INPUT AND OUTPUT CONSIDERATIONS IN ESTIMATING RATES OF CHEMICAL DENUDATION

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Abstract

Estimation of rates of solutional denudation in river basins necessitates some consideration of salt inputs as well as consideration of salt outputs. Recent work in nutrient cycling has stressed the complexity and importance of the input factor, particularly when throughfall chemistry is taken into account. Frequently the differences between rates of input and output of salt in a river basin are small, suggesting that many published rates of solutional denudation, which consider outputs alone, or inputs only in part, are excessive. The input of salts, which may take place in rain, snow, fog and throughfall are most important in coastal areas. Analysis of data for both the semi-arid United States and the Cotswold Hills in England, illustrate the need for long-term sampling, and for a detailed spatial network of sampling points.

The study of rates of solutional denudation has in the last decade been used to illustrate the role of different climates and lithologies in influencing rock weathering. In addition, some geomorphologists like Trendall (1962) have used such rates for assessing possible degrees of lowering of Tertiary surfaces, whilst ecologists and pedologists have been concerned with the removal of salts in drainage waters as a component of mineral nutrient cycling (Bormann and Likens, 1967).

Rates of chemical weathering in a river basin can be calculated from discharge, water chemistry and basin area data using a simple formula:

$$X_t = \frac{Q.T_l}{A_b} \qquad \text{(Formula 1)}$$

where X_t is the total rate of dissolved salt removal in tons/km²/year, Q is the annual discharge, and T_l the concentration of dissolved materials in tons per unit area of discharge. A_b is the basin area in km². An alternative, though essentially similar formula, is that used by Williams (1965):

$$Y = \frac{E.T.n}{10\,D} \qquad \text{(Formula 2)}$$

It is particularly applicable for estimating rates of limestone solutional lowering. Y is the value of limestone removed in solution in mm/1000 years, or in m³/km²/year, E is the mean annual water surplus in decimetres, T is the total water hardness in p.p.m., D is the density of the limestone, and $\frac{l}{n}$ the fraction of the basin occupied by limestone. Williams's formula is an improvement on that of Corbel (1959) as it allows for variations in rock density.

However, the main disadvantage of both Formula 1 and Formula 2 is that they make no allowance for the input of salts into the drainage basin under consideration, though it is the net loss of dissolved material, as opposed to the total loss, which is the real measure of rock weathering within the basin. The following formula, an adaptation of Formula 1, makes allowance for the input factor:

$$X_n = \frac{Q.T_i}{A_b} - \frac{P.T_2}{A_b} \qquad \text{(Formula 3)}$$

where X_n is the net rate of removal, P is the precipitation input in the same units as Q, and T_2 is the concentration of dissolved salts in tons per unit of P.

Whilst some early workers made allowance for inputs of dissolved salts in rainfall (Mellard Reade, 1877), many subsequent studies have neglected this factor in estimating rates of chemical weathering. Polynov, for instance, failed to allow for salt inputs in his classic work on mineral mobility, *The Cycle of Weathering* (1937). For this reason it appears likely that his table of order of element mobility is inaccurate.

Nevertheless, in recent years there has been a greater appreciation of the significance of rainfall chemistry for geological processes (Carroll, 1962; Douglas, 1968; Hembree and Rainwater, 1961), and the supposed high nitrate content and acidity of tropical rainfall has been a subject of contention in weathering studies in the humid tropics (Richard and Vialard-Goudou, 1953; Viemeister, 1960; Visser, 1964). Loewengart (1961) has gone so far as to propose that airborne salts are the major source of groundwater salinity in Israel, whilst a Soviet scientist has said that "ion runoff of rivers exceeds the income of ions through the atmosphere into river basins only in mountainous regions or where salt-bearing rocks occur extensively in humid climates" (Tsyganenko, 1968). Miller (1968, p. 330), working in New Zealand, has remarked that "for most elements, inputs from the atmosphere, losses to drainage and cycles through the plants are of the same order or are greater than amounts weathering from the soil".

Table 1. Salts in Rainfall, Throughfall and Streamwater.

Source	Location	Ca	K	P	Na	Mg	NH₄–N NO₃–N	
							$NH_4\text{–}N$ $NO_3\text{–}N$	
Will (1968)	New Zealand	3.0	5.0	0.3	–	–	–	Rainfall
		3.5	19.5	1.0	–	–	26.0	Throughfall
Attwill (1966)	S.E. Australia	2.7	2.0	–	16.8	5.4	–	Rainfall
		8.9	13.8	–	26.2	8.2	–	Throughfall
Carlisle *et al.* (1966)	N.W. England	7.3	3.0	0.4	35.3	4.6	9.5	Rainfall
		17.2	28.1	1.3	55.6	9.4	8.8	Throughfall
Madgwick & Ovington (1959)	S.E. England	11.0	3.0	–	19.0	4.0	–	Rainfall
		24.0	24.0	–	33.0	10.0	–	Throughfall
Miller (1968)	New Zealand	9.0	7.0	0.4	68.0	12.0	5.0	Throughfall
		26.0	6.0	0.2	76.0	22.0	2.4	Streamwater
Likens *et al.* (1967)	New England	3.0	2.5	–	1.0	0.7	–	Throughfall
		8.0	1.8	–	5.9	2.5	–	Streamwater

Note: the header also shows "Salts (kg/ha/year)" spanning the numeric columns.

