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In spite of the wide interest by naturalists in the Great Lakes of Nicaragua their limnology has received little study. Cole (1976) has reviewed the literature and contributed new data and interpretations. Our paper adds to his larger work by presenting chemical analyses of Lake Nicaragua and some of the small crater lakes near it. These smaller lakes have been neglected. The only information published about them is a fragmentary table in Riedel (1964), giving some comparative data on surface area, circumference, and depth.

Materials and Methods

During one day in late April, 1970, we sampled surface water near shore in four lakes, Nicaragua, Masaya, Jiloá and Apoyo. Some of the major features of these lakes have been summarized in Barlow (1976), and Cole (1976) has treated Lakes Nicaragua and Managua in detail. The chemical analyses were commissioned to Dr. J. Jaime Bengoechea of Laboratorios Medico-Quimicos in Managua. Dr. Bengoechea also kindly allowed us to examine the results of some earlier analyses of Nicaraguan lakes.

In April and May, 1974, we measured dissolved oxygen and temperature at various depths in Lake Jiloá. Temperatures were determined from a boat, using a reversing thermometer. Water samples were collected in Nansen bottles by a diver and were fixed immediately when brought to the surface. The oxygen concentration was established by the Winkler method.

Results

The water levels in the lakes fluctuate annually, falling during the dry and rising during the wet season. Obviously the dissolved solutes become more concentrated during the dry period, and vice versa. More complex chemical changes also occur as a consequence. The present study was free from at least this complication because all the samples were taken at the same time.

Among the more remarkable differences shown in Table 1 are the pH values. Lake Masaya was exceedingly alkaline. But Lakes Jiloá and Apoyo were not, being less alkaline than Lake Nicaragua.

Lakes Jiloá and Apoyo were also remarkable in the total amount of dissolved solids. Their waters were 19 and 22 times as concentrated as that of Lake Nicaragua (Table 2). On the other hand, Lake Masaya was only about twice as "salty" as Lake Nicaragua, roughly the same relationship that existed between Lakes Managua and Nicaragua (Table 1; note that the two Great Lakes were not sampled at the same time). However, Cole (1976) reported that Lake Managua, compared in the same way, was around five times more concentrated than Lake Nicaragua. Thus one would have expected the water of the completely cut-off Lake Masaya to be much more concentrated than it was, perhaps comparable to the other crater lakes.

A number of other differences appeared that are not simple consequences of a greater concentration of solutes in the crater lakes. In comparison to Lake Nicaragua, potassium was 40 times more abundant in Lakes Jiloá and Apoyo (Table 2). There were fewer chloride ions in the water of Lake Masaya, but 100 times as many in Lake Jiloá and 58 times as many in Lake Apoyo. Still comparing the water to that of Lake Nicaragua (Table 2), Lake Jiloá had 126 fold the boron ions, and Lake Apoyo 62.

Although an oversimplification, it is useful to think of each lake varying primarily in water content. If so, the ratio of one ion to another should remain relatively stable within a lake and hence should be an informative indicator of differences between lakes. It is also a convenient datum for comparing some of our results with those of Cole (1976). The Ca/Mg ratio for Lake Nicaragua (Table 2) falls within the range of 1.3-3.3 given by Cole. Our Ca/Na ratio of 1.45, however, is high compared with Cole's 0.73-1.2.

Comparing lakes and using our data only, Lake Masaya had lower Ca/Mg and Ca/Na ratios than did Lake Nicaragua (Table 2). The Ca/Mg ratio was also lower in Lake Jiloá, but about the same in Lake Apoyo. For both Lakes Jiloá and Apoyo, the Ca/Na ratios were very low compared with Lake Nicaragua, and appreciably lower than that for Lake Masaya. Thus, these lakes differ from Lake Nicaragua and between themselves as well.

Returning to Cole's (1976) data, the three crater lakes also differ in their Ca/Mg and Ca/Na ratios as compared with the other Great Lakes: Lake Managua has the lowest Ca/Mg ratio, 0.26. Its very low Ca/Na ratio of 0.047 is comparable only to that of 0.060 for Lake Jiloá.

