

AMAZONIANA	1	3	267—277	Kiel, Januar 1968
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Hydrochemistry and Geology in the Brazilian Amazon Region

by HARALD SIOLI,

In the Brazilian Amazon Region the interrelation between the hydrochemistry of the river systems and the geology of their catchment areas is quite obvious. Due to two facts the situation is less complicated and more instructive than in most other parts of the world.

Firstly, Amazon geology, considerably well-known for quite a long time, renders possible a subdivision of the entire Amazon Region into large specific units based on the geological origin of the surface layers determining the hydrochemistry of the water bodies of that region. Workers will therefore easily make out these relations without being obliged to examine small scale local peculiarities.

Secondly, population density in the Brazilian Amazon basin is insignificant. Large land strips between the big rivers are sparsely populated or even deserted. This is rather an important fact, as the densely populated industrial countries give rise to a considerable change in the hydrochemical composition of surface- (lakes, rivers, etc.) and ground-water bodies, in consequence of both highly polluted industrial and municipal waste waters and of a strongly mineralized return flow (mineral fertilizers) of agrosystems. As a matter of fact, there is hardly any longer an interrelation between natural environmental factors and hydrochemistry in densely populated industrial countries.

The chain of relationships between the geology of a country and the chemistry of its natural waters is a section of the net of interdependences, i. e. of the framework of causes and effects ("Wirkungsgefüge") composed by a good number of factors which constitute the ecosystem called a landscape.

In our point of view the most important factors are the following ones: the geological history with its results as e. g. the actual morphology of the earth's surface as well as the mineralogy and petrography of the substratum, climate, soil conditions, vegetation cover, and finally the physico-chemical and, with them, the biological characteristics of the waterbodies.

Especially the running waters — in the Amazon Region where lakes play a subordinate part, we have practically to deal only with those — might be called the "urine" of the landscape, because they receive and eliminate the final products of its metabolism, from the weathering of the bedrock and the edaphic processes up to the remineralization of the organic substances, all of which are eventually carried by them to the vast final receptacle of the ocean.

Climate and landscape of the Brazilian Amazon Region are extremely uniform. The central position of the area along the Equator, an entire belonging to the Tropics and the prevailing low land characteristics make it possible to neglect regional differences in some ecological factors such as climate and morphology in our considerations. In consequence, hydrochemical classification of Amazon waterbodies may be closely

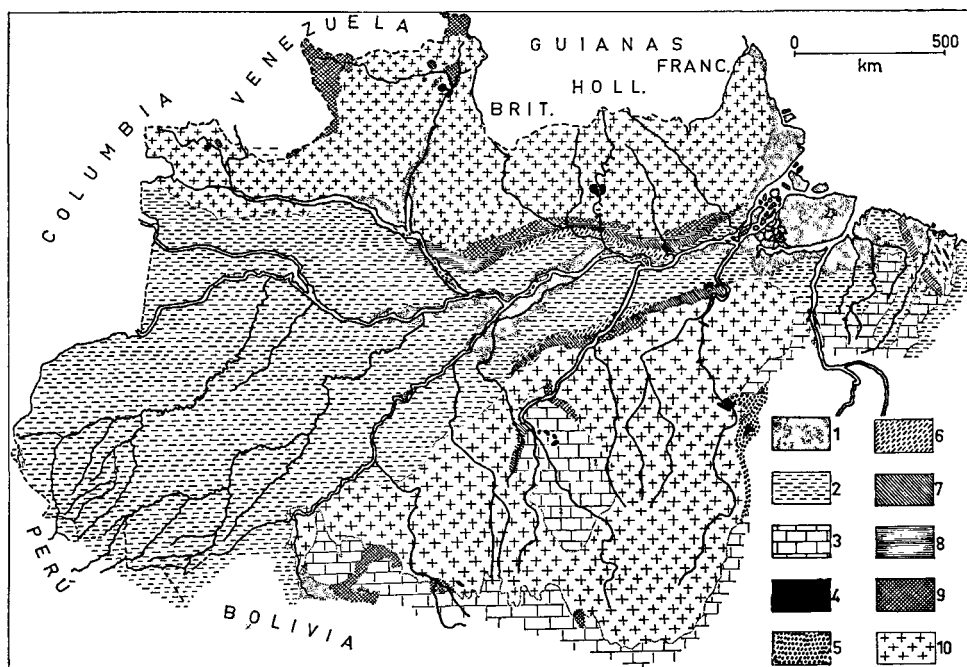


Fig. 1: Geological map of the Brazilian Amazon Region, after: A. I. DE OLIVEIRA, 1938.

