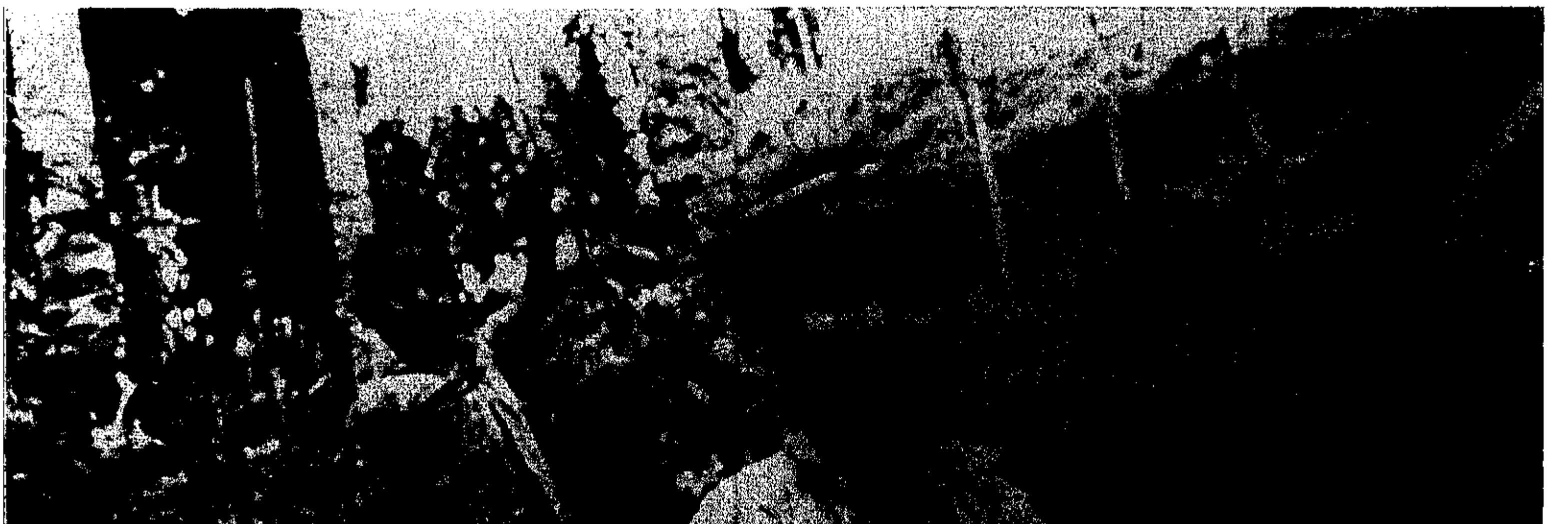
HYDROLOGICAL AND BIOGEOCHEMICAL ASPECTS OF MAN-MADE FORESTS IN SOUTH-CENTRAL JAVA, INDONESIA



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VRIJE UNIVERSITEIT TE AMSTERDAM

HYDROLOGICAL AND BIOGEOCHEMICAL ASPECTS OF MAN-MADE FORESTS IN SOUTH-CENTRAL JAVA, INDONESIA

ACADEMISCH PROEFSCHRIFT

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LEENDERT ADRIAAN BRUIJNZEEL
(SWAMI PREM SAMPURNO)
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Copromotores : Prof. dr. W. H. O. Ernst
: Prof. dr. J. M. Verstraten

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My effort is to create a man
who is not partial
who is total, whole, holy
A man should be all three together:
He should be as accurate and objective as a scientist
as sensitive, as full of the heart as the poet and
as rooted deep down in his being as the mystic
He should not choose
He should allow these three dimensions
to exist together

Bhagwan Shree Rajneesh
"The Book of the Books"
Poona, 8 July, 1979

Contents

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Drs. Tukidal and Drs. Jamulya are warmly thanked for their help with the description and sampling of soil profiles.

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Amsterdam, 2 November, 1982. L.A. Bruynzeel (Swami Prem Sampurno)

1. INTRODUCTION

1.1 Organizational framework

The present investigation evolved from a research proposal for the study of the chemistry of the watercycle in some small drainage basins (ENGELEN, 1973) within the framework of the NUFFIC/UGM "Serayu Valley Project" (ITC/GUA/VU/1), (Central Java, Indonesia). This project - a co-operation between the faculty of Geography of the Gadjah Mada University (UGM, Yogyakarta, Indonesia) and three scientific institutes in the Netherlands (the International Institute for Aerial Survey and Earth Sciences (ITC, Enschede), the Laboratory of Physical Geography and Soil Science of the University of Amsterdam (GUA, Amsterdam), and the Institute of Earth Sciences of the Free University (VU, Amsterdam) - is sponsored by the Netherlands Universities Foundation for International Cooperation (NUFFIC). Apart from the stimulation of Indonesian research in the field of river basin development and the realization of a well-equipped and experienced team of Indonesian earth-scientists, the main purposes of the project were :

- to investigate the effects of geomorphological variables on the water balance and the sediment yield of a tropical river basin;
- to survey the disturbances of the natural balance due to environmental changes induced by man, *i.e.* through deforestation, land-use, exploitation of natural water, etc.

The research program of the Serayu Valley Project consisted of work on a macroscale (the entire basin, *c.* 3700 km^2), a mesoscale (100 - 500 km^2) and a microscale (less than 10 km^2). Organizational and scientific details concerning the project can be found in FABER & KARMONO (1977) and ENGELEN (1980). Summaries of the results have been prepared recently by the same authors (ENGELEN, 1982; FABER, 1979). The above-mentioned hydrochemical study was intended as a subject for Ph.D. research (starting around November 1974), but no suitable project participant was available at the time. The main items of the original (field) research proposal, however, could be carried out in one catchment by the present writer between October 1975 and January 1976. The results of this investigation were laid down in an unpublished M.Sc. Thesis (BRUIJNZEEL, 1976). This report contained a number of suggestions for further research, the most important of these being the weathering mode of the amorphous fraction present in the volcanic soils and an evaluation of the role played by the vegetative cover with regards to the process and rate of chemical weathering. By the end of June 1976 the ITC/GUA/VU/1 project was terminated and a follow-up project started, in which the Dutch participants were to concentrate upon educational aspects, leaving no room for individual research. In order to carry out the original idea of investigating the hydro/geochemical behaviour of contrasting watersheds a successful application was made for a grant from the Netherlands Foundation for the Advancement of Tropical Research (WOTRO). Close cooperation with the "Serayu Valley Project" was maintained however. For this study three drainage basins with contrasting rock types (preferably located in the geologically diversified South Serayu Mountains, south-central Java) were to be selected to study :

- their net chemical output (*e.g.* the total load of dissolved matter carried away by the stream draining the basin minus the amount of nutrients derived from the precipitation falling upon the area);
- the weathering of rocks and the genesis of soils with due attention being paid to the chemistry of the soil moisture; and
- the possibility of checking the relative importance and the origin of the various sorts of runoff (such as direct overland flow and quick subsurface flow through the upper soil horizons) that constitute the runoff wave ('banjir') during and shortly after rainshowers, by using chemical data obtained by synchronous sampling of river water, overland flow and soil water at different locations in the catchment.

The inclusion of biological aspects of the weathering process was considered to be too laborious at that stage. The WOTRO-sponsored field research (Project Code W76-45) started on the fifteenth of November 1976 and lasted till the first of February 1978. Very soon after the field study commenced, it became apparent that the circumstances in most of the area were rather unfavourable for the intended type of research due to man-induced accelerated erosion. Natural hydrological regimes and undisturbed soil profiles (essential for the pedogenetic parts of the study) were restricted to forested areas (usually having volcanic ashes as their superficial geological substratum). The investigation was therefore concentrated in and around the forested part of one of the selected catchments, that of the Mondo River (the catchment where the early work referred to above had been performed), whereas the work could also be extended significantly in a forest-ecological direction thanks to a co-operation with the Ecological Institute of the Padjadjaran University in Bandung.

1.2 The scientific framework

The present work describes the biogeochemistry of several man-made forest types in south-central Java, Indonesia, as evolved from a basically earth-scientific investigation (hydrology, pedology).

In more detail, the following items have been studied :

- the waterbalance of a small (18.74 ha) catchment covered with *Agathis loranthifolia** and an undergrowth dominated by *Eu-*

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*Although recently different names have come into use for these species, viz. *A. dammara* for the former (WHITMORE & PAGE, 1980) and *Chromolina odorata* for the latter (K.F. Wiersum, personal communication) the still more common original names have been retained in the present work.

*patorium** *sp.*;

- the flux of chemicals through, and the output of particulate matter from the study basin;
- the cycling of nutrients through plantations of *Agathis loranthifolia* (35, 21 and 11 years old), *Tectona grandis* and *Pinus merkusii* and *Eupatorium* thicket;
- litterfall in additional stands of *Agathis* (7 years old), *Tectona* (28 years old) and "primary" forest, all in the vicinity of the experimental catchment;
- chemical aspects of the pedogenesis of the andesitic volcanic tuffs underlying these forests in the light of thermodynamic theory.

Taking into account the general paucity of biogeochemical data on tropical forest ecosystems (UNESCO, 1978), it will be no surprise that thus far no study has been published that has investigated the hydrological, biogeochemical and pedogenetic aspects of any tropical forest ecosystem in one comprehensive framework. This lack of integrated research also stems from the fact that interest in the chemistry of water emerging from woodlands either has come from ecologists (mainly concerned with the internal functioning of the ecosystem) or from geomorphologists (primarily interested in the estimation of denudation rates, *i.e.* the non-biotic portion of the ecosystem).

Clearly, however, the integrated study of hydrological, ecological and pedological processes at one location offers several advantages to both earth scientists and ecologists. For example, the chemical flux through a drainage basin is usually considered to represent the rate of ongoing chemical weathering. This holds true, however, only if the vegetation is in a steady state as far as its uptake and release of nutrients are concerned. The results of a nutrient cycling study thus may reveal to what extent the apparent weathering rate has to be modified (LIKENS *et al.*, 1977). On the other other hand, a thorough knowledge of pedogenetic processes will certainly enhance the understanding of the functioning of a forest ecosystem.

