A CHEMICAL SURVEY OF THE WATERS OF MOUNT MERU, TANGANYIKA TERRITORY,

ESPECIALLY WITH REGARD TO THEIR QUALITIES FOR IRRIGATION.

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In this paper are presented the results of a number of analyses of water-samples taken during the years 1931 and 1932 from the streams and minor lakes occurring on the slopes of Meru, the dominating mountain of the district of Arusha, Northern Province, Tanganyika Territory. The work originated in the examination at Amani of a few samples from streams on the south-west of the mountain, at the request of Mr. E. Harrison, Director of Agriculture for Tanganyika, who on the occasion of a visit to the area in December, 1930, expressed the opinion that alkali salts, either originating naturally in the soil or introduced by irrigation, were possibly causing injury to coffee, the principal economic crop of the district. It is common knowledge, locally, that the streams draining from Meru contain " soda " in greater or less amount, but in spite of this they have been employed for irrigation, sometimes on a lavish scale. The results of these first analyses made it clear that a systematic chemical survey was desirable if guidance was to be offered on the merits of this practice in the several divisions of the district, and one of us (D.S., in his capacity as District Agricultural Officer, Arusha) began a series of periodical samplings of the principal streams. The analyses were carried out by another of us (W.E.C.) in the soils laboratory at Amani. At a later stage, in view of the relevance of the whole subject to the study of the volcanic soils of the area, it was decided to extend the samplings beyond the range originally contemplated, so as to include all waters rising on the mountain whether or not they came into question for irrigation. This was done during a circuit of the mountain made by D.S. and W.E.C. in company in August, 1932.

There has resulted a body of information for which we use the word " survey " rather diffidently, for no chemical survey should be content with single samples, and at many points we were able to sample only once. Yet the number of sub-localities examined altogether is fairly large, some streams were sampled frequently and at several points in their course, and there is a fair distribution of the sampling-dates over the seasons. Also it would be misleading to call it a " preliminary survey," incomplete though it is in many ways; for there is no immediate prospect of further chemist's time being spared to amplify the work in the same district. The results are however sufficient to form a fairly clear picture.

Short accounts of the topography, climate, and (within the limits of very scanty data) geology of the mountain are prefixed to the analytical results as an aid to the discussion which follows them. Finally the agriculture of the district is briefly sketched, in so far as its practices touch irrigation. The conclusion is inevitably drawn that the waters are for the most part of undesirable quality for irrigation purposes. It should however be made clear that this paper is not a discussion of the existence of an " alkali problem " in the area, except on the evidence of stream-composition. Soil properties as such are touched upon only very briefly. The reconnaissance soil survey which is in progress as part of a joint programme of the Department of Agriculture, Tanganyika, and the Research Station, Amani, and to which this paper is in its degree contributory, should in due course enable irrigation-practice to take more account of soil properties.

TOPOGRAPHY OF THE MOUNTAIN.

Meru (14,995 feet) is the third highest of a series of volcanic peaks that occur along a line running approximately east and west across the north of the Territory. Its neighbours on the east are Shira (12,800 feet), Kibo (19,300 feet), and Mawenzi (17,580 feet), which together make up the Kilimanjaro massif; and on the west Meandet, Mondul, El Burko, and Essimongor, none exceeding 7,500 feet. The plains at the foot of Meru are about 4,000 feet above sea-level. It rises very steeply, making much of its height at a mean slope of 30° to the horizontal.* On the east there is an extending arm of the mountain, trending somewhat southwards, and containing a large subsidiary crater, Engurdoto, and a smaller one, Meruni, the latter at 5,000 feet. On the west there is a shorter arm with a high shoulder forming a plateau at 9,800 feet. On the northern face, below the edge of the main crater, there is a considerable conical mass (Little Meru) having the appearance of being the eroded neck or crater-wall of an older volcano; and at lower levels on this slope

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* See Meyer (¹) (1909), who compares this angle with that of Kilimanjaro, namely 8 degrees (except for the summit-slopes), and attributes the difference to a higher viscosity of the Meru lavas.

there are several notable lesser cones (e.g., Ol Doinyo Sambu, Longringo), some of which have relatively fresh craters. Around the settlement of Engare Nanyuki at the north-east foot, and also on the southern and south-western lower flanks, are found numbers of smaller volcanic hills. Of those on the south, Kibwezi (6,300 ft.) overhangs Arusha township, and still maintains a mantle of forest. Among these secondary hills to the south lies the crater-lake Ol Balbal Duluti.

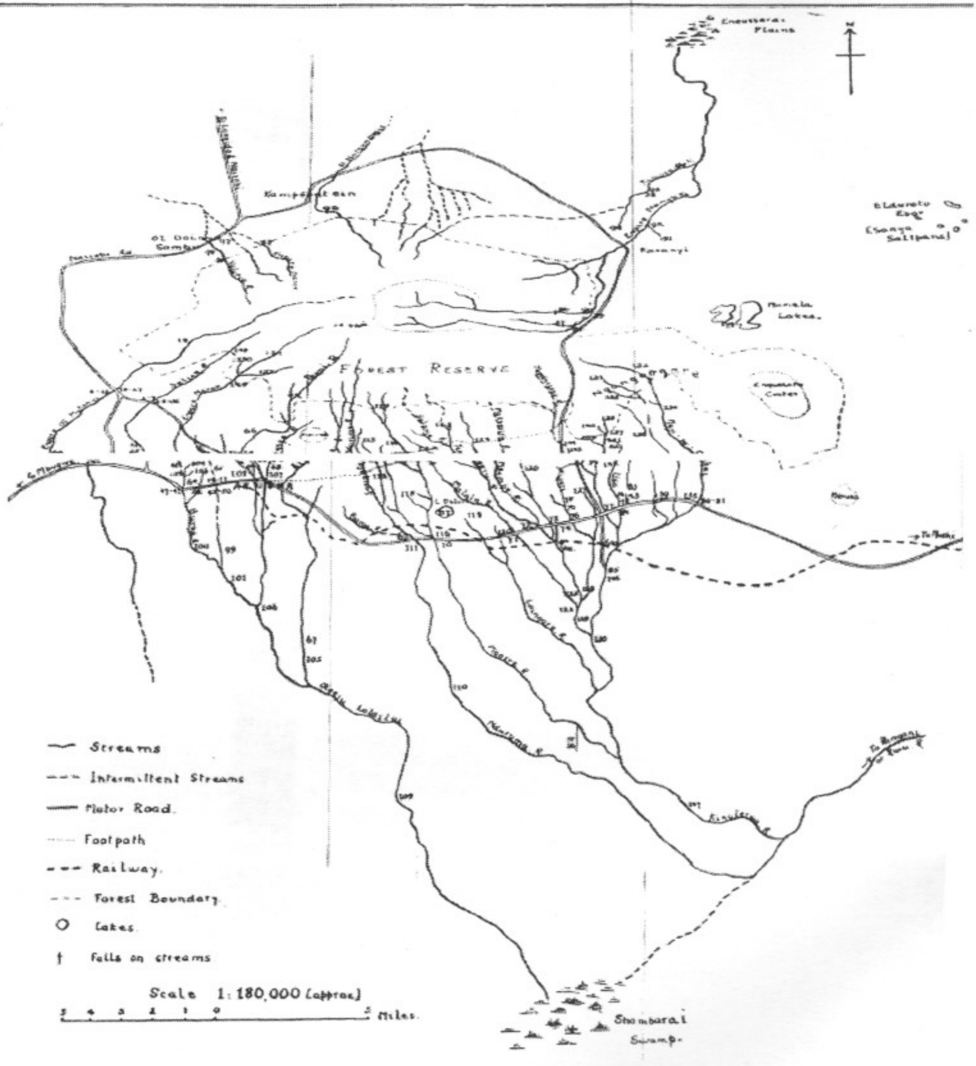
Above 9,000 feet the main mountain is but a hollow shell. From the north, west, or south it appears solid to the summit, but from the east the interior of the great crater is fully visible, for its whole eastern wall has been blown out and is scattered in a litter of lava-blocks over the countryside at the mountain-foot, towards Kilimanjaro. This scattering of the débris of the crater-wall has resulted in an irregular damming-up of the drainage from the eastern slopes in a number of small lakes, having no outlet, at the foot of the mountain. The chief of these are Elduroto Ebor (the Sanya salt-pans) and the Momela lakes. (See analyses, Table IX.) Within the remaining north, west and south walls three concentric crater-formations have been recognised (Uhlig (2) (1904), and (3) (1911)), and in the innermost is an immense ash cone of extremely recent appearance, with lava-flows at its foot so fresh that Uhlig was led to consider that the last outflow might have occurred within a few decades of his visit. The crater is 4 kilometres across internally, and is bounded by precipitous walls except at the eastern breach, where the floor is 8,900 feet above sea level. The highest point of the mountain is on the south-west edge of the crater lip.

It is from within the main crater that the Engare Nanyuki river flows, eastwards at first through the great breach, turning northwards after reaching the forest belt. It runs for some miles in a deep gorge, and after reaching the plain is lost in a swamp a few miles to the north. This is the only considerable river going in this direction, the other north-flowing streams to the west being represented for most of the year by dry gorges, or small streams barely reaching beyond the forest edge. (See Tables IX and X.)

The southward-flowing rivers may be divided into two groups, (i) those which run from the south-western slopes into the Masai steppe, and are lost in their river-beds or in swamps as are the northern streams; (ii) those which unite in the south-east corner of the area to form the Kikuletwa river, and later join with Kilimanjaro waters to form the Ruvu (or Pangani), finally reaching sea at Pangani. In the tables of analyses it has been found convenient to make several further sub-groupings of these south-flowing streams. The sketch-map shows the drainage of the whole area, and indicates the sampling points by numbers corresponding to the sample-numbers in the left-hand column of the tables.

SKETCH-MAP of MERU shewing STREAMS and SAMPLING POINTS.

Numbers correspond to sample-numbers in the Tables.



Including the settled lands on its lowermost slopes, the base on which Meru stands has an area of roughly 450 square miles, or about twice the size of the Isle of Man.

GEOLOGY OF THE MOUNTAIN.

Rock-exposures in the river gorges show that the older lavas of the main mountain and its secondary hills, while exposed and weathered to form maturing soils on the southern flanks, are still covered by ash, tuff, and conglomerate on the other three sides and also at the south-west and south-east corners. It will appear from the analyses that this principal distinction between the older (or at any rate more fully weathered) and the more recent (or at any rate fresher) rocks is well reflected in the dissolved matter of the streams.

