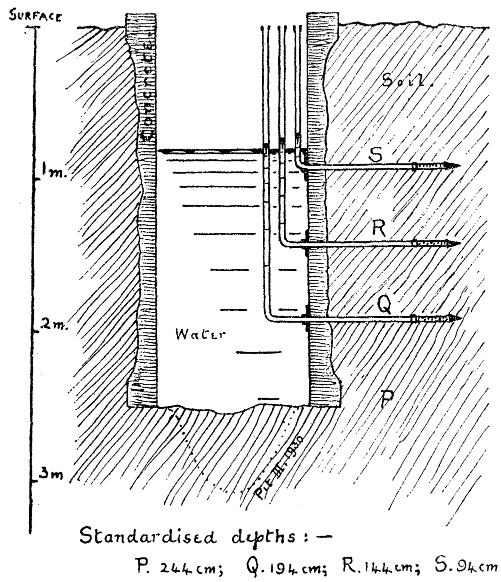

Fig. 2.—Section of a Pit, with its lateral wells.

The tube-well readings made concurrently with the actual pit readings are moderately interesting. They show the same phenomena as the simple grouped tube-wells had shown, including choking of the gauze ends. Such differences as exist between one well and another in the same pit are usually the simple consequence of the direction in which the soil water is moving; irrigation lifts the top tube-well first, while infiltration first lifts the deepest one (fig. 3, p. 344, Pits III and IV). Pit XVI in the same fig. 3 shows more discrepancy, the access of two waves of incoming water being much retarded in the deepest well, though the well above it and the much deeper pit itself move normally together; also, the uppermost well seems to be situated in a still more accessible layer of soil, so that it reaches all levels about a day sooner than the pit. Pit XVII is the most anomalous (fig. 3, also); at a season when the free water-table on the farm is falling steadily, as shown by Pit III, a very slow rise of water takes place in the floor of Pit XVII, which is evidently nearly impermeable. But the lowest tube-well in this pit, although it rises in the same way as the pit itself, and only a little less slowly, is nearly a free well so far as the effect of a canal at 120 m. distance is concerned. To the river it is an almost impermeable backwater, to the canal it is nearly free.

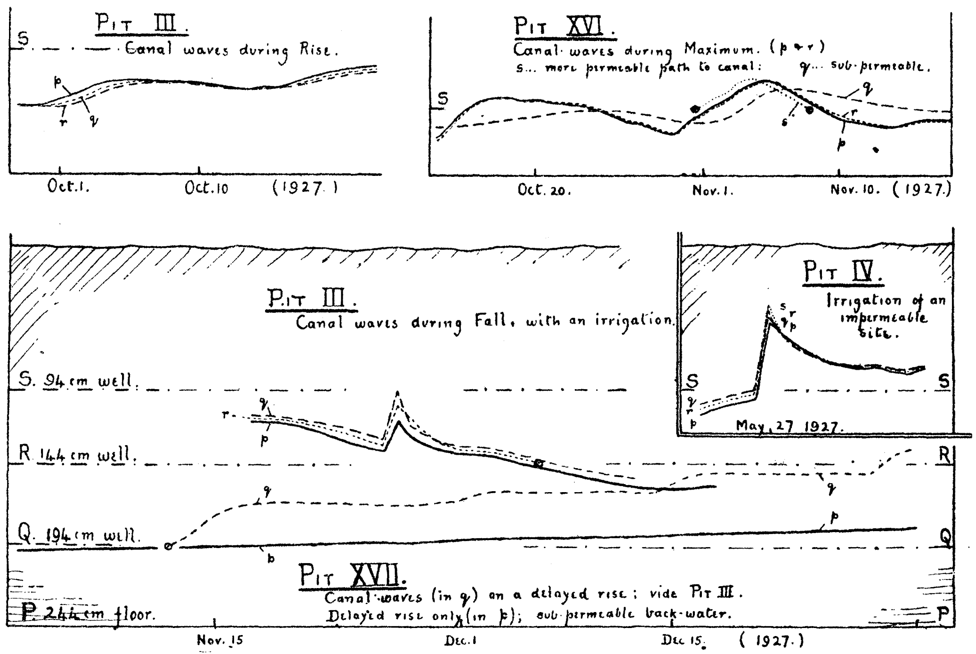

FIG. 3.—Pits and their pit-wells.

All these methods involve some soil-disturbance, at least to the extent of putting superposed strata into communication; geophysical methods might avoid this weakness. Additional information could be obtained if the changes of soil-water-content at levels above that of the actual water-table could be read off; we are trying to utilise an electrical capacity method for this purpose. For the present it must suffice that the tube-wells and the concrete pits give identical results, and that plain bore-holes also agree with the more permanent installations.

A.5. *Water-Table Differences within One Quarter-Acre.*

A pair of small plots, which have been cultivated as a separate unit since 1923, will serve to illustrate the variety of water-table conditions which can exist side by side, before we attempt the more general account of the whole farm.

The accidental circumstance that this area contains two of the Pits has focussed our attention upon it, but it will be seen when we come to examine fig. 28, p. 362, that there must be many similar areas within our 70 acres.

The quarter-acre is mapped separately in fig. 4, with a frame of reference whereby it can be located on the map of fig. 12, p. 350. Pit III is our standard of reference for the free-water tables of the farm, and "Well No. 1" of 1913 was equally free, its former site having been only 15 m. south-east of the present Pit. The water-movements in Pit III are presented in figs. 15 to 23 (pp. 351–356).

But although the other Pit, IV, is only 15 m. north of III, its movements are almost completely independent, as depicted in fig. 26, p. 361, being influenced solely by surface irrigations except for a slight seepage rise when the free water-tables are at their maximum.

Diagonally between these two pits runs a boundary shown on fig. 4, p. 345, which was located (fig. 28, p. 362) during the high well-maximum of 1929, when the south-east corner was soaked with infiltration water, while the north-west corner was dry and dusty ; obviously there is a soil-structure difference.

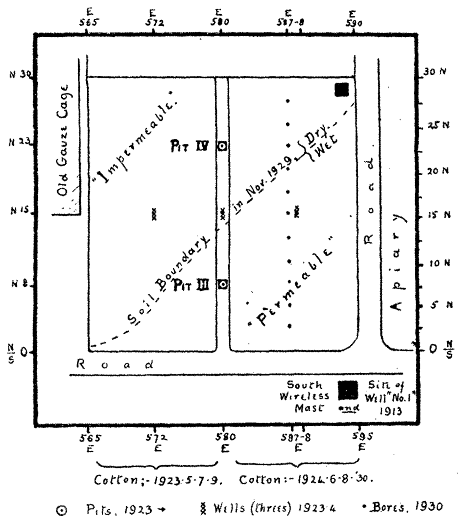

FIG. 4.—Map of one quarter-acre.

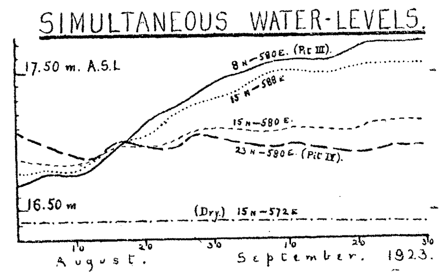

FIG. 5.

Some data smoothed from those taken by the original designers of the Pits in 1923 during the flood-rise of the free water-tables are shown in fig. 5. The difference between Pits III and IV is evident. The group of three tube-wells midway between the two pits is much more like Pit IV ; evidently the point of the deepest well at 2 m. does not penetrate the impermeable separating stratum. The western group (15*n*–572*e*) is even more isolated, for it remains completely dry at 220 cm. below the soil surface ; the cotton crop growing on this western half is transpiring enough water to prevent the irrigation water from raising the water-table above this level. Lastly we have the eastern group of tube-wells at 15*n*–580*e*, which approximate to Pit III and its free water-table ; but it may be owing to the less depth of the tube-well that the resemblance is imperfect, there being a gradient from tube-well down to pit at low water, which is reversed at the well-maximum ; the secondary undulations too are not entirely alike.

So far, the records of 1923 indicate the existence of an impermeable stratum dipping north-west, with its strike near the dotted line indicated in 1929. In 1930 the area was explored with a stratometer $1\frac{1}{2}$ m. in length, and this inference was confirmed. Another set of stratometer bores was then made to $3\frac{1}{2}$ m. depth, along the line 587*e*, with the results depicted in fig. 6. In the companion diagram, fig. 7, the variations of the water-table are not even spread over a quarter-acre but are confined to a single line which is only the length of a cricket pitch.

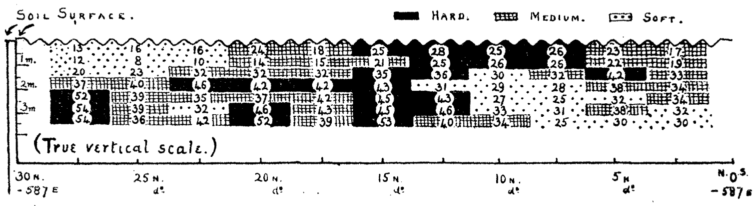

Fig. 6.—Stratometry.

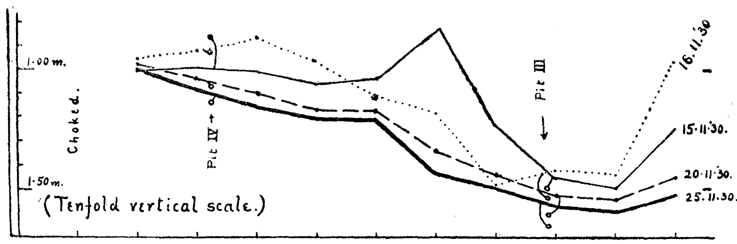

Fig. 7.—Water-tables (in the $3\frac{1}{2}$ m. stratometer bores).

In fig. 6 the vertical scale is true, and the numbers denote the number of constant impact blows required to drive the stratometer point through each $\frac{1}{2}$ m. at 11 localities. The side-resistance of such a long stratometer rod is appreciable at the greater depths, so in order to depict the three classes of hard, medium, and soft soil, we have used a sliding scale which increases by four blows per $\frac{1}{2}$ m. from 16, 20, . . . 36, 40, for the "soft soil," and by five blows per $\frac{1}{2}$ m. from 20, 25 . . . 45, 50 for the "hard soil"; intermediate numbers of blows at each level are denoted "medium." The sloping hard stratum, presumably impermeable, is clearly present. There is further an interesting anomaly, in that the superficial layers of the "permeable" area are impermeable, while those of the "impermeable" area are soft and permeable, so that one bore-hole in it was choked by falling silt; this may easily happen, and illustrates how little importance can be attached to surface indications, a point which is further emphasised by the physical analysis made when the Pits were dug (fig. 8).

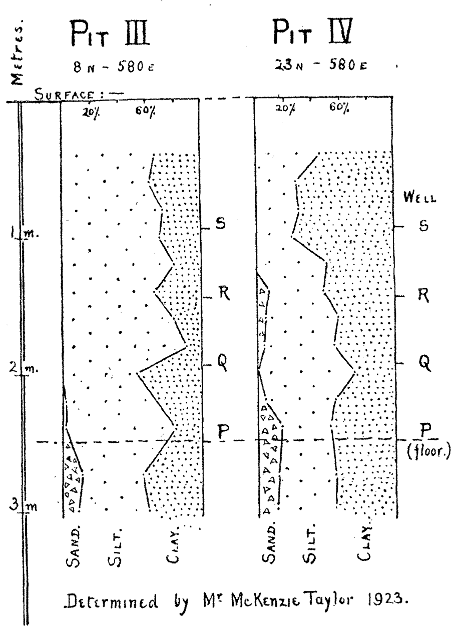

Fig. 8.

Fig. 7, above, shows the movements of the water-table in these same bore-holes as the soil dried up after an irrigation which had preceded the stratometer readings. On 15th November, 1930, the influence of the hard soil in checking drainage is very clear the water at the south end standing nearly $\frac{1}{2}$ m. lower than on the north side of the hard stratum. By 20th and 25th November, 1930, there had been some fall in the middle of the plot, which is explicable if we remember that these bore-holes were $3\frac{1}{2}$ m. deep and must, therefore, have penetrated nearly into the permeable layers. At the north end the hard layer was not reached by the stratometer, and the fall of water-table is less than 10 cm., due probably to evaporation only. Evidently the impermeable layer turns upward again at no great distance, thus forming a saucer within which this isolated water-table is perched.

The complications are not exhausted, for the thin dotted line shows that on 16th November, 1930, there had been a fresh access of water, not applied to the plot itself, but coming from irrigation of the adjacent field on the south side. It did not affect the borehole at $15n$, which continued to fall normally, but it raised the one at $2\frac{1}{2}n$ by nearly $\frac{1}{2}$ m., and found its way through some underground channel to $20n$ as well. This water was evidently moving near the surface, since the 3-m. Pits III and IV (also plotted on the diagram) continued to fall without any disturbance; its channel may have well been the filled-in trenches dug for the earthing of the wireless station in 1929, one of them crossing this line of bores near $20n$, at an acute angle, which might well allow it to affect three bores at once; this is certainly an abnormal variation of structure for cultivated land, but it illustrates the sensitivity of the water-table.

The preceding details should serve to emphasise the caution which must be observed in generalising about the underground water of any locality unless observations have been made at a number of points, and continued over a number of days. Even then it is desirable to be able to refer them to base-line observations covering at least a year in two or three permanent and representative wells or pits, as we are fortunately able to do.

B.1. *The Free Water-Tables and the River.*

We have described the location, arrangement, and general behaviour of Pit III, and stated that we regard it as our standard of reference for the free-water-tables of the farm. It is so regarded because its movements show a minimum of disturbance by subsidiary causes, and a maximum (for our farm) of effects due to the great annual water-table wave which is generated by the Nile flood, and which was extensively studied by FERRAR.

Although it is less than a kilometre from the river, and in such free communication with the river bed that alterations of river level are transmitted to it very rapidly (see Sept.-Oct., 1923, -24, and -26 in figs. 15, 16, and 18, pp. 351–353, etc.) yet it does not behave as a true free-water-table should do, in a "sakia" for example. FERRAR and AUDEBEAU have shown that the wave coming from the river bed through the sakia gravels cuts the steadily falling curve from last year's wave quite suddenly, and that although the pressure changes can be transmitted rapidly, the movement of the bulk of water occurs later than one might expect, so that the rise of a sakia pit on the Pyramids Road at 4 km. from the river is shown by FERRAR to take place fully two months after the river rise. This figure has to be reconciled with the fact that the wave affects similar pits in the lower Delta equally soon, at distances much greater ; this can be done by remembering that the water leaving the river flows down the valley (which slopes 1 m. in 13 km.) as well as falling outward, so that the water reaching a well situated 4 km. from the river may have traversed 40 km. underground from upstream. The water-paths would look like feathers if mapped.