However, salt input is not restricted to input in rainfall, for an increasing body of work by ecologists and foresters shows clearly that water that has percolated through a canopy of leaves in a forest is very greatly enriched in mineral matter. The enrichment probably results partly from the leaching of dust and animal excrement from leaves, partly because of exhalations by the leaves, and partly because the leaves catch a considerable amount of fog drip which is often relatively highly saline. Some extra enrichment may result from the flow of rainwater down tree-trunks. Table 1 shows rates of inputs of various salts by both rainfall and throughfall, and emphasises the importance of throughfall. An early study by Tamm (1951), for instance, established that throughfall increased the normal salt content of rain by about x 3 in sodium, x 4 in calcium, and as much as x 18 in potassium. However, a major problem is to determine what proportion of the throughfall salts should be regarded as a true input, for one can legitimately regard the exhalation contribution as a component of cycling within the basin. Similarly, some of the dust which provides dissolved material to precipitation washing the leaf canopy may be derived from within the basin. This produces an element of uncertainty

into determinations of rates of input, and hence of net removal of dissolved salts. Nevertheless, a comparison of rates of throughfall input with rates of total salt output shown in Table 2 indicates that the difference is often slight, and that many previously computed rates of chemical weathering are probably excessive. Certainly, the work of the Hubbard Brook Experimental Team in New England has clearly illustrated that chemical weathering within the Hubbard Brook basin provides only a very small proportion of the sulphates, chlorides, nitrates and ammonium leaving the basin in river water. The bulk comes from throughfall and rainfall (Juang and Johnson, 1967; Fisher, Gambell, Likens and Bormann, 1967). Similarly, Miller's work in New Zealand illustrates that phosphates, potassium and nitrates in stream water are derived largely from throughfall. Silicon inputs of 6kg/ha/year formed only a small part of the 49 kg/ha/year output of silicon (Miller, 1968). Likewise, Fisher, Gambell, Likens and Bormann (1967) found scarcely any silica in rainfall. Thus it seems likely that inputs of silica in rainfall and throughfall are unimportant in affecting stream silica concentrations. Air pollution tends to lead to excessive input values, especially for sulphates, and creates additional problems for the estimation of natural rates of denudation (Meade, 1969).

Table 2. Rate of Input in Throughfall.

Source	Location	(tons/km²/year)
Sviridova* (1960)	U.S.S.R.	2.16
Nye (1961)	Ghana	28.60
Will (1968)	New Zealand	6.40
Ehwald* (1961)	Germany	6.68
Madgwick & Ovington (1959)	N.E. England	(6.10 (4.94
Grunert* (1964)	Germany	11.00
Eriksson & Khunakasem (1969)	Israel coast	13.50
Tsyganenko (1968)	U.S.S.R.	19.00
Rate of Output in Streamwater (X_t)		
Carbonnel (1965)	Indo-China	6.80
Gibbs (1967)	Amazon	15.96
Gibbs (1967)	Congo	28.12
Gibbs (1967)	Mississippi	36.00
Crisp (1966)	N.W. England	8.30
Strakhov (1967)	Plate	18.00
Goudie	Semi-arid U.S.A.	17.87

* Cited by Rodin and Bazilevich (1967).

A further complication in the measurement of chemical weathering rates results from the need to make an accurate assessment of the precipitation input, P. This consideration is especially important in those areas where fog and cloud precipitation form a major proportion of the total precipitation, for normal precipitation gauges do not measure fog precipitation. In the Namib Desert of South West Africa, for instance, Nagel (1962) has shown that fog precipitation at the coastal station of Swakopmund is about 130 mm per annum, whilst ordinary precipitation only totals about 18 mm. The Namib fogs, which occur in that area on just over 120 days in the year, are highly saline, and Boss (1941) calculated that they deposited around 12 tons/km²/year of salts. The research station records at Gobabeb show that even at a distance of more than 60 kms from the coast the fog precipitation (30 mm) is greater than the annual rainfall (23 mm). Special gauges need to be constructed for fog measurements, and whereas in coastal deserts this input factor is obviously of prime importance, it should also be considered in mountainous areas such as parts of California, and the south-western Cape Province of South Africa. A second complication in

measuring the precipitation input results from geomorphic shelter, for Rutter and Edwards (1968) have demonstrated that, in the case of the coastal belt of central Wales, aspect with regard to on-shore winds strongly influenced the rate of salt deposition. This problem necessitates the careful selection of measurement stations within a catchment.

Table 3. Salt Inputs in Rainfall in Relation to Distance From Sea.