The hydrology and the biogeochemistry of some types of natural tropical forest have been described in great detail, *e.g.* the hyperhumid Lower Montane Rain forest of El Verde, Puerto Rico (ODUM & PIGEON, 1970), the lowland dipterocarp Rain forest of Pasoh, Malaysia (ANONYMUS, 1974) and the humid woodlands of Ivory Coast (ANONYMUS, 1975; MATHIEU, 1976). These are about the most comprehensive studies available, but their pedological information is limited to an inventory of available nutrients. Data on elements that have more pedogenetic than direct ecological significance, such as silicon, aluminum and iron, or estimates of the amounts of sediment removed in suspension, have not been published in most cases. Although the number of publications dealing with particular aspects of tropical forest ecosystems is growing rapidly since the initiation of the International Biological Program in 1963, detailed data on manmade forests in the tropics are still exceedingly scarce. (UNESCO, 1978). Examples of work conducted in natural forests are the investigation of the amount and chemistry of litterfall and the decomposition of the litter in such environments as the hyperhumid lowlands of Colombia (FÖLSTER & DE LAS SALAS, 1976), the central amazonian lowlands near Manaos (KLINGE & RODRIGUES, 1968ab; KLINGE, 1973), the alluvial plain of the Ganges near Varanasi (northern India) (SINGH, 1968; 1969) and the lowlands of northern Trinidad (CORNFORTH, 1970). For some of these environments the total biomass of the forest and its elemental composition have been determined as well (FÖLSTER *et al.*, (1976) for Colombia; KLINGE *et al.*. (1975) and STARK (1971) for Central Amazonia). Similar work, which also included an estimate of nutrient return to the forest floor via canopy leaching, has been carried out in humid secondary forest in Ghana (the classical study reported upon by GREENLAND & KOWAL (1960) and NYE (1961)) and more recently in Panama (GOLLEY *et al.*, 1975).

At present much of the work on man-made forests is carried out by foresters interested in nutrient uptake *cq.* depletion of the soil by fast-growing species such as *Gmelina arborea* and *Pinus caribaea* (Nigeria and Brazil, CHIJIOKE, 1980; EGUNJOBI & BADA, 1979), *P. patula* (Tanzania, LUNDGREN, 1978) or *Pinus oocarpa* (sub-tropical Brazil, CASTRO *et al.*, 1980). In these studies estimates of biomass and nutrient content have been made for trees of known age. (Total nutrient uptake over the tree's life span could thus be evaluated.) Older investigations of this type are those by SETH *et al.*, (1963) for teak, *Araucaria cunninghamii* and *Pinus roxburghii* in northern India and Monterey pine (*Pinus radiata*) in northern New Zealand (WILL, 1964). Both these papers do not pertain to the subtropics anymore but contain much useful reference material. More recent work has been reported by BERNHARD (1976) on nutrient cycling in *Terminalia ivorensis* in Ivory Coast and by BRASELL *et al.* (1980) on the element content of litterfall from Hoop's pine (*Araucaria cunninghamii*) in northern Queensland.

In contrast to the number of investigations describing the cycling of nutrients through tropical vegetation, publications on the chemistry of precipitation, soil- and stream water in tropical woodlands are very scarce indeed, indicating how much the study of tropical geomorphological processes is lagging behind that of tropical forest ecology. Apart from the three comprehensive studies already referred to, the material is restricted to the data given by TURVEY (1974) and KENWORTHY (1971) for Lower Montane Rain forest in Papua New Guinea and Malaysia respectively and by McCOLL (1970) for Lowland Rain forest in northern Costa Rica. Additional data on streamwater chemistry pertaining to various granitic terrains in the tropics can be found in DOUGLAS (1967). Working on a much larger scale GIBBS (1967) and SIOLI (1975) (among others) present a general picture of the hydrochemistry of the Amazon river basin, whereas GROVE (1972) and VINER (1975) did the same for West Africa and Uganda respectively. Similarly, up till the mid seventies virtually all work adding to an increased understanding of the hydrological behaviour of small river basins has been performed in the temperate zone. As important studies should be mentioned in this respect : the work of HEWLETT & HIBBERT (1963) and TISCHENDORF (1969) in Georgia (U.S.A.), that of DUNNE & BLACK (1970ab) in Vermont (U.S.A.), and that of WEYMAN (1973) and ANDERSON & BURT (1977) in Somerset (U.K.), whilst major theoretical contributions have been made by FREEZE (1972ab).

The hydrological work in the tropics remained of the "black box" type originally (e.g. PEREIRA *et al.*, 1962) LOW & GOH, 1972), but more recently the occurrence and chemistry of laterally moving soil water ("throughflow") has started to receive attention as well. Throughflow and/or overland flow (though not in the context of storm-flow generation) has been studied within the framework of the comprehensive ecological research projects referred to above (*e.g.* JORDAN, 1970a; KLINE & JORDAN, 1970 in Puerto Rico, LEIGH, 1978ab at Pasoh) or as an aim in itself (MORGAN, 1972 in Malaysia and ROOSE, 1970 in Ivory Coast).

Lately, work has been conducted in northern Queensland (BONELL & GILMOUR, 1978), Amazonia (NORTCLIFF *et al.*, 1979) and the Caribbean (WALSH, 1980). Despite these efforts a considerable amount of work remains to be done especially with regard to the occurrence and importance of pipeflow and the quantitative estimation of saturation overland flow.

That which has been said about the fundamental understanding of hydrological systems is equally valid for the study of rock weathering and soil formation. The powerful geochemical approach (involving the calculation of mass transfer based upon thermodynamic theory) which has been published during the 1960's (GARRELS & CHRIST, 1965; HELGESON, 1968; HELGESON *et al.*, 1969) has been applied almost exclusively to situations encountered in the temperate zone. An important contribution to the study of chemical weathering of rocks and the associated pedogenesis was made by the late Dr. J. VAN SCHUYLENBORGH. His combination of the translation of elemental analyses into normative soil minerals (VAN DER PLAS & VAN SCHUYLENBORGH, 1970) with thermodynamic theory proved quite helpful in elucidating trends in weathering and soil formation, especially for "climax" soils. Examples of this work can be found in MOHR *et al.*,(1972), BROOK & VAN SCHUYLENBORGH (1975) and DIRVEN *et al.*, (1976). Only recently such theoretical models of soil formation have been tested in the field by inserting actually determined chemical concentrations of the percolating solution (*e.g.* VERSTRATEN, 1977, 1980; WAYLEN, 1979). These authors arrived at a qualitative and quantitative description of the weathering process by combining the weathering model with the elemental flux through the investigated drainage basins. Such complete studies have not been published for the tropics as yet, but comparable work, be it of a more general nature, has been performed for volcanic rocks in Mexico (DREVER, 1971), Puerto Rico (NORTON, 1974) and New Caledonia (TRESCASES, 1976).

No studies dealing with the genesis of tropical volcanogenous soils in the manner referred to above have been published thus far. Studies of the chemical weathering of volcanic-ash deposits in tropical regions are relatively scarce anyway, the majority of the work again being carried out in the temperate zone (Japan, New Zealand). MOHR *et al.*, (1972) provide a fairly comprehensive review of the literature on tropical volcanogenous soils upto their time, with frequent use of examples from Indonesia, whereas also much relevant information is contained in WADA's (1977) account on the amorphous constituents of soils in general. Recently the Indonesian andosols have attracted the attention of Japanese soil scientists, resulting in papers on the clay mineralogy (KITAGAWA *et al.*, 1973) and the nature of the amorphous fraction of these soils (KITAGAWA, 1977). Some studies have been conducted on the weathering of tuffs from Papua New Guinea as well (*e.g.* RUXTON, 1968; PARFITT, 1972). Apart from the regular geological and soil-mapping programs most of the earth-scientific research performed in Indonesia has been related to the problem of soil erosion in some way or another. Most of this work has been conducted in pre-war times and after 1960, a notable exception to this being the pedogenetic work on andosols by VAN SCHUYLENBORGH and TAN KIM HONG during the 1950's. Many of the studies referred to above as well as a number of investigations of the Indonesian environment, catchment hydrology, sediment production and forest ecology will be discussed in more detail in the respective chapters of the present work : environmental background (chapter 2), hydrological aspects (chapter 3), material inputs and outputs (chapter 4), cycling of nutrients through various sorts of vegetation (chapter 5, which also contains a section on the implications for forest management as evolving from the results obtained in the present work) and finally (chapter 6) pedogenetical processes in the andesitic volcanic ash deposits.

2. PHYSIOGRAPHY OF THE INVESTIGATED CATCHMENT AND PLOTS

2.1 Introduction

The present chapter will provide data on the physical and biological characteristics of the investigated drainage basin and plots. The catchment is situated in the South Serayu Mountains, just south of the town of Banjarnegara near the small village of Watubelah (Fig. 2.1). It lies on the ridge that separates the Serayu river basin from that of the Lokuloh at an altitude of 508-714 m a.s.l. (7°27' S.L.; 109°43' E.L.).

The stream emerging in the catchment is called Mondo river and is tributary to the Kali Lokuloh (Fig. 2.1).