The depth profiles for oxygen and temperature were made at five sites in Lake Jiloá. Four were rather evenly spaced around the perimeter of the lake, and one (II) was located well off shore (Table 3). Site IV is where McKaye (see McKaye and Barlow, 1976) and Baylis (in prep.) have been studying the biology of cichlid fishes, and site III is near the public beach.

We were interested in the effect of wind, assuming that more wind and its consequent wave action would result in more oxygen at greater depths and a more even distribution of heat and oxygen. The wind was steadily out of the northeast, so the shore on that side of the lake (site I) had the calmest water. The south and west shores (sites IV and

TABLE 1. Chemical analyses of lakes in Nicaragua. Columns labeled A are data from our samples; B, from earlier analyses in the files of Dr. J. Jaime Bengoechea. All values except pH and conductivity are reported in p.p.m.

Determinations	Lake					
	Nicaragua		Managua	Masaya	Jiloá	Apoyo
	A	B	B	A	A	A
pH (electrometric)	8.35	7.0	8.5	8.75	8.00	8.15
Conductivity (micromhs 25°C)	200.0	201.0	---	414.0	5,580.0	4,095.0
Dissolved solids	120.0	151.0	274.0	228.0	2,268.0	2,680.0
Total hardness (as $CaCO_3$)	64.0	---	108.0	102.0	443.0	268.0
Calcium (Ca)	16.0	19.0	---	16.0	71.0	64.0
Magnesium (Mg)	6.0	3.5	---	13.0	63.0	26.0
Sodium (Na)	11.0	18.0	---	50.0	1,150.0	640.0
Potassium (K)	2.0	4.0	---	13.0	80.0	80.0
Carbonate (CO_3, as $CaCO_3$)	0.0	0.0	13.0	16.0	0.0	0.0
Bicarbonate (HCO_3, as $CaCO_3$)	74.0	67.5	231.0	204.0	314.0	160.0
Chloride (Cl)	19.0	16.0	8.8	11.0	1,910.0	1,110.0
Sulfate (SO_4)	0.0	9.1	1.0	0.0	102.0	41.0
Phosphate (PO_4)	0.100	---	---	0.180	0.075	0.080
Nitrate (NO_3)	13.0	---	---	2.200	0.000	0.000
Nitrite (NO_2)	0.013	---	---	0.013	0.080	0.000
Silicon (SiO_2)	3.20	---	---	3.40	3.60	18.40
Iron (Fe)	0.01	---	---	0.00	1.30	0.00
Manganese (Mn)	0.15	---	---	0.00	0.00	0.15
Copper (Cu)	0.00	---	---	0.00	0.00	0.00
Boron (B)	0.19	---	---	0.26	24.00	11.85
Fluorine (F)	0.25	---	---	0.25	1.30	0.88

V) had the greatest wave action. The fifth site was sampled twice, once (designated V) during a period of strong wave action (2 May, 1974), and once (designated VI) on the third day of windless weather that produced a dead calm (7 May, 1974).

The data indicate that the water in Lake Jiloá is well mixed at least down to a depth of 29 m (Table 4). The temperature and oxygen tend to decrease slightly with depth (we suspect that the slightly erratic values for O_2, particularly on 2 May at site V, were due to human errors of titration under less than ideal laboratory conditions). The stirring action of the wind was also evident. Dissolved oxygen was lowest at the calmest place, site I on the northeast shore. During a windless period at site V, the oxygen decreased slightly.

TABLE 2. Comparisons of selected chemical factors within and between some lakes in Nicaragua (based on p.p.m.).

Chemical Factor	Lake			
	Nicaragua	Masaya	Jiloá	Apoyo
Ca/Mg	2.67	1.23	1.12	2.46
Ca/Na	1.45	0.32	0.06	0.10
*Rel. Total dissolved solids	--	1.90	18.9	22.3
*Rel. K	--	6.50	40.0	40.0
*Rel. Cl	--	0.58	100.5	58.4
*Rel. B	--	1.37	126.3	62.4

*Relative to (divided by) value for Lake Nicaragua.

DISCUSSION

In any comparison of chemical analyses the first question to arise is that of error: to what extent are the reported differences artifactual? The best we can do in accounting for differences is to point out natural sources of variation within a body of water. Cole (1976) has already treated some of these, such as local differences that may arise through stratification.

