Multiple Regression Method for Estimating Rates of Weathering and Soil Formation in Watersheds

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A multiple regression method for estimating rates of soil formation in watersheds was described. Distributions of seven major elements (Al, Ca, Fe, K, Mg, Na, and Si) among rocks, soils, river water, precipitation, and vegetation in a watershed were formulated in seven mass balance equations, which include rates of rock weathering and soil formation as unknown variables. Multiple regression analysis gave one set of the most probable mean values of rates of weathering and soil formation in a watershed.

Key Words: **geochemical mass balance, multiple regression analysis, rate of soil formation, rate of weathering, watershed management.**

There are many data on soil erosion. Sediment loads in major world rivers are reported to range from 0.06 for the Ob river to 21.8 t/ha/y for the Huang He river, respectively. The mean rate of erosion on earth was estimated to be 0.9 t/ha/y (World Resource Institute 1989). However, little information is available on the rates of soil formation.

Although some reports have described methods for estimating the rates of rock weathering and soil formation (Owens and Watson 1979; Alexander 1985; Wakatsuki and Rasyidin 1992), these reports did not provide a calculation method to integrate a number of chemical elements to obtain one set of rates of weathering and soil formation in a given watershed. Owens and Watson (1979), which applied the equation of Barth (1961), calculated the rates of rock weathering, but the rates of soil formation were not computed. Although Alexander (1985) improved the Barth's equation for the calculation of both the rates of rock weathering (denoted as R) and soil formation (denoted as S), the method assumes that the R/S ratio can be determined from immobile elements, such as Al, Fe, and Si which are not detectable in the runoff. Element immobility, however, changes depending on the environmental conditions. Wakatsuki and Rasyidin (1992) developed seven mass balance equations using seven major elements (Al, Fe, Ca, K, Mg, Na, and Si) which include R and S as unknown variables. Solutions of 21 sets of simultaneous equations gave 21 sets of values of R and S. Reliability of the results was verified based on the $R>S>0$ criterion. A major limitation of the method is that each set of elements gives different rates of weathering and soil formation. It remained to be determined whether for all the cases when S is lower than R the calculation is valid.

We developed a more generalized and consistent method for the treatment of data, including the effects of precipitation and vegetation. Furthermore, we found that the application of multiple regression analysis gave only one integrated set of rates of rock weathering and soil formation in a watershed.

THEORY

Water cycling is a major driving force for rock weathering, soil formation, and biological activity, in a watershed, i.e.

Precipitation + Rocks → Soils + River water + Vegetation + Ground water.

Precipitation water causes rock weathering and soils are formed on the weathered crust. Soils support vegetation. The precipitation water gives rise to rivers and ground water which dissolve the elements released from the weathering of, mainly, primary minerals.

As an example, we will describe the procedure for determining the mass balance equation of calcium in a watershed. We assumed the following: Precipitation in a watershed is denoted by P ($\times 10^4$ m^3/ha/y) which includes mean P_{Ca} (g/m^3) of Ca. River and gound water discharges are D and G ($\times 10^4$ m^3/ha/y) which includes mean D_{Ca} and G_{Ca} (g/m^3) of Ca, respectively. The mean rate of net growth of vegetation is V (t/ha/y) which includes mean V_{Ca} ($\times 10^4$ g/t) of Ca. During these processes of water cycling, R tons of rocks are assumed to be weathered and S tons of soils are formed.

If the mean concentrations of Ca in rocks and soils were R_{Ca} ($\times 10^4$ g/t) and S_{Ca} ($\times 10^4$ g/t), respectively, the geochemical mass balance equation for Ca in a watershed could be written as,

$$PP_{Ca} + RR_{Ca} = SS_{Ca} + DD_{Ca} + VV_{Ca} + GG_{Ca}.$$

Likewise, mass balance equations can be formulated for other macro- and micro-elements which have no direct exchange with the atmosphere in the gas form, such as nitrogen, oxygen, sulfur, and carbon. Except for R and S in the equation, other terms can be measured directly.