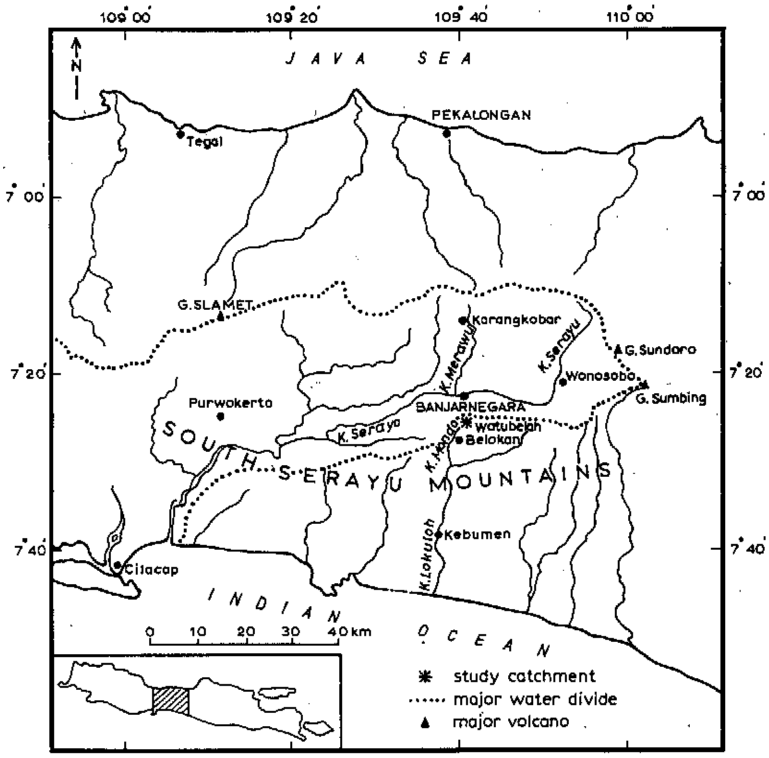


Fig. 2.1 General map of Central Java

The Serayu river basin has been the subject of a number of earth-science oriented investigations lately : *e.g.* SPEELMAN (1979) on (hydro)geological and VAN ZUIDAM *et al.* (1977) on geomorphological aspects, SUTIKNO (1981) on domestic water supply and ENGELEN (1982) on regional planning. The South Serayu Mountains mainly have attracted geologists in the past, but rural development projects have now entered the area and data collection on various subjects is in progress.

Climate

General considerations

Java lies within 8° south of the equator and is bordered by warm tropical seas. As such it experiences a climate which is hot and humid throughout the year. The year can be divided into two main seasons with two short transition periods in between. The principal seasons are associated with a distinct wind regime, brought about by the atmospheric pressure gradients between the continents of Asia and Australia as they are heated up and cool down during their respective summers and winters (HARE, 1966). The core of the rainy season (northwest monsoon) lasts from December till March, is relatively cloudy and shows very high values for humidity. On the other hand, during the southern winter (July till September) dry continental air comes from Australia and causes a distinct dry season over most of Java (southeast monsoon), especially towards the east. During this time of the year the weather is sunnier, mean daily temperatures lower due to greater eradiation at night and relative humidities drop somewhat too.

During the transition months (April, May, October and November) the pressure gradient between Siberia and Australia is weakening and the weather is mainly determined by the activity of the near-equatorial trough which often shifts its position erratically in response to the fluctuations of the trade wind circulations (KOTESWARAM, 1974). Strong convergence usually leads to the production of appreciable amounts of precipitation, but a weak confluence may result in oppressive weather conditions. Winds are feeble throughout the year.

Several attempts have been undertaken to characterize the climate of Indonesia for agricultural purposes (MOHR, 1933; SCHMIDT & FERGUSON, 1951; OLDEMAN, 1975). The most recent classification takes into account both the length of consecutive wet or dry periods and the water requirements of several regionally important crops such as rice, soybean, corn and peanut. OLDEMAN's definition of what should be regarded as a "wet" or a "dry" month differs considerably from the older approaches. A "wet" month is defined as having enough rainfall to grow a crop of lowland rice. (*i.e.* $\geq$ 200 mm), whereas "dry" month has less than 100 mm, *i.e.* the amount of water considered necessary for most upland crops. The fact, however, that the vegetation zonation in Southeast Asia largely corresponds with the climatic maps produced by SCHMIDT & FERGUSON in 1951 (WHITMORE, 1977), supports the old distinction between "wet" and "dry" months (> 100 and < 60 mm of rain respectively).

The study basin experiences two "dry" months in the sense of SCHMIDT & FERGUSON (1951) and three according to OLDEMAN (1975) (usually in the period July till September). This means that its climate is classified as "type B" in the older and as "type B_2" in the newer system.

Annual patterns

The general equatorial uniformity of the climate is significantly modified by the mountainous character of the island (BRAAK, 1921-1929). Many local wind systems, resulting from land-sea and hill-valley interactions, have to be superposed upon the general (monsoonal) movement of air. The spatial distribution of sunshine and rainfall in Central Java is therefore closely related to topographic factors (DE BOER, 1950; SCHMIDT, 1950). Figs. 2.2 (sunshine duration) and 2.3 (annual rainfall) illustrate this point. It is also seen that the study site on average receives less sunshine and more rainfall than most locations in the region due to its specific location on the South Serayu ridge.

Although certainly one of the wetter sites in the region with its 4768 mm

yr^{-1} (1926-1977) the variation in annual precipitation at Watubelah is quite large (Fig. 2.4). The study year (1977) happened to be a dry one with only 3527 mm as a result of an extremely severe dry season. Fig. 2.4 shows that smaller annual totals have been recorded in five years only, viz. 1929, 1944, 1963, 1965 and 1976.

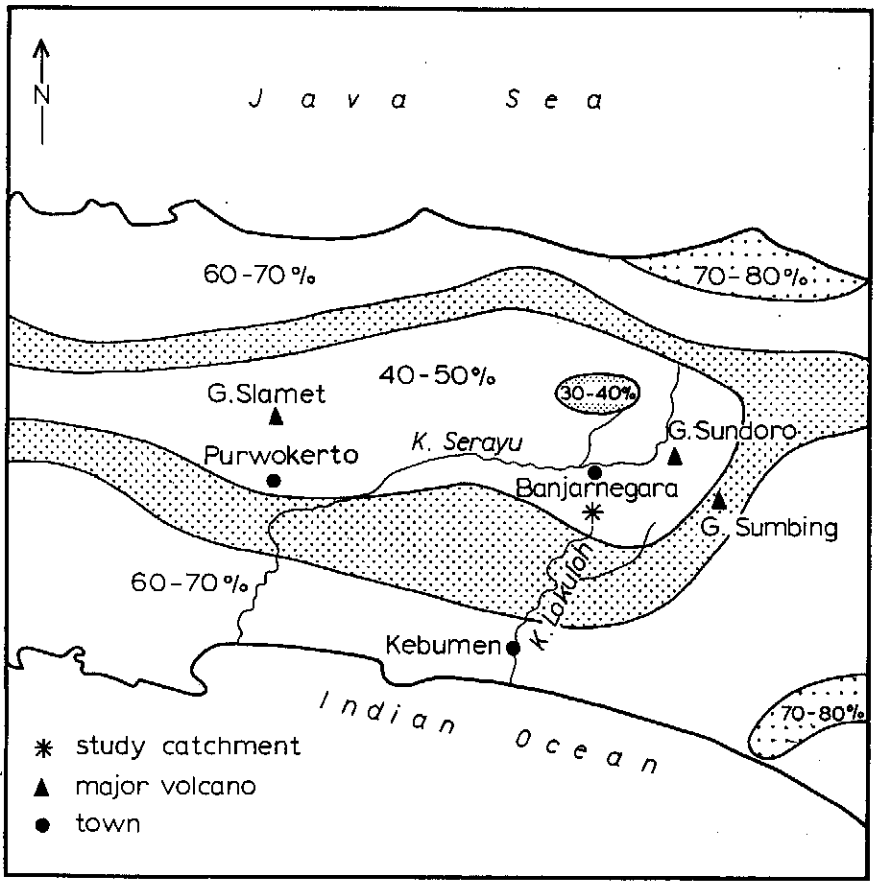


Fig. 2.2 Mean annual duration of sunshine expressed as % of the maximum possible between 8 AM and 4 PM (after SCHMIDT, 1950).

2.2.3 *Seasonal patterns*

Data (mostly pre-war) on sunshine duration, temperature, relative humidity and wind speed at various locations in Central Java have been related to elevation by ISNUGROHO (1975). The seasonal course of the above parameters at two elevations has been extracted from his generalized tables and is presented as Fig. 2.5. Also included are mean monthly amounts of precipitation at Watubelah (Fig. 2.5a), open-water evaporation, as computed from the other variables (Fig. 2.5f) and approximate effective precipitation (Fig. 2.5g). The figures mostly speak for themselves. Rainfall, sunshine

