Dissolved Loads of Rivers and Surface Water Quantity/Quality Relationships
(Proceedings of the Hamburg Symposium, August 1983). IAHS Publ. no. 141.

The chemical mass balance of a small basin in a wet monsoonal environment and the effect of fast-growing plantation forest

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ABSTRACT A chemical mass balance is presented for a 19 ha basin in central Java (Indonesia) underlain by andesitic tuffs. Net losses of major elements in kg ha^{-1} $year^{-1}$ amount to 19.1 (Ca), 26.5 (Mg), 14.1 (Na), 12.4 (K) and 527 (SiO_2). Ortho-P accumulates at a rate of 0.2 kg $ha^{-1}year^{-1}$. The vigorously growing vegetation (plantation forest of *Agathis dammara*) acts as a long-term sink of nutrients rendering the catchment chemical flux an underestimate of the true chemical denudation rate. Actual immobilization of nutrients by the basin vegetation during the study year was evaluated by determining its biomass and chemical content. Results indicate that the traditional budget approach underestimates the rate of chemical weathering by 75% (Ca), 33% (Mg), 17% (Na), 70% (K) and 12% (SiO_2). The need to evaluate the role of vegetation in budget studies is stressed. Comparisons with data from other locations are made and applications of the results in land and forest management are suggested.

Bilan chimique d'un petit bassin dans un environnement de mousson humide et influence d'une plantation forestière à croissance rapide
RESUME Un bilan chimique est établi pour un bassin forestier de 19 ha dans la partie centrale de Java (Indonésie), développé sur des tufs andésitiques. La perte nette en éléments majeurs (en kg $ha^{-1}an^{-1}$) s'élève à 19.1 (Ca), 26.5 (Mg), 14.1 (Na), 12.4 (K) et 527 (SiO_2). Les Ortho-P s'accumulent à une vitesse de 0.2 kg $ha^{-1}an^{-1}$. La végétation à croissance rapide (forêt plantée de *Agathis dammara*) constitue une réserve à long terme de nutrients, si bien que le flux chimique issu du bassin versant est déficitaire par rapport au matériel provenant de l'érosion. L'immobilisation des nutrients par la végétation pendant l'année d'étude a été évaluée par la détermination de la biomasse et de sa composition chimique. Les résultats montrent que la méthode traditionnelle d'établissement du budget sousestime la vitesse de l'érosion de 76% (Ca), 33% (Mg), 17% (Na), 70% (K) et 12% (SiO_2). On souligne la nécessité d'évaluer le rôle de la végétation dans les études par bilan. Ces résultats sont comparés à ceux d'autres localités et des applications

sont proposées pour la gestion des forêts.

INTRODUCTION

Traditionally the magnitude of dissolved loads of rivers has received attention from geomorphologists interested in chemical denudation rates. More recently the subject also has aroused interest from ecologists concerned with the functioning of ecosystems (Likens *et al.*, 1977). The difference in emphasis between these two groups is often reflected in the chemical parameters selected for study. Dissolved silica and sodium, for example, are usually lacking in the ecology-oriented studies, whereas loads of dissolved phosphorus or nitrates are of less importance to the geomorphologist. Ideally the input of chemical elements into the system, via precipitation and dry deposition, should be known for proper evaluation of solute export data. Such budget studies are bound to be limited in number by their very nature and mostly deal with temperate-latitude basins (Likens *et al.*, 1977).

Some investigations of the elemental flux through tropical basins have been carried out, but pertain either to a very small plot size (Jordan *et al.*, 1972), to a limited sampling period (McColl, 1970; Kenworthy, 1971; Turvey, 1974) or to a somewhat unfavourable climate as in the seasonally dry zone of the Ivory Coast (Mathieu, 1976). This paucity of relatively accurate data on the rate of release of chemical elements under tropical conditions stands in strong contrast to the need for this type of information in, for example, evaluating the effects of fast-growing plantation forests on soil nutrient reserves (Lundgren, 1978; Chijioke, 1980). The chemical flux from a drainage basin will only represent the ongoing chemical denudation rate if the vegetation has reached a steady state with respect to uptake and return of nutrients. As long as there is a net increase in biomass, a portion of the chemical elements released by weathering will be incorporated in the vegetation and the chemical flux will underestimate the true denudation rate.

