Total World Salt Balance

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ABSTRACT

The earth's crust contains 64 X 10[15] metric tons of salt (sodium chloride). Ocean water and water contained in ocean-bottom sediments hold 43 X 10[15] metric tons of salt, or about two thirds of the salt in the earth's crust. Rivers, lakes, and ground waters of the continents contain less than one one-hundred thousandth as much salt as the ocean. The balance of 21 X 10[15] metric tons of salt is contained in crustal rocks.

The continental salt cycle can be examined using units only one billionth as large as those used to describe the crustal abundance of salt. Of the 520 million metric tons of salt involved in this annual cycle of water moving from the land into the ocean, about 220 million metric tons are contained in precipitation and 210 million metric tons are derived from rock weathering. Industrial activity contributes an additional 90 million metric tons to the cycle annually. Approximately 80 percent of this salt is carried to the ocean in surface runoff, and 20 percent is removed by direct movement of ground water to the ocean.

Discharge of salt to the world ocean varies little between continents, either in terms of total salt discharge or in terms of salt discharge per square mile of drainage area. Variations in total salt discharge between large river basins are as great as two orders of magnitude, but variations in salt discharge per square mile are only slightly higher than for continents.

When smaller rivers are considered, variations in salt content take on increased significance. It is important that where the salt content of the water is a problem, the relative contributions of the several sources of salt be determined and present day technology be examined as a possible means for resolving the problem.

INTRODUCTION

Man has long recognized his dependence on salt. An adequate supply is required for his very existence, for man is a salt-water creature. Unlike the ocean fishes, who live in an external environment of salt water, man's salt-water environment is internal. Nevertheless, for his well-being, man must maintain the proper level of salinity in his body fluids or perish. A moderate loss of salt, unreplaced, may bring on fatigue; a larger loss may cause heat exhaustion. An extreme loss can result in death.

Just as salt is cycled through our bodies, so does salt move through the earth's life cycle. Some salt completes the short-term part of the cycle within a year. Other salt resides in the ocean or the earth's crust for hundreds of millions of years before moving into another part of the cycle. A small amount of juvenile salt, derived from the weathering of igneous rocks and from volcanic emanations, continuously is added to the short-term part of the cycle.

DISTRIBUTION OF SALT IN THE EARTH

First, where does the earth's salt reside at any given moment? Here "salt" refers to sodium chloride. Of course, it is known that there are separate sources of sodium and chloride, but here the inquiry is confined to environments where both occur together so that sodium chloride is at least potentially present even if the two elements are not directly associated at any particular moment.

Table I shows that in the outer skin of the earth (that is, in and on its crust and in the world ocean) the ocean

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TABLE I

Abundance of Salt in the Earth's Crust

	10^{15} Metric Tons
Hydrosphere	
Ocean water (6, 13)[1]	38
Water in ocean sediments (6, 13)	5
Rivers, lakes, and underground waters (13)	0.00031
Lithosphere	
Igneous and metamorphic rocks (2, 7, 13)	11
Sedimentary rocks (including evaporites)[2]	10
Total	64

[1]Refers to references at end of paper.
[2]Calculated by scaling up U.S. reserves of salt (15) in proportion to world land area, and assuming that world reserves represent only one-tenth of total salt in sedimentary rocks. Nonevaporite sedimentary rocks contribute only 0.32 x 10^{15} metric tons, or 3.2 percent of the total estimated abundance of salt in sedimentary rocks (2, 7, 12, 13).

TABLE II

The Continental Salt Cycle

	10^6 Metric Tons Per Year	
Precipitation		220
Volcanic emanations (5)[1]	4	
Combustion of coal (5)	0.2	
Airborne salt (mostly sea salt) (4, 5)	216	
Rock Weathering		210
Igneous and metamorphic rocks (5)	0.8	
Sedimentary rocks (including evaporites)[2]	209	
Industrial Production (10)		90
Total (9, 11)		520

[1]Refers to references at end of paper.
[2]By difference.

contains the largest part of the world's salt. Ocean water and water contained in ocean-bottom sediments hold 43 X 10^{15} metric tons of salt, or about two-thirds of the salt in the earth's crust. Rivers, lakes, and ground waters of the continents contain less than one one-hundred thousandth as much salt. Crustal rocks contain another 21 X 10^{15} metric tons of salt. Of course, the bulk of this salt is not available for incorporation in the short-term hydrologic cycle at any one time.