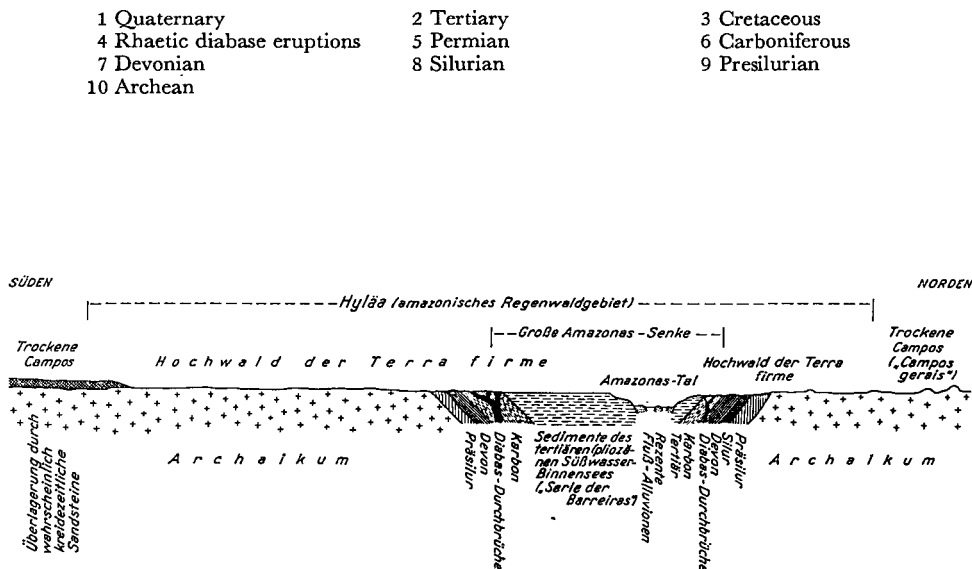


Fig. 2: Schematic cross-section in north-south direction through the geological structure of Lower Amazonia.

related to the distribution pattern of geological and mineralogical conditions as shown in the Geological Map of the Amazon Region (Fig. 1). In addition to the statement above, local changes in soil characteristics and vegetation cover (high forest or "campo" — latosols, brown loams; "caatinga" or "campina" — podsols) may contribute to a hydrochemical subdivision of some areas in a narrower pattern.

Macroclimatic effects again being insignificant, such local changes in soil characteristics are predominantly conditioned by recent soil erosion on valley slopes of rivers and rivulets or, on the flood plains, by riverwash. A long-term or repeated man-made deforestation is liable to induce selective erosion and to culminate in a more or less extensive sandy top-layer.

This paper is intended to be a study on the chemical composition of river flow in the different geological units of the Brazilian Amazon Region.

Chemical data are derived from water samples collected and analyzed by the author and by Dr. R. BRAUN, and partially from samples by Dr. E. J. FITTKAU, analyzed at the laboratories of Max-Planck-Institut für Limnologie, Plön (Holstein)/GERMANY.

For our purpose small waterbodies (brooks, rivulets, etc.) are suited best, as their catchment areas are generally uniform in geology, while the mixed water of the big rivers on the other hand, can hardly be traced to its origins from different geological formations.

A geological map (Fig. 1) and a schematic cross-section of lower Amazonia (Fig. 2) will recall the well-known geological structure of the area.

The archean masses of the Guianas and Central Brazil, consisting of granites and gneisses, partly covered with younger sandstone layers, represent the northern and southern border of the Amazon basin. Between the archean masses schists, limestone and gypsum beds, about 2500 m thick, deposited from presilurian to carboniferous periods, mark the extension of a large paleozoic minor sea, open to the west. At the outskirts of the old Amazon depression, land surface has been cut horizontally in successive strips of sediment layers. The Amazon trough was dry land in mesozoic era with rivers draining to the west, to the Pacific.