The equation can be written by using a general formula as,

$$(DD_i + VV_i + GG_i - PP_i) = R_i R - S_i S,$$

where, i = Al, Ca, Fe, K, Mg, Na, Si, etc. We can calculate the most probable values of R and S using multiple regression analyses in which $(DD_i + VV_i + GG_i - PP_i)$ are dependent variables on R_i and S_i that are independent variables and without constant terms. The values of R and S can be calculated as partial regression coefficients of R_i and S_i respectively, which minimizes the sum of squares of residues.

In a watershed with mature vegetation and balanced biological mineral cycling, we can neglect the term V. Ground water is also a possible sink in lowland areas. In a mountainous watershed, let us assume that the term G is negligible, due to the gravitational movement. In the three watersheds described here, the amount of water discharged plus the evapotranspiration accounted for more than 90% of the total precipitation in each watershed. These two parameters, V and G, can be handled, however, if we are able to collect relevant data in a given watershed using the above equation.

DATA USED FOR CALCULATION

The Iu-river watershed with a mature temperate mixed forest in southwestern Japan, contains subwatersheds characterized by granitic and basic pyroclastic lithologies. These subwatersheds were surveyed during the period April 1989–March 1991 (Rasyidin 1991; Wakatsuki and Rasyidin 1992). The major soils are Dystrochrepts and Eutrochrepts. Table 1 summarizes the survey data used for the present calculation. Figure 1 shows the location of the study sites.

The G. Gadut watershed with a mature tropical rain forest in West Sumatra was surveyed by Hotta and Ogino (1984) for the vegetation and by Wakatsuki et al. (1986) for the soils. Parent rocks are andesitic materials. Major soils include Dystropepts and Eutropepts. Collections and analyses of rocks, river water, and precipitation were performed during the period of June 1990–March 1991 (Rasyidin 1991).

In addition to the Iu and G. Gadut watersheds, Table 1 shows data from the Hubbard Brook watershed, New Hampshire, USA, reported by Likens et al. (1977) and Johnson et al. (1968) and data on the earth's crust (Kawaguchi and Kyuma 1977; Holland 1978; Bowen 1979; Drever 1988).

EXAMPLES OF CALCULATION

Using the data in Table 1 seven mass balance equations were derived for each watershed. The following are examples for the G. Gadut watershed.

	River		precipitation		rock		soil.
	$(D\times D_i)$	$-$	$(P\times P_i)$	$=$	(R_iR)	$-$	(S_iS).
Al:	4.7×0.32	$-$	5.9×0.30	$=$	$9.15\,R$	$-$	$11.99\,S$
Ca:	4.7×4.12	$-$	5.9×1.96	$=$	$4.65\,R$	$-$	$0.14\,S$
Fe:	4.7×0.043	$-$	5.9×0.043	$=$	$4.62\,R$	$-$	$6.52\,S$
K:	4.7×0.74	$-$	5.9×0.18	$=$	$0.92\,R$	$-$	$0.68\,S$
Mg:	4.7×0.73	$-$	5.9×0.05	$=$	$1.86\,R$	$-$	$0.26\,S$
Na:	4.7×0.78	$-$	5.9×0.06	$=$	$0.78\,R$	$-$	$0.06\,S$
Si:	4.7×8.72	$-$	5.9×0.46	$=$	$27.17\,R$	$-$	$25.73\,S$