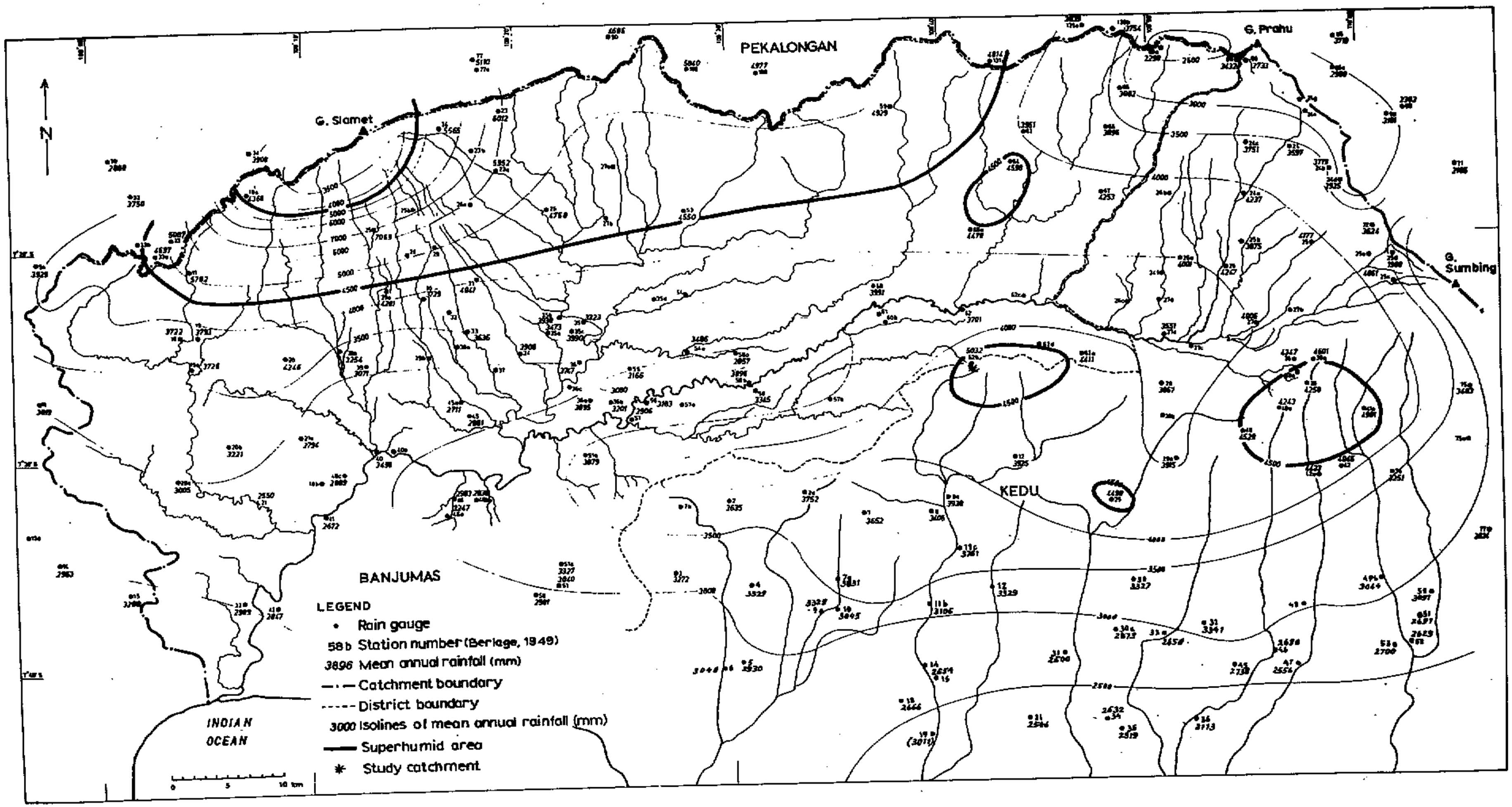


Fig. 2.3 Isohyetal map of South-Central Java (partly after SMEC, 1974). Data from Berlage (1949).

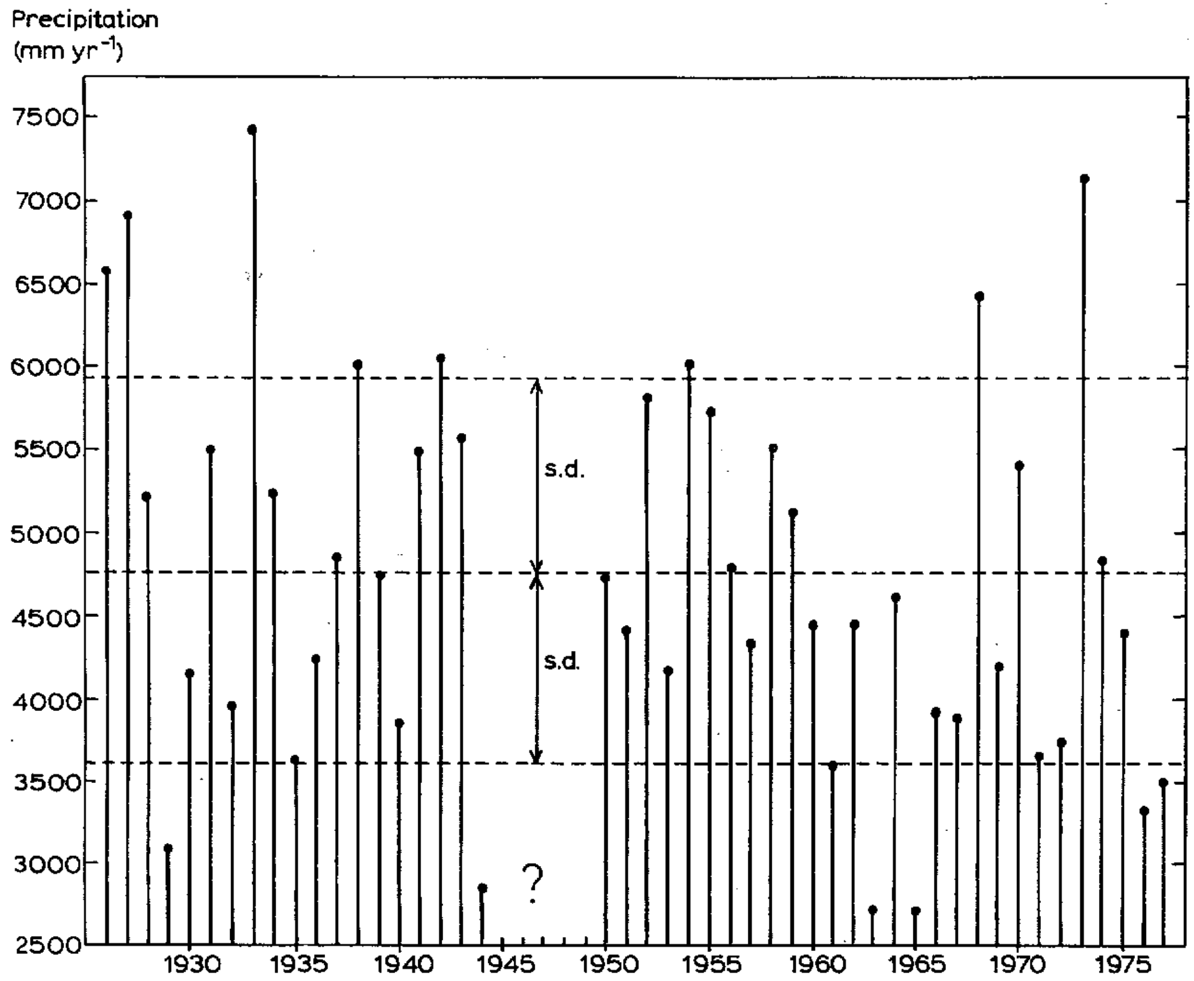
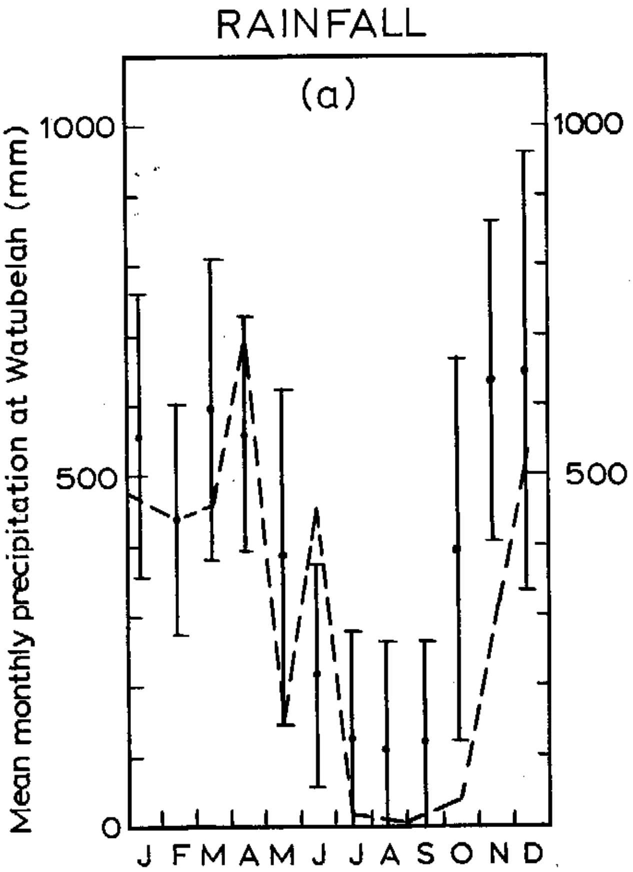


Fig. 2.4 Annual precipitation at Watubelah (1926-1944; 1950-1977).

Source of data : Annual publications of the Meteorological Observatory, Jakarta, Own observations .
-- : line of average annual total; S.D. standard deviation of the mean.



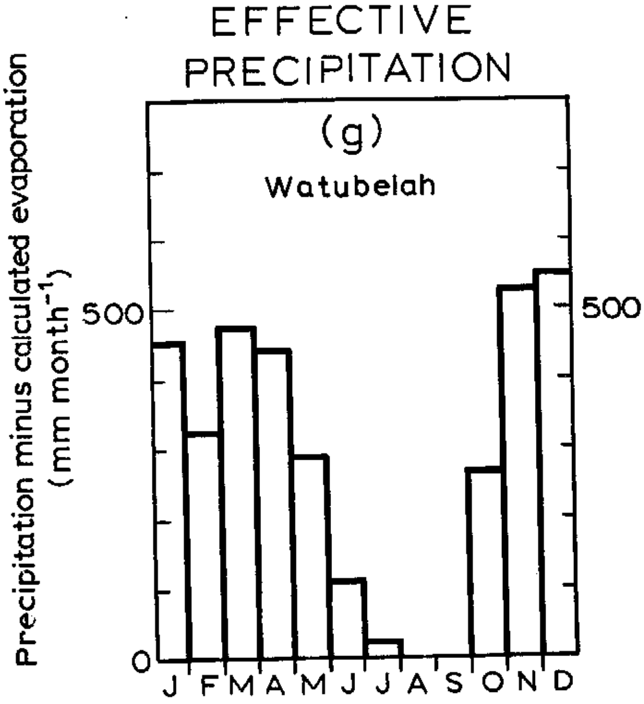
(Observation periods :
1926-1944; 1950-1977)