CONTINENTAL SALT CYCLE

The total abundance of salt in the earth's crust is so great that it provides little basis for our comprehension of the continental salt cycle. First the components of this cycle are considered alone, using units only one-billionth as large as those used for the information on the earth's crust.

Table II shows that salt that is present in precipitation and salt derived from rock weathering contribute about equally to the salt content of water moving from the land into the ocean, with industrial activity contributing a significant but lesser fraction of the total. From our knowledge of the relative contributions by surface water and ground water to water discharged from the continental United States to the ocean (Nace, 1964, and Kohout, 1967), and a survey of chemical analyses of this discharging water, the survey suggests that the content of sodium chloride in ground water is about twice that in surface water, one can obtain a rough estimate of the distribution of salt discharge between surface water and ground water that can be extrapolated to the world. This estimate suggests that 80 percent of the salt is carried to the ocean in surface runoff, and 20 percent is removed by direct movement of ground water to the ocean.

Looking now at the variability between the continents of the world in their average annual discharge of sodium chloride to the world ocean, Table III shows the annual continental discharges in terms of total salt load and in terms of the amount of salt removed per square mile of land area. It is readily apparent that, with the exception of Australia, the discharge of salt to the oceans varies little between continents, both in terms of total annual discharge and annual discharge per square mile. This is no doubt due to the fact that each of the large continents spans a broad range in latitude and thus in climatic conditions, each is large enough to contain the whole gamut of rock types, and the continents do not differ greatly in size. Australia, partly because it is a small, rather arid continent, but primarily because one-third of its land area does not drain to the ocean, contributes relatively little to discharge of salt from the continents to the ocean. The contribution from Antarctica is assumed to be negligible.

Even on a smaller scale, such as that of large river basins, there is only slightly greater variability in salt discharge per square mile of drainage area, except under special circumstances. Table IV shows the measured average annual salt discharge for the period 1966–69 from four large river basins in the United States. Table V shows the same information for five major groups of river basins in Russia. Except for the Colorado River, whose water and its contained salt load is largely "used up" before it can get to the ocean, salt discharges per square mile drained by these basins vary by no more than a factor of 8. In all of these large rivers, the total load of salt discharged to the ocean is more strongly influenced by the total volume of water discharged than by either the size of the basin or the salt content of the water.

In spite of the lack of great variability in the transport of salt by large rivers, when one looks at somewhat smaller rivers the variability of the salt content becomes significant. Whether the source of salt is man's activities, as in the case of the Tuscarawas River in Ohio where ground water has been made unpotable by infiltration of salty river water, or the source is natural, as in the case of the Pecos River in New Mexico where saline springs are ma-

TABLE III

Continental Discharge of Salt to the Ocean

Continent	Area 10^6 mi^2	Diss. Solids[1] Content, ppm	Diss. Solids[1] Discharge to Ocean, Metric Tons/mi^2 yr	Mean Chloride[1] Content ppm	NaCl Discharge[2] to Ocean, 10^6 Metric Tons/yr	NaCl Discharge to Ocean, Metric Tons/mi^2 yr
North America	8.172	142	85	8	64.6	7.9
South America	7.561	69	73	4.9	64.6	8.6
Europe	4.211	182	110	6.9	29.0	6.9
Asia	17.985	142	83	8.7	150.8	8.4
Africa	11.500	121	63	12.1	119.5	10.4
Australia	2.970	59	6	(Na) 2.9[3]	2.2	0.8
World Total	52.389[4]				430.7	

[1]From Livingstone (1963).
[2]Calculated from preceding columns by formula: (area) (diss. solids discharge) $\frac{\text{Cl}}{\text{diss. solids}}$ (1.65).
[3]Sodium used to calculate NaCl because insufficient Na to combine with all of Cl.
[4]Does not include Antarctica.

TABLE IV

Salt Discharge from Four Large River Basins in the United States[1]

River	Area Drained, mi^2	Mean Annual Discharge of Water, cfs	Mean Annual Discharge of NaCl: Metric Tons	Mean Annual Discharge of NaCl: Metric Tons/mi^2
Columbia	258,200	281,200	1,645,000	6.37
Colorado	245,000	63,600	12,700	0.05
Mississippi	1,262,000	650,000	27,930,000	22.13
Potomac	11,560	10,790	270,800	23.42

[1]From Leifeste, written communication; for period 1966-69.