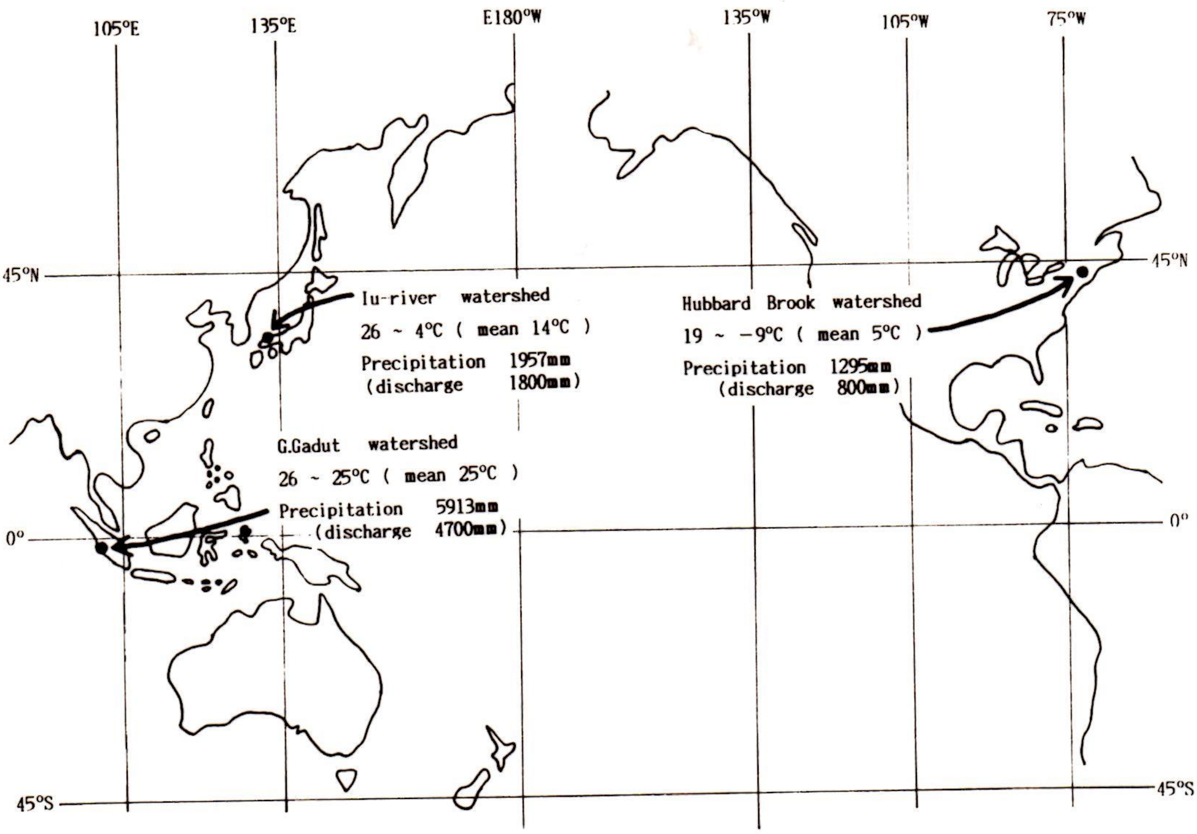

Fig. 1. Map showing the location of the study sites with basic climatological and hydrological data.

Table 1. Mean composition of rocks, soils, river water, and precipitation in the earth's crust, granitic subwatershed and basic pyroclastic subwatershed in the Iu river basin, Japan, G. Gadut watershed, Indonesia and Hubbard Brook watershed, USA.

	Al	Ca	Fe	K	Mg	Na	Si
Earth's crust[a]							
R_i, rocks ($\times 10^4$ g/t)	8.2	4.1	4.1	2.1	2.3	2.3	27.7
S_i, soils ($\times 10^4$ g/t)	7.9	1.3	4.1	1.5	0.56	0.50	33.0
D_i, river (g/m^3)	0.3	15	0.5	2.2	4.0	6.0	7.0
P_i, precipitation (g/m^3)	—	—	—	—	—	—	—
Iu-river, granitic subwatershed							
R_i, rocks ($\times 10^4$ g/t)	8.11	1.60	2.77	2.20	1.40	3.10	28.7
S_i, soils ($\times 10^4$ g/t)	11.58	1.40	2.80	2.50	1.10	1.20	25.4
D_i, river (g/m^3)	0.19	1.73	0.08	0.98	1.25	8.18	6.16
P_i, precipitation (g/m^3)	0.12	1.36	0.012	0.48	0.25	3.51	0.14
Iu-river, basic pyroclastic subwatershed							
R_i, rocks ($\times 10^4$ g/t)	8.20	2.10	3.93	1.50	1.90	2.40	27.8
S_i, soils ($\times 10^4$ g/t)	8.78	1.40	3.44	1.80	1.20	1.00	28.4
D_i, river (g/m^3)	0.21	7.01	0.02	0.79	1.76	9.38	7.74
P_i, precipitation (g/m^3)	0.12	1.69	0.018	0.57	0.26	3.88	0.46
G. Gadut, andesitic watershed							
R_i, rocks ($\times 10^4$ g/t)	9.15	4.65	4.62	0.92	1.86	0.78	27.17
S_i, soils ($\times 10^4$ g/t)	11.99	0.14	6.52	0.68	0.26	0.06	25.73
D_i, river (g/m^3)	0.32	4.12	0.043	0.74	0.73	0.78	8.72
P_i, precipitation (g/m^3)	0.30	1.96	0.043	0.18	0.05	0.06	0.46
Hubbar Brook granitic watershed[b]							
R_i, rocks ($\times 10^4$ g/t)	8.3	1.4	—	2.9	1.1	1.6	30.7
S_i, soils ($\times 10^4$ g/t)	5.1	0.40	—	2.4	0.1	1.0	37.7
D_i, river (g/m^3)	0.24	1.68	—	0.23	0.38	0.87	2.1
P_i, precipitation (g/m^3)	—	0.15	—	0.07	0.04	0.12	—
Accumulation in vegetation ($\times 10^4$ g/ha/y)	—	0.95	—	0.61	0.09	0.02	—