-- : 1977 only

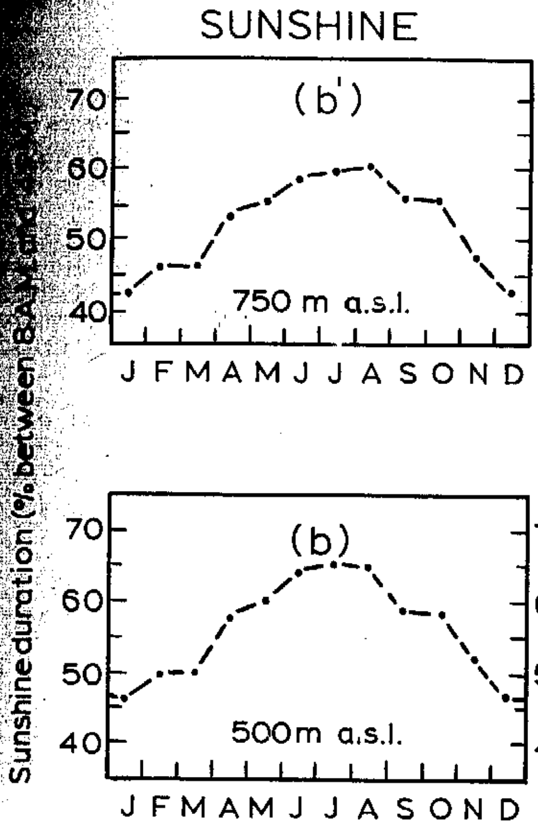
I standard deviation

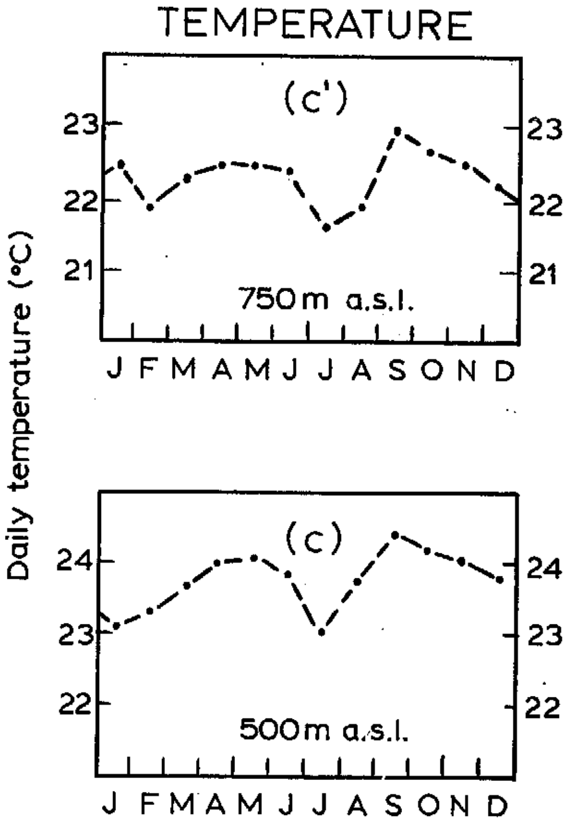
Fig. 2.5 Seasonal course of selected meteorological parameters in Central Java (generalized values for two elevations). Precipitation data for investigated location only. Source of data :

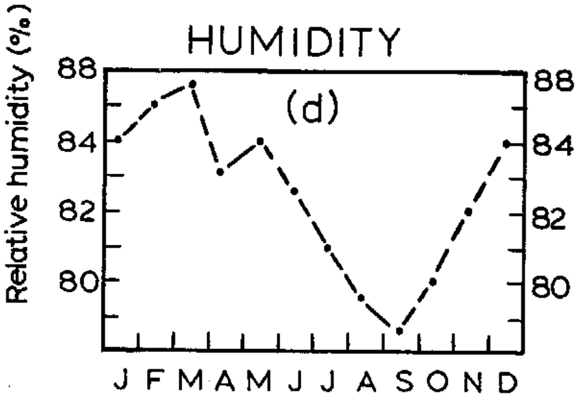
a) Meteorological Observatory Jakarta, plus own observations (1976, 1977);
b-e) Isnugroho (1975);
f-g) present work.

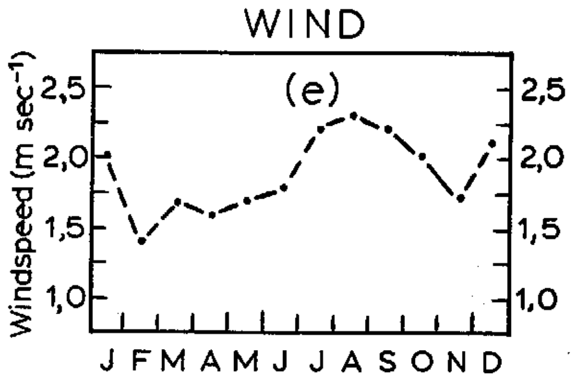


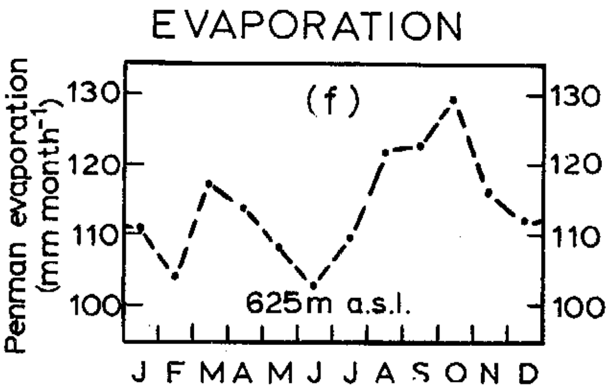
(Rainfall data pertain to same period as in Fig. 25a; observation period for evaporation parameters unspecified).


SUNSHINE
(b')
70
60
50
40
750 m a.s.l.
J F M A M J J A S O N D
(b)
70
60
50
40
500m a.s.l.
J F M A M J J A S O N D
Sunshineduration (% between 8 A.M. and


TEMPERATURE
(c')
23
22
21
750m a.s.l.
J F M A M J J A S O N D
(c)
24
23
22
500m a.s.l.
J F M A M J J A S O N D
Daily temperature (°C)


HUMIDITY
(d)
Relative humidity (%)
88
84
82
80
J F M A M J J A S O N D


WIND
(e)
Windspeed (m sec⁻¹)
2,5
2,0
1,5
1,0
J F M A M J J A S O N D


EVAPORATION
(f)
Penman evaporation (mm month⁻¹)
130
120
110
100
625m a.s.l.
J F M A M J J A S O N D

duration and relative humidity exhibit distinct seasonal patterns that are related to the general air circulation. Temperature, daily wind runs and evaporative demand vary within a rather narrow range. Greatest extremes in air temperature, maximum daily wind runs and highest evaporation levels are attained during the dry season, however. For a detailed account of Java's climate the reader is referred to BRAAK (1921-1929).

Rainfall at Watubelah during the investigation was about normal during the first seven months (December 1976 till June 1977) with April and June being wetter and March and May drier than normal. Rains did not return before mid November really, resulting in the above-mentioned low annual total (see Fig. 2.5a).

Although the station on average receives the impressive dry-season total of 352 mm, it appears that 23 out of 45 years had at least two consecutive dry months (in the sense of SCHMIDT & FERGUSON, 1951) with seven years having at least two months without any precipitation at all. Other years with four to five practically rainless months occurred in 1929, 1961, 1967 and 1972.

Values for the *duration of sunshine* over the study catchment were derived from the meteorological stations at Singomerto (310 m a.s.l., situated 5 km to the northeast in the Serayu Valley) and Karangkobar (1015 m a.s.l. and situated 30 km further north). From these data it appeared that December 1976, January, March, April, September and October 1977 were on the bright side with June and December 1977 and January 1978 cloudier than normal. The seasonal extremes in *air temperature* as observed at Watubelah are about twice as large as expected from ISNUGROHO's generalized extrapolations. Wet season values are very close to 24° C with a minimum of 21.4° C recorded in August. No major differences between "expected" and observed values of *relative humidity* were encountered for Watubelah. *Windspeeds* as determined on a freely exposed hilltop 6 km south of the catchment again were very similar to what ISNUGROHO (1975) reports. Determinations made on-site (fairly protected to the northwest but better exposed to the southeast) are distinctly lower. Total *Penman evaporation* over 1977 appeared to be virtually equal to the long-term estimate, viz. 1345 mm yr^{-1}. Actual figures will be presented in section 3.3 on the catchment water balance.

2.2.4 *Diurnal patterns*

Most weather parameters exhibit distinct diurnal patterns reflecting the mechanism of convection. *Precipitation* for example shows a strong tendency to fall in the late afternoon and most showers do not last for more than a few hours. Highest intensities are usually observed at the start of a storm. Similarly, *cloudiness* tends to increase during the morning and early afternoon until a decrease is observed around sunset when downslope evening winds take over (BRAAK, 1921-1929). Daily range in *temperature* may amount to 5° C during the rainy season, but may rise to 10° C during the southeast monsoon. Maxima tend to fall a little earlier on the day during the rainy season. The diurnal pattern for *relative humidity* in the uplands is a decrease in the morning associated with the rising temperature, followed by a distinct rise in the afternoon as the humidity of the air is increased by upward flows of air due to convection. Despite cooling during the night the relative humidity does not necessarily continue to rise as downslope winds may carry off the humid air. Windspeeds generally attain their maxima in the early afternoon.

2.3 Geology

The South Serayu Mountains - along the northern rim of which the study catchment is located (Fig. 2.1) - constitute a geanticlinal structure of over 100 km length running more or less parallel to Java's longitudinal axis. They are bordered to the north and northwest by the Serayu valley, to the east by the West Progo mountains and to the south by the coastal plain.

The Mondo catchment is part of a zone of Tertiary deposits that surrounds the so-called "crystalline basement complex" (Van BEMMELEN, 1949). This complex consists of quartzo-feldspatic metamorphic rocks, phyllites and graywackes of Mesozoic origin, while shales, tuffaceous marls and volcanic breccias make up the Tertiary fringe (HARLOFF, 1933; TJIA, 1966). The geological history of the area is well treated by HARLOFF (1933), VAN BEMMELEN (1949), TJIA (1966) and SPEELMAN (1979). The latter also included absolute age determinations for a number of intrusive phases. Moreover, the area to which the investigated catchment belongs has been re-mapped recently by the Geological Survey of Indonesia. Results can be found on a 1 : 100,000 scale map (Banjarnegara quadrangle) published by CONDON *et al.*, (1975).

The rocks that can be found in the greater part of the catchment are strongly weathered volcanic breccias, containing huge core boulders of basaltic to andesitic composition covered by Quaternary deposits of andesitic volcanic ash of variable thickness. TJIA (1966) assigns a Lower-Miocene age to these breccias (HARLOFF's first breccia horizon). In the lower reaches of the basin strongly folded and overturned sedimentary rocks are exposed. These consist of soft shales containing white quartz pebbles with some intercalations of coarse arenites and conglomerates rich in white quartz. They are cut off by a (Pliocene/Pleistocene ?) erosion surface marked by a line of milk-white quartz pebbles with a thin (about one metre) cover of volcanic ash. The stratigraphic position of these thoroughly weathered rocks is uncertain. According to TJIA (1966) they belong to HARLOFF's first tuffaceous marl unit, but both HARLOFF himself and CONDON *et al.* (1975) restrict this formation to an area further southeast. Since the lithology of these deposits very much resembles that of Eocene strata exposed nearby the present author is inclined to assign an Eocene age to them rather than a Miocene one. Relevant petrological information on the various deposits will be given in chapter 6.