The situation lasted up to the Tertiary. In the Rhaetic period, however, eruptions of diabase occurred, reaching the actual land surface in several parts of the Amazonian depression border zones.

In the south-west a cretaceous sea-transgression extended from the Pacific to the Brazilian Acre-territory, depositing brackish water sediment-series.

Miocene tectonic uplifts of the Andes blocked gradually the Pacific drainage systems of the Amazon rivers. Covering the entire area between the foothill-zone of the Andes in the west and the Atlantic coast in the east, there was a vast fresh-water lake up to the Pleistocene. Up to 300 m thickness the fresh-water lake bottom was covered by deposits of material washed out of the old massifs of the Guianas and of Central Brazil from the north and south. The main part of the "Barreiras-Series", covering the eastern regions of the Amazon basin, originates from the deposits mentioned above. On the other hand western lake deposits, the Formation "Pebas", are mainly composed of outwash of the Andic complex; irregular occurrences of brackish and marine fossils within the Pebas area indicate locally limited lagunar conditions as well as temporary transgressions of the Caribbean Sea probably along the Upper Rio Negro Region.

At the eastern margin of today's Amazonia, the "Zona Bragantina", a minor miocene sea-transgression, is represented by the Formation "Pirabas" with limestone deposits. During pleistocene phases the extensive Amazon fresh-water lake got into contact with the Atlantic Ocean and run dry. The drainage pattern of the emerged land consequently changed direction, now to the east. The rivers which formed themselves carved the soft bottom layers of the former Amazonian fresh-water lake and cut their drainage systems into the land surface.

A back-water drift from the Atlantic Ocean, caused by a post-pleistocene (after the glacial period) world wide rise of the sea-water level; drowned extensive parts of the former valley terrains and gave rise to a significant sedimentation cycle in lower Amazonia.

As examples for the waters draining the archean massifs of the Guianas and of Central Brazil, clear-water rivulets and brooks of the Upper Rio Negro Region, including the Rio Marauia system, shall be cited. These clear waters take origin only in areas with brown loam soils, weathering products of granite and gneisses. Black waters that are also met with in this as well as in other geological zones will be dealt with later as a subject of its own.

The maximum-minimum values of the analyzed river water samples (see Table Nr. 1) show an extraordinary chemical purity with a low pH as a consequence of an insufficient bicarbonate-buffering.

Granites and gneisses as bedrocks of recent soil building processes have resulted in an extremely low calcium content. But the magnesium standard compared with the calcium content, is fairly higher than the respective values in Europe. Alkali-ions (sodium and especially potassium) are relatively frequent, too. Compared with European conditions the sodium-potassium/calcium relation is greater. But on absolute standards all these values are extremely low.

Anion-conditions show a considerable shortage of bicarbonates (low pH) and sulphates, while silicate is comparatively abundant. According to KLINGE and OHLE (1964) the hydrochemistry of European river systems is dominated by ions of alkaline earths and bicarbonate. In Amazon water samples, however, alkali- and silicate-ions play the main part not only in the archean complex, as stated above, but also in the areas with tertiary "Barreiras"-sediments. The iron content in these waters is low, aluminium is lacking almost completely. These elements are stored in the yellow brown-loam complex ("latosols"). The sparse phosphate content indicates in the "latosols" an extremely low amount of nutrient reserves for plant growth.

Nitrogen, in wet climates, seldom originates in bedrock material, but its form and amount are determined by biological processes.

Similar hydrochemical characteristics occur in the zone of "Barreiras-Series", layers which cover the central part of the Amazon depression joining eastwards the so-called "Formation Para" (cf Tab. 2), apart from the fact that the chemical poorness and purity of the waters (lower pH) is apparently more distinct than in the precincts of the archean complex.