Recorded geological information on the mountain is scanty. J. W. Gregory (^{4}) (1921) emphasizes the fact that the lavas of East African volcanoes belong generally to the alkalic division, rich in soda and poor in lime, and he quotes Mauritz (^{5}) (1908) as follows on particular rocks collected on Meru: " Mauritz shows the predominance of the alkaline lavas and kenyte . . . . He describes nephelinite . . . . from tuffs at Elduroto Ebor; also kenyte (trachydolerite) at 4,250 feet at the southern foot. On Meru as often elsewhere the lavas are especially alkaline, and include the phonolitic kenyte of the Meruni crater and Towaila on the S.E., and a leucite-nepheline-tephrite tuff at 5,900 feet on the E." It should be observed that the above quotation, though carrying Gregory's authority, is perhaps misleading as to the state of petrological knowledge for the mountain, for Mauritz had actually no more than one specimen each from the five localities quoted, and in his original paper offers no generalisation. The rocks of the mountain as a whole, and particularly the ash, pumice, and tuffs which bulk so largely in the superficial covering of the west, north and east sides, still await the attention of petrologists.* The apparently very recent date of some of the rocks within the crater has already been referred to.

CLIMATE.

Meru receives rain during two wet seasons, a short one in late October and early November, and a long one from the middle of March to the latter half of May. Following the long rainy season there are two months of cold weather, after which temperatures gradually increase till the break of the next rains. Rainfall records have only been taken within the narrow belt alienated for European settlement, but from the scanty figures available an approximate rainfall map has been prepared sufficient for the purposes of this paper.

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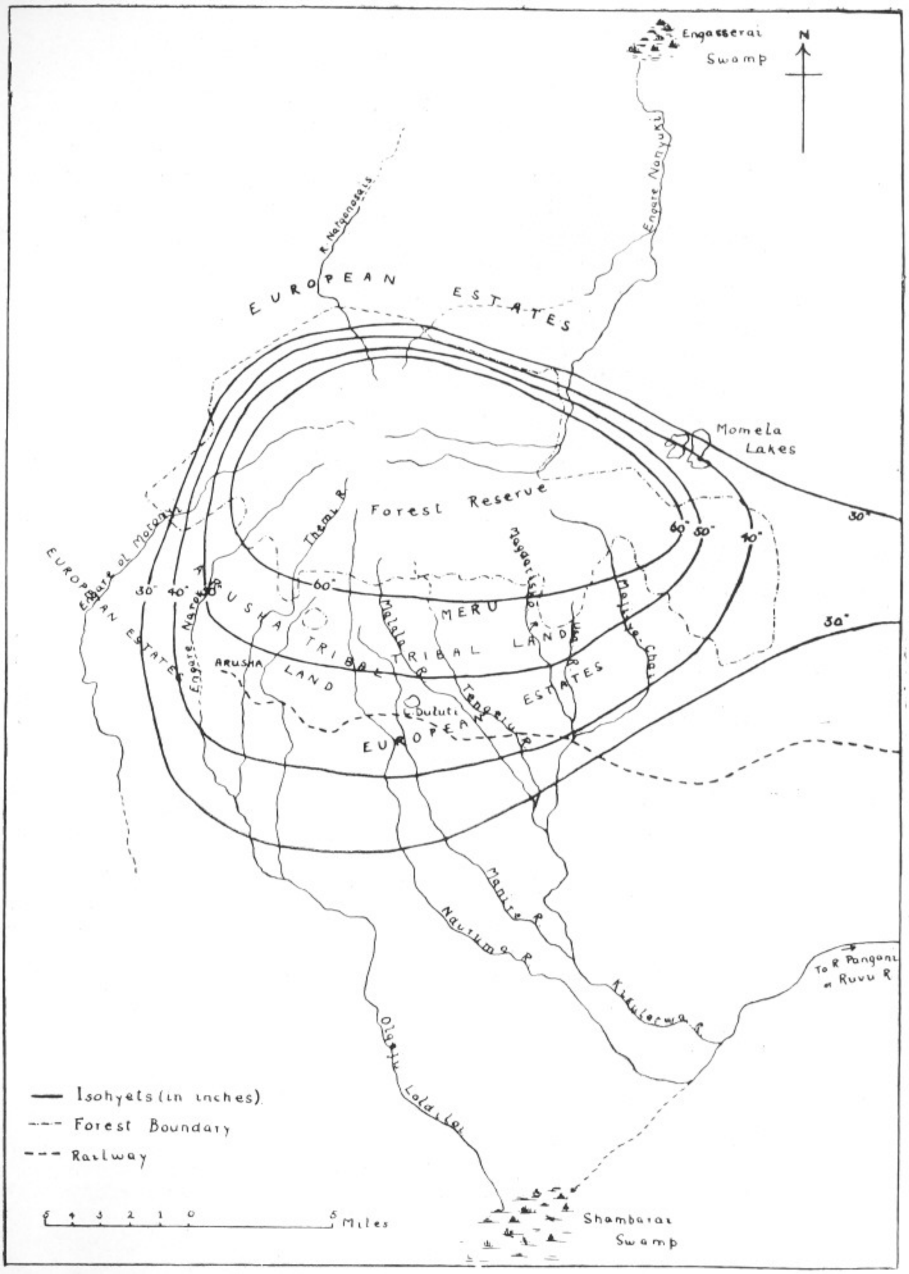
* By the kindness of the Director and officers of the Tanganyika Geological Survey, a number of rock-specimens collected in 1932 by one of us (G.M.) in connection with the soil survey are now under examination at the Survey laboratory at Dodoma.



Approximate Map of Rainfall of Mount Meru.

The effect of an unequal distribution of the rainfall around the mountain is shown by the natural vegetation. On the southern slopes Meru has been forest-clad from about 4,500 feet to 8,900 feet, above which continuous forest ceases. Cultivation has now destroyed this forest up to about 6,000 feet, above which the forest is reserved. On the other three sides the forest has never come so low down as on the south, but there is little doubt that the line to which it now reaches, and at which it is reserved, is a line to which it has been thrust back, by grass fires, in quite recent times. On the north the lowest edge of the forest barely reaches down to 7,000 feet, and in one place a gap occurs right through it.

The areas of highest rainfall and of broadest intervals between isohyets are to the south and south-east. In this respect Meru differs slightly from its neighbour Kilimanjaro, which receives its greatest rainfall to the south and south-west.

SAMPLING.

The collection of samples began in May, 1931, towards the close of the long rainy season. The streams then first sampled (Engare ol Motonyi, Selian, Engare Narok) were those near which the question of alkali damage to coffee had arisen, and could be visited at approximately fortnightly intervals in the course of other duties. The sampling was later extended as already described. Samples were taken from as near as possible to the swiftest flow of the current. Some time necessarily elapsed during transit to Amani for analysis, but it is not considered that the analytical determinations, directed as they were to ends quite different from those in view when waters are examined for potable quality, were vitiated by the delay except in the case of pH values, to which reference is made in the next section.

ANALYTICAL METHODS.

The short account of these that follows will assist in the interpretation of the results.

Total bicarbonate.—This reflects the total alkalinity of the water, i.e. the sum of the bases lime, magnesia, soda and potash, not combined as sulphate or chloride. It was determined by titration with N/20 sulphuric acid using methyl orange, and is expressed as " parts of bicarbonate-ion (HCO_3) per million of water." For every 100 parts of bicarbonate-ion recorded, about 85 parts of solid alkaline matter (mixed calcium, magnesium, sodium, and potassium carbonates) could be realised as residue on evaporation of the water.

" ***Soda*** " was determined by a method adopted by the American Association of Official Agricultural Chemists (6) (1925) for the examination of waters suspected to contain " black alkali." It represents the sodium and potassium bicarbonates (or carbonates) present in the water, calculated for convenience as sodium carbonate (Na_2CO_3), in parts per million. The alkalinity it represents is included in, and is not additional to, that recorded as total bicarbonate. In column 8 of the tables of analyses the " soda " alkalinity of the water is calculated as a percentage of the total alkalinity after reducing both to the same units.

Sulphate and *chloride* determinations, by the usual methods, are recorded as parts per million of the respective ions.

The *pH* values that are recorded were determined colorimetrically by the Hellige comparator or electrometrically by the quinhydrone electrode. Salt errors were corrected for by making the assumption that the total dissolved-salt concentration was effectively represented by the total bicarbonate. The colorimetric figures are in brackets. At the beginning of the investigation it was thought that the colorimetric pH tests would serve usefully in the field for diagnosis of alkalinity. It was soon found, however, that the method was subject to several errors, e.g. the salt-error mentioned above, which for these waters is by no means negligible and cannot be estimated in the field. Also it often failed to distinguish between waters of very different soda-content. The pH determinations were therefore given up, more especially as we were not concerned with biological conditions in the waters. The values are however given in the tables as a matter of interest. The results of determinations made on long-bottled samples cannot be expected to give very accurate or very useful information.

The determinations above-described are sufficient to classify the waters from the original viewpoint of the survey (suitability for use in irrigation), but lead to only a partial statement of their chemical composition and leave several questions of interest unanswered. They will be referred to below as the partial analyses. A more complete analysis has been possible for certain streams only, for which the numbers of samples available at one time were sufficient to allow of composite samples of large volume being made up. The results for these streams are reported in Table XIII, which follows after the discussion of the partial analyses.

COMPOSITION OF THE WATERS—PARTIAL ANALYSES.

(See Tables I to X.)

TABLE I. ENGARE OL MOTONYI.

No.	Locality.	Date.	1 Total Bicarbonate, HCO_3. p.p.m.	2 " Soda," Na_2CO_3. p.p.m.	3 Per cent. Soda-alkalinity in total. %	4 Sulphate, SO_4. p.p.m.	5 Chloride, Cl. p.p.m.	6 pH
19	Forest Station	2/ 9/31	278	180	74	12	7	7.5
8	Nairobi Rd. Drift	8/ 6/31	302	208	79	9	7	
9	,,	20/ 6/31	355	248	80	10	8	
10	,,	10/ 7/31	385	246	74	12	6	
11	,,	24/ 7/31	315	227	83	12	6	
16	,,	7/ 8/31	315	240	88	14	6	
13	,,	22/ 8/31	314	237	87	34	6	
18	,,	2/ 9/31	328	215	75	11	7	(8.1)
20	,,	19/ 9/31	311	208	77	14	7	(7.6)
21	,,	2/10/31	338	222	75	15	7	(7.4)
22	,,	19/10/31	313	200	73	13	7	(8.6)
23	,,	6/11/31	307	202	76	12	7	(8.6)
24	,,	24/11/31	294	203	79	11	6	(7.6)
25	,,	19/12/31	312	210	78	12	6	(8.1)
26	,,	25/ 2/32	327	225	79	15	7	(7.9)
27	,,	22/ 3/32	237	168	81	12	5	(7.6)
	Mean (15 samples)		317	217	79	14	6.5	
60	Mbugwe Rd. Drift	1/ 6/31	282	189	77	24	5	7.6

TABLE II. SELIAN RIVER.