The area experienced several minor erosion phases during the Miocene and Pliocene until a major uplift occurred during the upper Pliocene (TJIA, 1966). It may have been during this phase that the Miocene breccias were broken into the distinct block- and fault-structures that can be observed nowadays in and around the Kali Mondo catchment. The fact that even the youngest deposits of volcanic ash are affected by movements along these older lines of weakness points to quite recent tectonic activity. This is also indicated by the incision of the stream into its own bed at places where it has not reached the more resistant breccias. Although the numerous fault lines running through the catchment theoretically may promote leakage of deep ground water out of the drainage basin it is shown in chapter 3 that such leakage is probably of minor importance.

2.4 Geomorphology

The relief of the Mondo catchment and its immediate surroundings closely reflects the underlying block-fault structure believed to have originated in the upper Pliocene (TJIA, 1966). Most slopes are steep and the fault scarps are usually straight and smooth, again pointing to a relatively young age. At some locations within the catchment remnants of reddish soils are exposed at the base of these scarps. Similar red soils are encountered over large parts of the South Serayu Mountains, often covered with a stone line and sometimes a layer of dark brown volcanic ash.

These reddish soils may well originate from the upper Pliocene when the fresh uplift and a hot and humid climate favoured intense chemical weathering (ENGELEN, 1973) with subsequent rubefaction and truncation during the drier glacials of the Pleistocene (VERSTAPPEN, 1974). Such periods of truncation by sheetwash will have alternated with wetter interglacial times when a well-developed forest cover limited extensive surface erosion (VERSTAPPEN, 1974).

As such the geomorphological history of the region is characterized by the occurrence of a number of orogenic and denudational phases. Such denudational phases are reflected in the accumulations of pebbles and gravel observed at several depths within the volcanic cover, which is deposited on the red soils from mid-Pleistocene onwards (VAN BEMMELEN, 1949). Depending upon the permeability of the substratum, topography and distance to local base levels, these ashes have also been removed by mass wasting (VAN DER LINDEN, 1978). The fact that in the investigated catchment the volcanic ash cover appears to be thinner (or is even completely absent) in the lower reaches where clayey rocks are exposed seems to support this conclusion. Higher up in the basin, however, a similar situation is found on level ground in a graben structure developed in the volcanic breccia. One must assume therefore that tectonic movements (*e.g.* block tilting) locally have been important as well.

The well-developed organic horizons overlying the thick deposits of ashes in the forested study basin point to a stable situation where hillslope erosion has been of minor importance for some time. It is inferred therefore that during most of the Holocene period erosion in the basin has been active mainly in the form of channel incision and to some extent as mass wasting. This is in strong contrast to the areas further south and west where accelerated soil erosion during the last 180 years (DAMES, 1955) has caused the truncation or complete disappearance of the ash cover, thus exposing the red palaeosols or the underlying bedrock.

Finally some quantitative geomorphological information on the study catchment is presented below.

Table 2.1 Selected quantitative geomorphological parameters of the Mondo catchment

A	B	T	H	L	L'	R	R'	Dd	Dw
18.74	510	716	206	1080	1286	0.19	0.16	2.16-3.47	5.82

where

A = basin area (ha)
B = elevation of catchment outlet (m a.s.l.)
T = elevation of highest point (m a.s.l.)
H = maximum basin relief (m)
L = maximum basin length (m)
L' = idem measured along principal drainage line (m)
R = H/L, basin relief ratio
R' = H/L'
Dd = average drainage density during dry season (km^{-1})
Dw = idem during very wet spells (km^{-1})

2.5 Soils and parent materials

No detailed soil maps are available as yet for the South Serayu Mountains. The area is covered, however, by the general soil map of Central Java (scale 1 : 250,000) compiled by GO BAN HONG (1966) and some work is going on presently (1980/81) within the framework of the NUFFIC/UGM "Earth Sciences Project" (written comm. Dr. P. van der LINDEN).

The investigated catchment belongs to a fairly narrow belt of volcanic ashes overlying the weathered volcanic breccias north of the crystalline basement complex. In the areas of the basement complex an intricate pattern of truncated red palaeosols and lithosols is observed.

Within the belt of andesitic ashes the main soil types (FAO/UNESCO, 1974) are fine-textured luvisols (either chromic or vertic) and humic andosols or, in older terms (VAN SCHUYLENBORGH, 1958) : "podsolized brown latosolic soils" and "acid brown forest soils" respectively. The latter are found mainly in the zone where a forest cover has remained.

As mentioned before, the investigated catchment is covered entirely by Quaternary deposits of andesitic volcanic ash of variable thickness. This aeolian cover is less than one metre thick in some parts of the basin (*e.g.* occasionally in the vicinity of the main stream, especially in the lower reaches where pre-Miocene (?) rocks are exposed), but shows a thickness of at least four metres at most other locations. This was revealed by an intensive augering programme, whereas some deeper borings up till 5.5 m depth did not meet the underlying volcanic breccias either.

Another attempt to estimate the vertical extension of the volcanic ashes, this time by means of geo-electric soundings in November, 1977, was not succesful in establishing the boundary between weathered bedrock and volcanic ash either, although at a number of locations a definite reduction in electrical resistivity was observed between 8 and 12 m depth (pers. comm. dr. W. GEIRNAERT).

The observed drop is thought to reflect a deep zone of high moisture content in the volcanic ashes, possibly caused by the underlying reddish rottenrock. The latter may be somewhat less permeable due to its stronger rock-like nature (the clay content being similar to that of the ashes).

Generally, the depth of the volcanic ash cover will range from six to twelve metres on most of the water divide, becoming progressively thinner along the steep slopes.

The *soils* that have developed in these deposits do not show very distinct profile differentiation indicating their relatively youthful age. They have been tentatively classified as humic andosols (FAO/UNESCO, 1974).

Some relevant morphological and physico-chemical data are given in Tables 2.2 and 2.3. It should be noted that these descriptions and figures are averages taken from several profiles to give a general impression of soils present in the basin. These data strongly suggest a clay fraction dominated by allophane, with molar Si/Al-ratios in the clay fraction between 1.3 and 1.5. Moreover, the bulk densities of oven-dry soil samples are quite low as well (*c.* 0.55 gcm^{-3}).

A more complete representation and treatment of the physico-chemical characteristics of these soils can be found in chapter 6, which deals with the weathering mode of the volcanic ashes.

Eroded volcanic soils are found in the immediate (cultivated) surroundings of the catchment, which exhibit much lower amounts of amorphous matter (± 5 %), a molar Si/Al ratio in the clay of about 1.85, a much higher bulk density and a cation exchange capacity of 26-28 meq 100 g^{-1} dry soil. Clearly these soils are older than the ones described before and they are thought to represent an intermediate state of weathering between the fresh andosols and deeply weathered ferralsols. Although traces of clay illuvation can be seen there is no argillic horizon present rendering a classification as luvisols, acrisols or nitosols (FAO/UNESCO, 1974) impossible. Since weathering has not proceeded far enough for these soils to become ferralsols a classification as dystric cambisols (soils with a cambic B-horizon, an ochric A-horizon and a base saturation of less than 50 %) seems the best approximation.

Table 2.2 : Generalized morphological description of humic andosols in the Kali Mondo catchment according to the FAO Guidelines for soil profile descriptions (FAO, 1968).

horizon notation	horizon thickness (cm)	moist colour (Japanese scales)	field texture	structure	consistence	other information
A_1	0-30	7.5.YR3/3(dark-brown) to 10YR3/2 (brownish black)	fine sandy loam to silty loam	crumbly	friable	many pores; common to many fine to medium roots; common to high biologic activity
		clear and wavy to				
AB	30-75	7.5YR3/4 (dark brown) to 7.5.YR 4/4 (brown)	silty loam to silty-clay loam	crumbly to weak fine angular blocky	friable to slightly firm	many pores, few fine roots;
		clear and slightly wavy to				
IIB_{21}	75-105	7.5YR3/4 (dark-brown) to 7.5YR 4/4 (brown)	slightly gravelly silty loam to silty-clay loam	crumbly to weak fine angular blocky	friable to firm	many pores; few fine roots;
		gradual and slightly wavy to				
$IIIB_{22}$	105->200	7.5YR 4/4 (dark-brown)	silty clay loam	moderate fine to medium angular blocky	slightly firm to firm	common pores; few to very few fine roots; low biologic activity; few dark reddish brown (5YR3/6) to very dark-brown (7.5YR2/3) mottles

Table 2.3 : Generalized physico-chemical characteristics of humic andosols in the Kali Mondo catchment

Horizon	% organic carbon^{1,2}	pH$(H_2O)^1$	CEC pH 7^1 (meq 100g^{-1})	base saturation^1(%)	clay (< 2 µm^{1,2})	oxalate-extractable amorphous matter (%)^{1,3}
A_1	4.3-4.5	5.2-5.5	40	5-10	30-40	30-40
AB	1.9-2.1	5.7-5.8	37.5	5-7	35-45	30-40
IIB_{21}	1.8	5.7-5.9	49	4	32-42	35-45
$IIIB_{22}$	1.0-1.2	5.9-6.1	49-55	3-4	40-55	45-60

1 : for analytical details see section 6.2

2 : expressed as a percentage of total weight of absolute dry soil (< 2 mm)

3 : *ibidem* of absolute dry clay

2.6 The vegetation of the investigated basin and plots

2.6.1 *The study catchment* (Agathis loranthifolia *plantation*)

The investigated catchment is part of the larger forest reserve of Watubelah which is managed by the state enterprise Perum Perhutani and consists largely of *Agathis loranthifolia* Salisb. plantations of 40 years old and less. Together with the *Agathis* forests around Gunung Slamet and those in West Java these plantations are at present "the only extensive and continuing operation anywhere in the world where *Agathis* is being grown in this way" (WHITMORE, 1977).