The present paper reports on a chemical element budget study carried out in the wet monsoonal environment of south-central Java, Indonesia, between 1 December 1976 and 1 February 1978. Since the vegetation of the drainage basin consisted of vigorously growing plantation forest, the actual immobilization of nutrients in the vegetation has also been evaluated through a programme of biomass and chemical content determinations (Bruijnzeel, 1983a).

THE STUDY AREA

The 19 ha Kali Mondo basin is situated in the hilly northern rim of the South Serayu range at 7°26'S and 109°45'E, and lies between 508 and 714 m a.s.l. The area is underlain by Quaternary volcanic ashes of an andesitic nature in which humic Andosols (FAO/UNESCO, 1974) have developed. Ash cover thickness is generally at least 6 m on the divides, but may locally become as thin as 1 m on steep slopes near the stream. The Kali Mondo has incised itself into the underlying Lower Tertiary rocks, which consist of andesitic breccias and, in the lower reaches of the basin, shales. The site receives on average

4770 mm of rain per year (1926-1977) with a dry season between July and September, when on average two months experience rainfall totals of less than 60 mm. Mean annual evaporation (Penman estimate) amounts to 1345 mm and seasonal extremes in temperature range between 21.5 °C (dry season) and 24 °C (rest of the year). Basin vegetation consists of *Agathis dammara* plantations ranging in age between 11 and 35 years. These exhibit different degrees of stocking and show growth rates that can be considered as average for volcanic soils in central Java (Team Vegetation & Erosion, 1979). Further details on catchment characteristics are given by Bruijnzeel (1983a).

FIELD AND LABORATORY PROCEDURES

Precipitation over the basin was determined from four standard raingauges (100 cm^2 orifice at 100 cm above the surface) and a centrally located Thiessen pluviograph. All instruments were checked daily. Bulk precipitation was sampled on a weekly basis from the pluviograph and every other week from two plastic containers, equipped with polyethylene funnels and placed close to each other at an elevation slightly higher than that of the pluviograph. The plastic gauges were equipped with paper filters to hold back any coarse (organic) debris. Funnels and containers were rinsed with dilute hydrochloric acid and demineralized water after each sample collection, but this was not always adequate to prevent the growth of a green film in the collectors exposed to the sun. The latter phenomenon may account for the different potassium levels found in the two types of precipitation samples, and the mean of both estimates has been used. Streamflow was determined using standard techniques (V-notch; water level recorder; daily volumetric gauging and/or the area-velocity method) and was generally sampled on a weekly basis. Numerous samples of storm runoff were taken as well. All samples of precipitation and streamflow were collected in two clean 100 ml polyethylene bottles: one for the initial determination of pH, electrical conductivity and alkalinity and the second, after filtration through a 0.45 μm Millipore filter and the addition of 0.07 ml HNO_3 conc. plus two drops of CCl_4, for further analysis in the Netherlands. Samples awaiting transport were stored in the dark at 20 °C for a period of one to three months, flown to Amsterdam and stored again in the dark at 8 °C until analysed for calcium, magnesium, sodium, silicon, iron, aluminium and manganese by emission spectrometry, and potassium by flame photometry. Phosphorus was analysed by colorimetry.

Solute input into the basin was obtained by multiplying weekly amounts of rainfall by the corresponding element concentrations and summing to monthly values. Solute output from the drainage basin was calculated by multiplying weekly amounts of baseflow by the average of the concentrations observed at the beginning and end of that particular week, followed by summing to monthly values. Amounts transported in quickflow were derived by sampling a number of runoff events in detail and computing weighted mean concentrations for various constituents (Ca, Mg, Na, K and dissolved SiO_2). These were then multiplied by quickflow volume in a particular storm to give the individual solute loads transported. The latter were highly correlated with quickflow volume. This procedure was applied to estimate stormflow solute export per storm and, by summation, per month.