No.	Locality.	Date.	1 Total Bicarbonate, HCO_3. p.p.m.	2 “Soda,” Na_2CO_3. p.p.m.	3 Per cent Soda-alkalinity in total. %	4 Sulphate, SO_4. p.p.m.	5 Chloride, Cl. p.p.m.	6 pH
148	Forest boundary	23/ 8/32	259	216	96	21	5	—
1	Drift, Farm 194	23/ 5/31	268	182	78	25	6	—
2	,,	8/ 6/31	279	197	81	22	5	—
3	,,	20/ 6/31	286	205	83	25	3	—
4	,,	10/ 7/31	272	195	82	22	6	—
5	,,	24/ 7/31	266	196	85	20	5	—
6	,,	7/ 8/31	316	211	77	nd*	2	—
7	,,	22/ 8/31	271	196	83	9	6	—
28	,,	2/ 9/31	295	184	72	8	8	(7.0)
29	,,	19/ 9/31	272	192	81	9	6	(7.1)
30	,,	2/10/31	269	189	81	12	5	(7.6)
31	,,	19/10/31	420	216	59	12	9	(6.3)
32	,,	6/11/31	271	193	82	10	6	(7.5)
33	,,	24/11/31	252	189	86	9	6	(7.7)
34	,,	19/12/31	252	184	84	12	5	(8.6)
36	,,	22/ 3/32	267	197	85	12	6	(7.4)
Mean (14 samples, No. 31 excluded)			274	193	81.5	15	5	
35	Selian-Sunoni Furrow	25/ 2/32	288	202	81	16	6	(7.5)
61	,,	9/ 5/32	203	137	78	17	3	7.55

* nd—not determined.

TABLE III. ENGARE NAROR.

			1	2	3	4	5	6
			Total Bicarbonate, HCO_3'.	" Soda," Na_2CO_3'.	Per cent Soda-alkalinity in total.	Sulphate, SO_4''.	Chloride, Cl.	pH
No.	Locality.	Date.	p.p.m.	p.p.m.	%	p.p.m.	p.p.m.	
150	W. trib. within forest	23/ 8/32	159	133	96	5	4	
151	Middle ,,	23/ 8/32	76	66	100	6	2	
152	E. ,,	23/ 8/32	98	76	89	2	3	
149	Main stream, forest boundary	23/ 8/32	146	114	90	5	4	
14	Mbugwe Road bridge	20/ 6/31	141	98	80	9	3	
15	,,	24/ 7/31	150	104	80	11	3	
12	,,	7/ 8/31	153	101	76	5	4	
17	,,	22/ 8/31	161	111	80	4	4	
42	,,	2/ 9/31	288	122	49	7	6	(6.5)
43	,,	19/ 9/31	160*	119	86	5	6	(9.0)
44	,,	2/10/31	160	105	76	7	5	(7.5)
45	,,	19/10/31	159	103	74	5	5	(7.7)
46	,,	6/11/31	163	111	79	5	4	(8.2)
47	,,	24/11/31	149	100	77	3	5	(7.3)
48	,,	19/12/31	153	77	58	5	6	(6.9)
49	,,	25/ 2/32	156	101	74	8	5	(7.5)
50	,,	22/ 3/32	127	78	71	7	4	(7.2)
65	,,	9/ 5/32	94	51	63	18	2	7.45
Mean (13 samples, No. 42 excluded)			148	97	75.5	7	4	
99	Above junction with Burka	11/ 7/32	212	133	72	20	6	

* Contains free sodium carbonate.

TABLE IV. BURKA—THEMI RIVER SYSTEM.

No.	Locality.	Date.	1 Total Bicarbonate, HCO_3. p.p.m.	2 “Soda,” Na_2CO_3. p.p.m.	3 Per cent Soda-alkalinity in total. %	4 Sulphate, SO_4. p.p.m.	5 Chloride, Cl. p.p.m.	6 pH
63	Burka Spring No. 2 (W)	1/ 6/32	301	207	79	31	4	7.5
102	,, ,,	11/ 7/32	316	231	84	18	8	
103	,, No. 1 (E)	11/ 7/32	364	250	79	20	9	
104	,, No. 3 (upper)	11/ 7/32	376	262	80	19	10	
62	Mololosyoke affluent	9/ 5/32	247	136	63	9	4	7.85
37	Burka R. at Mbugwe Rd. bridge	19/10/31	327	222	78	19	12	(6.7)
38	,, ,, ,, ,,	6/11/31	325	227	80	16	10	(7.5)
39	,, ,, ,, ,,	24/11/31	335	233	80	14	10	(7.4)
40	,, ,, ,, ,,	25/ 2/32	337	226	77	14	8	(7.4)
41	,, ,, ,, ,,	19/ 3/32	333	209	72	10	8	(7.0)
64	,, ,, ,, ,,	1/ 6/32	349	229	75	30	7	7.8
	Mean (6 samples)		334	224	77	17	9	
100	Burka above junction with Engare Narok	11/ 7/32	480	346	83	30	13	
101	Burka below junction with Engare Narok	11/ 7/32	316	212	77	22	9	
51	Themi at Arusha	3/10/31	117	56	55	5	4	(7.2)
52	,, ,,	19/10/31	126	76	69	8	4	(7.1)
53	,, ,,	25/ 2/32	124	78	73	4	3	(7.3)
54	,, ,,	31/ 3/32	117	72	71	7	4	(7.3)
68	,, ,,	6/ 5/32	62	25	47	14	?Tr.	7.45
107	,, ,,	12/ 7/32	102	59	67	6	2	
	Mean (6 samples)		108	61	65	7	3	
108	Nauru R., Arusha Township	12/ 7/32	143	58	47	12	4	
66	"Loloda" Furrow, Themi R.	2/ 5/32	89	40	52	10	1	7.4
106	Themi below junction with Burka	12/ 7/32	208	121	67	9	6	
109	Olgeju Loldiloi (Themi) below gorge	13/ 7/32	209	125	69	8	5	
67	Kijenge R.	2/ 5/32	119	33	32	16	2	7.45
105	Kijengi R. near house, Farm 151	12/ 7/32	192	61	36	8	5	

TABLE V. NDURUMU R., AND MANIRE—DULUTI AREA.

No.	Locality.	Date.	1 Total Bicarbonate, HCO_3'. p.p.m.	2 " Soda," Na_2CO_3'. p.p.m.	3 Per cent Soda-alkalinity in total. %	4 Sulphate, SO_4'. p.p.m.	5 Chloride, Cl. p.p.m.	6 pH
112	Nduruma, Upper Rd. bridge	16/ 7/32	83	41	57	4	3	
111	Nduruma, Moshi Rd. bridge	16/ 7/32	104	47	52	5	3	
69	,, ,, ,,	2/ 5/32	82	37	52	15	1	7.35
110	,, at Olgedereda (lower Nduruma)	16/ 7/32	105	49	53	9	3	
	Mean (4 samples)		94	44	54	8	2.5	
113	Manire Springs	16/ 7/32	65	8	14	5	2	
114	Sinana Springs	16/ 7/32	89	15	19	5	2	
115	Mkumbundu Springs	16/ 7/32	133	49	42	15	3	
116	Manire R. at Moshi Rd. bridge	16/ 7/32	167	55	38	5	3	
70	,, ,, ,,	2/ 5/32	157	55	40	15	3	7.55
117	L. Duluti (N.E. edge)	16/ 7/32	198	89	52	6	6	
118	Loingare Springs, Farm 97	16/ 7/32	141	72	59	15	4	

TABLE VI. TENGERU RIVERS.

No.	Locality.	Date.	1 Total Bicarbonate, HCO_3' p.p.m.	2 "Soda," Na_2CO_3. p.p.m.	3 Per cent Soda-alkalinity in total. %	4 Sulphate, SO_4'' p.p.m.	5 Chloride, Cl. p.p.m.	6 pH
119	Malala R., Upper Rd. bridge	16/ 7/32	66	35	61	9	2	
120	Malala R., Moshi Rd. bridge	16/ 7/32	91	49	62	8	3	
71	,, ,, ,,	2/ 5/32	75	36	55	13	1	7.35
55	,, furrow, Farm 131	30/10/31	112	70	71	5	5	(7.1)
56	,, ,, ,,	13/11/31	122	81	76	2	5	(7.1)
122	Nsungu-Makitengo junction (Upper Road)	15/ 7/32	85	55	74	5	5	
123	Tengeru, above junction with Uriilo	15/ 7/32	80	35	50	4	4	
124	Mpembe, Upper Rd. bridge	15/ 7/32	63	24	45	2	2	
72	Tengeru, Moshi Rd. bridge	2/ 5/32	103	47	52	4	2	7.45
126	Makumira R. above in-fall of Karamu	15/ 7/32	119	72	70	35	3	
73	,, Moshi Rd. bridge	2/ 5/32	146	71	56	2	4	7.55
75	Kigeri R., Capt. Rydon's dam	9/ 6/32	105	64	71	5	2	7.6
76	,, Moshi Rd. bridge	9/ 6/32	114	65	66	5	2	7.35
74	,, ,, ,,	2/ 5/32	112	70	72	4	2	7.6
127	Kigeri Ndogo Spring, farm 76	16/ 7/32	174	105	70	8	4	
128	Kigeri R. at junction with Tengeru	15/ 7/32	123	72	68	6	3	
125	Tengeru R. at junction with Kigeri	15/ 7/32	112	65	67	3	4	
121	Malala R. ,, ,,	15/ 7/32	96	46	55	4	4	
129	Combined Tengeru Rivers below Malala-Kigeri junction	15/ 7/32	117	69	68	6	5	

TABLE VII. USA RIVERS.