TABLE V

Salt Discharge from Five Large Drainage Areas in Territory of the USSR[1]

Seas Receiving Drainage from the Area	Area Drained, mi^2	Mean Annual Discharge of Water, cfs	Mean Annual Discharge of NaCl: Metric Tons	Mean Annual Discharge of NaCl: Metric Tons/mi^2
Barents and White	386,000	386,400	2,818,000	7.30
Black and Azov	463,000	177,000	4,303,000	9.29
Baltic	232,000	177,000	1,046,000	4.50
Laptev and Chukchi	4,130,000	2,940,000	36,000,000	8.72
Bering, Okhotsk, and Japan	1,236,000	952,000	3,504,000	2.84

[1]Calculated from Durum, Heidel, and Tison (1960) after Alekin and Brazhnikova (1957), and others.

jor contributors of salt, it is important that the sources be identified and the salt content of the water be monitored. With adequate knowledge of the relative contributions of the various sources and present-day technology, significant progress in pollution abatement can be made, as demonstrated by the measurable decrease in salt content of the Arkansas River at Van Buren, Arkansas, after improvement of brine disposal practices far upstream in the Canadian River basin (Steele, 1971).

As the late W. T. Pecora, former Director of the Geological Survey, said, man's ability to maintain an acceptable environment can be hindered by failure to recognize fundamental earth processes. Physical and chemical degradation at the land surface is a natural occurrence on earth; but man is beginning to contribute to that degradation in significant measure in certain areas. It would be inexcusable for us to fail to take into account Nature's responses to our actions. We can take heart in the fact that man has begun to develop an awareness that better housekeeping of the earth must be practiced as he continues to take from the earth the things he needs.

If we will weigh our alternatives properly, extraction and use of our precious natural resources and the quality of our environment can be brought into reasonable balance for the benefit of mankind.

REFERENCES

Alekin, O. A., and Brazhnikova, L. V., 1957, New data on the discharge of dissolved substances from the Territory of the USSR: *USSR Acad. Sci. Proc.*, v. 114, no. 1–6.

Clarke, F. W., 1924, The data of geochemistry: *U.S. Geol. Survey Bull.* 770, p. 34.

Durum, W. H., Heidel, S. G., and Tison, L. J., 1960, World-wide runoff of dissolved solids: *Internat. Assoc. Sci. Hydrology, Surface Waters Comm.* Pub. 51, Gen. Assembly of Helsinki, p. 618–628.

Eriksson, Erik, 1955, Airborne salts and the chemical composition of river water: *Tellus*, v. 7, p. 243–250.

———, 1959, On the geochemistry of chloride and sulfate, *in Atmospheric chemistry of chlorine and sulfur compounds*, James P. Lodge, Jr., ed.: Geophysical Monograph No. 3, Am. Geophysical Union.

Goldberg, E. D., 1963, Chemistry—The oceans as a chemical system, *in* Hill, M. N., *Composition of sea water, comparative and descriptive oceanography:* Vol. 2 of The Seas, Interscience Publishers, New York, p. 3–25.

Horn, M. K., and Adams, J. A. S., 1966, Computer-derived geochemical balances and element abundance: *Geochim. et Cosmochim. Acta*, v. 30, p. 279–297.

Kohout, F. A., 1967, Relation of seaward and landward flow of ground water to the salinity of Biscayne Bay at Miami, Florida: *U.S. Geol. Survey* open-file report, 98 p.

Livingstone, D. A., 1963, Chemical composition of rivers and lakes, *in* Data of geochemistry, Michael Fleischer, Tech. ed.: *U.S. Geol. Survey Prof. Paper* 440-G, p. 1–64.

McMillan, R. T., and Foley, J. M., 1960, Salt, *in Minerals Yearbook*, 1959: U.S. Bur. Mines.

Nace, R. L., 1964, Water of the world: *Natural History*, v. 73, p. 10–19.

Pettijohn, F. J., 1957, *Sedimentary rocks*, 2d edition: Harper and Row, Publishers, New York, Evanston, and London, p. 11.

Poldervaart, Arie, 1955, Chemistry of the earth's crust, *in* Crust of the earth, A. Poldervaart, ed.: *Geol. Society of America Special Paper* 62, p. 119–144.

Steele, T. D., 1971, A study of the chemical quality of streamflow in Arkansas: *U.S. Geol. Survey* open-file report.

U.S. Geological Survey, 1968, Geological Survey Research 1968: *U.S. Geol. Survey Prof. Paper* 600-A, p. 13.