KATZER (1903, pp. 44ff.) already realized the extraordinary purity of the waters of the lower Amazon and its affluents and stated that "the water of many small creeks contains even less suspended or dissolved components and is of astonishing purity" Katzer's latter statement refers to analyses of creek-, spring- and groundwaters of the "Barreiras-Series". All analyses marked these waters as "extraordinarily soft and pure".

Table (1—3): Analyses of waters from the different geological zones of Amazonia

	Nr. 1: Archean (systems of the upper Rio Negro, Rio Içana, Rio Marauá) clear waters	Nr. 2: "Series of the Barrei- ras" and "Formation Pará" clear waters	Nr. 3: "Formation Pebas" clear waters
μS_{20} (conductivity) . . .	0.57 —5.34	—	3.7 —171.0
pH	4.8 —6.6	4.4 —5.3	4.7 —6.4
Humus colour	0 —4	—	1 —23
diss. O_2 p.p.m.	1.5 —8.6	1.7 —8.0	4.2 —6.8
free CO_2 p.p.m.	1.8 —81.4	0.5 —82.6	10.1 —237.6
Na ⁺ p.p.m.	0.460—2.240	0.847—2.530	—
K ⁺ p.p.m.	0.262—1.000	0.534—1.52	0.91—16.15
Ca ⁺⁺ p.p.m.	0—18.400	0— $\pm$ 5	0—19.5
Mg ⁺⁺ p.p.m.	0—9.900	0—0.38	0.10—3.5
Mn ⁺⁺ p.p.b. (Y/l)	0—212	0—82	0—28
Fe ⁺⁺ + $\dots$ p.p.b. (Y/l) . .	0—137	0—440	54—1830
Al ⁺⁺⁺ p.p.b. (Y/l)	0—173	0—traces	0—650
HCO_3^- mval/l	0—0.174	0—0.04	0—1.35
Cl ⁻ p.p.m.	0—1.870	0—3.5	0.11—2.25
SO_4^{--} p.p.m.	0—1.250	0—0.48	0—15.0
P p.p.b. (Y/l)	0—110	0—50.2	8—514
N (NO_3^-) p.p.b. (Y/l) . .	0—15.2	0— $\pm$ 200	3.9 —418.0
N (Kjeldahl) p.p.b. (Y/l)	0—1430	138—724	150—814
Si (diss. SiO_2) p.p.m. . .	0.502—6.650	$\pm$ 0.5 —4.5	2.0 —15.6

"Barreiras-Series" and "Formation Pará" as a whole, extending from west to east about 1500 km or more, show of course certain hydrochemical differences in detail. The purest and poorest waters, astonishingly uniform ones, can be found in the Rio Arapiuns river system (the only big tributary of the lower Rio Tapajós from the west) (SIOLI, 1954a).

All these waters, even those draining the archean complex may be described as "very slightly polluted distilled water".

Waters of the archean massifs and the "Barreiras-Series" show a peculiar difference not yet explained. According to observations by E. J. FITTKAU (oral information) no Podostemonaceae appear in rapids and water falls of "Barreiras-Series" river systems. The situation changes immediately if river systems drain the archean massifs or other geological formations or if mixed waters occur in them. The absence and presence of trace elements should play a main part in the explanation of this remarkable fact. But up to now our knowledge about trace elements by which in some Amazon areas agriculture, i. e. cattle-breeding, is affected, is rather limited.

Obviously the waters of the "Barreiras-Series" are chemically more pure than those of the archean massifs, although the main part of the material of the "Barreiras-Series" is originally coming from the granites and gneisses of the archean complex. But here, in the latter, recent weathering is still affecting the archean bedrocks themselves; their soluble products, now extracted by rain water percolating the soil layers into the groundwater and by means of springs into the creeks, have mostly remained in primary deposits. The clays, loams and sandy layers of the "Barreiras-Series", however, were leached and re-deposited in the pliocene-pleistocene Amazonian lake era. After

the desiccation of the lake, the deposits have been extremely leached for tens of thousands of years or even much more by tropical Amazonian precipitation (2000—2500 mm/year) so that only small amounts of mineral matter can still be set free by weathering and be traced in river water samples.