No.	Locality.	Date.	1 Total Bicarbonate, HCO_3' p.p.m.	2 " Soda," Na_2CO_3' p.p.m.	3 Per cent Soda-alkalinity in total. %	4 Sulphate, SO_4' p.p.m.	5 Chloride, Cl. p.p.m.	6 pH
145	Tema Springs, Magdarisho R.	15/ 7/32	124	72	67	5	4	
144	Magdarisho R., lower end of Tema Estate	13/ 7/32	149	81	62	5	4	
57	Ndurumanga Spring, Magdarisho R.	9/ 8/31	113	64	66	5	5	(7.8)
77	Magdarisho R., Moshi Rd. bridge	2/ 5/32	128	72	65	7	3	7.55
140	Usa Springs	14/ 7/32	136	99	84	6	5	
139	Usa R. from Western Springs	14/ 7/32	112	83	86	3	3	
138	Usa R. from Eastern Springs (above tributary from Ngongongare)	14/ 7/32	166	123	85	8	6	
137	Tributary to Usa R. from Ngongongare Swamp	14/ 7/32	279	221	91	6	1	
141	Usa R. at Kilimanjaro Saw Mills	14/ 7/32	130	99	88	6	4	
82	Usa furrow, intake	9/ 6/32	143	89	71	15	4	7.75
83	Usa furrow, end	9/ 6/32	146	101	79	10	3	7.65
142	Loliondo Spring, Usa R.	15/ 7/32	121	71	68	4	3	
78	Usa R., Moshi Rd. bridge	2/ 5/32	140	96	79	4	4	7.65
84	„ „ „	9/ 6/32	136	88	74	5	3	7.65
143	„ „ „	16/ 7/32	130	87	77	5	4	

TABLE VIII. MAJI-YA-CHAI AND COMBINED USA RIVERS.

No.	Locality.	Date.	1 Total Bicarbonate, HCO_3. p.p.m.	2 "Soda," Na_2CO_3. p.p.m.	3 Per cent Soda-alkalinity in total. %	4 Sulphate, SO_4. p.p.m.	5 Chloride, Cl. p.p.m.	6 pH
79	Chem Chem R., Moshi Rd. bridge	2/5 /32	277	201	84	3	4	7.9
136	Maji ya Chai Ndogo, on path to Loliondo's Chai Estate	14/ 7/32	341	277	93	3	4	
131	Garden Spring, Ngongongare, Maji ya Chai	14/ 7/32	174	124	82	8	6	
132	"Forest Stream," Ngongongare, Maji ya Chai	14/ 7/32	194	141	84	6	5	
133	Southern tributary, Ngongongare, Maji ya Chai	14/ 7/32	166	122	84	4	2	
134	Maji ya Chai, Loliondo's Chai Estate	14/ 7/32	305	231	87	14	9	
135	Maji ya Chai, Moshi Rd. bridge	16/ 7/32	340	265	90	11	11	
80	,, ,, ,, ,,	2/ 5/32	326	264	93	14	10	8.1
81	,, ,, ,, ,,	8/ 6/32	244	177	84	8	5	7.75
146	Combined Usa Rivers, Kalangai Drift	14/ 7/32	202	145	83	7	5	
85	Combined Usa Rivers, Kalangai Drift	9/ 6/32	244	167	79	5	4	7.9
130	Kikuletwa R. below junction of combined Tengeru & Usa Rivers	15/ 7/32	151	98	75	6	1	
147	Kikuletwa R. at Engare Rongai Sisal Estates	14/ 7/32	150	102	78	5	4	

TABLE IX. ENGARE NANYUKI RIVERS.

No.	Locality.	Date.	1 Total Bicarbonate, HCO_3. p.p.m.	2 “ Soda,” Na_2CO_3. p.p.m.	3 Per cent Soda-alkalinity in total. %	4 Sulphate, SO_4. p.p.m.	5 Chloride, Cl. p.p.m.
88	Engare Nanyuki (Mangas), Main Stream at Momela	8/ 7/32	872*	732	97	159	76
87	Engare Nanyuki sweet stream at Momela	8/ 7/32	627	522	96	59	32
86	Engare Nanyuki below falls at Momela	8/ 7/32	723	579	92	93	39
89	Engare Nanyuki small stream, Momela Gate	8/ 7/32	740*	624	97	112	56
90	Engare Nanyuki larger stream, Momela Gate	8/ 7/32	742*	636	99	102	55
92	Engare Nanyuki at Kiranyi Ford	9/ 7/32	672	565	97	65	40
91	Kiranyi stream flowing across salterns	8/ 7/32	1446*	1278	(>100?)	63	73
93	Kimosan Spring	9/ 7/32	412	317	89	33	19
94	Kimosan furrow to Farm 29	9/ 7/32	414	317	88	25	19
58	,, ,, ,,	16/ 3/32	452	318	81	33	25
95	Kimosan “ Spruit,” below Police Post	9/ 7/32	532	388	84	34	16

* Contains free sodium carbonate.

174 Momela Lake (2nd or principal lake) CO_3, 2494 ppm $=$ Na_2CO_3, 4404 ppm.
HCO_3, 3177 ppm. $=$ $NaHCO_3$, 4376 ppm.
SO_4, 890 ppm. $=$ Na_2SO_4, 1316 ppm.
Cl, 369 ppm. $=$ NaCl, 608 ppm.

TABLE X. OL DOINYO SAMBU AND NORTHERN STREAMS.

No.	Locality.	Date.	1 Total Bicarbonate, HCO_3. p.p.m.	2 “Soda,” Na_2CO_3. p.p.m.	3 Per cent Soda-alkalinity in total. %	4 Sulphate, SO_4. p.p.m.	5 Chloride, Cl. p.p.m.	6 pH
96	Natgonosais R., furrow to Farm 227	9/ 7/32	205	158	89	18	9	
97	Engare Narok (N) R., furrow to Farm 217	9/ 7/32	390	275	81	20	6	
98	Valatia R., furrow to farm 214	9/ 7/32	316	222	81	18	3	
59	,, ,, ,,	14/ 3/32	331	217	76	11	4	(8.3)

For those streams which were sampled repeatedly at the same point the tables include an average figure, but the samplings are also reported individually in full, as the detailed figures possess an interest which a mere statement of averages would withhold. The averages should be regarded only as convenient signposts. For most of the streams we can offer only a single analysis at any one point. Interpretation of detail in particular cases should therefore be cautious, as small differences may have no significance.

In spite of sampling-limitations, however, the tables show very clearly the features common to the Meru waters as a group, and also that well-marked differences exist which correspond to the geographical grouping of the streams and their head-waters around the mountain.

The outstanding common features are, *first*, a high, frequently very high, proportion of “ soda ” in the total alkalinity, and a correspondingly low content of the alkaline-earth bases; *second*, a relatively low content of neutral salts (sulphates and chlorides).

The first point is illustrated by the following summary of the figures bearing upon it in the tables. The samples came in all from 90 localities within the area. The streams at only 10 localities (11 samples) contained less than 50 per cent. of their alkalinity as “ soda.” 75 localities (126 samples) contained 60 per cent. or more, 60 localities (110 samples) 70 per cent. or more, 37 localities (57 samples) 80 per cent. or more, and 14 localities (15 samples) 90 per cent. or more of their alkalinity as " soda." The absolute amounts of " soda," calculated as parts of sodium carbonate per million of water, ranged up to 280 p.p.m. outside the Engare Nanyuki area, and up to 730 p.p.m. including that area but still excluding some extreme cases.

With regard to the second point above-mentioned, it will be seen that figures exceeding 20 p.p.m. of sulphate or 10 p.p.m. of chloride are rare, except in the Engare Nanyuki area.

Turning now from the common features to the differences, and considering first the soda-alkalinity, the range of variation met with and the position of individual streams can be judged from the diagram, Fig. 1. Here the total alkalinity is plotted horizontally and the percentage of soda-alkalinity in the total is plotted vertically. The data are those of columns 1 and 3 of the tables, and the points are labelled by their serial sample-numbers. Each locality (i.e. each separately-sampled point along the course of a stream) is represented once only, the averages being employed, in the " signpost " sense, for localities sampled repeatedly. In these cases the designating number on the diagram is that of the earliest sample taken.

The scattering of points is considerable, but they lie mainly in the upper half of the diagram above the 50 per cent line. The higher total alkalinities lie entirely above the 70 per cent. line, and there is a general upward trend of the points towards the right-hand side of the diagram. It appears from this that the local circumstances which lead to a high total amount of alkaline dissolved matter lead also, on the whole, to a high proportion of soda in it. (Two examples of non-conformity with this will be noted later.) The converse is however not true. There are points above the 80 per cent. line across the whole width of the diagram: that is, streams of quite low or moderate total dissolved matter may still contain a high proportion of it as " soda."

With the aid of Fig. 1 and the data of the tables, it is possible to group the waters by composition, adopting the percentage of " soda " in the total alkalinity to define the groups. The result is Table XI.

TABLE XI.

GROUPING OF STREAMS BY PERCENTAGE OF SODA IN TOTAL ALKALINITY.

Group.	Per cent. soda in total.	Name of stream.	Total bicarbonate (approx. range).
A	85—100%	Engare Nanyuki	400—800 p.p.m.
		Maji-ya-Chai	250—350 p.p.m.
		Headwaters of Selian	
		Headwaters of Usa	75—150 p.p.m.
		Headwaters of Engare Narok	
B	75— 85%	Ol Doinyo Sambu streams	200—400 p.p.m.
		Burka	
		Selian	
		Engare ol Motonyi	
		Headwaters of Maji-ya-Chai	150—200 p.p m.
C	65— 80%	Engare Narok	100—200 p.p.m.
		Themi (variable)	
		Usa River	
		Magdarisho	
		Kigeri	
		Kikuletwa	
		Tengeru, lower reaches.	
		Malala furrow	
D	50— 60%	Malala, except Malala furrow	50—150 p.p.m.
		Tengeru, upper reaches.	
		Nduruma	
		Loingare	
		Themi (variable)	
E	30— 50%	Kijenge	100—200 p.p.m.
		Manire.	
		Nauru	

The significance of this grouping is at once apparent when it is compared with the sketch-map and the notes on topography and climate already given. Groups A and B, with the highest proportion of soda, form a horseshoe enclosing the mountain but open to the south, having its horns on the S.W. and S.E. flanks. These groups include the dry northern and western, ash- and tuff-covered slopes, also the region of the crater and the slopes carrying recent eruptive material, below its great eastern breach. Proceeding south-westward from the eastern extremity of the horseshoe, and south-eastward from its western extremity, Group C, with more moderate proportion of soda, is entered upon from both directions, but it is not continuous across the southern slopes, for the wettest, southern face of the mountain is occupied by Groups D and E, with the lowest soda-content. Groups D and E drain the geologically less recent, or at any rate more fully-weathered, formations, which carry brown or grey-brown loam soils, as distinct from the powdery grey or yellow-grey immature soils of the east, north and west.

The streams differ less markedly amongst themselves in neutral-salt content, except for the Engare Nanyuki and Kimosan, which to their high total alkalinity and Group A soda-proportion add a high content of both sulphate and chloride. It is, however, possible to distinguish a grouping amongst the other streams. Their content of sulphate and chloride is low and fairly uniform, but the ratio of these to total alkalinity shows an interesting geographical distribution round the mountain. In Table XII, total bicarbonate is put at 100 for all samples, and sulphate and chloride recalculated proportionately. The streams are listed in the order in which they would be encountered in proceeding round the mountain counter-clockwise, starting from Ol Doinyo Sambu.