Contrary to our original impression, however, there is little sign of this in Pit III. The river levels at Giza are within the " pond " of water held up by the Delta Barrage, and indicated by the readings of Roda Gauge, opposite Giza village. The pond extends about 40 km. further upstream, above which the true river levels are recorded on El Leisi gauge, and we are unable to find any movements of Pit III which conform to the latter rather than the former with certainty ; the nearest indication is in January, 1931 (fig. 23, p. 356).

In general, Pit III shows an annual wave of an amplitude corresponding to a much greater distance from the river, and yet a suddenness of response appropriate to a site even closer to the river ; an arrival at a maximum which is as late as if the river were much further off, and yet an absence of the pronounced fall in level during summer which is characteristic of the true sakia pits. Later on we shall be able to trace the excesses of water in Pit III to leakage from certain canals, which only leaves us with the problem of its small amplitude, and this can be accounted for if it is on a line of very easy drainage in and out of the river, and also in and out of the easy water-way which FERRAR has already demonstrated to exist midway between our farm and the desert edge at the Pyramids ; that such an easy drainage-line exists we shall presently show.

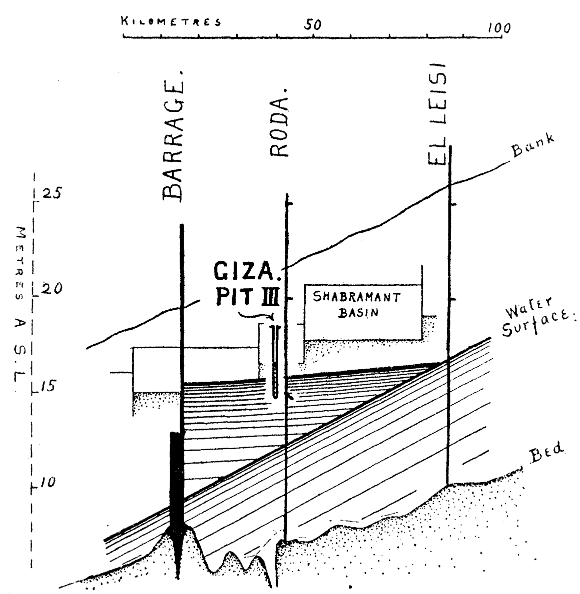

FIG. 9.—Longitudinal section of the Nile valley during low stage.

Following this general description we may examine the lie of the land more closely, beginning with a longitudinal section in fig. 9, p. 348. This shows the situation during the summer months, when the Delta Barrage is holding back a pond of water nearly to El Leisi gauge ; in the absence of the Barrage—*e.g.*, when it is open during the January work on canal-clearance—the true water-surface would be as indicated. The position and levels of Pit III are shown, while the thin lines behind it are drawn to show the positions of the last three " basins " of the Upper Egypt basin system, none of which except the Shabramant Basin, could affect our farm, though any of the basins upstream of Shabramant might do so.

The timing of the filling of Shabramant Basin is shown in figs. 15, 19 and 21 (pp. 351–5), as well as for the very abnormal year 1913 in fig. 14. We need not elaborate a description of the basins, since we have satisfied ourselves from the data here depicted that no direct effect can be traced from them to Pit III, other than their important contribution to the general flow of underground water roughly parallel to the river. This flow is much augmented by their drainage (from water-surfaces well above country-level) (fig. 9) from the time when they are filled (as soon as the flood is sufficiently high), until well on into the following spring.

The importance of this general effect is best shown in 1913 (fig. 14, p. 351), when the behaviour of " Well A," the equivalent of Pit III at that time, is clearly quite unrelated to that of the river during October and November ; it is regrettable that these unique observations were not carried on a month longer ; Well A was a 6-m. tube-well, at $5n$–$510e$, scarcely distinguishable in its movements from Well No. 1 (already mentioned in fig. 4, p. 345) which links us up to Pit III.

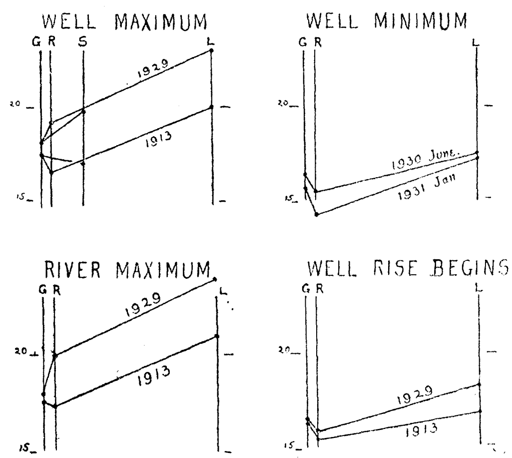

Fig. 10.—Longitudinal section of Nile valley Simultaneous levels at Giza Pit III (G), Roda (R), El Leisi (L) and Shabramant Basin (S) in the high flood year 1929, and low flood year 1913.

In fig. 10, we have drawn four skeletons of fig. 9, showing only the water-levels at certain times, and using the abnormal flood of 1913 to emphasise the fact already noted, that Pit III (or Well A) does not simply follow the river movements. In the invaluable 1913 data we see that the maximum of the water-table was higher than the level of Shabramant Basin at that time, and higher than the river itself.

The general relation between the river and the free water-table of our farm is demonstrated in fig. 24, p. 356, as an eight-year mean for Roda Gauge and for Pit III. The interesting portion for the latter during January is imperfect, as it was not until 1930 that the pit was deepened sufficiently to show water all the year round ; the first complete record is available in fig. 23, for 1931. The failure of the pit to follow the river during summer low-stage is noticeable, and can be contrasted with the immediate response to river changes on October 10th, when the emptying of the basins lifts the Nile gauges against the falling flood. Another rapid response is shown on December 20th, when the canal-clearance starts, but less importance should be attached to this, since it necessarily synchronises with the emptying of certain canals which affect the farm, to be discussed later; indeed, the effect of their first re-filling can be seen in this fig. 24 as a crest and trough in the Pit III curve on February 10th and 20th. In fig. 27, p. 361, the partial breakdown of the general resemblance during the floods of particular years is self-evident.

It may assist the reader to visualise the situation if temporary reference is made at this stage to fig. 39, p. 370, which is a transverse section of the valley corresponding to the vertical section of fig. 9. The topographic map of the farm in fig. 11, together with figs. 12 and 13, can also be consulted.

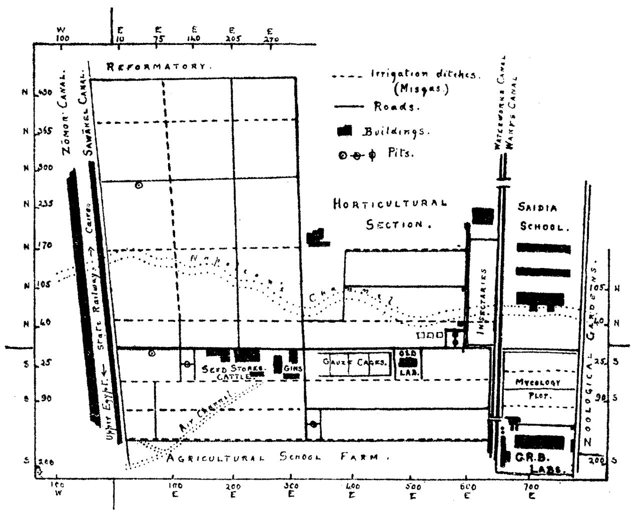

FIG. 11.—Map of farm :—topographical.

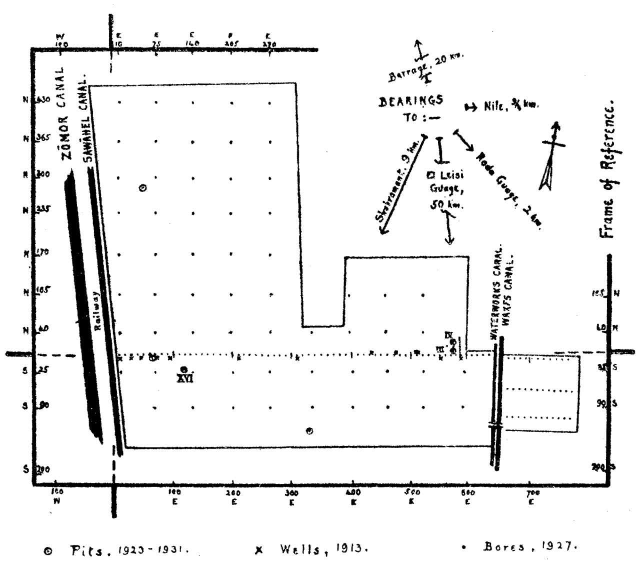

FIG. 12.—Map of farm :—observation points.

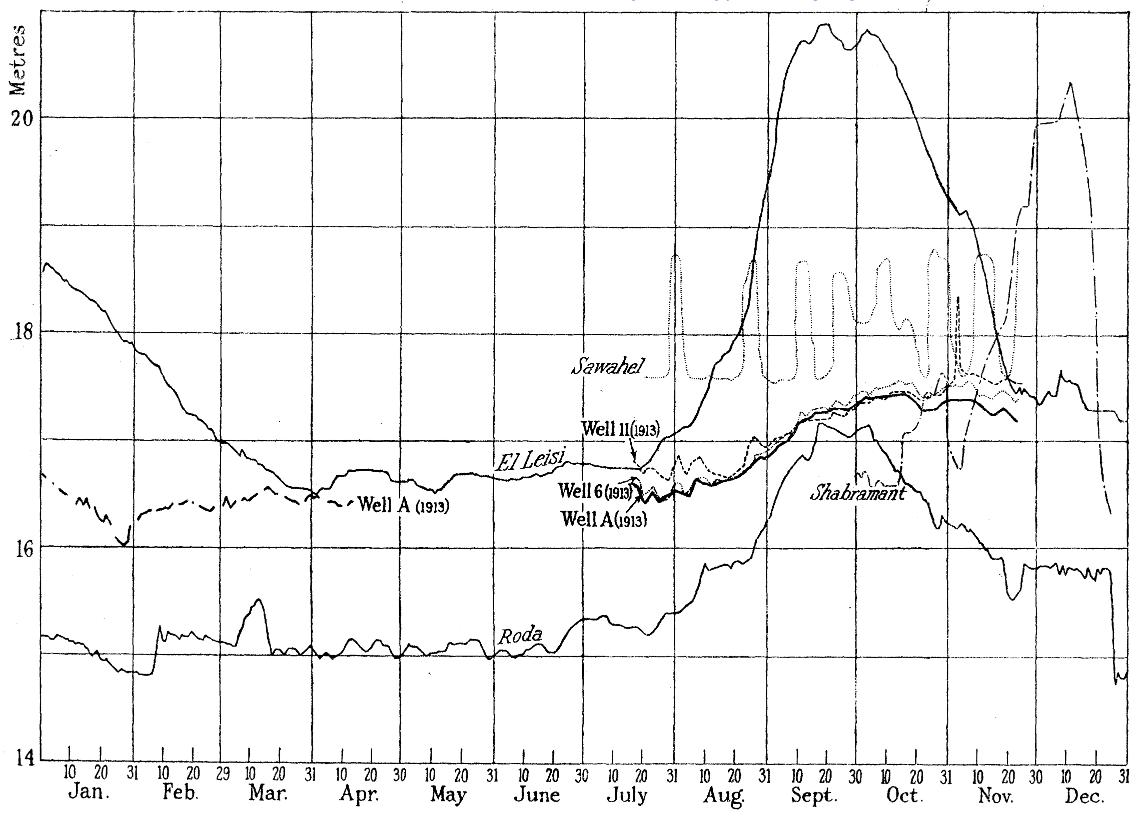

FIG. 14.—Diagram of Nile Gauges at Roda and El Leisi for the year 1913. With readings of Wells A. 6 and 11; Sawahel Canal levels approximately, Shabramant basin levels correctly.

Well A—6 m. at 0·510 E.
Well 6—3 m. at 0·310 E.
Well 11—3 m. at 0· 30 E.

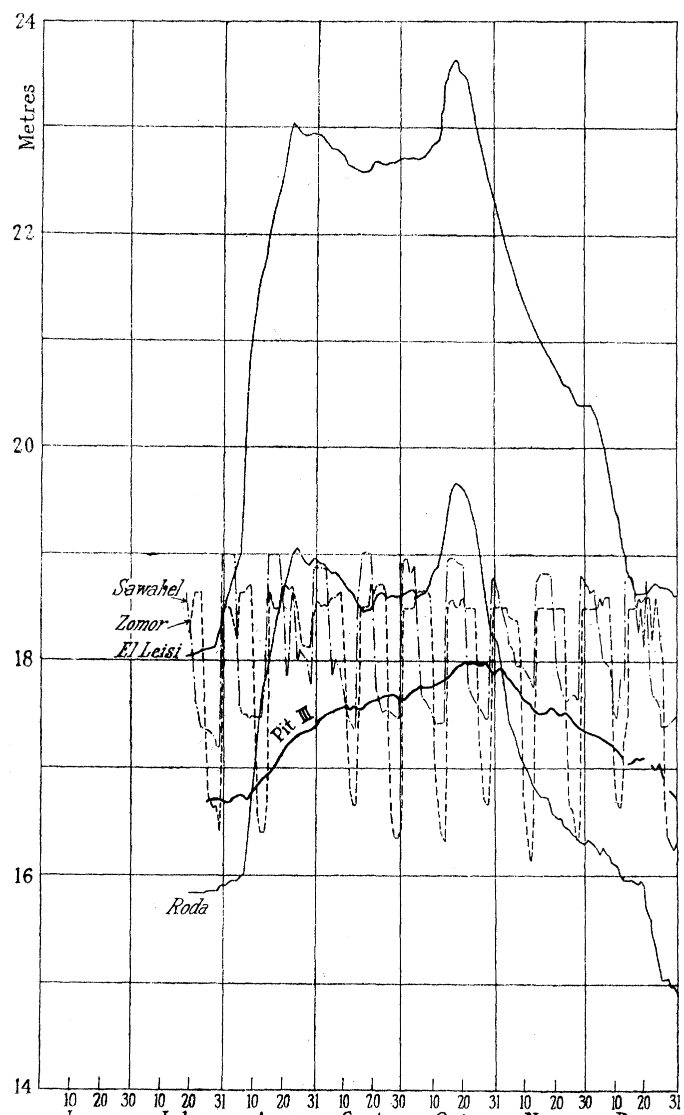

FIG. 15.—Diagram of Nile Gauges at Roda and El Leisi in the year 1923, with readings of Pit III and of Sawahel and Zomor Canals.