[a] Mean annual precipitation, 740 mm and mean annual water discharge, 260 mm (Kawaguchi and Kyuma 1977; Holland 1978; Bowen 1979; Drever 1988; World Resource Institute 1988). [b] Data from Likens et al. (1977) and Johnson et al. (1968). —: no data available.

The results of multiple regression analysis were as follows: rate of rock weathering, $R=3.0\pm0.8$ t/ha/y, rate of soil formation, $S=1.8\pm0.8$ t/ha/y, and multiple correlation coefficient (MCC)=0.95 (significant at 1% level).

For the granitic subwatershed in the Iu river watershed, $R=1.4\pm0.5$, $S=1.1\pm0.5$, and MCC=0.88 (significant at 1% level). For the subwatershed with basic pyroclastic materials of the Iu watershed, $R=5.9\pm1.7$, $S=5.3\pm1.7$, and MCC=0.89 (significant at 1% level).

For the Hubbard Brook watershed, $R=0.07\pm0.12$, $S=0.02\pm0.10$ t/ha/y, and MCC=0.76 (significant at 10% level). Since the forests were in a young stage of growth, if we include the contribution of annual accumulation of mineral elements in the vegetation (Likens et al. 1977) into the term ($DD_i+VV_i-PP_i$). In the Hubbard Brook, $R=0.16\pm0.2$, $S=0.08\pm0.2$, and MCC=0.46 (significant at 30% level). The results of calculation in the Hubbard Brook gave significant levels between 10–30%, suggesting that the data set contained some substantial errors.

The earth's mean values were calculated as $R=0.83\pm0.2$ t/ha/y, $S=0.66\pm0.2$ t/ha/y, and MCC=0.88 (significant at 5% level), in assuming that the contribution from precipitation was negligible (no available data). These results were similar to those recorded in the preliminary report of Wakatsuki and Rasyidin (1992).

DISCUSSION

The effect of parent rocks on the rate of weathering and soil formation was significant. For the subwatershed with basic pyroclastic materials in the Iu river watershed the rates of weathering and soil formation were 4.2–4.7 times higher than those for the granitic subwatershed. The effect of the climate on the rate of weathering and soil formation was also significant. For the granitic subwatershed in the Iu river basin with a mean annual temperature of 14°C and precipitation of 1,957 mm, the rates of weathering and soil formation were 9–14 times higher than those for the Hubbard Brook granitic watershed with a mean annual temperature of 5°C and precipitation of 1,295 mm.

Although the preliminary results for the granitic subwatershed (Wakatsuki and Rasyidin 1992) gave values more than two times higher than those calculated in this work, the basic pyroclastic watershed showed similar results. The present results may be more accurate, because the preliminary calculations did not include the data on Al, Fe, and Si as well as the precipitation input. Furthermore, the former method did not give integrated calculations that would be suitable mathematically. Since the primary objective of this report is to describe the methodology, the data used in the report are, therefore, still tentative. Further analysis of data used for the calculations may result in the improvement of the results.