There is some evidence that variation occurs across years as well as seasonally. This point is best made in the case of Lake Asososca, although it is not possible to separate clearly seasonal from longer term fluctuations. The city of Managua has been taking its drinking water from Lake Asososca, so its chemistry has been monitored. Sample data from 1961 to 1970 (personal files of Bengoechea) show the pH varying drastically from 7.5 to 8.75, the total dissolved solids from 236 to 348 p.p.m., and the hardness from 60 to 98 p.p.m. The constant removal of water from Lake Asososca must create a flushing action, so its dynamics may not be typical of the other crater lakes. But Lake Jiloá has also experienced appreciable fluctuation. In December, 1958, its dissolved solids were recorded as 3,900 p.p.m. as compared with only 2,268 p.p.m. here (Table 1; note also the differences for Lake Nicaragua). On the other hand, the dissolved solids in Lake Apoyo were 2,604 p.p.m. in August, 1963, in reasonable agreement with the value of 2,680 p.p.m. in Table 1 for 1970.

TABLE 3. Major features of sites where oxygen and temperature were measured at varying depths in Lake Jiloá.

	Site				
	I	II	III	IV	V
Location	NE shore	500 m off W shore	SE shore	S shore	W shore
Bottom	Sand, no plants	--	Sand, plants	Rocky	Rock cliff
Exposure	0	++	++	+++	+++

These differences are probably related to the varying relationship between gain and loss of water in each basin, consequences of rainfall, evaporation, and porosity of lake basin. Whether the basin is drained by a river or is enclosed will play a vital role in concentrating the solutes that enter (Cole, 1976).

Comparison of the three crater lakes in terms of relative trophic states may help explain some of the observed differences in carbonate, bicarbonate, phosphate and soluble nitrogen. Lake Apoyo was the least turbid of all the lakes sampled, and is the least eutrophic. Lake Masaya lies at the other extreme, having a continual bloom of planktonic algae that usually limits visibility to one meter or less. Lake Jiloá falls between the extremes of Lake Masaya and Lake Apoyo (Barlow, 1976).

Carbonate, bicarbonate, phosphate and soluble nitrogen compounds are all influenced by aquatic vegetation. The highest pH, 8.75, found in Lake Masaya can be accounted for by the rapid photosynthetic activity accompanying an algal bloom. This results in a reduction of free CO_2, and an accompanying precipitation of calcium carbonate (Ruttner, 1966, pp. 61–73). This interpretation is supported by the relatively high proportion of carbonate to bicarbonate in Lake Masaya, a condition not obtaining in the other crater lakes (Table 1).

Further evidence of the trophic states of these three lakes is provided by the nitrogen available as nitrate and nitrite. Note that the lake with the highest concentration of soluble nitrogen in these forms was Lake Masaya, which was undergoing a particularly vigorous algal bloom when sampled. Apoyo showed virtually no soluble nitrate or nitrite, lending further credence to its status as an oligotrophic lake. The phosphate concentration in the three lakes showed a similar pattern. The exception is Lake Jiloá, which had a phosphate concentration only slightly below that of Lake Apoyo.

All three crater lakes exhibit a phenomenon closely related to their 'hard' waters. Rocks in the shallow inshore areas show an encrustation of calcium carbonate reminiscent of the thick deposits at Pyramid Lake, Nevada. Although the deposits in the crater lakes are not so massive as those at Pyramid Lake, they are striking. These deposits are probably caused by the precipitation of calcium carbonate due to the uptake of CO_2 from bicarbonate by aquatic vegetation. The most extreme case of this is to be seen in Lake Apoyeque, a Nicaraguan crater lake not included in this study due to its remoteness. When visited, it had a thick algal bloom that limited visibility to a few centimeters, and calcium deposition was so heavy that in many inshore areas the loose rocks on the bottom were fused into a solid matrix.