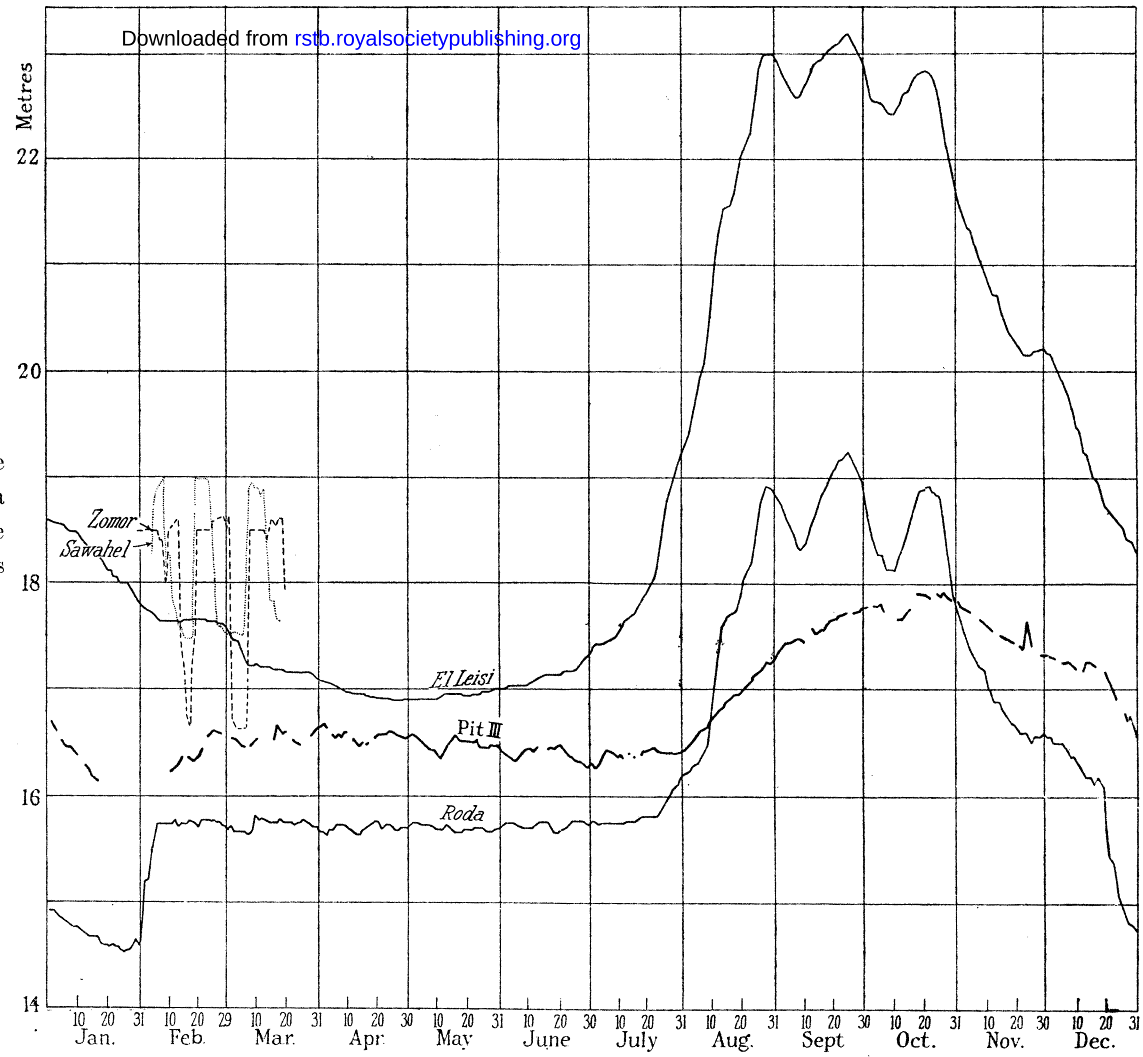

FIG. 16.—Diagrams of the Nile Gauges at Roda and El Leisi for the year 1924, with readings of Pit III.

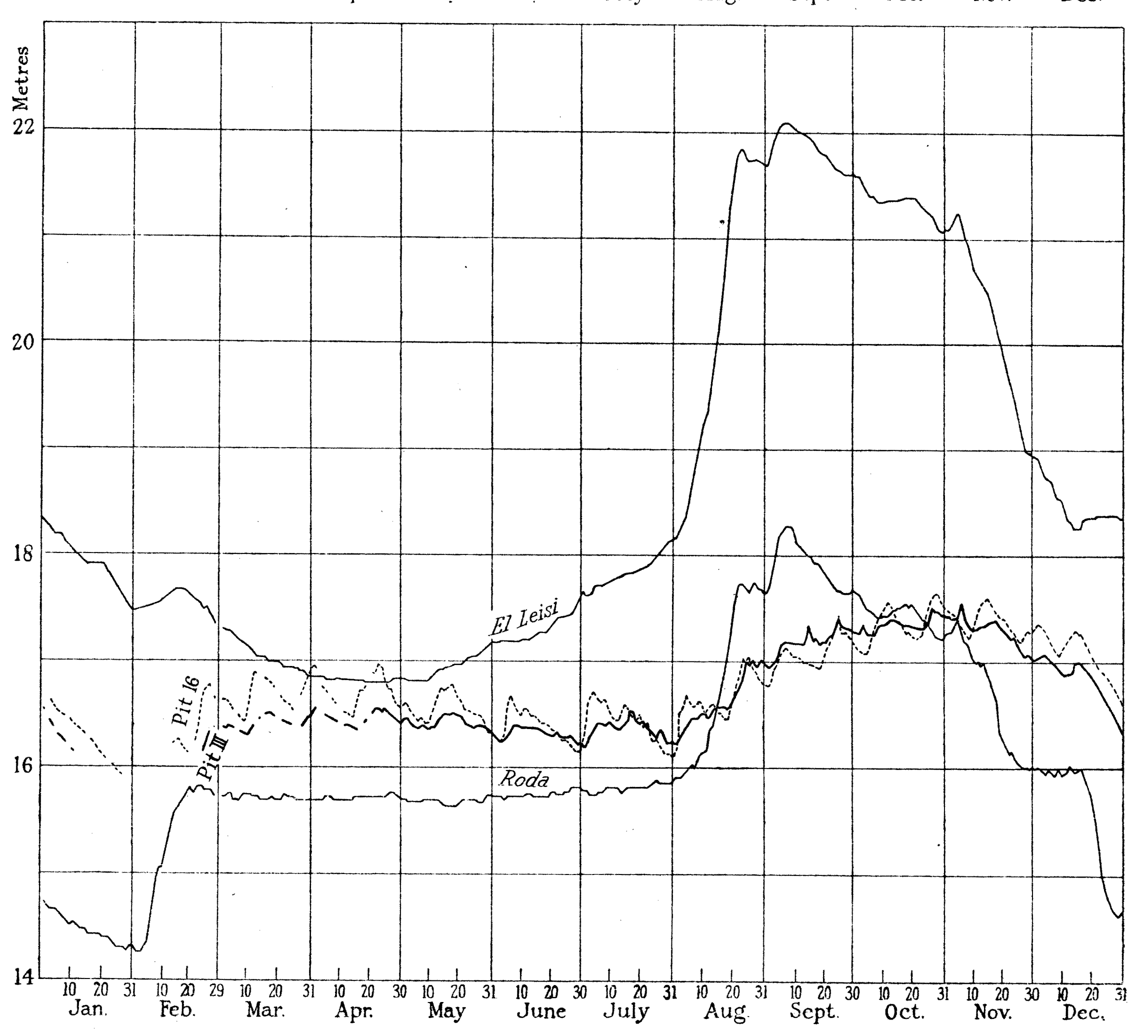

FIG. 17.—Diagrams of the Nile Gauges at Roda and El Leisi for the year 1925, with readings of Pits III and XVI.

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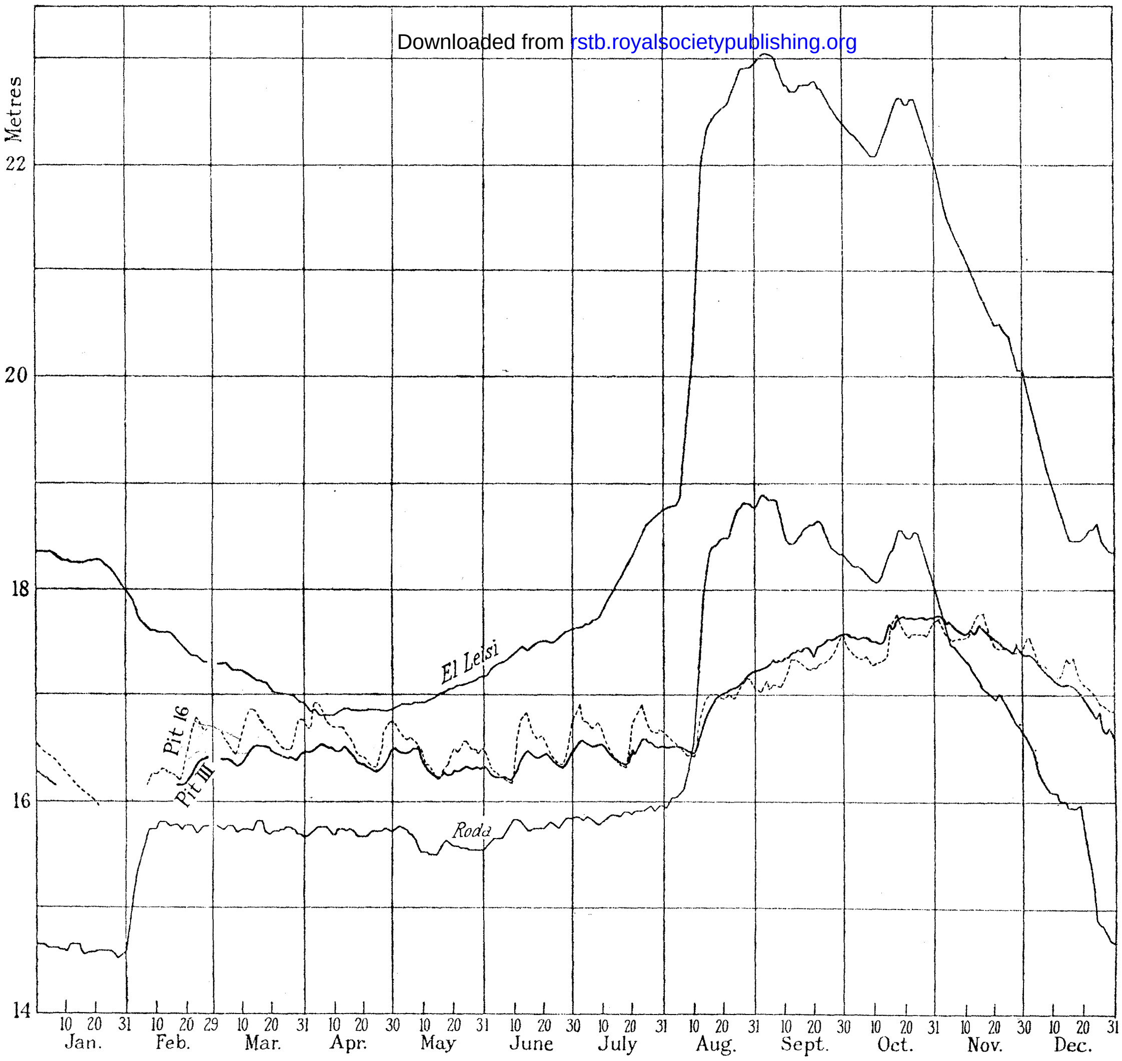

FIG. 18.—Diagrams of the Nile Gauges at Roda and El Leisi for the year 1926, with readings of Pits III and XVI.

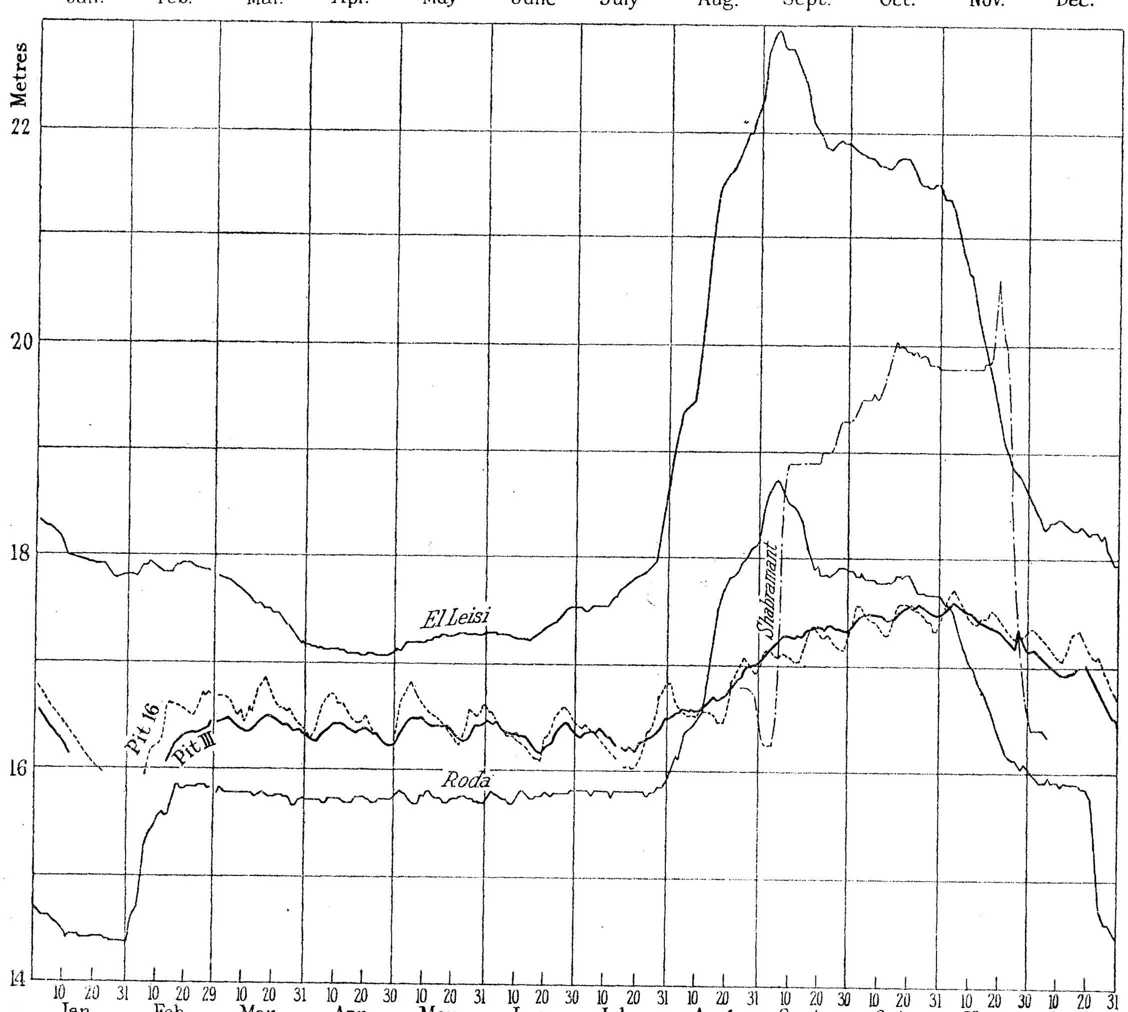

FIG. 19.—Diagrams of the Nile Gauges at Roda and El Leisi for the year 1927, with readings of Pits III and XVI.