Forest biomass was estimated by multiplying the weight of trees with average dimensions (two specimens per age class) by stand density. Samples from the "average" trees were analysed, after wet ashing, by means of atomic absorption and emission flame photometry. Details are given in Bruijnzeel (1983a).

RESULTS AND DISCUSSION

Chemical element flux

The year 1977 experienced an unusually long dry season of almost five months instead of two or three, which resulted in a relatively low runoff total. In order to derive an estimate of "normal" solute export, use was made of the observation that chemical concentrations in the streamwater varied within a very narrow range for most of the year. Monthly outputs of individual elements, expressed as kg ha^{-1}, are therefore highly correlated with monthly runoff (Bruijnzeel, 1983a). Approximately 3460 mm of streamflow left the basin between 1 December 1976 and 1 February 1978. Rainfall input over this *14-month* period amounted to 4670 mm, which is close to the 50-year average *annual* total. If this amount of rain fell in one year the corresponding runoff total would rise to *c.* 3590 mm, because of the shortened period of evaporative demand (Bruijnzeel, 1983a). Table 1 summarizes observed and "normalized" chemical element budgets for the Mondo drainage basin. Dissolved silica clearly provides the bulk of solute export; it constitutes almost 80% of the total load, and is followed in order of decreasing load values by calcium, magnesium and sodium (4.3 ± 0.2%) potassium (3.2%), iron and aluminium (*c.* 2%), manganese (0.2%) and phosphorus (0.1%).

Highest solute outputs were observed at the end of the wet season (April 1977) when extreme rainfall coincided with wet antecedent conditions. Despite increased concentrations in the streamwater

Table 1 Chemical loads in bulk precipitation and streamflow for the Kali Mondo basin, non-rounded values

	Bulk precipitation (kg ha^{-1})*	*Streamflow: Recorded* (kg ha^{-1})*	*Streamflow: Normalized† (kg $ha^{-1}year^{-1}$)*	*Flux: Recorded* (kg ha^{-1})*	*Flux: Normalized† (kg $ha^{-1}year^{-1}$)*	*Input*/output* (%)*
Ca	9.9	28.0	29.0	-18.1	-19.1	35
Mg	4.0	29.4	30.5	-25.4	-26.5	14
Na	13.3	26.4	27.4	-13.1	-14.1	50
K	9.6	21.2	22.0	-11.6	-12.4	45
SiO_2	<10.6	519	538	-508.5	-527	<2
Al§	<1.5	<15		-13.5	-14	10
Fe§	-	<12		-12	-13	-
Mn§	-	<1		-1	-1	-
P§	0.9	0.7		+0.2		>100

**1 December 1976-1 February 1978.*
†Runoff: 3590 mm.
§Limited data.

during the dry season, especially in September and October, the smallest export of solutes was recorded in October 1977, when runoff had dropped to a mere 4 mm $month^{-1}$. Input of elements via bulk precipitation, which occurs mainly as dry deposition, only exceeds solute output, except for dissolved (SiO_2), in the second half of the dry season. During the remainder of the year solute exports were much larger than solute imports, and the study basin exhibited large annual net losses of dissolved silica and, to a lesser extent, bases. Bulk precipitation, nevertheless, provided significant contributions of calcium, potassium and phosphorus to the basin (cf. Kenworthy, 1971; Jordan *et al.*, 1972; Mathieu, 1976). The latter element even appears to accumulate in the basin.