The results of the present calculation, however, showed significant differences from those of the former calculation for the Hubbard Brook. The multiple regression analysis showed that 85% of the total errors resulted from the mass balance of Ca and 11% from that of Al. For all the other elements the mass balance between inputs and outputs was satisfactory, i.e.,

	river	veget.	soil	precipitation	rock	
	$(D_i \times D)$ +	(VV_i)+	$(S_i \times S)$ −	$(P_i \times P)$	− $(R_i \times R)$	=(error).
Al:	0.24×0.8+	0*	+ 5.1×0.084−	0*	−8.3 ×0.16=	−0.71
Ca:	1.68×0.8+	0.95	+ 0.4×0.084−	0.15×1.295	−1.4 ×0.16=	1.91
K:	0.23×0.8+	0.61	+ 2.4×0.084−	0.07×1.295	−2.9 ×0.16=	0.44
Mg:	0.38×0.8+	0.04	+ 0.1×0.084−	0.04×1.295	−1.1 ×0.16=	0.18
Na:	0.87×0.8+	0.02	+ 1.0×0.084−	0.12×1.295	−1.6 ×0.16=	0.41
Si:	2.10×0.8+	0*	+37.7×0.084−	0*	−30.7×0.16=	0.04

(0*: assumed to be negligible.)

The mass balance of Ca can be calculated, if the rates of weathering and soil formation increase by 10 times, i.e. $R=1.6$ and $S=0.8$ t/ha/y. However, these values are too high, because, the discharge output of most of the elements in the Iu-river granitic subwatershed, where $R=1.4$ and $S=1.1$ t/ha/y in a warmer and wetter climate, were far greater than those in the Hubbard Brook. Therefore, the authors consider that some of the data used for the calculations contain errors. In contrast to the large accumulation of data on river water and precipitation, the data on the soils and rocks in the Hubbard Brook watershed are very limited. The authors attributed the abnormally high mobility of Ca in the Hubbard Brook watershed (Likens et al. 1977) to the fact that the estimation of the Ca content in the bedrock was too low. The authors consider that there may be unknown materials rich in calcium in the Hubbard Brook watershed. Alexander (1985) also suggested that neglected sources of Ca

Table 2. Mean concentrations of major anions and ammonium ion in precipitation and river water in the Iu river watershed, Japan, and G. Gadut watershed, Indonesia.

		Mean concentration (10^{-6} mol·L^{-1})				
		NH_4^+	SO_4^{2+}	NO_3^-	Cl^-	HCO_3^-
Iu watershed	Precipitation	6.7	54	3.2	106.2	79.6
	River, basic[a]	2.0	229	27	241	226
G. Gadut	Precipitation	trace	12	7.9	4.2	189
	River water	trace	17	6.9	5.9	489

[a] Mean composition in river water from basic pyroclastic subwatershed.

may be present in the Hubbard Brook watershed.

The effects of the climatic conditions were not clear in the case of the G. Gadut watershed in Indonesia, which is characterized by a typical humid tropical climate, i.e. a mean annual temperature of 25°C and precipitation of 5,913 mm. The air temperature exceeds ten degrees and the precipitation is three times higher than that in the Iu river watershed in Japan. If we assume that Q_{10}, the reactivity quotient per ten degrees Celsius, of chemical weathering is 2, then we may predict that the rates of weathering and soil formation in the tropical G. Gadut watershed could be about 6 times higher than those in the temperate Iu river watershed. However in the subwatershed with basic pyroclastic materials in the Iu river watershed even higher rates of weathering and soil formation than those in the G. Gadut watershed were recorded. The granitic subwatershed also showed relatively high rates of weathering and soil formation. These abnormally high values may partly be due to the difference in the nature of the parent rocks.

However as shown in Table 2, precipitation in the Iu-river watershed contains abundant quantities of anions of strong acids, such as sulfate and chloride, whereas the major anionic component in the G. Gadut watershed is bicarbonate. These findings may indicate that acid precipitation promotes weathering and soil formation in the Iu-river watershed. Possible effects of acid precipitation on the rates of weathering and soil formation in watersheds will be reported using the method proposed here.

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