Before the establishment of the *Agathis* forest the area was either covered with remnants of natural forest or a secondary shrub vegetation. Considering the thickness of the A-horizons in most soil profiles, agriculture is not believed to have been very important in the catchment (apart from that during the first two years after planting in some parts of the basin). However, old topographical maps indicate the presence of a coffee culture just outside the uppermost reaches of the catchment around 1900 which may have extended into the catchment as well. Indeed *matrans* (accumulations of parts of the soil material on the walls of the voids) have been observed in some soil profiles and may represent the temporal instability caused by such agricultural disturbances.

Although *Agathis loranthifolia* is not native in Java (it has its greatest ecological amplitude in Borneo, but is also found in Malaysia and the Philippines) it may thrive there as long as a well-drained but continuously moist soil is available (WERKGROEP TROPISCHE HOUTTEELT, 1973).

The initial growth of the trees is slow, but after that productions may be quite high : the volume produced after 30 years (including thinnings) ranges from 15-28 m^3 ha^{-1} yr^{-1} depending on the fertility of the site and it is estimated to range from 16-23 m^3 ha^{-1} yr^{-1} after a rotation period of 50 years (SUHARLAN *et al.*, 1975).

The tree produces besides light-weight timber of good quality which can be used for the manufacturing of paper as well a resin called "damar".

Agathis may reach heights of 45-60 m. The boles, which have a scaly bark, are usually cylindrical or taper somewhat and are free of branches over considerable lengths depending on the density of the stand. The branches are radial and frequently droop (especially with older trees), while the evergreen crowns are quite narrow and conical.

Fig. 2.6 shows the distribution and quality of the various *Agathis* stands in the catchment, whereas additional data on height, diameter, crown cover, number of trees per hectare and undergrowth are given in Table 2.4.

These figures indicate average growth under Javan circumstances, although the average height in the more poorly-stocked stands is somewhat less and the diameter somewhat larger than usually considered as ideal (SUHARLAN *et al.*, 1975).

The areas classified as open in Fig. 2.6 formerly contained more trees and are covered nowadays by a dense shrub thicket of 1.5-2.5 m height. It consists of the secondary species that make up the forest undergrowth as well and is dominated either by *Eupatorium* sp. and *Melastoma polyanthum* (moister sites) or *Imperata cylindrica* with *Melastoma, Eupatorium* and *Stachytarpheta jamaicensis* (drier sites).

Occasional cutting (at some places even quite regularly) of grass and shrubs for fodder or fuel maintains these associations.

Sometimes concentrations of *Gleichenia* ferns or *Rubiaceae* can be observed,

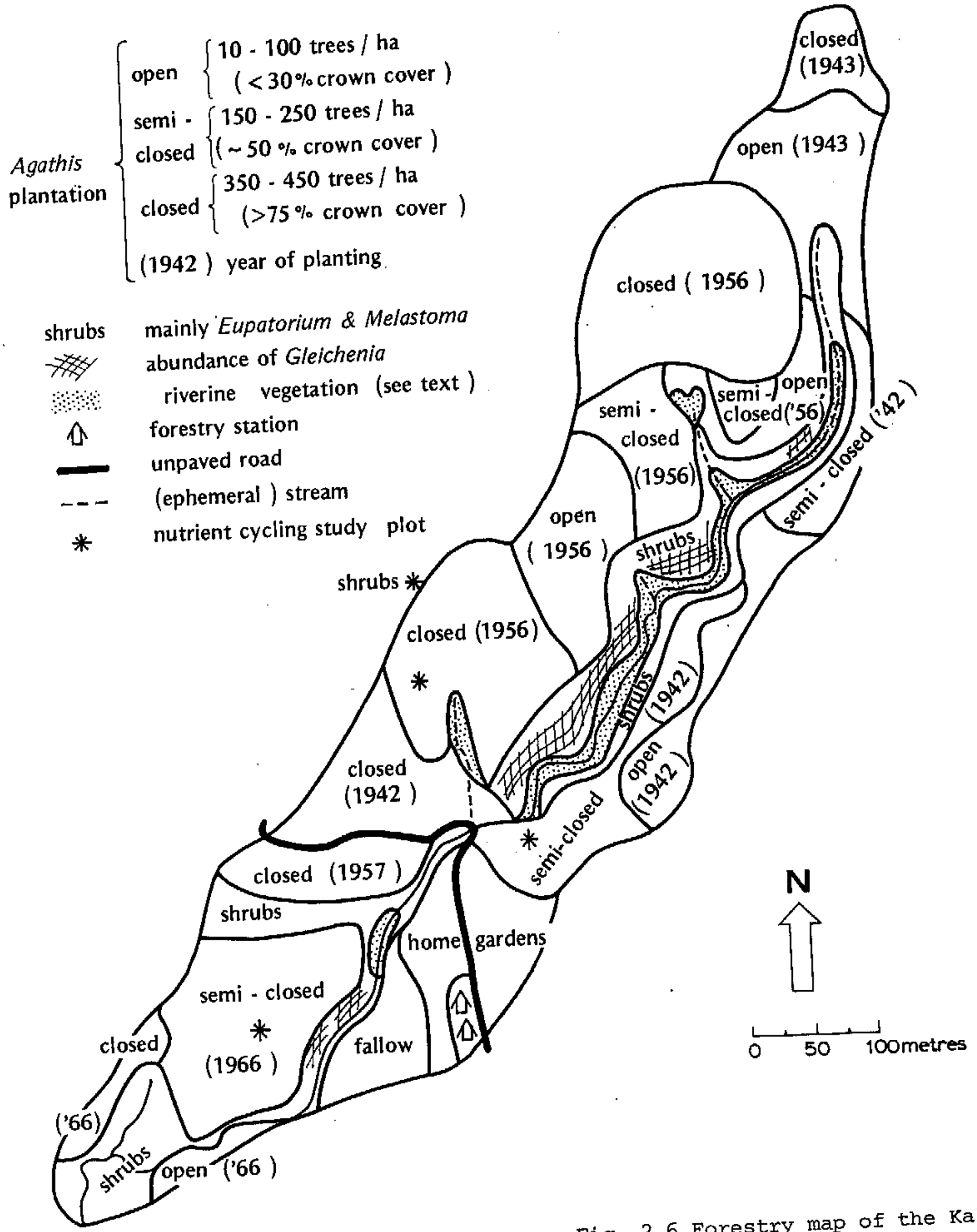


Fig. 2.6 Forestry map of the Kali Mondo catchment

Table 2.4 : General structural and floristic characteristics of the investigated plots within the Kali Mondo catchment (after TEAM VEGETATION AND EROSION, 1979b). Figures between brackets represent variation over the catchment (*cf.* Fig. 2.6).

Stand and year of planting		Height (m)	Diameter at breast height (cm)	Cover (%)	Number of trees (ha^{-1})	Undergrowth
Agathis	1942	20-30	44.5	(25-)45	160	*Eupatorium, Clidemia Melastoma with ferns Panicum, Selaginella* and *Hemidioida* on wetter sites and *Imperata* on drier sites
shrubs		1-2.5		90		
Agathis	1943	20-30	45	80	± 300	
shrubs		0.5-1		50		
Agathis	1956	20-25	32	(20-)80	450	
shrubs		0.5-2.5		20-50		
Agathis	1966	8-17	16.5	40(-80)	580	
shrubs		0.5-2		100		

mainly on steep lower slopes near the stream and on the flatter divides respectively.

In the vicinity of the stream no *Agathis* has been planted, although most of the original trees have been removed. Isolated *Arthocarpus, Ficus* and *Schoutenia* trees are the only remnants of a more exuberant past. Here, species characteristic for young secondary vegetation are (a.o.) *Piper aduncum, Omalanthus populneus, Gleichenia, Donax cannaeformis*, etc.

The well-terraced homegarden behind the Forestry Station (Fig. 2.6) contains a great variety of indigenous fruit trees (e.g. *Annona muricata* (Soursop), *Carica papaya* (Papaya), *Cocos nucifera* (Coconut palm), *Durizibethinus* (Durian), *Musa paradisiaca* (Banana) etc.). Some parts are dedicated to the growing of coffee (*Coffea robusta*) with *Albizzia falcataria* as a shadow tree, maize and cassava. Fallow parts are adequately covered with grasses.

A provisional list of species encountered (about 60 in total) is given in Table 2.5. Animals observed regularly include wild boar and rodents, apart from a variety of butterflies, insects and snakes. Birds appear to be remarkably scarce.

Table 2.5 Provisional list of plant species in the Kali Mondo catchment based upon PRAWIRA (1973), TEAM VEGETATION AND EROSION (1979b) and own observations.

Family	Species
Araceae	*Alocasia indica* Lour. Koch.
Araliaceae	*Travesia sundaica* Miq.
Araucariaceae	*Agathis loranthifolia* Salisb. (=*A. dammara*)
Balcaminaceae	*Impatiens platypetala* Lindl.
Compositae	*Eupatorium inulifolium* HBK (=*E. pallescens*)
	Eupatorium odoratum L.f
	Clibadium surinamense L.
	Sigesbeckia orientalis L.
Convolvulaceae	*Ipomoea pestigridis* L.
Cucurbitaceae	*Bryonopsis laciniosa* Naud
Cyperaceae	*Carex filicina* Nees.
	Cyperus cyperoides OK.
Dioscoreaceae	*Dioscorea* sp.