TABLE XII.

PROPORTION OF SULPHATE AND CHLORIDE TO TOTAL ALKALINITY.

Streams.	Bicarbonate. HCO_3	Sulphate. SO_4	Chloride. Cl.
West and South-West.			
Engare Narok (N.)	100	5	2
Valatia	100	5	1
Engare ol Motonyi	100	4	2
Selian	100	5	2
Burka	100	6	3
Engare Narok	100	5	3
Themi	100	6	3
Mean for the group	100	5	2.5
South.			
Nauru	100	8	3
Kijenge	100	8	3
Nduruma	100	9	3
Manire	100	7	2
Loingare	100	11	3
Malala	100	10	4
Mean for the group	100	9	3
South-east.			
Tengeru	100	4	3
Kigeri	100	4	2
Magdarisho	100	4	3
Usa	100	4	3
Maji-ya-Chai	100	3	2
Kikuletwa	100	4	2
Mean for the group	100	4	2.5
East.			
Momela Lake	100	14	7
Engare Nanyuki	100	11	4
North..			
Kimosan	100	7	4
Natgonasais	100	9	4

The figures for each natural group of neighbouring streams are closely consistent among themselves, but those for different groups are well contrasted. It appears that there is more sulphate per unit of dissolved matter in the streams of the wet south side of Meru than elsewhere on the mountain except in the Engare Nanyuki and its two small northern neighbours. This point has some geochemical interest, which is discussed later; but the table as a whole emphasizes the non-significance of dissolved neutral salts in the region generally.

A number of items of local interest in connection with particular streams may be mentioned here before proceeding further. The order followed is that of Tables I to X.

ENGARE OL MOTONYI (Table I). This is the farthest west of all the streams on the south side, and eventually loses itself in the Masai steppe between Meru and Ol Doinyo Lolkisale to the south-west. The Forest Station is some miles upstream and about 500 ft. higher than the Nairobi Road Drift, whereas the Mbugwe Road Drift is downstream and about 100 ft. lower. The samples are consistent in composition throughout.

SELIAN (Table II). The Selian river loses itself in irrigation channels and in its own bed before joining the Burka stream below the Burka Springs, but the dry watercourse can be traced to the junction. The samples are somewhat lower in absolute amounts of dissolved matter than those of Table I, but the percentage soda-alkalinity is similar. The sulphate-content varies rather more, but about the same mean. No 148, taken at the forest boundary, upstream of the other points of sampling, contains a markedly higher percentage soda-alkalinity than the rest—contrast the parallel sample, No. 19, for Engare ol Motonyi.

ENGARE NAROK (Table III). This joins the Burka-Themi river-system at certain seasons, but for much of the year the lower part of its river-bed is dry. It has only about half the total alkalinity of its neighbours to the west, but with a similar proportionate soda-percentage. Samples Nos. 150, 151, and 152 are of interest in that it was noted at the time of sampling that the tributary which now proves to contain the greatest absolute soda-content (No. 150) drained a conglomerate formation while the other two came from lava. The forest samples as a group resemble the Selian forest sample (No. 148, Table II) in containing a larger proportion of soda than the main stream below; their alkaline-earth content is extremely low. Samples 42 and 48 present an anomaly which is discussed later (p. 25). The high pH value of No. 43 corresponds to its content of free sodium carbonate—an exceptional occurrence, not paralleled in this part of the district in any other sample, but occurring frequently in the Engare Nanyuki area (see Table IX). The usual form in which the " soda " occurs is of course sodium bicarbonate, with a much less alkaline reaction to indicators.

BURKA-THEMI RIVER SYSTEM (Table IV). The Burka and the Themi join some way south of Arusha, and thereafter are known as the Olgeju Loldiloi, which flows south-east in a deep gorge. On leaving the gorge it turns due south and loses itself 10 miles further on in the Shambarai swamp.

The Burka clearly belongs as to composition to the group of alkaline streams to the west. It has a maximum alkalinity just above its junction with the Engare Narok, and it appears from this and from a comparison of sample No. 99 of Engare Narok, taken near this point, with the rest of the Narok samples (Table III), that both streams receive an accession of very alkaline seepage water from the ground near their junction.

The Nauru, Themi, and Kijenge are of variable composition, but belong as a whole to the less alkaline groups. Some of the samples were amongst the purest waters found in the area. The Kijenge has its alkalinity mainly in the desirable form of alkaline-earth bicarbonates.

NDURUMA (Table V). Few samples are available for this, but they are enough to make it clear that it is one of the purer rivers. The Nduruma flows into the Kikuletwa at a point below any sampling that was made of the latter river. It collects practically the full amount of its flow within the forest reserve, and runs for the greater part of its course in deep gorges lined with trees. It appears from samples 112, 111, and 110, all taken on the same day, that an accession of alkaline water is received, containing however a smaller proportion of soda, between the crossing of the upper foot-road and that of the Arusha-Moshi main road. Presumably this is from the Songota and Baraa tributaries.

MANIRE-DULUTI AREA (Table V). The Manire and Loingare rivers follow separate courses south-east, and eventually join the Kikuletwa. They are amongst the purer streams. The Manire receives its water from springs arising below the forest level. These (Nos. 113, 114, 115) vary a good deal amongst themselves.

Sample 117 was taken from the N.E. edge of Lake Duluti and may not fairly represent the lake as a whole. It contains somewhat more soda than the streams of the neighbourhood, which may be due merely to a precipitation of alkaline-earth bicarbonates on the lake-bottom, and a slight accumulation of soda in solution. The water is quite " fresh," though there is no known surface inlet or outlet.

TENGERU RIVERS. (Table VI). Under this head have been grouped the Malala and all streams east of it which join with the Kigeri before flowing south-east to the Usa River to form the Kikuletwa. They belong to Groups C and D of Table XI, and in general the head-waters have less alkalinity than the lower courses.

USA RIVERS (Tables VII and VIII). In this group are placed all the remaining rivers of the south side of the mountain. They all join together above the railway bridge at Usa River Station, and further down join the Tengeru rivers to form the Kikuletwa.

The Usa River proper falls into Group C, but its own headwaters and the Maji-ya-Chai fall into Group A with a very high proportionate soda-alkalinity. All samples to the east of the Usa furrow (which itself appears to receive more soda as it passes along) contain considerably more soda than any others on the south of the mountain as far as beyond Arusha on the west. The sources of the Maji-ya-Chai at Ngongongare carry much less dissolved matter than the main stream further down, and by the time it reaches the Moshi road it has approximately doubled its content of soda. Much alkaline seepage-water evidently reaches it about its middle course.

The Kikuletwa in its lower course, after leaving the Meru foothills, receives the waters of the Shira stream and the Kikafu River, both draining from western and south-western Kilimanjaro; but continues under the same name until, at Arusha Chini, it receives the Weru-Weru, carrying the combined waters of the south flank of Kilimanjaro. An observation made by one of us (G.M.) at this junction is of interest. The Kikuletwa, carrying mainly Meru water with some addition of purer water from Kilimanjaro, was turbid, with pH=8.7 (a rough colorimetric test). The Weru-Weru, carrying Kilimanjaro waters only, was quite clear, with pH=8.0 (March 26th, 1932). The confluence is shown in the photograph, Plate II.

ENGARE NANYUKI (Table IX). The course of the main stream has already been described (p. 3). The Kiranyi stream flows across grassy flats, on which, in many bare or scorched patches, soda-incrustations were much in evidence at the time of sampling.* Sample No. 87 is from a small tributary to the Engare Nanyuki, locally considered a " sweet " stream.

These streams are by far the most alkaline, and also the most saline, of all the flowing waters of the Meru drainage. In four of the samples free sodium carbonate was present, giving a red colour with phenol-phthalein.

The sample from the Momela lakes (No. 174) is a very concentrated water. The high soda- and salt-content of these lakes is due to their lying in a closed drainage area, into which much water of the

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* Soil samples taken in the green turf of these flats have been found to have a pH=10.2, measured by the hydrogen electrode in a 1:2½ soil:water suspension.

Engare Nanyuki character enters, and there concentrates by evaporation.

OL DOINYO SAMBU (Table X). These streams flow off the western and north-western slopes, in deep-cut, precipitous gorges, and are lost in the plain. On the whole they resemble the streams of the south-west.

COMPLETE ANALYSES OF COMPOSITE SAMPLES.

These are available for the Tengeru, Usa, and Maji-ya-Chai groups of rivers only. The results are contained in Table XIII. The total content of dissolved inorganic solids is represented by the figure "salinity,"* in parts per million. The figure "soda" has the same conventional meaning as in column 2 of Tables I to X. The remaining figures express the percentage composition of the dissolved inorganic solids, all bicarbonates being calculated to their equivalent in normal carbonates in arriving at the figure CO_3. The absolute content of silica is also given, in parts per million.

TABLE XIII. COMPLETE ANALYSES, COMPOSITE SAMPLES.

	Tengeru R.	Usa R.	Maji-ya Chai.
Salinity	151 p.p.m.	155 p.p.m.	281 p.p.m.
CO_3	38.43%	46.14%	49.75%
Cl	2.05	2.65	2.35
SO_4	2.32	3.11	2.39
Ca	9.74	7.96	4.21
Mg	1.13	0.52	0.57
Na	16.17	24.79	29.54
K	4.24	6.28	7.13
$Fe_2O_3 + Al_2O_3$	2.52	3.11	2.21
SiO_2	23.40	5.44	1.85
	100.00	100.00	100.00
"Soda," p.p.m.	57	91	201
SiO_2, p.p.m.	35.5	8.5	5.2

The new features brought out by the complete analyses are the great differences in the silica-content of the three rivers, the great excess of calcium over magnesium, and the considerable amounts of potassium present, occurring in a constant ratio of about one quarter of the amounts of sodium.

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* An unfortunate term in the present connection, since the waters in question are not appreciably "saline" as the word is usually understood, i.e. their neutral-salt content is small. We use the term here for the sake of uniformity with the form of statement adopted throughout in F. W. Clark's standard compilation (9) (1924), from which some analyses are quoted at the end of this paper for comparison.

It is clear that the materials from which the three rivers derive their soluble matter are very different in character, or if originally similar, are now in very different stages of weathering. This will be discussed presently.

OTHER DETERMINATIONS.