Source	Location	kg/ha/year				kms. Distance
		Ca	Na	K	Ca:Na	from sea
Yaalon (1964)	Israel	73	73	4	1:1	0.1
		25	20	4	5:4	11.4
		25	14	3	5:3	17.6
		20	16	5	5:4	34.5
		43	9	2	5:1	46.0
		16	2	1	8:1	72.0
		23	4	1	6:1	96.0
Thornton (1965)	Gambia	3.9	8.5	5.3	1:2.2	14.4
		2.4	7.9	3.8	1:3.3	125.6
		1.5	5.2	2.5	1:3.5	217.6
Hutton (1968)	Australia				0:8	0.8
					0:5	80.0
					0:4	80.0
					0:1.7	190.0
					0:3	160.0
					2:1	260.0
					4:0	320.0

The input of salts falls off markedly from coasts, as Table 3 shows, and as was appreciated by Douglas (1968). Nevertheless, the values for inputs listed in Table 2, are unless stated, for inland stations. The concentrations of different salts also change relatively as one moves inland, with sodium becoming relatively less important than calcium in inland areas. In general one can say that input to output ratios are especially high in coastal areas, and in areas of rocks which are only slightly soluble, but that the input of salts is nearly everywhere going to be a major influence on surface water chemistry.

The measurement of the various output factors presents problems additional to those already discussed in relation to the input factors. For instance, in assessing the value of some published rates of solutional denudation one must remember the importance of the length of sampling period. Many studies of rates have been based on only a few years of water chemistry and discharge observations, yet analysis of records of nine semi-arid basins in Texas, New Mexico and Arizona showed that over a thirteen-year period there was a mean ratio between maximum and minimum values of X_t of 10.30. This reflected a ratio of maximum to minimum annual discharge of 11.36 over the same period. Ratios for individual basins reached as high as x 34. This data suggests the need for long periods of observations if rates of any meaning are to be obtained for comparative use in climatic geomorphology. In many river basins the correlation between X_t and Q is very high, so that it might be safe to interpolate values of X_t from long-term records of discharge and short-term records of dissolved load concentrations, but high correlations are not invariable (Table 4) and in Kentucky, Hendrickson and Krieger (1960) found no straightline or simple curvilinear relationship between stream discharge and dissolved mineral concentration. Moreover, different salts may react in different ways to discharge fluctuations (Johnson, Likens, Bormann, Fisher and Pierce, 1969).

Table 4. Denudation and Discharge Rates in the Semi-arid U.S.A.

River			X_t (tons/km²/year)		Ratio of Max. to Min. annual dis- charge.	Correlation (r) of an- nual discharge with annual X_t values
			Mean	Max/Min.		
South Platte	......	......	7.54	7.58	11.87	0.97
Red	......	......	36.11	5.23	7.19	0.97
Neches	......	......	20.15	4.03	6.45	0.99
Trinity	......	......	25.65	5.45	11.21	0.78
Brazos	......	......	15.59	34.11	8.89	0.94
Colorado	......	......	4.73	4.63	5.95	0.98
Guadalupe	......	......	27.50	19.33	29.29	0.99
Nueces	......	......	3.42	10.88	18.85	0.99
Pecos	......	......	21.11	1.49	2.56	0.13

Source:

Data for the period 1951-1965 from United States Geological Survey Water Supply Papers, 1264, 1362, 1380, 1430, 1465, 1485, 1524, 1575, 1746, 1886, 1946, 1952 & 1960.

A parallel consideration, if values of solutional denudation are to be useful in making comparisons between areas of different lithology or different climate, is to ascertain the variability of values within areas of uniform lithological or climatic conditions. Work on limestone solution rates in the Jurassic oolitic lime-stone terrain of the Central Cotswolds in England by the author and also by Ingle Smith (1965) indicate that whilst calcium carbonate concentrations were relatively constant through time, in spite of fluctuating discharge, the spatial variability between springs draining areas of similar lithology was very great. For example, the mean concentrations of calcium carbonate in July 1965 and December 1966 (two months of widely different discharges) were 255 and 261 p.p.m. respectively, but the ranges were 123-398 and 124-400 respectively. A sample of 23 springs was used. This emphasises the need for detailed sampling within small areas, even when, as in the case of this 300 km² area of the Cotswolds, climate and lithology were reasonably uniform.

Furthermore, the location of a sampling point within a basin may be important because of the possibility of precipitation of salts, particularly calcium carbonate, or the uptake and release of salts by riverain swamps. Talling (1957) found the chemistry of the Nile changes markedly in the Sudd, with total iron increas-ing sharply in the swamp waters, but sulphates being very greatly reduced.

CONCLUSION

This note has been an attempt to show some of the major problems that have often been neglected in the study of rates of chemical denudation. In particular it draws attention to the need to consider the drainage basin as a chemical system in which both output and input considerations are fundamental. As Douglas (1969, p. 3) put it, "To a large extent the ecosystem and denudation system, at a given point in time and space, are identical, and thus geomorphological pro-cesses can be discussed in terms of the dynamics of ecosystems." The input factor, which is difficult both to measure and to evaluate, has too frequently been omitted from drainage basin studies, whilst the output factor needs to be measured in considerable spacial detail over a long period if computed rates of chemical denudation are to have general value.

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