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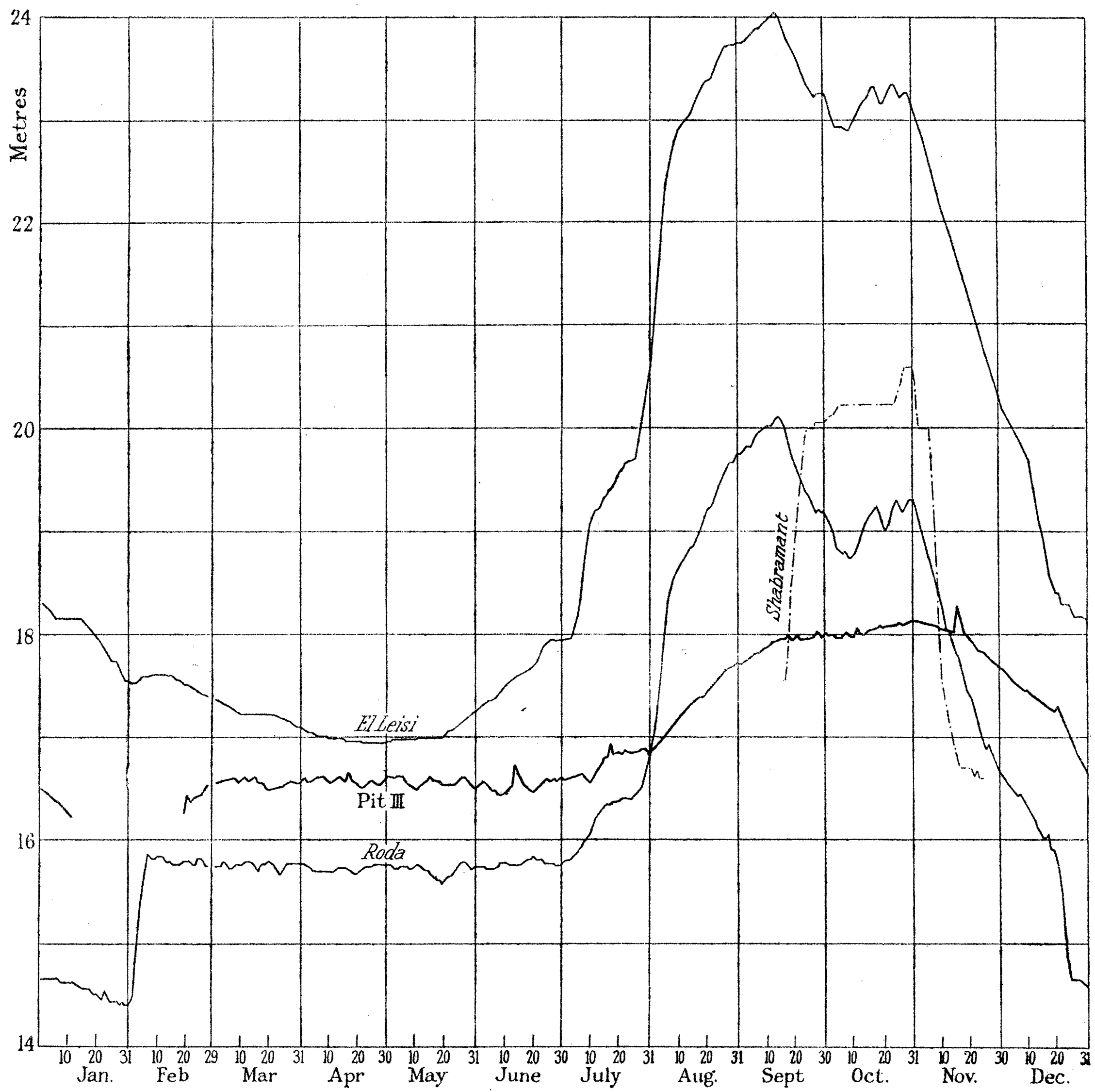

FIG. 20.—Diagrams of Nile Gauges at Roda and El Leisi for the year 1928, with readings of Pit III.

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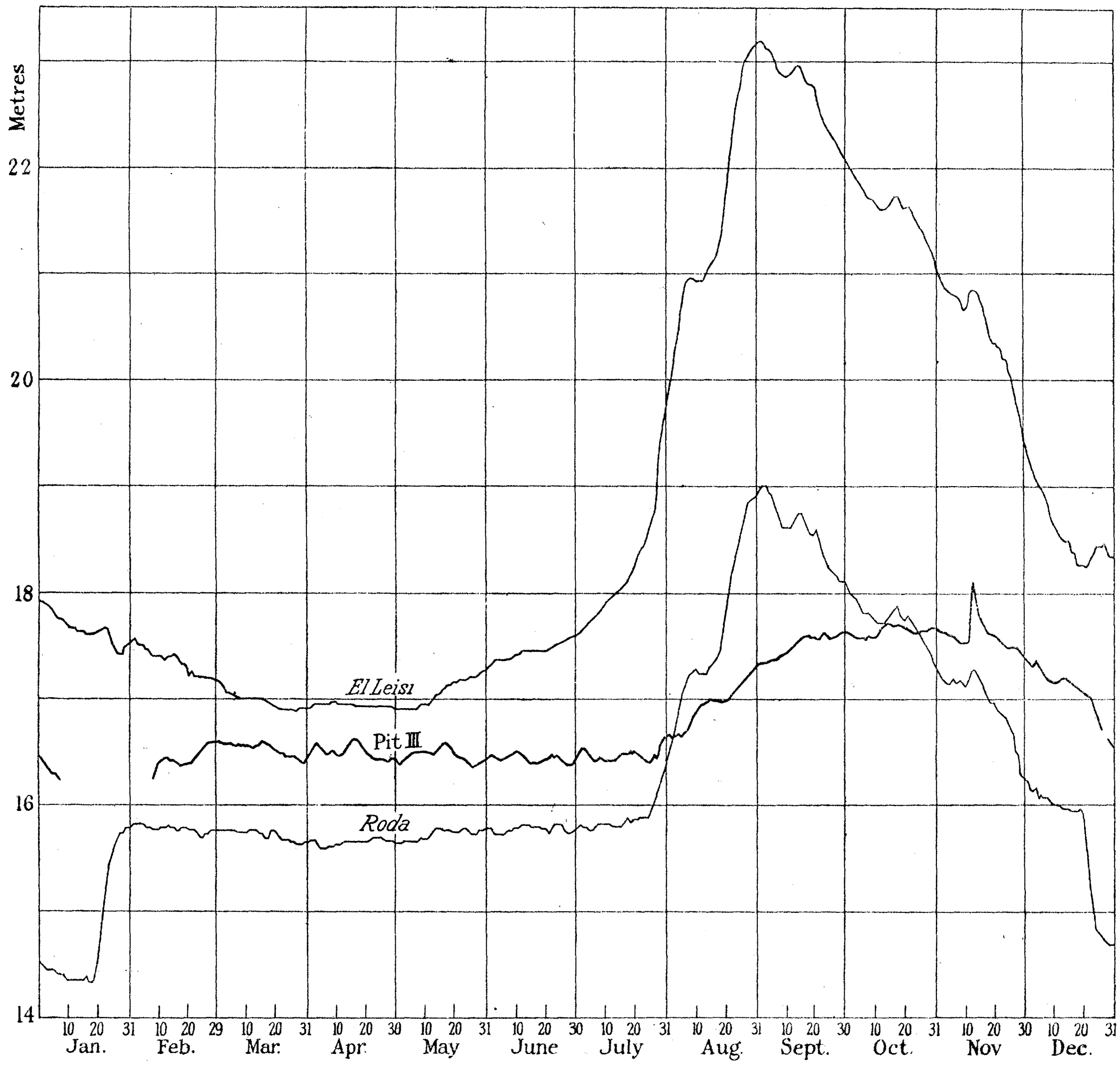

Fig. 21.—Diagrams of Nile Gauges at Roda and El Leisi for the year 1929, with readings of Pit III and Shabramant basin levels.

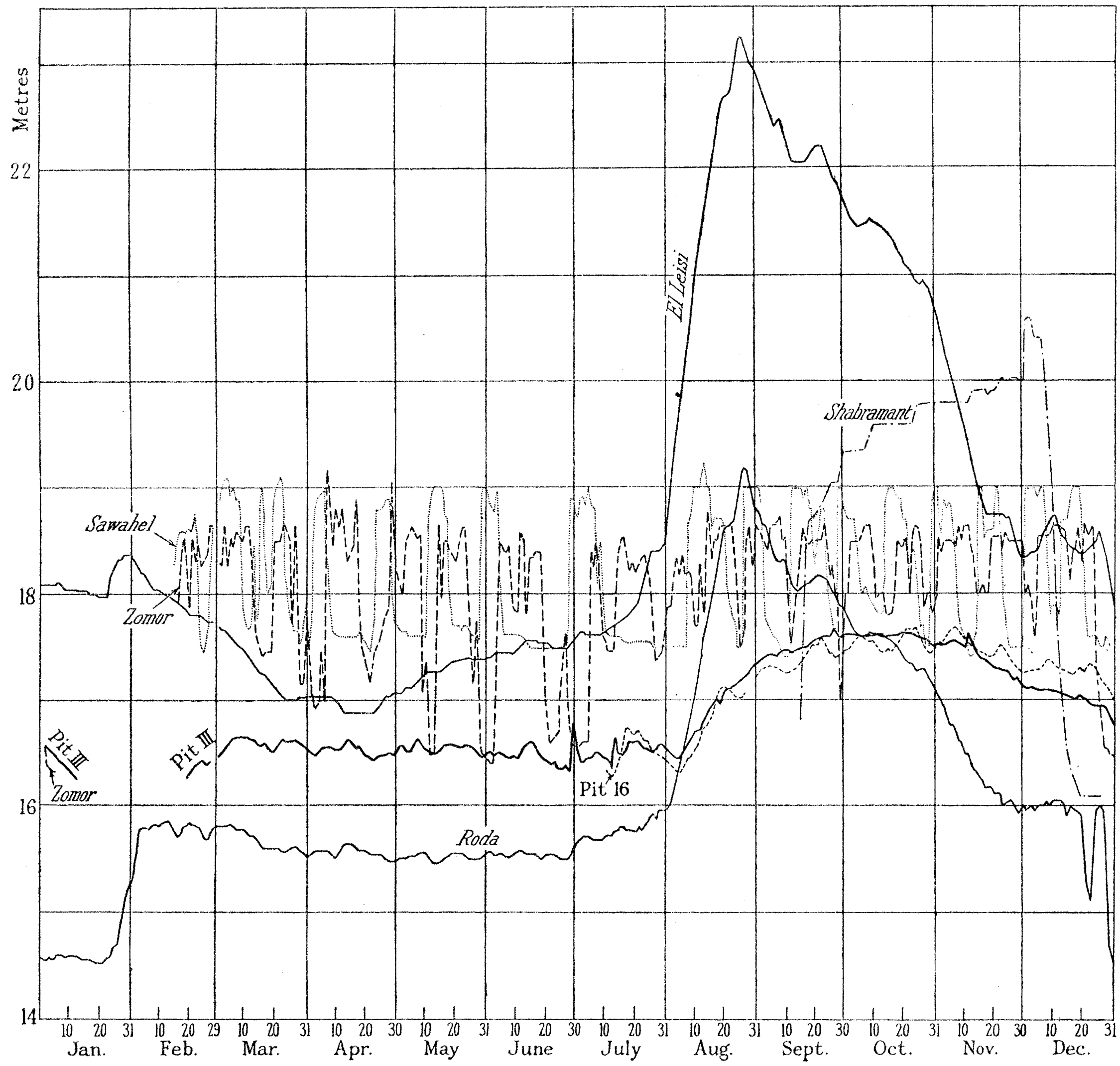

Fig. 22.—Diagram of Nile Gauges at Roda and El Leisi for the year 1930, with readings of Pits III and XVI, Sawahel Canal, Zomor Canal, and Shrabramant basin levels.

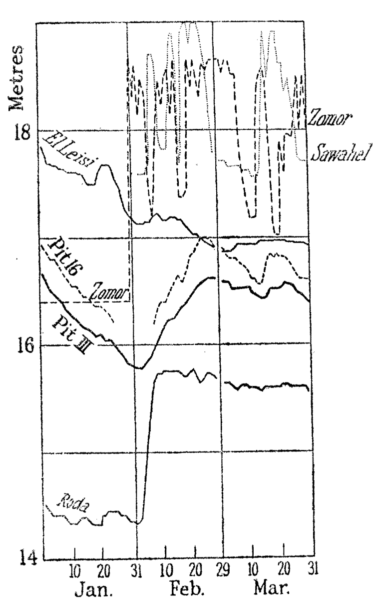

Fig. 23.—Diagram of Nile Gauges at Roda and El Leisi for the year 1931, with readings of Pits III and XVI, and Sawahel and Zomor Canal levels.