As has been mentioned, the determinations of hydrogen-ion concentration were abandoned at an early stage, but the figures obtained may be briefly commented on. In general they are well on the alkaline side, but afford little further guidance to the amount or composition of the matter in solution. In two instances, however (No. 31, Selian, and No. 42, Eng. Narok), an anomaly occurs, which may indicate the presence in those samples of fair amounts of *phosphate*. The pH values fall on the acid side of neutrality, yet they are accompanied by an unusually high titratable alkalinity, of which an unusually low proportion consists of " soda." A third example, not so well marked, is No. 48 (Eng. Narok). Phosphoric acid is the only one of all the weak acids likely to occur in natural waters that has a greater dissociation-constant than carbonic acid; and the suggested explanation is supported by qualitative tests on the waters, by the occurrence of phosphate in the salt-deposit samples to be described later in this paper, and from the mention by Mauritz (loc. cit.) of apatite as an accessory mineral in all the rocks he examined. The kenyte from south Meru which he analysed had 0.63% P_2O_5, a fairly high figure.

It is of interest to note an example of how imperfect a picture of a water's dissolved alkaline matter is given by either total alkalinity or pH, separately, or even by the two together when the soda-content is not stated, from the recently-published accounts by Worthington and others ((^{7}) and (^{8}) (1932)) of the results of the Cambridge expedition of 1930-31 to the lakes of Kenya and Uganda. Lake Edward, with a titratable alkalinity of .01 normal, had pH=8.7 to 8.9. Lake George, alkalinity .002 normal or one-fifth of the other, had pH =9.3 to 9.9. The local evidence adduced as to soda-content is that L. George receives none but relatively pure waters from Ruwenzori, a non-volcanic massif, while Lake Edward receives soda-bearing waters from the Mfumbiro volcanoes. Yet from the figures quoted above it might have been concluded very reasonably that it was L. George that had the higher proportion of soda in its total alkalinity, as shown by its much higher pH values.

The possibility that the Meru waters contain *borates* has been considered, as boron compounds are often associated with the products of volcanic action. When present in water used for irrigation they may be a cause of injury to crops. Thus certain Californian waters (see Schofield and Wilcox (^{10}) (1931)) were found to be damaging fruit trees from this cause, and it was concluded that a boron-content of more than 1 part per million may be injurious to boron-sensitive plants.

The determination of boron in waters in such small amounts as these, even qualitatively, requires rather large samples and considerable precautions, particularly in the use of boron-free laboratory glassware, and in the present work both chemist's time and the quantities of sample were too limited for us to proceed far in the matter. Some of the Selian, Engare ol Motonyi, and Engare Narok samples were examined with results that were inconclusive except as indicating that no very large quantities of boron are present. The matter may deserve fuller investigation at some time if any question on the point arises in the district as a field problem.

The brown colour of the Maji-ya-Chai, and the red colour of the Engare Nanyuki—the origin of both their names—appear to be due simply to the fact that these alkaline rivers pass through, or receive seepage from, swamps containing much humic material readily soluble in alkali. Though already alkaline, the Engare Nanyuki at Momela Gate (far upstream) is quite clear and colourless, and the Maji-ya-Chai upstream of Ngongongare has the same appearance. The Momela Lake sample (No. 174) is much more alkaline than any of the Nanyuki samples, but is practically colourless when its greenish scum is filtered off.

INTERPRETATION OF THE RESULTS.

The trend of the conclusions to be drawn from the analyses, from the point of view of the use of the waters in irrigation, will have become apparent during the foregoing partial discussions. The features common to the area as a whole were noted on p. 16. It is clear that sodium sulphate, the characteristic salt of certain types of alkali-soils, and sodium chloride, can be dismissed from consideration throughout most of the district. The amounts of them are negligible, except in the Engare Nanyuki area, where in any case the waters are unsuitable on other counts.

The soda-content of the waters, and its relation to the alkaline earth bicarbonates present, is however a matter not to be dismissed so summarily. The state of affairs represented by the analytical data is one that renders caution necessary in matters of irrigation *throughout the whole area.* This is not to say that water-qualities as a whole are so bad that none of the streams may be safely used if proper precautions are taken. But soda-alkalinity is an undesirable property, and it is so widespread in these streams, and its degree so high in many localities, that the general attitude in the district should be towards avoidance of irrigation wherever possible: and if the case for irrigating a particular farm or a particular crop is strong on all other counts and a decision to irrigate is taken, then the local water should be examined and advice sought on the best methods of using it safely.

The analysis by groups given in Table XI may be re-stated as follows. The risk of encountering the disadvantages of high soda-content diminishes as one passes from the districts of Groups A and B, where it is almost a certainty, through Group C where the total alkalinity is likely to be less and the proportion of soda slightly less, to Groups D and E where lime-alkalinity bulks more largely in the total and soda-alkalinity, though still present, is not very great.

The agricultural literature of semi-arid regions contains many attempts to frame criteria by which a water may be judged when the local circumstances attending its use are known. For example, Hoagland and Christie ([11]) (1919) consider the dissolved matter found in the water under four categories: primary and secondary alkalinity, which we may label for convenience I and II, and primary and secondary salinity, III and IV. Category I is approximately the " soda " of our tables, II is the alkaline earth bicarbonates, III the alkali sulphates and chlorides, IV the alkaline earth sulphates and chlorides. Roughly speaking, a water is the better the more it has of II, and the worse the more it has of I and III, IV being indifferent in moderate quantities. If calculated in these terms, for most of the Meru streams I is fairly high, II variable but on the whole low, III and IV almost absent. The conclusions on quality would therefore be similar to ours above.

It is impracticable to attempt, on the data to hand, a labelling of particular streams as good, bad, or indifferent, except as above in a generalised statement of probabilities, and this is all we are justified in offering. For most of the streams we have not examined seasonal fluctuations in composition, and uncertainties always attach to the analysis of single samples. But apart from these limitations, it is impossible to judge a water finally without reference to how it is to be used, and especially to the drainage that is to be provided. A relatively pure water may do damage if it is used irresponsibly; and one of poor quality may do good service in the hands of one who is prepared to go to trouble and expense in providing against the risks he is incurring.

As regards the other factors entering into one's judgment of an irrigation-water, an essential one, namely the degree of tolerance of the irrigated crop to concentrations of salt or soda in the soil, is almost unknown for the principal crop of this area. Coffee elsewhere in the world is usually grown in places where the rainfall is ample and the soils are leached, so that the question does not arise. The Meru area will itself no doubt provide the information, when its established population of coffee-trees comes to be studied in detail from this viewpoint. Mention of the gross amounts of " soda " likely to be involved per acre when irrigating with typical waters, is made in the concluding section of this paper.

From a geochemical point of view the composition of the streams fits in very well with the other components of the picture for the mountain. As has been mentioned, petrological information is scanty, but that available is to the effect that the rocks of Meru have been derived from a magma which is basic or moderately basic, and alkalic, i.e. having a low to medium silica-content, and a predominance of soda-bearing minerals. Such rocks weather rapidly. Their first stages of decomposition yield carbonates of the alkalies (Na, K) and alkaline earths (Ca, Mg), the former in considerable excess. At a later stage, under humid conditions of weathering where the soluble products can be carried off, the silicates break down further, yielding again carbonates of the bases, together with silica, to the percolating waters; but as this stage is reached after the original excess of alkali-bases has been lost in the drainage, the carbonates are now principally those of the alkaline earths. Weathering is assisted by fineness of sub-division, and an ash or pumice will decompose throughout its bulk more rapidly than a compact glassy or crystalline lava under similar climatic conditions. Under moderate but periodic rainfall and high evaporation, an ash of the given composition will develop an abundance of alkali carbonates to be washed into the periodic streams which drain it; but they will be very incompletely washed out, and the onset of the second (lime- and silica-yielding) stage of weathering will be slow. The streams therefore receive much soda, proportionately little lime, and very little silica. This is the condition of Groups A and B of Table XI. On the south of the mountain, however, zones of high or moderate rainfall occupy the whole of the slopes. Such of the superficial rocks as were ash or tuff are probably weathered by now quite beyond their first (soda-yielding) stage, and the main bulk of their soluble products has long since gone in the drainage of the past. In so far as they have survived bodily removal by mechanical erosion, their soluble products of to-day will be those of stage 2. The underlying hard lavas, more resistant to mechanical erosion and weathering more slowly, are likely to be yielding soluble products of both stages, i.e. still containing much soda but with fair amounts of lime and silica. This corresponds with the ascertained composition of the southern streams. The variable nature of the rocks from point to point, and in particular the occurrence of relatively young deposits in the neighbourhood of subsidiary craters or vents formed late in the volcanic history of the mountain, will account for the few local anomalies. The fact that the rivers of Tables VII and VIII (Usa and Maji-ya-Chai) lie on a sector having broad high-rainfall zones, and yet include some with notably high soda-content, is by no means an anomaly, for the high-soda streams lie to the east, and drain the slopes below the great breach of the main crater. The superficial rocks here are either a fine powdery ash that must belong to a relatively late eruption, or shattered lava débris from the destroyed crater-wall. They form a large bulk of material well advanced into, but not past, the early stages of weathering.

In view of the evidence from the complete analyses (Table XIII) that potassium occurs in a steady ratio along with sodium in the waters, it will be understood that the word " soda " in the above discussions generally means soda and potash. The ratio of potassium to sodium in the waters is however less than that commonly found in eruptive nepheline-bearing rocks. Mauritz (loc. cit. (5)) gives no analysis for his nephelinite, but a somewhat less basic trachydolerite (or kenyte) from the plain at the S. foot of Meru contained

SiO_2	CaO	MgO	Na_2O	K_2O
52.7%	5.0	1.6	8.0	3.9

This is fairly typical of the usual proportions of the alkali-bases in such rocks. They are therefore yielding soda more rapidly, as they weather, than potash, in proportion to the amounts present. The effect may of course also be due in part to the occurrence of eruptive material on Meru much richer in soda than such rock-analyses as that above-quoted would lead one to expect. The discussion cannot however be carried further until more complete analyses are available, both of rocks and waters.

Mauritz's petrographic descriptions include mention of *sodalite* as an accessory mineral, and he reports 0.32% Cl in the above-mentioned trachydolerite. This is sufficent to account for the small and very steady chloride content of the waters (except Engare Nanyuki). It is unlikely that chloride is derived in appreciable amounts either from human pollution or as " cyclic " salt, i.e. salt returning from the sea *via* the rain-bringing winds.