Quickflow comprised only 6.5% of total runoff in the Kali Mondo which reflects the highly permeable nature of the volcanic ashes (Bruijnzeel, 1983b). In turn, only a small proportion of total dissolved load is transported by storm runoff, viz. 2.2% in the case of dissolved SiO_2 and 4.1 ± 0.3% for the bases. In contrast, over 95% (i.e. 291 t km^{-2}) of suspended sediment export from the drainage basin occurred during flashy stormflows (Bruijnzeel, 1983a). A value for total solute yield of 80.7 t km^{-2} over the study period (or 83.6 t km^{-2} for a "normal year") has been calculated by converting data on chemical element output given in Table 1 to oxides. Bed load transport in the study period amounted to 43 t km^{-2}, which when added to sediment and solute loads gives a value of 430 t km^{-2} (1 December 1976-1 February 1978) or 442 t km^{-2} ("normal year") for material output from all sources (see Bruijnzeel, 1983a for further discussion).

Comparison with other locations

Comparing results obtained in the present study with those from other forested basins is not an easy task. Numerous hydrological measurements and chemical determinations are needed for the computation of a basin mass balance and many sources of error are present (Lee, 1970; Foster, 1980). Also, fluxes vary greatly with amounts of rainfall received, and may be above or below average during any year of investigation (Likens *et al.*, 1977). The latter remark is particularly relevant to the present study. Table 2 collates information collected for various tropical and temperate latitude basins. Data for the study basin represent a "normal" year, and all data are listed according to annual runoff total.

With respect to annual *inputs of solutes*, the main factor, apart from the amount of rainfall, appears to be the position of a sampling station relative to any solute sources, such as the sea (Plynlimon, El Verde) or dust producing lands (Amitioro, Ca at Plynlimon, dissolved SiO_2 at East Twin). Analytical problems may also sometimes influence the results. Turvey (1974), for example, has reported cation input rates for a rainforest site in Papua, New Guinea, which are noticeably low, except in the case of sodium, when rainfall amounts are considered. Anomalous results obtained for calcium were discussed in terms of analytical procedures (Turvey, 1974). Brasell & Gilmour (1980), working in a very similar environment in northern Queensland, quoted values of 2.3, 2.9, 20.8 and 4.5 kg $ha^{-1}year^{-1}$ for Ca, Mg, Na and K which seem more realistic.

TABLE 2 Solute budgets for selected basins

Location	Input (kg ha^{-1} $year^{-1}$)	Output (kg ha^{-1} $year^{-1}$)	Net loss or gain (kg ha^{-1} $year^{-1}$)	Annual precipitation (mm)	Annual runoff (mm)	Vegetation[a]	Geology[b]
CALCIUM							
A Jamieson Creek (BC, Canada)[8]	7.2	41.7	-34.4	4540	3670	Df	till plut
B Kali Mondo (Indonesia)[1]*	9.9	29	-19.1	4668	3590	Agathis	ava avb
C H.J.Andrews (Oregon, USA)[6]	3.6	49.4	-45.9	2370	1545	Df	avb ava
D Ei Creek (Papua, New Guinea)[2]*	0[c]	24.8	-24.8[c]	2700	1480	LMRF	avb ph
E El Verde (Puerto Rico)[3]*	21.8	43.1	-21.3	3760	(1350)	LMRF	and
F Plynlimon (Wales, UK)[7]	25.1[d]	12.0	+13.1[d]	1850	1350	pg	till gw
G Hubbard Brook (NH, USA)[5]	2.2	13.9	-11.7	1320	830	Nh	till gn
H Amitioro (Ivory Coast)[4]*	<13.1	6.1	<7.0	1320	<120	MSDF	sch
MAGNESIUM							
A	2.2	8.8	-6.6				
B	4.0	30.5	-26.5				
C	1.2	12.8	-7.4				
D	0.3	51.0	-50.7				
E	4.9	15.0	-10.1				
F	4.4	8.7	-4.3				
G	0.6	3.3	-2.7				
H	<1.3	3.3	-2.0				
SODIUM							
A	13.2	25.6	-12.4				
B	13.3	27.4	-14.1				
C	5.7	30.3	-24.6				
D	8.4	66.0	-57.6				
E	57.2	64.5	-7.3				
F	27.2	44.0	-16.8				
G	1.6	7.5	-5.9				
H	<6.6	4.2	<2.2				