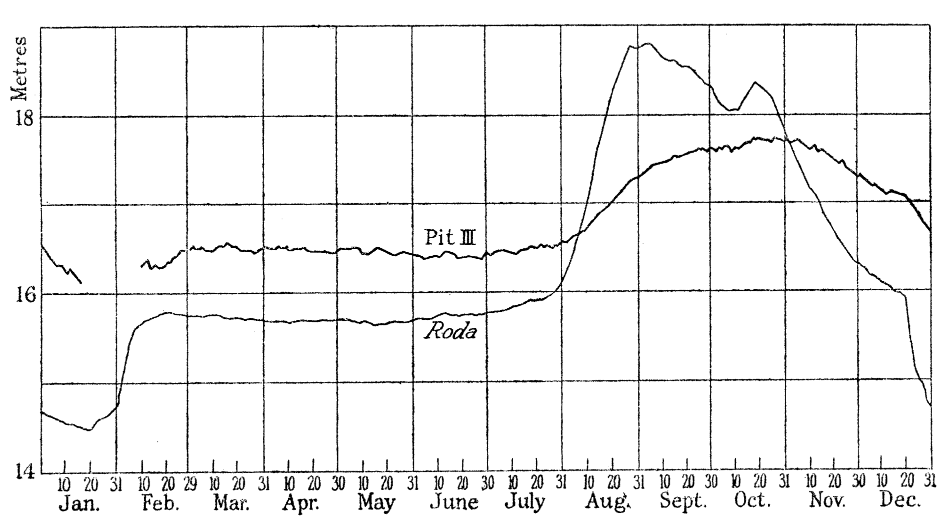

Fig. 24.—Diagram of Nile Gauge at Roda, eight years mean 1923–30, with readings of Pits III, also eight years mean 1923–30.

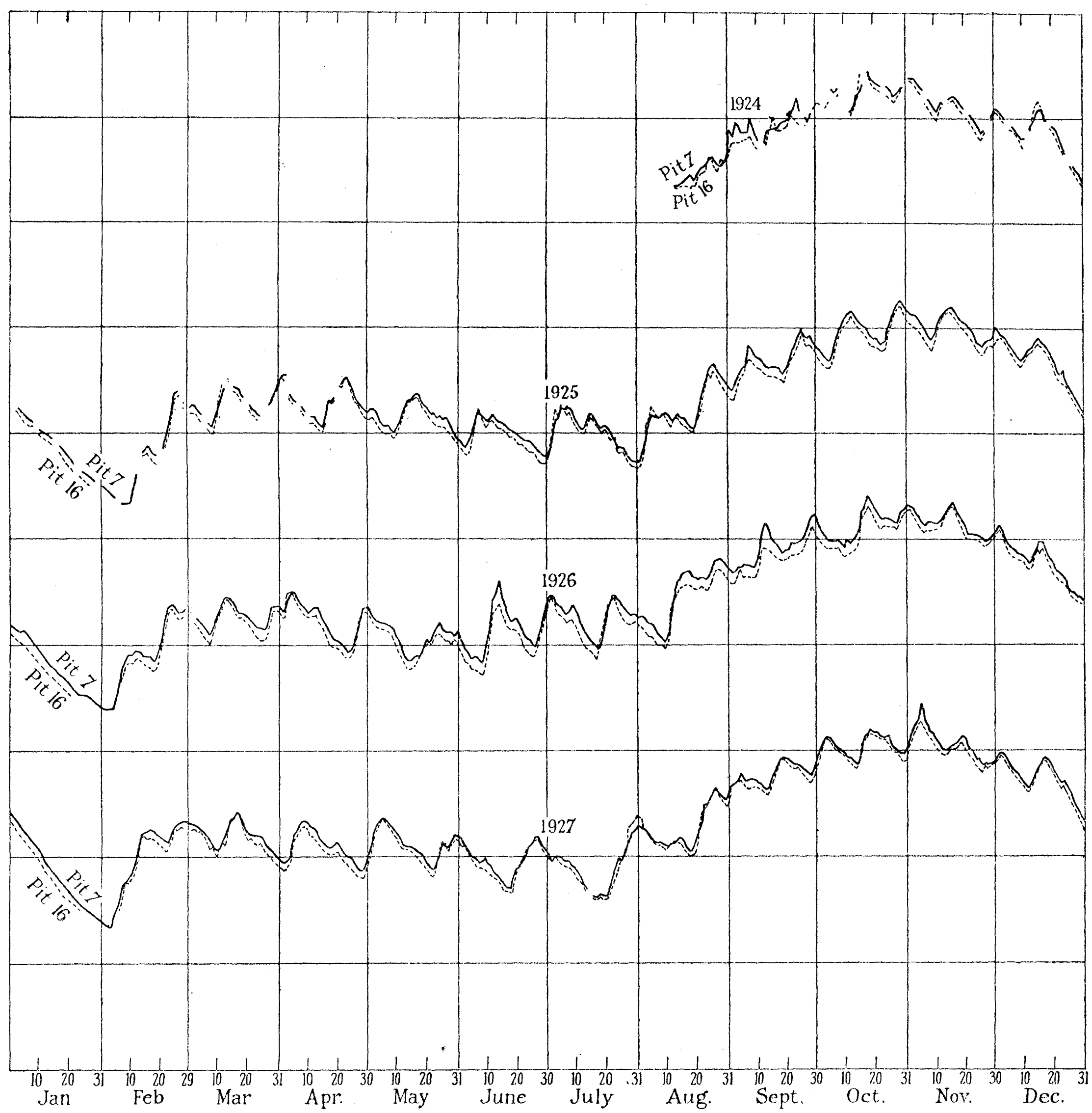

FIG. 25.—Two Western Pits, 1924 to 1927.

B.2. *The Effect of Some Canals.*

Consulting the map in fig. 12, it will be seen that four canals adjoin the farm. The two small ones on the east side can be dismissed at once; neither in 1913 nor later has any trace of leakage from them been detected on the records. The Zomor and Sawahel on the west side are very different, and from their discharges (about 750,000 cm. per day each) they both contribute to some of our water-tables. We shall presently estimate the amount of their contribution.

Two of the pits are situated within 100 m. of these canals at $275n$–$50e$, and at $25s$–$120e$ (Pit XVI). The latter will be mentioned so frequently that it will be convenient to use its number for reference.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY B BIOLOGICAL SCIENCES

These two canals are usually filled at the same time, being worked on the same 21-day summer rotation. Details of their levels in the vicinity of the farm are indicated for the Sawahel in 1913 in fig. 14, and shown in detail for both in figs. 15, p. 351, 30 and 31, pp. 363, 365, from data provided by the Irrigation Department. From these graphs it will be seen that the effect of canal rotations is to cause them to run alternately full and partly or wholly empty, while only occasionally is there any marked difference between them. During flood-season their minimum head is rarely lower than the water in Pit III, while during low-stage their minimum level is lower. They are closed during January for clearance, as shown in figs. 22–23, p. 356. Thus the regime of these canals is such as might generate a wave of underground water with a 21-day period if there were any appreciable leakage from them. It may be noted that in irrigation estimates such un-lined canals are usually reckoned to lose 10 per cent. of their discharge by such leakage. We proceed to examine our records for this Canal-wave Effect.

The records of the two western pits are superposed for three years and a half in fig. 25, p. 357. They are obviously waved, these waves being superposed on a curve which broadly resembles that of Pit III. Also the curves are interesting as a check on the exactitude of the observations, since the most trivial fluctuations are shown by both. By inspection of such fluctuations it can be seen that the waves tend to reach Pit XVI rather sooner than the other pit, though the latter is slightly nearer the canals; this might be correlated with the fact that in 1913 the senior author found an actual spring of water at 60*s*–0*e*, emerging from the Sawahel canal through a sand bed; water from this region would reach Pit XVI sooner. There is, however, a consistent difference in level at all times of the year, the northern pit standing higher than Pit XVI, which would indicate that the difference is due to permeability differences along the water-paths, such as have already been noted for the tube-wells of Pit XVI in fig. 3. This difference in level is not shown by fig. 25, p. 357, which is plotted with the curves closely superposed to emphasise their similarity.

We can thus take Pit XVI as being typical of the free water-table conditions on the west side of the farm, subject to later confirmation by bore-hole data. Its movements are plotted concurrently with those of Pit III in figs. 17–19, pp. 352–3, where it is instantly obvious that its waves are transmitted eastward over $\frac{1}{2}$ km., generating similar waves of lessened amplitude (about one-third) in Pit III. At minimum of this canal-wave effect there is a gradient from west to east in March, and from east to west in September. But in spite of the lessened amplitude of the Pit III waves in the latter month, they are still visible; with the gradient running from Pit III towards their origin, their formation in Pit III can only be due to obstruction of the flow to the west; we might describe the canal waves of Pit III as being positive in March and negative in September. The question of these gradients will be more fully described later.

Meanwhile we have begged the question in describing them as canal-waves, but reference to figs. 22 and 23, p. 356, as also to 14 and 15, will justify the title. The resumption of the observations on Pit XVI, using a continuous recorder, in July, 1930 (fig. 22), was particularly fortunate since it happened to coincide with one of the rare occasions when the two canals were notably different in their movements; the nearer Sawahel remained half empty, while the Zomor (on the far side of the railway embankment) was filled up; the resulting wave shows that the Zomor is as important as the Sawahel in generating these waves, and a comparison of the wave-form in Pits III and XVI strongly suggests a conclusion substantiated by other evidence, namely, that Pit III is affected more by the Zomor than by the Sawahel, though the latter is dominant in Pit XVI; similar episodes also occur in February and in March, 1931 (fig. 23).

We have described these western pits as being typical of the free water-table on this side of the farm. Again we have to remember that soil-structure variations can modify the form of the wave, or destroy it. In fig. 35, p. 369, is plotted the result of observing a line of bore holes which ran north and south at an acute angle to the canal; five readings are given for each bore-hole during one filling and emptying of the canals; the holes were about 170 cm. deep. The holes at 25*s*, 300*n*, and 430*n*, are completely isolated from the canal, although the first one is only 10 m. away from it. The remaining five all rise together and fall together, broadly speaking, but again there are detail differences in that the one at 235*n* takes half a day longer to reach the maximum, while the amplitude of the wave at 170*n* is only half of the amplitude at 365*n*. With this reservation we shall continue to regard Pit XVI as a fairly true representative.

The amplitude of the canal waves is shown in fig. 36, p. 369, by joining together the wave crests in both pits, and also the wave troughs; the space enclosed between the two lines has been blacked. This shows that the amplitude at Pit III is about one-third of that at Pit XVI, $\frac{1}{2}$ km. away. It also shows how the amplitude in both is reduced when the water-table rises, a necessary consequence of the reduced head of water; in fig. 22 it can be seen that the head of the Sawahel when full is rather more than 1 m. above the water-table in the pits during October, that of the Zomor being rather less than 1 m.; in June the Sawahel head is $2\frac{1}{2}$ m., and that of the Zomor more than 2 m.

The thickness of the layer of water represented by the blackened areas is of course much less than this. The waves are water-table waves, not actual water, and we may conservatively assume the ratio of height to be 4 : 1, following WILLCOCKS and CRAIG, so that the summer amplitude of about 50 cm. in Pit XVI and of 16 cm. in Pit III corresponds to 12 cm. and 4 cm. of actual water respectively. Further, the waves are roughly triangular, reducing these amounts to one-half, or 6 cm. and 2 cm. of water respectively. Thus, the leakage from the canals produces a sur-elevation of the water on our farm—in the permeable areas only—which corresponds to a wedge-shaped layer of water 6 cm. thick at 65 m. from the canals,* thinning down to 2 cm. thick after $\frac{1}{2}$ km. Disregarding details which the data do not warrant, it will suffice to assume that this layer of water is wedge-shaped, and extends for 1 km. from the canals before thinning

* Subsequent data from an old sakia-pit between the two canals show the summit of the wedge to be 10 cm. at zero distance.

out to zero thickness. Its mean thickness over this 1 km. will then be 3 cm., and there will be a similar 1 km. belt on the other side of the canal. But we shall show later (fig. 32, p. 367) that approximately half our farm consists of impermeable soil, and if the farm is a reasonably true sample of the district traversed by the canals, the water-loss from the canal on the other side can be disregarded in order to allow for this.

However, the true thickness of this water-layer, 1 km. wide, must be much more than 3 cm., since we have taken the wave-trough as its base, whereas the form of the waves in fig. 25, p. 357, shows that the wave has still a long way to fall when the next wave arrives. Reasoning on the basis of the lines sketched in fig. 41, p. 372, it seems quite conservative to assume that the true thickness of the water-layer is about 10 cm. instead of 3 cm., and the volume of such a layer is 100,000 cub. m. per sq. km.

The two canals discharge together 1,500,000 cub. m. per day, commanding about 250 sq. km. of cultivated land at its usual water-duty of 25 cub. m. per acre per day, which is 6,000 cub. m. per sq. km. per day. The canals are running about 330 days yearly, making a total supply of 2,000,000 cub. m. per sq. km. Out of this amount we have found 100,000 cub. m., or 5 per cent., of the total in the underground water of our farm. Since the conventional allowance of irrigation design is 10 per cent., as already stated, it is clear that our estimate of the amount is not excessive. More important from a general irrigation point of view is the fact that although these canal waves are most striking phenomena on our farm, and contribute notably to its water-table phenomena, yet their importance—as here assessed—is actually less on the Giza farm than in Egypt as a whole. Our inferences from our farm cannot therefore be regarded as exaggerations based on the accident of possessing abnormally leaky canals ; on the contrary, our canals seem rather better than usual.

The east–west gradient reversal already mentioned is brought out more clearly in fig. 37, p. 370, by joining wave-crests and wave-troughs as in fig. 36. The canals are seen to act as a source of water to Pit III when full, and even when empty until June. After June the minimum " canal-wave effect " curve shows that drainage is proceeding from east to west (Pit III to Pit XVI), flowing away from the river, presumably to the drainage line half-way to the Pyramids, formerly mentioned. This is somewhat unexpected.