Sulphur-bearing minerals are not mentioned by Mauritz, but it seems likely that in these rocks the sources of sulphate are minerals of the noselite or häuynite type. As in other volcanic regions, native sulphur and sulphides may possibly occur. Table XII appeared to indicate that the sources of sulphur occur more variably around the mountain than do the sources of chloride. The waters of south and of north Meru contain more sulphate per unit of bicarbonate than the rest. As regards the north, this effect and the high chloride-content are probably both ascribable to the extremely fresh state of the recent ejecta, and especially the ash-cone, in the main crater where the Engare Nanyuki rises. Sulphates and chlorides are not improbably there as direct reaction-products of acid volcanic gases upon alkali-rich minerals. As regards south Meru, the greater proportionate sulphate-content may conceivably reflect mineral differences, but may simply be due to the greater activity of vegetation under the more generous rainfall, and hence to a more rapid turnover of sulphur in the decomposition of plant-protein.

THE INFLUENCE OF RAINFALL. SEASONAL VARIATIONS.

It is to be expected that the composition of a stream at any given point will bear some relation to season, and in particular to rainfall, for the different formations of the catchment area will not contribute in the same proportions to the total volume of flow in times of heavy and light rainfall. For two of the streams sampled (Eng. Narok and Eng. ol Motonyi) we hoped to be able to trace the relationship. There are rainfall-measuring stations in the forest belt at their headwaters, and rough gauges of stream-volume were fixed at the points visited for the periodical samplings. The graphs constructed to compare the three sets of observations have however afforded no conclusions except an indication that the effect of heavy rainfall is to dilute the water somewhat—not a startling result, but showing that run-off water, in spite of its greater erosive power, carries off less dissolved matter than does percolating water penetrating the deeper soil horizons.

Some points however deserve mention. The fluctuations in chemical composition are relatively slight, except at the onset of the long rains for the Engare Narok (samples 50 and 65). There is a low flow in both streams from August to October inclusive, which, as measured at the gauges, is partly due to the great demand for water for irrigation purposes during those months at points upstream. The demand is very much reduced by January when the main crops are harvested or are approaching harvest time, and still further by February. The actual lowest water in the rivers if this is allowed for is probably at the end of January or early February, or some six weeks after the end of the short rains. It may be noted that for the Usa River, on the wetter southern slopes, it is locally well known that the greatest flow comes two to three months after the greatest rain. The samples taken from the Usa in early May, mid-June, and mid-July (Nos. 78, 84, 143) therefore correspond approximately with periods both before and at the peak of the long rains; yet the differences in dilution are relatively slight.

The graphs have not been considered worth reproducing for publication. Their inconclusiveness has an interest as a demonstration that the seasonal behaviour of streams cannot be profitably studied without setting up a thorough organisation for the work. The readings of a single rain-gauge near the headwaters of a river are altogether too slender a basis on which to form an estimate of the precipitation in its whole catchment area. If sampling-dates are spaced more than a few days apart, a spate or high-water peak may easily be missed and critical information thus lost. Yet if sampling is done very frequently, the burden both of travelling and of analytical work becomes serious. Stream-gauging with accuracy is no easy matter. And the observations should relate to the full cycle of seasons over several years. That such work upon some of the Meru streams would produce results of much scientific interest and local value, there can be no doubt; but it seems unlikely that the importance of the streams will justify undertaking it on economic grounds.

COMPOSITION OF SALT-DEPOSITS.

While collecting the water-samples the opportunity was taken to examine and sample certain minor salt-accumulations that occur here and there in the district. Analyses of these are given below (Table XIV).

TABLE XIV. SALT-DEPOSITS.

	No. 1. Sanya.	No. 2. Kiranyi.	No. 3. Engare Nanyuki Falls.	No. 4. Burka.	No. 5. Usa.	No. 6. Tengeru.
SiO_2 ...	6.87%	14.55%	18.73%	12.47%	9.10%	10.51%
Fe_2O_3 Al_2O_3 } ...	4.36	11.08	23.43	7.13	11.57	10.02
$Ca_3(PO_4)_2$	1.16	2.36	2.80	1.04	1.52	0.83
$CaSO_4$ ...	3.68	5.41	2.26	tr.	—	3.33
$CaCO_3$ ...	0.48	—	2.72	8.54	5.37	0.34
$MgCO_3$ ...	1.54	—	—	tr.	tr.	0.45
Na_2SO_4 ...	—	2.69	—	—	—	—
$NaCl$ ...	4.74	2.95	1.64	tr.	0.60	3.48
Na_2CO_3 ...	43.08	34.92	30.03	56.89	54.40	47.76
$NaHCO_3$ ...	34.09	26.04	18.39	13.93	17.44	23.28
	100.00	100.00	100.00	100.00	100.00	100.00

They consist of deposits at lake edges, and the residues left by seepage waters as they evaporate. No. 1 is a dirty grey amorphous material which is deposited at the edges of the Sanya salt-lakes, whose waters are very alkaline in reaction. No. 2 is a similar sample from the Kiranyi salt flats near the Engare Nanyuki. No. 3 was collected from the cliff face at the Engare Nanyuki Falls at Momela. It has a light brownish colour and occurs in a conglomerate formation at a depth of about 100 ft. from the surface. Nos. 4, 5, and 6 are " seep salts " that occur on the surface of the ground at Burka, Usa and Tengeru respectively.

They are all essentially soda-deposits, and confirm the general picture given by the water-analyses. The results are expressed as percentages (in the sample) of constituents soluble in hot dilute hydrochloric acid. The alkali carbonates and bicarbonates, putting sodium and potassium together, were calculated from the excess of CO_3 and HCO_3 over that required to combine the alkaline earths. The sesquioxides are conspicuously high in No. 3, and appear to be mainly alumina. All samples contain phosphate in appreciable amounts, from which it would appear that the soils and rocks of the district carry phosphate in fair quantities. Sulphates and chlorides are present in minor amounts only, as in the waters. The molecular ratio of Na_2CO_3 to $NaHCO_3$ in the two lake-edge deposits is very nearly that of the mineral *trona*, which is the chief soda mineral worked at Lake Magadi in Kenya.

All these salt deposits are collected locally by the natives and fed to cattle. Those at Sanya are in the Chagga country, the remainder are used by the Wa-Meru except that at Burka, which is the property of the Wa-Arusha.

THE AGRICULTURE OF MOUNT MERU.

It remains to add a short account of the relevant features of native and European agriculture, to assist in placing the subject of stream-composition in its proper relation to local economics.

NATIVE AGRICULTURE.

Two tribes are found on Meru, namely the Wa-Meru, who are akin to the western branches of the Wachagga of Kilimanjaro, and the Wa-Arusha, a tribe speaking a language similar to that of the Masai of the surrounding plains, and further imitating many Masai customs. The Wa-Meru occupy the southern foothills of the mountain between the Usa and Nduruma rivers, and the Wa-Arusha the south-western foothills between the Nduruma and the Engare ol Motonyi. Both adopt almost the same agricultural practices. Neither tribe has been long in the land, but no trace of former inhabitants, if any, is to be observed.

Old native furrows exist taking water from all the streams in the areas above-mentioned except the two, Usa and Engare ol Motonyi, which form respectively their eastern and western boundaries. Furrows of recent date are taken from all the streams on the southern slopes without exception. The Masai of the steppes surrounding Meru have two large furrows for the purpose of watering stock. One, in the north, carries water from the Engare Nanyuki on to the Engasserai plains between Kilimanjaro and Longido. The other carries water from the Engare ol Motonyi to the Kisongo plains south of Mondul mountain, west of Arusha. The construction of this latter furrow played a very important part in the history of the district, for it was for this purpose that the Wa-Arusha were brought by the Masai as slaves from the area south of Moshi now known as Arusha Chini. After the completion of this work they were released and settled on the slopes of Meru.

Both the agricultural tribes settled in forest country, approximately between 4,500 and 6,000 feet above sea level, and did not use the grasslands for cultivation. This forest country has a soil of light yellowish grey colour, dusty when dry and very open and light in texture, but apparently more mature than the grey soils of the grasslands. They irrigate extensively with water of the better qualities, the principal streams used by them being those of Groups C, D, and E of Table XI. The crops irrigated are chiefly maize, eleusine, and to a less extent bananas.

The rainfall over the original area occupied by the tribes varies from 25 inches in the extreme south-west of the Wa-Arusha country to 60 inches and more along the forest boundary, and for the most part averages 45 to 50 inches.

PLANTATION AGRICULTURE.

From 1908 to 1914 under the former German Government large areas of land about Meru were alienated, and the cultivation of coffee was commenced. Most of the early plantations were started in or immediately adjoining the "Loliondo"* forest which formed the southern (lower) boundary of the land in native occupation. The soil here is usually of a heavier type than elsewhere. Though still dusty when dry, it tends to cake in hard lumps, and is inclined to form a sticky pan about one foot down. On these estates shade was usually established, using *Grevillea robusta*. The principal exceptions to the generalisation that the alienation was in or adjoining the Loliondo forest were the Usa—Maji-ya-Chai block of farms and the South African Dutch settlements of Engare ol Motonyi, Ol Doinyo Sambu, Kampfontein, and Engare Nanyuki, around the west and north of the mountain. The Dutch were however at that time almost entirely graziers and cereal growers, and did not turn their attention to coffee. Their farms, and the other exceptions mentioned, are grasslands with a proportion of thorn and scrub, and have a soil consisting of a relatively fresh volcanic ash. These ash soils may be divided into two

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* Loliondo (a Masai name) = *Olea Hochstetteri*, Baker, or *Linociera Welwitschii*, Baker, both Oleaceae, valuable timbers.

main types: those which are shallow and overlie a table of hard lava, more or less weathered, as at Usa and Engare Nanyuki, and those which are deep and overlie loose eruptive material, principally pumice, or semi-consolidated tuff.

The coffee planted in the early years was all heavily irrigated. For the most part the waters used were those of the comparatively pure central southern streams, as in the native-farmed belt, but the Burka, Selian, and also the Usa began to be used at this stage. Since the war there has been a great increase of coffee-growing, and practically all the rivers have been employed for irrigation except those at Ol Doinyo Sambu, where there is not enough flow. Planting has taken place to a greater or less extent in every part of the district, including large acreages on the immature grassland soils mentioned above, where the cheap clearing costs proved an attraction. On many plantations developed since the war shade has not been used, and especially is this the case on the grassland soils.

Failures to establish coffee are only recorded twice. Both were in very dry areas where the waters of the Engare Nanyuki were employed for watering nurseries. Sample No. 92 may be taken as representing the water used. In one of these cases the land had been periodically flooded for years, to encourage a short turf for sheep grazing. Here not only coffee, but maize too, failed. In the other case, though coffee failed, maize is grown and irrigated successfully with the water in question. In one further instance the coffee planted has died out almost entirely after yielding very large crops for two or three years. The water used was the Kimosan Spruit, a tributary of the Engare Nanyuki. The district where all these failures have occurred has probably not more than 20 inches of rain per annum, and the irrigation would be heavy.