Hydrochemical conditions of the "Formation Pebas"-region in the western parts of the Amazonian basin are slightly different from those of the "Barreiras-Series". Up to now only a few pick-up samples could be taken in that region. Tab. 3 indicates significant chemical irregularities of the waters of these geological formations. Taking into account local brackish- and sea-water deposits within the "Formation Pebas"-zone, these chemical irregularities are pretty obvious; near São Paulo de Olivença even thin limestone layers have been found.

Bleached sand layers are common in some areas of the archean region, occur also in the "Barreiras-Series" and in the "Formation Pebas" (according to oral information by the late Sr. Ricardo de Lemos Fróes) and occupy great areas in the sandstone-beds (cretaceous or silurian?) along the Rio Cururú (upper Rio Tapajós). The vegetation cover of these soils is fairly different from the common high forests. "Black-waters" drain these areas.

Extremely low inorganic ion-content classifies these "black-waters" as the purest water bodies of the Amazon region (see Tab. 4). The bleached sand layers, mentioned above, represent tropical lowland podsol. The soil building process and the origin of these podsol will not be discussed here in detail, as Dr. H. KLINGE, an expert on tropical soils, is working on these problems intensively. As a matter of fact, organic matter (litter fall) will not be completely oxydized but be decomposed to acid raw-humus only, and brown humus-substances are dissolved into the groundwater-bodies. Their waters, draining into the river systems, cause them to be "black-waters".

Humus matter seems to act as cation-exchanger. The ions of alkali and alkaline earths, extremely low in amount, are retained and substituted by H-ions, causing the low pH of these waters. These results may also be verified by the following observations: In the Upper Rio Negro region Caatinga-vegetation covering podsol plots is quite common. At Cararapoço (Rio Içana) a high forest strip on brown-loam was cut clear and burned for agricultural purposes. (Podsol plots are not used in shifting cultivation.) Occasionally, however, the vegetation cover of a small podsol strip along the river bank was affected by the fire. Brown waters drained from this podsol plot, where ash salts of the burned wood had accumulated on the bleached sands. In consequence seepage water should have become richer in dissolved salts and less acid. But contrary to expectation these waters (pH 3.7) proved to be the most acid "black-waters" I ever met in Amazonia. These results can only be explained by exchange-effect of the humus matter in soil and water.

All these "black-waters", chemically extremely pure, bear higher EC-values (Electric conductivity) than "clear-waters". This results from low pH-values. The lowest EC-values have been found about pH 5. Below this limit the EC-values rise again in consequence of the greater mobility of the lighter H-ions in comparison with the heavier, more inert cations.

"Black-waters" play a minor part in many parts of Amazonia, namely in those areas where podsol soils are rare. They are completely lacking in the carboniferous strips.

In the Upper Rio Negro region bleached sand plots are extraordinarily frequent and determine the character of the biggest and classic "black-water" river of the world, the Rio Negro, which was named by the early discoverers after its coffee-black, transparent waters. At the confluence with the turbid, ochre-coloured Solimões river, the difference in the water colours is specially striking.

With regard to the palaeozoic marine deposits accompanying the Amazon depression in north and south, again fairly acid and chemical pure waters (see Tab. 5) are draining schists and sandstone-layers of the devonian strips. (In presilurian and silurian formations no creek waters have been studied.)

Entering the carboniferous strips, however, hydrochemical conditions change immediately. Limestone layers, gypsum beds as well as rhaetic diabase up-lifts frequently contact the land surface of carboniferous areas (e. g. on Rio Tapajós and Rio Cuparí). These land strips usually bear rather fertile red soils with waters of higher salt content, less acid or alkaline. Tab. 6 shows water samples analyses from the northern and southern carboniferous strips of lower Amazonia. Many dissolved substances can be found in higher values than usual in Amazonia, e. g. hardness (Ca^{++} , Mg^{++}) and especially sulphate. Silicate content may be rather high, depending among others on the pH. In consequence of the considerably complicated stratigraphical pattern of these carboniferous land strips, local differences in the chemical composition of ground- and surface waters are quite common.