The minimum positions of Pit XVI show a remarkable feature, depicted more fully in fig. 38, p. 370, in that the curve approximates much more closely than that of Pit III to a typical " sakia " curve as drawn by FERRAR or AUDEBEAU. In spite of the repeated accessions of water from the canals, the level at the trough of the canal-wave sinks steadily lower during summer, and is more suddenly intercepted by the flood-rise than in Pit III. Again the importance of the western drainage line is emphasised, in contradistinction to the backflow to the river on the east, which we should otherwise have assumed.

But if we examine, *e.g.*, fig. 27, p. 361, bearing this fact in mind, it will seem very likely that—at any rate in July—the source of the water in Pit III ought to lie

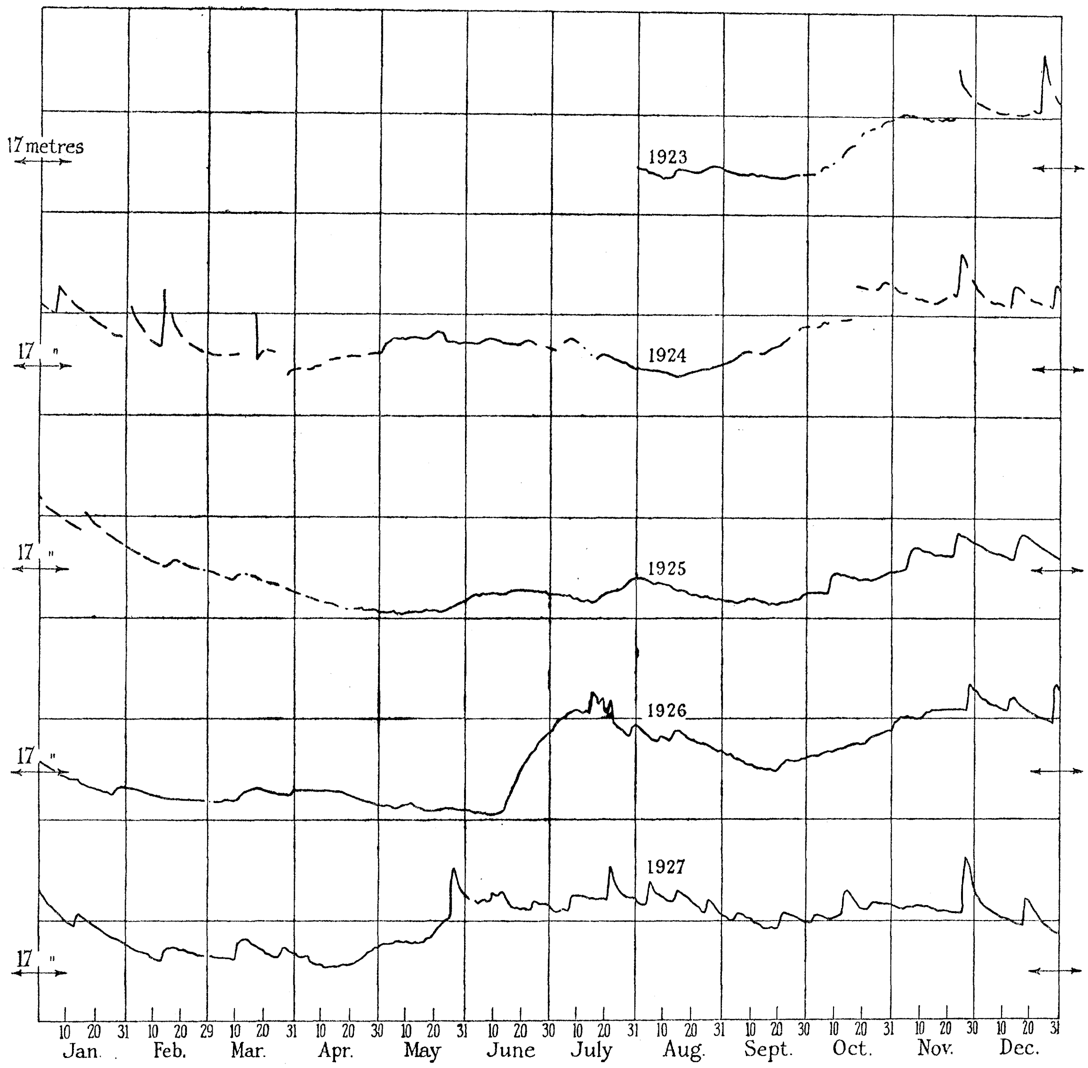

Fig. 26.—An isolated water-table, Pit IV, 1923 to 1927.

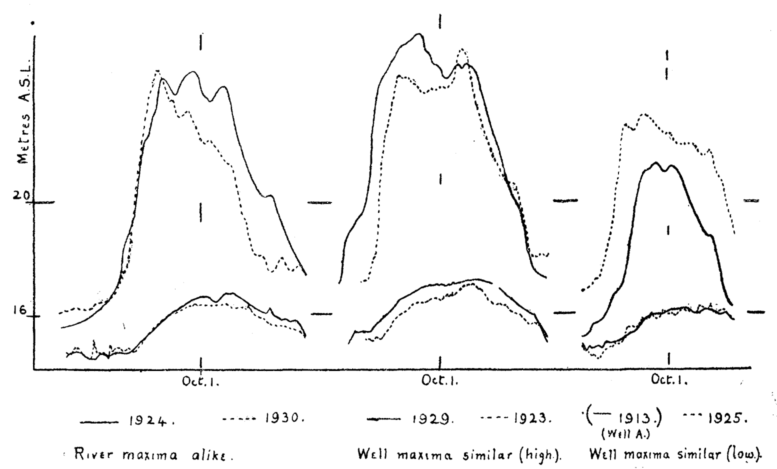

Fig. 27.—Nile floods and Water-tables (El Leisi Gauge), Pit III.

up-stream, about half-way to El Leisi gauge, in order to provide a driving head of water. This is an error, however, in that it neglects to take into account the water due to canal leakage, which has raised the head in Pit III artificially, but it rather accentuates the importance of the western drainage line; we shall return to this point when describing figs. 39–41, pp. 370–372.

We have now assessed the principal factors influencing the free water-tables on our farm, and are in a position to attempt a survey of the whole area.

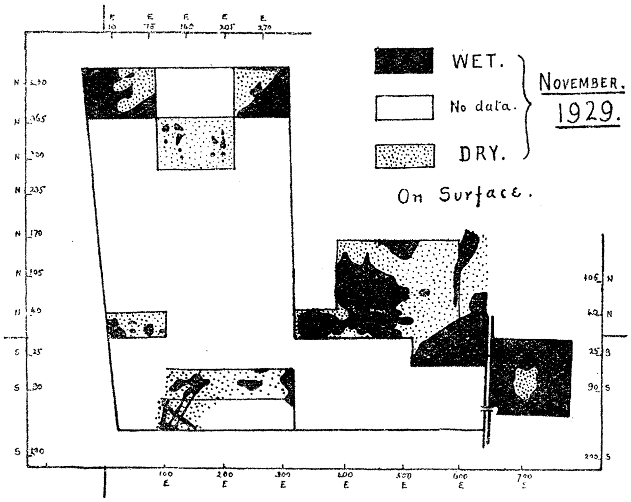

Fig. 28.—Map of farm during high water-table of November, 1929.

B.3. *Water-Table Survey of the Whole Farm.*

The map of the seventy acres in fig. 12, p. 350, shows the points at which observations have been made. The zero line of reference from west to east has been studied more intensively than the rest, with stratometer bores at ten-metre intervals, to a depth of 175 cm., and subsequent water-table readings in these bores during two months. It is convenient to examine this line first.

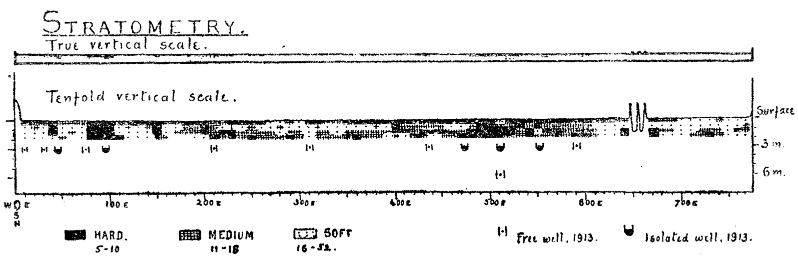

Fig. 29.—Section of farm.

The stratometer readings are depicted in fig. 29, and again classified into hard and soft by an arbitrary grouping based on the frequency distribution. The extra

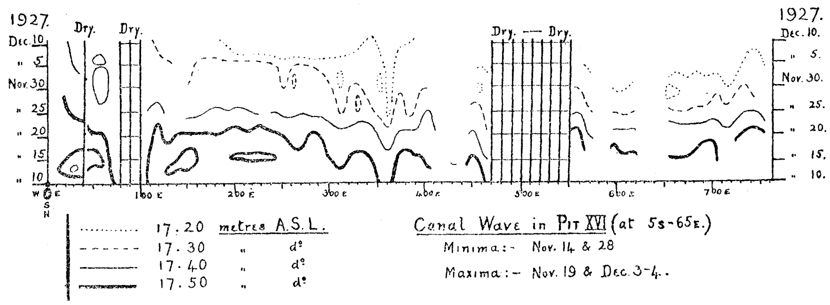

FIG. 30.—Water-height contours in Time (at Stratometer bores).

friction in the lower depths is disregarded, being less important than in the $3\frac{1}{2}$ m. bores formerly illustrated. The shading is applied as follows :—

Ten blows or less per half metre	Soft soil.
Eleven to fifteen ,, ,, ...	Medium soil.
Sixteen or more ,, ,, ...	Hard soil.

The number of blows varied as follows :—

Top half-metre	8—38
50—100 cm.	5—52
100—150 cm.	7—40
150—175 cm. (doubled)	8—40

The results given along the same line by the 3 m. tube-wells of 1913 are indicated underneath the lowest depth reached by these bores. It will be seen that they agree with the soil-hardness distribution except that for the 6 m., "Well A," at 510*e*, which, as mentioned above, penetrates an impermeable layer, whose lower face slopes rapidly downward to not less than 13 m. depth, just south of this line. There must be an enormous mass of clay in this region, but it is bye-passed to the north by a permeable subterranean channel (figs. 33, 34, p. 368), which puts Pit XVI into communication with Pit III, as noted in the previous section.

The variety of soil structure is evident, but the extreme localization of these variations is not so evident ; the hard patch at 40*e* is quite real and probably continues to the 3 m. depth at 45*e* ; we have already demonstrated on the Quarter-acre that 10 m. intervals between bore-holes can omit to discover notable variations.

The readings taken in these bore-holes during the fall from maximum water-table level are grouped together in the single contour-diagram of fig. 30 above, which shows the dates on which all bores stood at the same height. The diagram may be considered as a solid model, consisting of the curves obtained from all the bores standing side by side at right angles to the plane of the paper, with contour lines run round them. For the labour of levelling the reference points of these and other bore-holes, we are much indebted to the Survey Department. A flanged zinc pipe in the mouth of each hole was the reference from which readings were taken, and from which all the bores have had their readings reduced to metres above sea level (A.S.L.).

The bores in the hard soil at 40*e*, 80*e*, 90*e*, and 100*e* contained no water at all; they were typically isolated. At 520*e* the bores were dry, though located in medium soil; evidently this soil was perched on an impermeable layer lower down. At 560*e* the water-table was free, although the surface soil was hard, and so forth.

The canal-wave effect is clearly shown by islands in the contours dying out and recurring with less intensity as we pass from 30*e* to 150*e* and again to 220*e*, etc.

The drainage gradient evidently passes right underneath the hard dry soil at 460*e*, probably to the north of it as already noted, and there is a second drainage sump about 640*e* which happens to be immediately under the Wakfs and Waterworks Canals, themselves quite water-tight. It looks as if the water at this end was banked up against the east side of the impermeable mass at 550*e*, while finding its way round to the north side of it.

At 360*e* there is a most interesting bore-hole which loses its water so quickly that it must be in communication with some very permeable layer giving easy access to the main drainage line. If we refer to the aerial photograph, fig. 13, Plate 33, we can find indications of an old water-channel formed by the junction of two channels just outside the south-west corner of our farm, on the Agricultural School farm. This channel can be traced on other photographs along the line shown in fig. 11, p. 350, as "air channel," until it is lost under the buildings, but if it did not bend much in the next 100 m., it should pass directly under the site of this very permeable bore-hole at 360*e*, thus accounting for its permeability.

We have some reason to think that the main water outflow is to the north of the impermeable mass round 500*e*. It is tempting to assume that this is accounted for by another old channel, also shown on fig. 11 as "Napoleon's channel." Its position in this figure is a transcript from the map of Cairo district compiled by the savants of Napoleon's expedition to Egypt, or rather, from a reprint of that map superposed on the modern map of Cairo, published by the Survey Department. It is hardly likely that the location of the four or five channels which this map shows in the cultivated land should be exact, but the fact remains that one of them does cross the map of our farm in a most suitable position to account for the line of free underground movement of water in accordance with our observations.

From the examination of this line of 75 bores it is concluded that 13 are completely impermeable and one excessively permeable, that at least 20 are obviously in contact with the canals and many more may be, while a dozen or so would seem to be of the backwater type.

From this base line we next extend as far as possible over the remainder of the farm, by means of 70 bores put down at 65 m. intervals on a grid of rectangular co-ordinates, one to each acre, as shown in fig. 12, p. 350. Several of these gave no readings, notably around 100*n*–500*e*, where the surface soil was sandy and choked the holes. It seems scarcely necessary to discuss them all, and a representative selection of two dozen has therefore been picked out.