The differences between the crater lakes and Lake Nicaragua are so large as to make it improbable that they are due to sampling or to technical error. (Fragments of old reports in Dr. Bengoechea's files are consistent with these more complete analyses, further bolstering our confidence in them.) In keeping with the lack of an outlet, the crater lakes tend to concentrate solutes. Lake Masaya, however, is more dilute than one might expect. This indicates some flowing through of its water, perhaps through subterranean channels.

The analysis of temperature and dissolved oxygen in Lake Jiloá suggests that the crater lakes are well oxygenated and thermally uniform, at least in the depth range where most of their fishes occur. But Lake Jiloá is more wind

TABLE 4. Dissolved oxygen (p.p.m.) and temperature (°C) at different depths at five sites in Lake Jiloá. The fifth site was sampled on a windy day (V) and on a calm day (VI).

	Site													
	I (5/3/74)		II (5/2/74)		III (5/22/74)		IV (4/30/74)		V (5/2/74)		VI (5/7/74)		Mean Values	
Depth (m)	Temp	O_2	Temp	O_2	Temp	O_2	Temp	O_2	Temp	O_2	Temp	O_2	Temp	O_2
Surface	28.00	6.4	27.45	8.0	29.80	7.3	28.50	7.2	28.10	7.8	28.00	6.4	28.3	7.2
1.5	27.65	--	27.40	7.8	29.60	--	28.00	7.0	27.70	7.4	27.65	--	28.0	7.4
4.6	27.60	6.3	27.40	7.2	29.50	7.8	27.80	7.1	27.90	6.0	27.60	6.3	28.0	6.8
7.6	27.50	--	27.40	7.2	29.10	--	27.80	6.6	27.80	8.5	27.50	--	27.9	7.4
10.7	27.48	6.2	27.50	7.1	28.60	8.4	27.80	6.6	27.70	7.9	27.48	6.2	27.8	7.1
14	27.40	--	27.45	7.3	28.10	--	28.00	6.5	27.60	6.9	27.40	--	27.7	6.9
17	27.45	5.7	27.45	6.8	27.70	5.8	28.00	6.4	27.45	5.6	27.45	5.7	27.6	6.0
20	27.45	--	27.40	7.5	27.65	--	28.00	6.6	27.50	7.2	27.45	--	27.6	7.1
23	27.40	6.0	27.40	7.2	27.70	5.6	28.00	6.3	27.50	6.2	27.40	6.0	27.6	6.2
26	27.45	--	27.40	6.0	27.70	--	28.00	6.7	27.65	4.6	27.45	--	27.6	5.8
29	27.45	5.5	27.40	5.8	27.70	5.8	28.00	6.7	27.80	5.8	27.45	5.5	27.6	5.9

swept than the sunken craters in which Lakes Masaya and Apoyo lie. It would be interesting to see how they compare.

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SUMMARY

Chemical analyses were done on water from Lakes Nicaragua, Masaya, Jiloá, and Apoyo. The salt content of the waters of Lakes Jiloá and Apoyo is about 20 times as great as that of Lake Nicaragua, but Lake Masaya is only about twice as salty. Rocks along the shore of Lake Apoyeque are encrusted with calcium carbonate, indicating that its water is also hard. The ratio of ions differs radically among the lakes. For example, potassium is about 40 times as abundant in Lakes Jiloá and Apoyo as in Lake Nicaragua. Chloride and boron ions show comparable or even greater deviations. In Lake Jiloá, heat and oxygen are rather uniformly distributed down to a depth of 29 m.

RESUMEN

Se efectuaron análisis químicos del agua de los lagos de Nicaragua, Masaya, Apoyo y Jiloá. El contenido de sales de Jiloá y Apoyo es unas 20 veces mayor que el del Lago de Nicaragua, pero el de Masaya es sólo 2 veces más salado. Rocas del borde de Apoyeque se encuentran incrustadas de carbonato cálcico, lo que indica que también sus aguas son saladas. La proporción de los iones difiere radicalmente en todos estos lagos. Por ejemplo, el potasio es unas 40 veces mayor en Jiloá y en Apoyo que en el Lago de Nicaragua. Los iones de cloro y boro muestran desviaciones comparables o aún mayores. En Jiloá, la temperatura y el oxígeno se encuentran distribuídos más bien uniformemente hasta unos 29 m de profundidad.

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