POTASSIUM							
A	0.9	2.6	-1.7				
B	9.6	22.0	-12.4				
C	0.95	5.25	-4.3				
D	0.8	14.9	-14.1				
E	18.2	20.8	-2.6				
F	1.6	2.6	-1.0				
G	0.9	2.4	-1.5				
H	<6.6	2.3	<4.3				
DISSOLVED SiO_2							
Jamieson Creek (BC, Canada)[8]	0.75	92.0	-91.3	4540	3670	Df	till plut
Kali Mondo (Indonesia)[1]*	<10.6	538	-527	4668	3590	Agathis	ava avb
Behana Creek (Queensland)[10]*	-	279		4000	2325	L(M)RF	gran
H.J.Andrews (Oregon, USA)[12]	trace	113.6	-113.5	2370	1545	Df	avb ava
Ei Creek (Papua, New Guinea)[2]*	0	288	-288	2700	1480	LMRF	avb ph
Davies Creek (Queensland)[11]*	-	180		1400	900	L(M)RF	gran
Sungai Gombak (Malaya)[10]*	-	128		2360	856	LMRF	gran
Hubbard Brook (NH, USA)[5]	0	23.8	-23.8	1322	833	Nh	till gw
Rio Tanama (Puerto Rico)[9]*	-	165		2000	630	L(M)RF	and
East Twin (Somerset, UK)[13]	5.2[d]	27.4	-22.2	1078	514	gh	sst
Haartsbach (Luxembourg)[14]	0.5	27.5	-27.0	774	383	be	sl
Kaingaroa (NI, New Zealand)[15]*	-	49.0		1500	170[e]	Pinus	rva
Amitioro (Ivory Coast)[4]*	13.1	10.3	2.8	1323	120	MSDF	sch

*(Sub)tropical region
[1] Present study
[2] Turvey (1974)
[3] Jordan et al. (1972)
[4] Mathieu (1976)
[5] Likens et al. (1977)
[6] Sollins et al. (1980)
[7] Cryer)1976)
[8] Zeman (1975)
[9] Norton (1974)
[10] Douglas (1969)
[11] Douglas (1967, 1973)
[12] Fredriksen (1972)
[13] Waylen (1979)
[14] Verstraten (1977)
[15] Knight & Will (1977)

[a] Vegetation abbreviations: be = beech; df = Douglas fir; gh = grass and heathland; LMRF = Lower Montane Rainforest; MSDF = moist semideciduous forest; Nh = northern hardwoods; pg = peaty grassland.
[b] Geology abbreviations: and = andesite; ava = andesitic volcanic ashes; avb = andesitic volcanic breccia; gn = gneiss; gran = granite; gw = greywacke; plut = various plutonic rocks; rva = rhyolitic volcanic ashes; sch = schists; sl = slates; sst = sandstone.
[c] Analytical error.
[d] Contamination.
[e] Lysimeter drainage water.

Output of solutes is generally determined by the nature of the geological substratum (Miller, 1961) and the prevailing hydrological regime. With respect to the first factor, it is clear that the relatively high amounts of certain cations removed from some drainage basins listed in Table 2 reflect the weathering of feldspars (e.g. H.J.Andrews forest) or Mg-bearing phyllites (Ei Creek). The effect of the hydrological regime is best illustrated by the example of the Amitioro basin in Ivory Coast, where the annual runoff is extremely small and most elements, in fact, accumulate in the system (Mathieu, 1976). Also, the solute loads from the extremely wet Jamieson Creek basin, Canada, are much larger than those of the Hubbard Brook area (USA), which reflects the higher annual runoff volumes of the former basin, despite lower solute concentrations (Zeman, 1975). In turn, losses from the Hubbard Brook area (annual rainfall 1320 mm, mean annual temperature $<10^{\circ}C$) are greater than observed for the Ivory Coast basin which experiences on average the same amount of rainfall but a much higher mean annual temperature ($>20^{\circ}C$).