At the top of fig. 31 are plotted the readings for Pits XVI and III, using only those dates on which the bore-hole readings were taken, for the purpose of classifying the

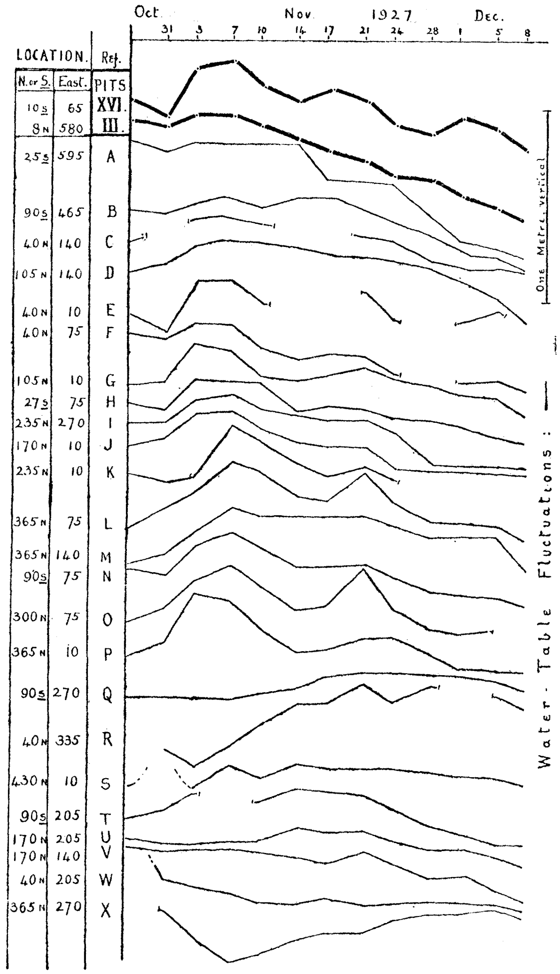

FIG. 31.—Acre Bores.

latter. Reference letters are attached to each curve for temporary convenience in describing the diagram, as well as the proper localizations in the frame of reference. Curve A resembles the very permeable bore at 0*n*–360*e*, in that the water drains away even more rapidly than from Pit III. In B we find a fairly free bore, showing the canal waves, but resembling tube-well *q* in Pit XVII (fig. 3) in the delay of its rise to maximum level; it is a backwater moving like Pit XVI, though nearly 500 m. away, whereas D, which is only 100 m. from Pit XVI, is similar to Pit III. The bores E to H are near the canals, and are markedly affected thereby, but with timing differences like those demonstrated in fig. 35. In I and J we have two excellent examples, already quoted, of free water-tables becoming perched after falling to a certain level; they are far apart. The group K to O shows various degrees of freedom and of canal-wave effect, like the group E to H, but with a consistent difference, in that the crest of each wave is much later. We have no canal details for this period, but a comparison with other periods suggests strongly that K–O are predominantly influenced by the Zomor canal, whereas E–H are mainly controlled by the Sawahel. Curve P is anomalous in its second wave.

With Q we change over to impermeable localities and isolated water-tables; R is rising against the general fall, probably collecting seepage from its higher neighbours. The land round S was irrigated after the first reading, without effect on the third reading; it may be an impermeable area, or a backwater, but it is evidently a big one which can absorb a single surface watering with scarcely any disturbance; actually we can see in fig. 28 that it is a backwater, subject to infiltration. Curves W and X are somewhat of the same type, while V is inserted to give the contrast of a free water-table again, showing a definite canal effect, but not draining very easily.

In conjunction with the previous figure, these curves illustrate the immense variety which the water-table can present. Before using them all to spot a map of the farm with markings to indicate the water-table types found at each place, we must examine fig. 28, p. 362. This figure has already been mentioned as an illustration of the valuable results which could be obtained by an aerial photographic survey of Egypt made during October and November in a year of unusually high Nile flood; the photograph would be nearly as sharp as this diagram. Circumstances and the cropping arrangements did not allow the whole farm to be mapped by measurement, and changes in the Royal Air Force had, most unfortunately, led to discontinuance of the taking of training-photographs over our farm at this critical time, but sufficient has been depicted to show the complex nature of infiltration water-paths: old walls are revealed at 150*s*–100*e*; spots of soil which have repeatedly been observed as peculiar under deep-rooted crops reappear in the field around 300*n*–140*e*; on the eastern edge of the backwater already noted at 430*n*–10*e* we can see the water creeping through gaps and along semi-permeable pathways; the island of impermeable soil around 90*s*–700*e* had been located in 1927 by the stratometer bores, and here again we are able to ascertain from them that the source of this water is to the north, so that all the south side is back-water.

We have previously mentioned that fresh water can conceivably bring salt water up to the surface (or over the roots of plants), and an attempt which had formerly been made by some colleagues to use open trap drains around this last area was most informative, though the drains themselves were inevitably useless. The infiltration water accumulating in them attracted our attention on account of obvious differences in the alga flora, and some analyses made for us by the Chemical Section showed that the four isolated sections of these trap drains contained as much as 200 parts of NaCl per million in the northern portion, and rose to 800 parts in the southern portion. Yet we have seen in fig. 30 that there was a typically free water-table with easy drainage along the north-west corner, and the causative water, such as was found in free wells in 1913, only contains 10–20 parts per million.

When this map (fig. 28, p. 362) was made it was not possible to walk on the wet areas, but the island in the centre was dry and dusty, the boundary was so sharp that dust could be picked up with one hand and mud with the other.

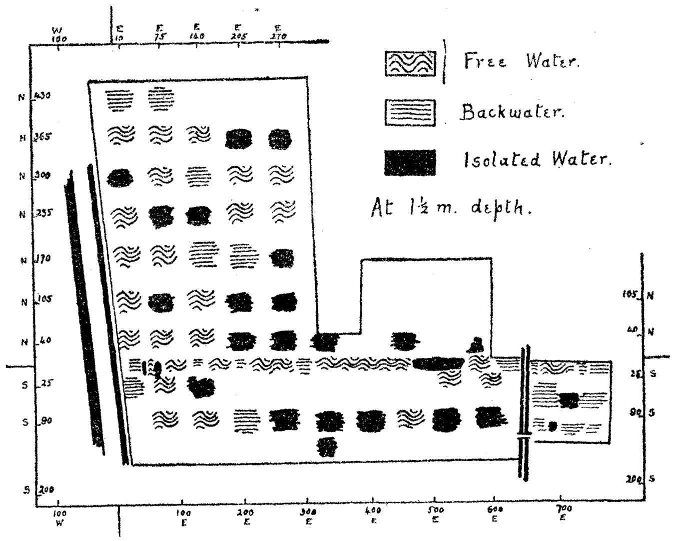

FIG. 32.—Map of farm. Distribution of types of water-table.

We can now attempt to estimate the relative importance of permeable and impermeable soils in the working of our farm. This has been done in fig. 32, by spotting the map; blanks in some of the fields can be filled in by comparison with fig. 28, p. 362. Approximately half the area is impermeable, or rather less, and about a quarter of it is not only permeable, but carries a free water-table; rather more than a quarter is backwater. Evidently it would be a complicated matter to lay out a drainage system appropriate to this farm: thus, the big impermeable area round 105*n*–270*e* might be drainable into a sump at that point which penetrated to permeable soil below, but we do not know how deep the sump would have to be; it might be 13 m., as at 10*s*–510*e*. Collection to a central drainage pump would necessitate the use of water-tight drain pipes when passing through permeable areas, otherwise the drained impermeable areas would be back-filled with infiltration water in the autumn. Any attempt to arrest water from the canals by trap drains, which was actually tried by the senior author in 1912, is evidently entirely futile; the true-scale section of fig. 29, p. 362, exemplifies this.

In spite of all the evidence obtained from this area, it is clear that any attempt to fit a drainage scheme to it would still be largely a process of trial and error, on account of the fact that we have merely scratched the surface with one observation at 13 m., one series at 6 m., two dozen at 3 m., and 200 at $1\frac{1}{2}$ m. In any intelligent planning a knowledge of the "surface-geology" to much greater depths would be needed, and herein we see no hope except from geophysical methods. The one thing quite clear is that a lining to the canals would deepen our available soil appreciably.

A little more can be extracted from our data with respect to the direction of water-movements, though but little as to its actual paths, by comparing the reduced levels observed in those bore-holes which alone have given typically free curves. This has been done in the form of two contoured maps, fig. 33 which shows the levels in October, when the free water-table is at its maximum, taking a date which lies in the trough of the canal wave effect, and fig. 34 which does the same at a time when the fall of the free water-table is proceeding most rapidly. We would advise caution in reading these contours, which are obviously based upon too few observations for safety, but the broad outlines are probably correct.

Fig. 33 shows two sources of water, one at 17·62 cm. A.S.L. on the river side, the other

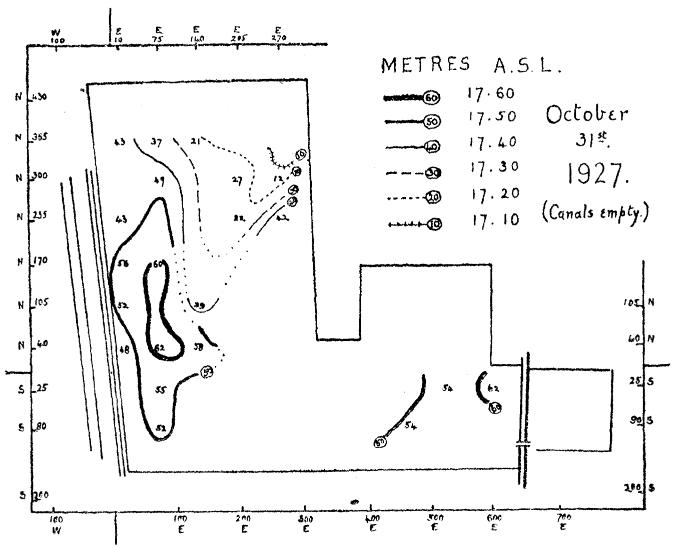

Fig. 33.—Map of farm. Free water-table contours at maximum, in October.

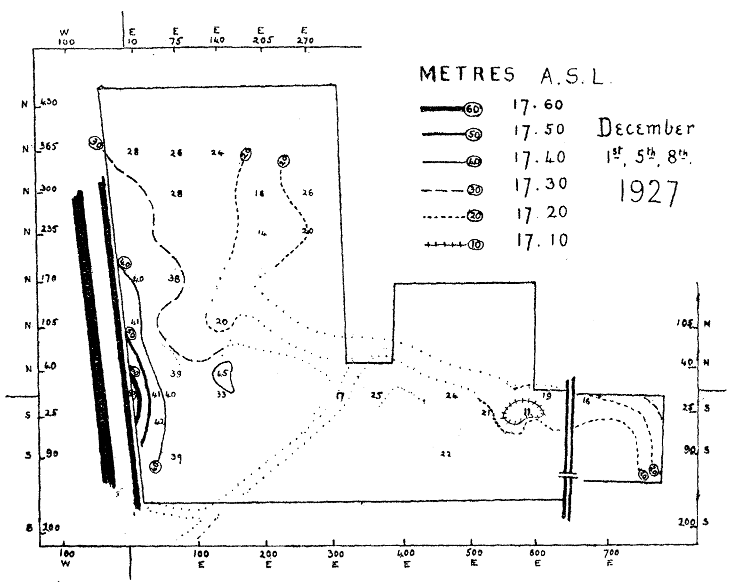

Fig. 34.—Map of farm. Free water-table contours during fall, in December.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY B BIOLOGICAL SCIENCES

standing also at 17·62 cm. A.S.L. near the canals; whether the latter is residual water from the last filling of the canals to 18·60 and 19·00 respectively, or whether it represents the emergence of long-distance water through some underground path, we cannot attempt to say. But the map shows very clearly that there is a rapid out-fall of water to the north or north-east on a gradient of 1 m. per km. This fall would just about reach river level on this date (fig. 19) at the required distance in this direction, if nothing were allowed for lag, but it might equally well turn west to the western drainage-line (fig. 39, p. 370).

A month later, at the beginning of December, when the water is falling quickly, the conditions are very different. Three days readings have been averaged. The edge of the canal (which is now full) is supplying water at the head of the same outlet-path as was noted in the previous figure, just where the spring of water was found in 1912, but an additional and more important outlet has developed around 25*s*–600*e*, which had been a water-source in October. This can only be the direct path to and from the river, and we have ventured to connect it with the west of the farm, under the impermeable area round 105*n*–270*e*, by means of Napoleon's Channel, while the Air Channel also fits in, as a tributary.

It may be possible in the future to make these maps more adequate, and to extend them to other seasons of the year, but the labour of reading levels in several hundred semi-permanent wells seems too cumbersome a method for obtaining the required information.

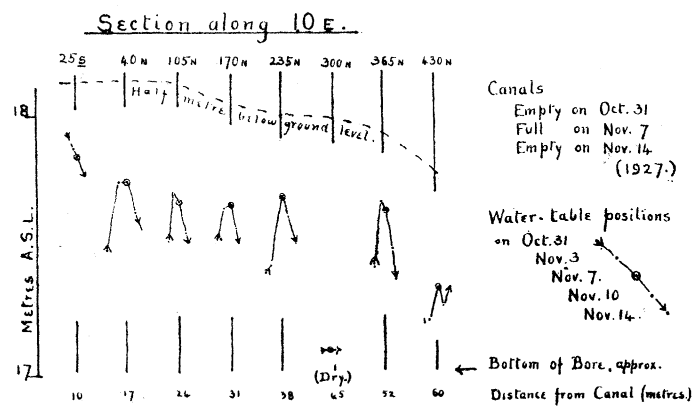

FIG. 35.—Variations of Canal Wave effect.

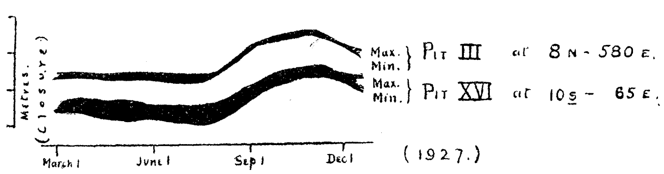

FIG. 36.—Amplitude of Canal Wave.

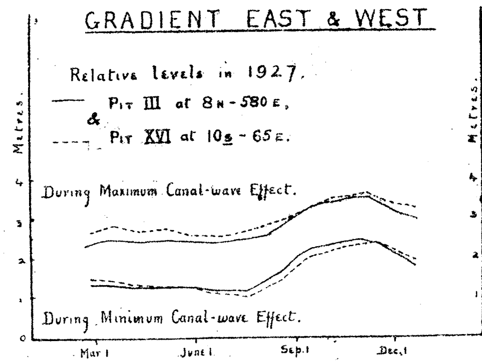

FIG. 37.