Elsewhere around the mountain, including places along the forest edge at Engare Nanyuki, coffee is being successfully grown both with and without irrigation. There is, however, room for improvement in the bearing life of the trees in certain areas. At present they mature in a very short time, and too large a proportion of them bear a few heavy crops and then suffer serious defoliation and die. This condition occurs chiefly on the immature "ash" soils of the grass-and-thorn-scrub region.

For a period of years immediately following the war, practically every plantation was irrigated—it could be said to be the universal practice of the district. The irrigation of coffee is not now, however, carried on to the same extent as formerly. Many estates have abandoned the practice altogether in recent years, and a number of new plantings exist that have never been irrigated.

A Water Board under the Natural Water Supply Ordinance controls the use of water from all streams.

The practice most often adopted when irrigating coffee has been to fill with water a plate-like depression (termed a *sahani*, Kiswahili) around each tree. Thirty to forty gallons per tree at each watering would be applied in this way up to bearing age, and between 100 and 150 gallons per tree to bearing coffee, these estimates including the loss by seepage in the network of furrows within the plantation. As an average there may be 700 trees to the acre. A bearing plantation would therefore receive between 70,000 and 100,000 gallons per acre at each watering. This may be done once, twice, up to as many as five times per annum. In one case an irrigation was given every six weeks except when rain fell fairly heavily. Taking now an example of the significance of the data presented in this paper in the light of local irrigation-practice, let us suppose 100 gallons given per tree, of a water containing 200 parts per million of sodium carbonate. The amount of soda added per tree would be 100 x 10 x .0002 lb. = 0.2 lb. per tree, or 140 lb. per acre, at each irrigation. If three irrigations per annum are given, 420 lb., or nearly 4 cwt. of soda per acre are brought on to the land. This may not be a net figure, for no account is taken of any loss in through-drainage. But it is clear that in such an example sodium carbonate, undoubtedly an undesirable soil constituent, is being brought in in quantities comparable with ordinary dressings of artificial fertilisers.

It is not the purpose of this paper to pursue the matter further, for its agricultural significance cannot be fully assessed without a much closer analysis of factors of soil, soil management (especially drainage), climate, tolerance of crop to alkali, and so on, than is at present possible. A knowledge of the composition of the waters should however be of assistance, within its limits, in the further handling of some of the questions that must inevitably be raised by such a disturbing conclusion as that of the last sentence of the paragraph above.

Comparison with Other Waters.

Partial analyses are available for a few other water-samples from northern Tanganyika received at Amani during the course of the Meru survey. They contrast strongly with the Meru waters. Thus three samples from Kiru and Ndareda, near Babati, had 30, 41 and 53 parts per million of total bicarbonate, containing 0, 5% and 17% of the total as soda, respectively; sulphate and chloride from 2 to 6 p.p.m.; pH 6.5 to 6.9. Volcanic rocks occur locally in the area in question, near the wall of the Eastern Rift Valley, but the drainage is mainly from the gneiss. Typical waters from gneiss are those of

East Usambara, two examples of which, both from feeders of the Sigi River in the rain-forest at 3,000 to 3,500 feet, had 13 and 15 p.p.m. total bicarbonate, no soda, sulphate and chloride about 6 p.p.m., pH 6.2.

An irrigation-water used at Engare Nairobi, N.W. Kilimanjaro, had 18 p.p.m. total bicarbonate, sulphate 20 p.p.m. On the opposite side of Kilimanjaro, at Taveta, two springs of a hard alkaline-earth water occur, both having 165 p.p.m. total bicarbonate, with only 9% of it as soda, and very little sulphate and chloride. It will be of great interest to explore the Kilimanjaro waters in detail, when opportunity offers.

With a view to assisting further a comparison of the Meru waters with others, we reproduce below in Table XV, from various authorities, some complete analyses of waters from elsewhere in East Africa, and also some from Europe. These are stated in similar terms to those used for the complete analyses of the three Meru rivers of Table XIII.

TABLE XV. COMPOSITION OF DISSOLVED MATTER, OTHER WATERS.

					Typical European Waters.[1]			
	Lake Victoria.[1]	White Nile nr. Khartoum.[1]	Blue Nile.[1]	Lake Naivasha.[2]	From granite.	From basalt	From cretaceous rocks.	Thames at Thames Ditton.[1]
Salinity, p.p.m.	135	174	130	162 (approx.)	65	343	603	272
CO_3 %	42.1	43.0	41.8	39.0	30.5	46.9	33.0	41.9
Cl ...	9.3	4.6	2.2	4.3	6.4	1.7	2.9	5.2
SO_4 ...	1.9	0.25	5.6	7.4	14.1	8.0	27.7	11.8
Ca ...	7.0	9.8	18.4	7.0	11.9	20.0	22.1	30.1
Mg ...	5.1	3.0	4.7	3.0	3.6	5.7	5.3	2.0
Na ...	25.1	17.7	5.4	17.7	10.6	6.2	3.4	2.3
K ...		6.8	1.3	8.2	5.6	3.2	2.7	2.2
Fe_2O_3&Al_2O_3	1.9	—	—	2.6	—	0.6	—	0.5
SiO_2 ...	7.6	14.7	20.6	10.8	17.3	7.7	2.9	3.3
	100.00	99.85	100.00	100.00	100.00	100.00	100.00	99.3

1. Quoted from the original sources by F. W. Clark (9) (1924).
2. Calculated from the data given by L. C. Beadle (8) (1932), pp. 171 and 207.

SUMMARY.

A chemical survey of the streams draining Mount Meru has shown that their characteristic common features are a considerable, sometimes high, soda-alkalinity, and a small, usually negligible, content of alkali sulphates and chlorides.

The differences in the above respects, and particularly in the percentage contribution of the alkali carbonates and bicarbonates to the total alkalinity, enable a grouping of the streams to be made, which corresponds very well with the climatic and lithological features of the mountain on its various slopes.

The state of affairs represented by the analytical data is one that renders caution necessary throughout the whole area, when considering the use of any stream for irrigation. Guidance is given on the likelihood of encountering serious soda-alkalinity in the various districts. The greatest risk lies in the Engare Nanyuki area, the least in the middle area of the southern slopes.

Seasonal fluctuations in composition are discussed for several streams, but this part of the work has been inconclusive.

An account is given of the relevant features of both native and plantation agriculture, with an example of the significance of water-composition in terms of current irrigation-practice.

The discussion of "alkali," in the sense in which the word is commonly used in regard to soils, is confined throughout to the evidence given by stream-composition only, in order not to anticipate the conclusions of the soil-survey and of field studies of coffee-behaviour that are in hand.

Certain minor salt-deposits in the area have been examined, and found to yield evidence in corroboration of the water-analyses.

ACKNOWLEDGMENTS.

We wish to thank Mr. E. Harrison, Director of Agriculture, Tanganyika Territory, and Mr. W. Nowell, Director of the East African Agricultural Research Station, Amani, for the facilities which they have afforded for the carrying out of the work; and also Mr. A. J. Wakefield, Senior Agricultural Officer, Moshi, for his interest and active assistance.

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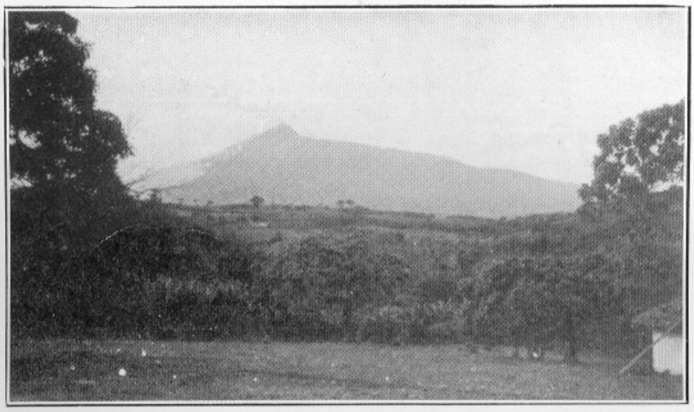
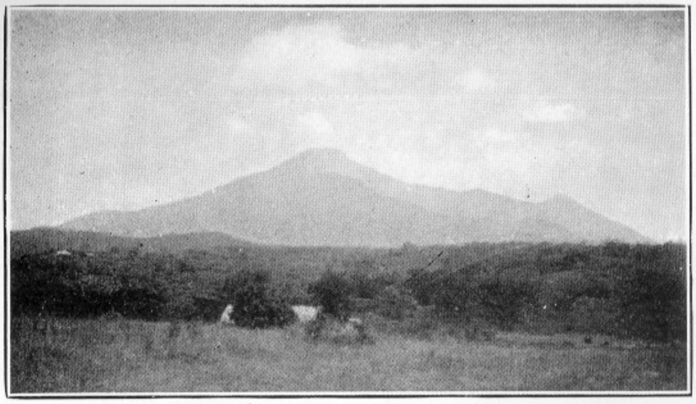
PLATE I.



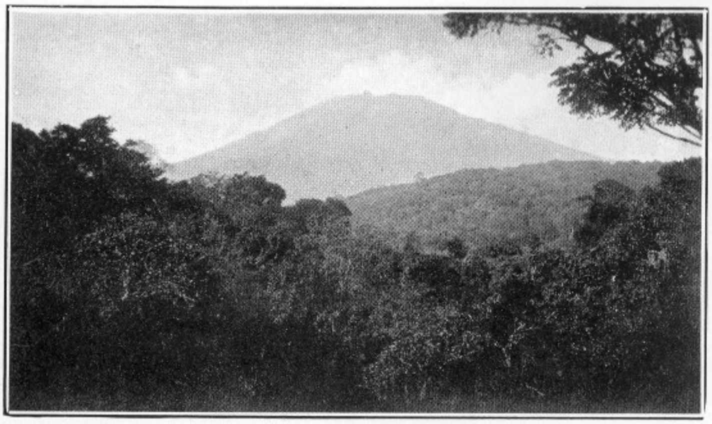
Meru from the south slopes.

Photo: D. Sturdy.



Meru from the south-east slopes, showing both walls of the crater.

Photo: D. Sturdy.



Meru from the forest edge, near the headwaters of the Engare Narok (south-west slopes)

PLATE II.

Confluence of Kikuletwa (l.) and Weru-Weru (r.) in gallery-forest at Arusha-Chin
Photo: G. Milne.

Lolondo forest, Tengeru, south slopes of Meru.
Photo: G. Milne.