The higher salt content and lower acidity of the waters draining the carboniferous strips of Amazonia are of special interest for the resident people. Firstly these waters may serve for soil classification purposes in land use practice. The carboniferous strips of lower Amazonia bear soils of considerably fair natural fertility. On the other hand the hydrochemical composition enables growth and expansion of planorbis-snails, the intermediate hosts for *Schistosoma mansoni*, the agent of the dangerous Schistosomiasis (Bilharzia disease). This unpleasant human disease has been traced only in the carboniferous strips in the environment of Fordlândia (Rio Tapajós) and does not occur in any other place of the Amazon region. It was probably brought in from heavily infected northeastern Brazil.

Nothing can be said whether manganese content of the waters draining especially the carboniferous areas is closely related to manganese beds. Only in the Rio Cuparí system a well-known manganese deposit may have brought about a black manganese and iron crust on stones of the river bed. Usually people are right in arguing that manganese-free waters prove a complete lack of manganese beds in the upper surface layers of the entire catchment area.

Finally some information will be given about "Formation Pirabas" (miocene sea transgression deposits) contacting the "Formation Pará" at the eastern border land of the Amazonian hylaea. In the "Formation Pará"-area, where about 38 creeks were studied, the chemical composition of the waters is extraordinarily uniform. pH-values vary between 4.4 and 5.5, but mostly between 4.5—4.7. The chemical uniformity of the waters alters however at once when entering the "Formation Pirabas". A first short visit to the land east of Belém already showed a considerable increase of creek water pH-values (up to 7.2) which is uncommon apart from the carboniferous areas in the Amazon region. Later on some detailed studies of the "Zona Bragantina" made possible a rough delimitation of "Formation Pirabas", using pH-values of creek water samples as indicator. Up to then a border pattern had only been made out by known limestone deposits, but according to our studies, the extension of "Formation Pirabas" had been considerably underrated (cf. Fig. 3).

The pH-values of the "Formation Pirabas" creek water samples are far from being uniform. 43 creeks were studied, pH-values varying from 4.8 to 7.2. To illustrate the situation, 7 analyses of different creek waters are shown in Tab. 7. Chemical deviation of creek analyses are due to the fact that the entire "Formation Pirabas" is locally covered by "Pará"-sediments and the limestone beds occur in different depths.

Table (4—7): Analyses of waters from the different geological zones of
Amazonia

	Nr. 4: Archean, "Series of the Barreiras" and "Formation Pará", black waters	Nr. 5: Devonian strips of lower Amazonia	Nr. 6: Carboniferous strips of lower Amazonia	Nr. 7: "Formation Pirabas"
μS_{20} (conductivity) . . .	1.06 —44.1	—	—	—
pH	4.0 —4.6	4.9 —6.2	5.2 — ≥ 7.8	4.5 —7.2
Humus colour	7 —5800	—	—	—
diss. O_2 p.p.m.	1.9 —6.0	3.22 —7.38	2.13 —6.14	1.20 —9.37
free CO_2 p.p.m.	13.5 —68.2	4.0 —20.5	3.4 —82.0	0.7 —78.0
Na' p.p.m.	0.245—0.540	—	—	—
K' p.p.m.	0.143—1.002	—	—	—
total hardness calculated as Ca'' p.p.m.				
Ca'' p.p.m.	0.02 —9.200	2.9 —6.16	3.1 —204	2.4 —41.5
Mg'' p.p.m.	0—0.420	—	—	—
Mn'' p.p.b. (γ/l)	0	0—190	0—160	0—0.09
Fe'' + ... p.p.b. (γ/l) . .	109—250	0—300	0—650	0—30
Al''' p.p.b. (γ/l)	260—314	—	—	0—traces
HCO_3' mval/l	0	0.026—0.06	0.068—6.3	0.007—2.0
Cl' p.p.m.	0.01 —1.12	traces—0.8	traces—16.5	1.5 —11.5
SO_4'' p.p.m.	0—2.69	0—traces	0—556.7	—
P p.p.b. (γ/l)	0—33	—	0— ± 350	—
N (NO_3') p.p.b. (γ/l) . . .	0—23.8	0— ± 600	0— ± 400	0— ± 5000
N (Kjeldahl) p.p.b. (γ/l)	153—2620	—	0— ± 600	0— ± 100
Si (diss. SiO_2) p.p.m. . .	0.8 —2.7	2—3	1.4 —22	0.7 —1.3