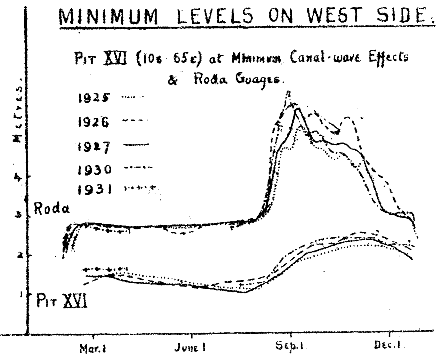

FIG. 38.

C.1. *The Composition of the Free Water-Tables on the Farm.*

A transverse section of the valley, passing through the farm and extending about half-way to the desert edge near the Pyramids, is given in fig. 39. The map of the French Expedition savants is utilised to insert a mass of necessarily permeable alluvium deposited since 1800 on the west bank of the river, which brings the river water even nearer to us.

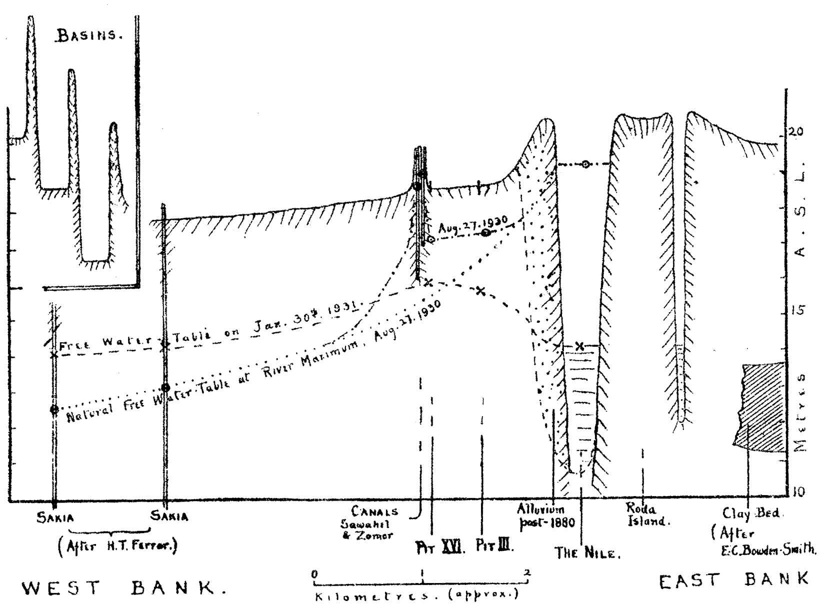

FIG. 39.—Transverse section of valley through the Giza farm.

The two sakias to the west are those measured by FERRAR (1909), and the various levels credited to them are based on his readings in 1908, with an estimated correction for the smaller flood of 1930. Two "natural" free water-tables thus derived from FERRAR'S data are inserted, passing under our farm, at the maximum and minimum readings of Roda Gauge during and after the 1930 flood. The actual levels recorded in

Pits III and XVI are entered, showing the reversal of gradient between flood and low stage, and the effect of the two canals during flood ; the latter had been dry for over a month when the January 30th points were recorded, thus giving us a near approximation to the undisturbed free water-table.

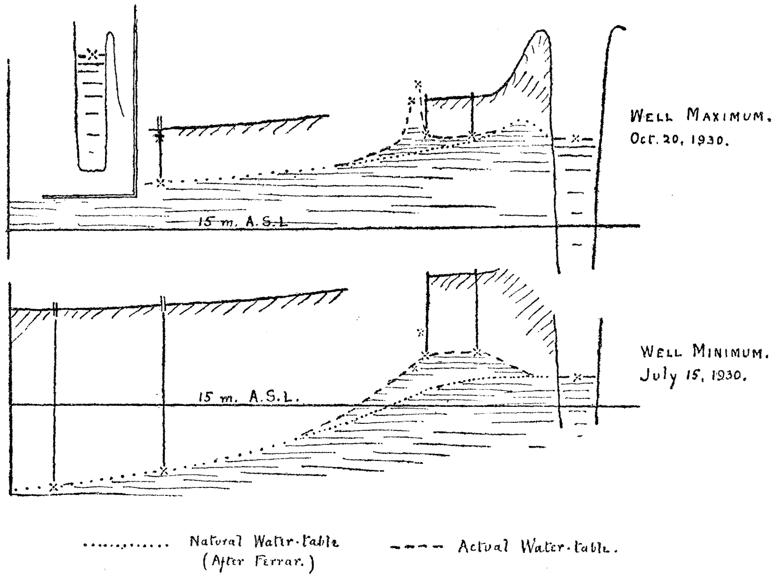

FIG. 40.—Transverse section of valley (continued).

Fig. 40, above, is the same diagram, repeated twice in skeleton. During the " well maximum " we have the additional source of water in the basins, whereof the Shabramant level is shown (inset). The river is falling, but the natural water-table, shown by the small dots and based on FERRAR's diagram, is sufficiently near the levels observed in our pits to require but little additional seepage from the canals to account for their height, and especially for the fact that in 1913 our wells rose above the river level.

During the " well minimum " we seem to require much more water from the canals, but it is evident from previous figures that such is actually available. The rise of water-table near the canals obstructs the leakage from them, and, conversely, the lower the underlying natural water-table the steeper the gradient from the canals, and the more they will lose. The double wedge of leakage water-table shown in this figure is 1 m. high and 2 km. wide, equal to a rectangle $\frac{1}{2}$ m. high and the same width, during the period of maximum leakage, as against our considered estimate of nearly $\frac{1}{2}$ m. (10 cm. water is taken as 40 cm. water-table) over the same width in the permeable soils for an average over the whole year, so it is not unreasonable.

We are now in a position to divide the well readings on our farm into their components. We do not pretend that this division is more than an estimation by graphic methods, as in the two previous figures, but it seems to be a fairly close approximation when tested against the facts observed, and, besides being informative, it is somewhat surprising. It is presented in fig. 41, based on the eight-year mean curve of fig. 24, p. 356, which is repeated through two seasons for clearness. The rapid drop in amplitude of the flood wave, upon which we have already commented, is still more emphatic when thus taken out of the well-curve from Pit III, but meanwhile we have largely justified this reduction of amplitude to less than a half in less than 1 km. by

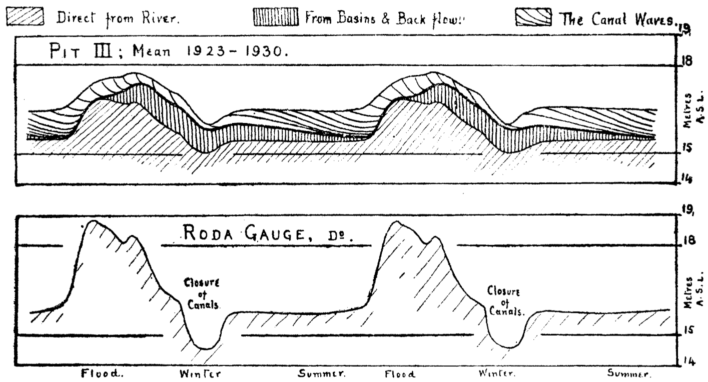

Fig. 41.—Estimation of sources of "free" water.

showing that a rapid run-off does exist (in fig. 33, p. 368). Upon this water "direct from river" is superposed the water lagging behind in the valley trough and moving roughly parallel with the river, depicted here as coming "from basins and back-flow"; this gives us the true "sakia-type" of free water-table curve, as depicted by Ferrar and Audebeau to which Pit XVI makes a partial approach at its minima (fig. 38, p. 370). Upon this foundation is finally loaded the series of canal-waves, and while they appear in this diagram to be excessive and exaggerated, we have seen that they are actually quite reasonable, and occupy a rather smaller part of this diagram than one is entitled to expect on the average of irrigation experience.

C.2. *The History of Water-Table Levels in Egypt Generally.*

These Giza data have formerly been regarded, even by ourselves, as having only a local interest. The site is so close to the river, inside the Barrage Pond, that the dominance of the river seemed obvious. The 1913 flood corrected this impression somewhat, and fig. 41 corrects it still further. In conclusion, therefore, it seems legitimate to attempt to relate our observations to the broader issues of the old "water-table controversy," formerly mentioned.

The history of water-tables in Cairo, as measured by Lucas about 1900, and of the free water-table on the Giza farm as measured by us later, is shown in fig. 42. The maximum and summer-minimum readings of Roda gauge are plotted for 48 years. The Cairo data of Lucas (1904), for a well in a similar position to ours, are not directly comparable, since there are no canals in the city, and his points simply follow the Roda levels very closely; nevertheless, there is a definite hint that the maxima run higher towards the end of his series, given similar river levels.

Shifting to Giza in 1912 there is a differential rise of both maximum and minimum

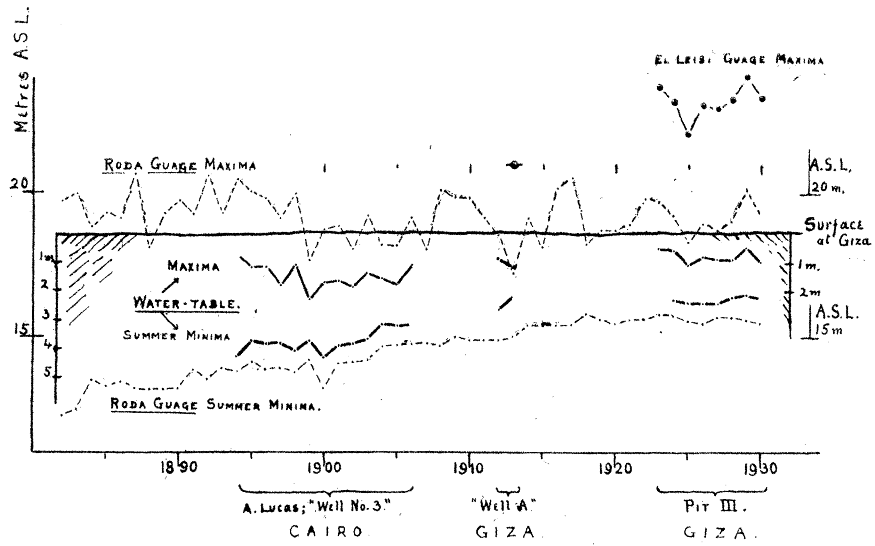

Fig. 42.—Barrage Pond and Water-table, 1882-1931.

well levels, which we can now assert definitely to be due to the canals. It could reasonably be contended that earlier records for Giza would similarly be much higher than those of Lucas, but it so happens that the Sawahel and Zomor canals were built about 1900, which makes it certain that our farm had a free water-table lying 5 m. below the surface in the summers of 50 years ago, and a maximum in flood which was not—on the average—very much higher than our present summer minima. The depth of available soil has been halved, mainly by the successive raisings of the Delta Barrage (which can be seen as steps in the " Roda Gauge summer minima ") and partly by the high-level canals, whose invaluable services have been obtained at the cost of disadvantages.

Finally, we venture once more to generalise still further, for the whole Delta, on the basis of Ferrar's work. In fig. 43, we reproduce a section through Lower Egypt,

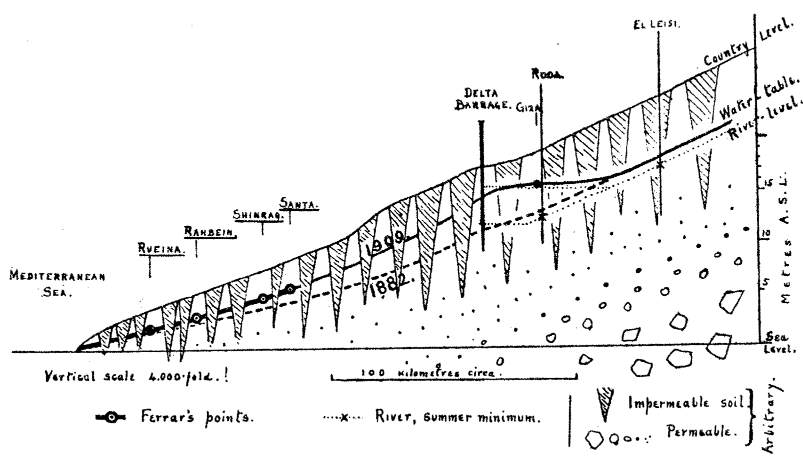

Fig. 43.—Section of Lower Egypt, adapted from H. T. Ferrar, showing Summer minimum of Water-table in 1882 and 1909.

copied from FERRAR (1910) and extended up to El Leisi gauge. The four points plotted by FERRAR on this section are his own actual measurements, which we have drawn with a very heavy line. For the rest of the diagram we are responsible. FERRAR noted in 1909 that the minima of four observation stations lay on a very slightly curved line, which pointed northward to sea-level if extrapolated. He did not extrapolate in the other direction, and this we have ventured to do along a catenary, which FERRAR suggested should be the form of the curve, joining up to the reading of summer water-level at the Delta Barrage (fig. 42, p. 373) in that year. The water-table droops in passing round the Barrage, so we have taken the continuous line slightly lower, and carried it on to the probable minimum level at Giza (fig. 42) estimated for that year. Thence it is continued (slightly above river level to allow for back-flow) into Middle Egypt.

The extrapolation is perhaps unjustified, even though we have been careful to sketch conventionalised wedges of impermeable soil, to indicate that our presentment only applies to the permeable soils, and so can only affect about half the soil of Egypt. We have independent evidence indicating such to be the relative proportion.

Nevertheless, it seems so plausible that we have completed the diagram by inserting an entirely imaginary water-table for 1882, the only justification for which is the river-level in that year (fig. 42). This again seems plausible, and the two curves give a clear picture of the way in which the Barrage Pond may have altered the underground water regime of the whole Delta, in conjunction with the high level canals which it feeds. The levels to-day stand slightly higher even than those of 1909.

PLATE 33.

FIG. 13.—Aerial photograph of Giza Farm.

References.

The classic "Egyptian Irrigation" of Sir William Willcocks contains in its 3rd edition much information on water-table work.

Most of the relevant papers are contained in the "Cairo Scientific Journal" referred to below as 'Cairo Sci. J.,' and in the "Survey Notes" from which it originated. The journal is now extinct, but copies can still be obtained through the Secretary of the Cairo Scientific Society.

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PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY B BIOLOGICAL SCIENCES

Fig. 13.—Map of farm :—Aerial photograph taken by courtesy of the Royal Air Force, Middle East.

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FIG. 13.—Map of farm :—Aerial photograph taken by courtesy of the Royal Air Force, Middle East.