The data therefore suggest that lithology and the rate of flushing are the dominant factors in determining net solute losses from undisturbed basins, rather than prevailing temperatures. This conclusion agrees with the observations of Douglas (1969), who explained the higher loads of dissolved silica carried by tropical streams in terms of higher runoff volumes prevailing in the humid tropics. It would seem, however, that concentrations of dissolved SiO_2 in the water of (sub) tropical streams presented in Table 2 are generally higher than those for the temperate-latitude catchments. Average values of dissolved SiO_2 for the "tropical" and "temperate" groups are 18.1 ± 4.7 and 5.0 ± 2.3 mg l^{-1} respectively, and a t-test reveals this difference to be significant at the 1% level. However, more data will be needed to test the above observation, and factors such as catchment rock type, catchment size and climatological conditions should be included in such a study.

Element uptake by catchment vegetation

Part of the chemicals released by weathering of the volcanic ashes is taken up by the catchment vegetation and incorporated in structural biomass. The actual immobilization of nutrients in plantation forest of the Mondo basin (expressed as kg $ha^{-1}year^{-1}$) is given in Table 3 along with the apparent rate of chemical denudation presented above.

The degree to which the basin budget for chemical elements underestimates the actual rate of chemical denudation differs depending on how essential a particular element is for plant growth. Micronutrients or non-essential elements, such as sodium, iron and aluminium are taken up in relatively small quantities and the sink effect of the vegetation is accordingly moderate. In contrast, macronutrients, such as calcium and potassium, are taken up quite actively. The overall effect of uptake on the weathering estimate is damped by the fact that dissolved silica makes up the bulk of dissolved load. Consideration of element uptake also clarifies the phosphorus balance, since virtually all phosphorus released by weathering is consumed by the forest.

TABLE 3 Annual uptake of nutrients by the vegetation of the Kali Mondo basin in relation to chemical denudation, non-rounded values

	Ca	Mg	Na	K	SiO_2	P	Al	Fe	Mn
Uptake by vegetation ($kg\ ha^{-1} year^{-1}$)	57.3	12.6	2.6	27.0	71.9	5.2	3.6	2.3	1.1
Apparent (1) denudation ($kg\ ha^{-1} year^{-1}$)*	19.1	26.5	13.1	12.4	527	-0.2	14	13	1
Actual (2) denudation ($kg\ ha^{-1} year^{-1}$)	76.4	39.1	15.7	39.4	599	5	18	15	2
(1) as % of (2)	24	67	83	30	88	-	82	85	50

*Normalized flux of Table 2.

CONCLUSIONS AND APPLICATIONS

Data presented here show that the greater net losses of chemical elements from tropical basins as compared to temperate latitudes are a function of high flushing rates rather than high concentrations in streamwater. Dissolved silica, however, is an exception since concentrations for this constituent are generally higher in tropical streams. The sink effect of vegetation is obvious for this basin with its fast-growing production forest, and should be taken into account when studying the supply of chemicals by weathering. Knowledge of the latter item is of vital importance in evaluating the effects of fast-growing species planted on the often poor tropical soils (Lundgren, 1978; Chijioke, 1980).

Comparison of nutrient inputs into the soil system, through bulk precipitation and weathering, with losses, through drainage and nutrient uptake by trees that eventually will be harvested, will allow an estimate of the extent to which trees can be harvested from an ecosystem without a decline in site quality. An example of this approach is given by Bruijnzeel (1983a) for *Agathis dammara* plantations growing on volcanic soils of medium fertility in a 40-year rotation scheme in central Java, Indonesia.

ACKNOWLEDGEMENTS The investigations were supported by a grant from the Netherlands Foundation for the Advancement of Tropical Research (WOTRO) under project no. W76-45. Assistance in the field by Mr.A. Riyadi and in the laboratory by Messrs A.Hansen, H.Nelissen, P.Overweg and H.Wesselman is gratefully acknowledged. Prof.Dr. I.Simmers and Prof.Dr. G.B.Engelen are thanked for their critical remarks on an earlier draft. Romée de Vries typed the manuscript and Prof.Dr. J.L.R.Touret kindly helped with the french translation.

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