The hydrochemical studies in the "Formation Pirabas" creek systems, and about the limitation of the area led also to a practical result, although this had not been the proper aim of the investigations: people became interested in limestone beds. Sr. Fritz L. Ackermann, geologist, prospected the entire area intensively. Where previously one "caboclo" dug and burnt limestone for local needs only, now a modern cement factory exploits the limestone district. "Progress" cannot be stopped, and it seems to be an immanent hubris of all investigations in natural sciences that the result of all research work carried out with pure aims of better understanding nature, be finally used by other people for the manipulation of nature. The complex consequences of these procedures for nature as well as for mankind can never be foreseen.

But this statement is not the idea of this paper. By means of the splendid example of Amazonia should be represented one link in the great framework of causes and effects which is the scientific aspect of nature, namely that of the dependence of the chemistry of waters on the geological-mineralogical data of their natural surroundings.

SUMMARY

In the Brazilian Amazon Region the relations between chemistry of waters (ground- and running waters) and the geology of their catchment areas are quite obvious.

The archean massifs in the north and south of Amazonia produce chemically very poor and pure waters, with low pH. Still poorer and more acid are the waters in the pliocene-pleistocene "Series of the Barreiras" and "Formation Pará" areas, while in the west, in the zone of the "Formation Pebas", of same geological age, also richer and less acid waters occur.

In all these geological zones, there are spots of bleached sands (podsoils), covered with a special vegetation type, which produce "black" waters, while from the yellowish brown-loams (latosols), with high forest cover, clear waters come. The "black" waters contain huge amounts of colouring humus substances while their content in inorganic ions and their pH values are the lowest in all Amazonia.

Quite different from the waters in the mentioned geological zones are those in the carboniferous strips, where there are limestone and gypsum layers and diabase outcrops, and in the miocene "Formation Pebas" with also limestone deposits. These waters are generally richer in inorganic ions and have higher pH values.

The importance of the chemistry of the Amazonian waters for an estimation of soil fertility and for human health is mentioned.

RESUMO

Na Amazônia Brasileira, as relações entre a química das águas naturais (água freática e águas correntes) e a geologia das áreas de influência sobre as mesmas são notavelmente nítidas.

Os massiços do arqueano ao norte e ao sul do Amazonas, produzem águas que são quimicamente bastante pobres e puras e que possuem valores de pH bem baixos. Mais pobres e mais ácidas ainda são as águas nas zonas da "série das Barreiras" e da "Formação Pará", ambas de origem plioceno-pleistocena, enquanto que no oeste da Amazônia, na zona da "Formação Pebas", de igual idade geológica, ocorrem também águas mais ricas e menos ácidas.

Em todas estas áreas geológicas encontram-se manchas de aréias esbranquiçadas (podsoils), cobertas de um tipo especial de vegetação, as quais produzem águas "pretas"; dos latosolos amarelos que supportam a floresta alta geral, entretanto, provêm águas cristalinas. As águas pretas contêm grandes quantidades de substancias corantes, de humus, enquanto que os teores em iônios inorgânicos e os valores de pH são os mais baixos em toda a Amazônia.

Bem diferentes das águas nas mencionadas áreas geológicas são aquelas das faixas do carbonífero nas quais se encontram depósitos de calcáreo e de gipsita e ocorrências de diabase, como também da "Formação Pirabas", do mioceno, também com jazidas de calcáreo. Tais águas são geralmente mais ricas em iônios inorgânicos e possuem valores de pH mais altos.

Menciona-se a importância do quimismo das águas, na Amazônia, para uma avaliação da fertilidade dos solos e para a saúde humana.

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Author's address:

Prof. Dr. Harald Sioli
Max-Planck-Institut für Limnologie
Abteilung Tropenökologie
D-2320 Plön (Holstein)
P. O. Box 165
FED. REP. GERMANY