Table 2.5 continued

Family	Species
Euphorbiaceae	*Omalanthus populneus* Pax.
Gramineae	*Imperata cylindrica*
	Panicum incinatum Redd.
	P. distachum Back. (=*Brachiaria subquadripara*)
	P. brevifolium L.
	P. barbatum Back (=*Setaria plicata*)
	Digitaria sanguinalis Scop. (=*D. adscendens*)
	Oplismenus burmanni Beauv.
	Saccharum spontaneum L.
Laminaceae	*Hyptis brevipes* Poit.
Naranthaceae	*Donax cannaeformis* K. Schum.
Malvaceae	*Urena lobata* L.
Melastomataceae	*Clidemia hirta* D. Don.
	Melastoma malabathricum (=*M. polyanthum* Bl)
Mimosaceae	*Acacia villosa* Willd.
	Albizzia falcataria Fosb.
	Leucaena leucocephala De Wit
Moraceae	*Arthocarpus* sp.
	Ficus hirta Vahl.
	Ficus septica Burm. f
Polygalaceae	*Polygala* sp.
Papilionaceae	*Dolichus lablab* L.
Piperaceae	*Piper aduncum* L.
Pittosporaceae	*Pittosporum ferrugineum* Ait.
Rubiaceae	*Geophila repens* Johnston
	Psychotria valetonii Hechr.
	Ophiorrhiza marginata Bl.
	Hemidiodia ocymifolia (=*Diodia ocymifolia*)
	Pavetta indica L.
	Hedyotis sp.
	Mussaendra frondosa L.
	Rubus moluccanus L.
Sapindaceae	*Harpullia cupanioides* Roxb.
Scrophulariaceae	*Torenia fournieri* Lind.
Tiliaceae	*Schoutenia ovata* Korth.
Urticaceae	*Leucosyke capitellata* Wedd.
Verbenaceae	*Stachytarpheta jamaicensis* Vahl.
	Lantana camara L.
Vitaceae	*Leea indica* Merr.
Zingiberaceae	various unidentified species
Polypodiaceae	*Pteris ensiformis* Burm. f
	Drypteris appendiculata C. Chr.
	Gleichenia
	Asplenium nidus L.
Lycopodiaceae	*Lycopodium cernuum*
Selaginellaceae	*Selaginella ciliaris* Spring.

Data on catchment biomass, litter production and the interception of rainfall by the trees will be given in chapter 5 (nutrient cycling).

2.6.2 *The Pinus merkusii plot*

This species has attracted the attention of the Forestry Service of Indonesia since a long time because of its productive qualities (BRANDTS BUYS *et al.*, 1928). In Sumatra, the natural habitat of the species, heights of 30-35 m are common. As with *Agathis* the boles are cylindrical and taper somewhat and may be devoid of branches over considerable lengths in dense stands.

Deviations from this pattern are frequently observed in plantations with a lower tree density. The bark is rough and shows distinct grooves with increasing age, while the branches become drooping after a number of years. The evergreen crowns are pyramid-shaped usually, although there is a tendency for older trees to become more flattish, especially under less favourable conditions. As long as a moderately well-drained soil is available the species grows well. Compared to *Agathis* the initial growth rates are remarkable.

Total volume produced in 30 years (including thinnings) generally ranges from 14.9 - 16.2 m^3 ha^{-1} yr^{-1} depending on site class (SUHARLAN *et al.*, 1975). *Pinus merkusii* can stand a dry season of four months and does not require a high nutrient status of the soil (FERGUSON, 1949). All this, taken together with its ability to supersede the *Imperata* grasses makes *P. merkusii* quite a popular tree in the combatment of erosion (SOERJONO, 1964). In the Southern Serayu Mountains the planting of *P. merkusii* recently has gained more importance in view of the intended large-scale production of paper in the Cilacap area (pers. comm. Ir. Atang Soemaatmadja).

The selected plot for the study of the cycling of nutrients through *Pinus merkusii* is situated some 3 km west of the Kali Mondo study basin on a gentle slope of eastern aspect consisting of fairly weathered soils derived from andesitic volcanic ash at a height of about 430 m a.s.l. The stand has an areal extension of 4.0 hectares and was planted in 1965 on a field formerly occupied by teak. It contains 720 trees ha^{-1} that reach an average height of 19.8 m (with extremes recorded of 12 and 22 m respectively) and have an average diameter at breast height of 23.7 cm (TEAM VEGETATION AND EROSION, 1979b).

The crown cover is almost complete (about 90 %) and the stand needs to be thinned considerably (a normal tree density under similar conditions amounts to 372 trees ha^{-1}). Growth can be considered as excellent according to yield tables.

The high tree density of the stand is also reflected by the poor development of the shrub-layer (dominated by *Clidemia hirta* and *Eupatorium inulifolium*) and the herb layer (mainly ferns and grasses).

The total living biomass of the forest has been estimated at 174 tons ha^{-1} ovendry material. A discussion of this figure and additional data on the chemical composition of the forest, the production of litter and the interception of rainfall by the stand can be found in chapter 5 (the cycling of nutrients).

2.6.3 *The Tectona grandis plots*

The areal extent of teak plantations in Java amounts to some 800,000 hectares according to various sources. The bulk is situated in the northern lowlands of East and Central Java which exhibit a distinct dry season of 3-5 months. The species is not very demanding as far as nutrients are concerned and it thrives on a variety of soils derived from such different parent materials as limestones and volcanic ashes, provided that adequate drainage is present. Fair levels of lime and phosphate seem to be appreciated, but the physical state of the soil is much more critical : heavy-textured soils with temporary water-logging have definitely very unfavourable consequences for the development of the stand (BEUMÉE-NIEUWLAND, 1922). Heights for 50 years old trees usually are about 30 m, the boles being columnar and smooth. However, they may become less straight under adverse conditions. The deciduous crowns are light and irregular. Except for the first years *Tectona* grows quite slowly in comparison with *Agathis* or *Pinus*. Based on a 50 yr rotation period the production of teak is about one-third of the production rate of the former two species, although the timber is of outstanding quality.

Litterfall- and biomass measurements have been carried out in a slightly degraded stand of *Tectona* (planted in 1952) some 500 m south of the Kali Mondo forest on weathered andesitic volcanic ashes on a south-facing slope. It is situated at an altitude of about 500 m a.s.l. and experiences almost the same amount of rain as the study catchment. In other words these trees are growing under conditions that can be regarded as marginal for this species. Despite its small extent this plantation was chosen because of its accessibility and soil type. However, additional measurements of litterfall on a more protected and better-stocked location were considered necessary leading to the establishment of a second plot. This one is situated about five km to the south on a west-facing moderately steep slope which is covered with colluvium from weathered silica-rich Mesozoic rocks. For this plantation (planted in 1946) no biomass measurements have been carried out due to shortage of time and manpower available for the UNPAD-team. Such measurements were hampered in the 1952-stand as well, because permission to cut sample trees for detailed observations could not be obtained. In this plantation the tree density amounts to 340 trees ha^{-1}, whereas average height and diameter were 17.3 m and 23.8 cm respectively (TEAM VEGETATION AND EROSION, 1979b). These figures indicate somewhat retarded growth accordingly to Javanese standards (SUHARLAN *et al.*, , 1975). Undergrowth is dominated by a poorly developed stratum of 1-1.5 m high shrubs of *Eupatorium* sp. with a denser layer of "herbs", mainly consisting of *Eupatorium* seedlings, remnants of *Acacia villosa* (also planted ?) and an abundance of *Imperata* grass. The low value of the undergrowth biomass is partly due to grazing but can partly also be ascribed to seasonal influence. The amount of litter (about 0.5 g m^{-2}) is comparable to that of the *Agathis* forests. Cycling of nutrients through this species will again be dealt with in chapter 5.

2.6.4 *The Pringombo Lower Montane Rain Forest*

The nearest site where the local climax forest of south Central Java has been preserved is the Pringombo Forest Sanctuary II, situated in the remote head-water area of the Kali Pingit, a small tributary of the Serayu River, some 8 km east of Banjarnegara near the village of Pringombo, at an elevation of 600-1000 m a.s.l.

It was established as a forest sanctuary in October, 1920 after it appeared to contain an association of trees which could be regarded as typical for south Central Java including some extremely rare species (such as *Firmiana malayana*, *Heliciopsis incisa* and *Palaquium ottolanderi*, KOORDERS, 1916; updated names). Back in 1891 it was considered as one of the last bits of primeval Rain forest in the northeastern part of the South Serayu Mountains (KOORDERS, 1894). Soils and rainfall distribution are essencially the same as in the investigated catchment and the type of forest therefore expected is the Lower Montane Rain forest (applying the classification of GRUBB, 1977). Knowledge of the botanical composition of this forest is based on observations by S.H. KOORDERS in 1891 published by Mrs. A. KOORDERS-SCHUMACHER (1910-1913). The names of the species given by KOORDERS have been updated by Ir. K.F. WIERSUM using the "Flora of Java" (BACKER & BAKHUIZEN VAN DEN BRINK, 1963-1968) and are presented as Table 2.6, in the same order as in the original publication. Activities undertaken in the Pringombo forest were restricted to the measurement of litterfall and the monthly sampling of a spring as the area is quite remote. The litterfall is discussed in section 5.3.

Table 2.6 Details of the vegetation in the investigated plot after KOORDERS-SCHUMACHER 1910-1913; botanical names according to BACKER & BAKHUIZEN VAN DEN BRINK 1963-1968

Species	Height (m)	DBH* (cm)
Cratoxylon formosum (Korth.) Benth. et Hook	19	25
Acrocarpus fraxinifolius Wight	50	410
Palaquium ottolanderi Kds et Val.	16	74
Planchonella duclitan (Bl.) Bakh.	35	78
Actinodaphne procera Nees.	32	60
Terminalia citrina (Gaertn.) Roxb., ex Flem.	30	64
Heliciopsis incisa (K. & V.) Sleum.	7	17
Semecarpus heterophylla Bl.	18 (20)	28 (190)
Crypteronia paniculata Bl.		
Elaeocarpus macrophyllus Bl.	24	57
Litsea amara Bl.		
Bischofia javanica Bl.		
Canarium denticulatum Bl.	19	222
Actinodaphne macrophylla Nees.	27	100
Croton argyratus Bl.	27	170
Gomphandra javanica Val.	24	160
Antocephalus chinensis (Lamk.) Rich. ex Walp.	37	230
Terminalia subspathulata King	18	180
Radermachera gigantea (Bl.) Miq.	33	270
Cinnamomum sintoc Bl.	35	220
Neesia altissima Bl.	23	160
Knema cinerea (Poir.) Warb. var. Sumatrana (Miq.) Sincl.	23	120
Pygeum arboreum (Bl.) Endl. ex F.v.M.	24	125
Sterculia macrophylla Vent.	23	150
Sterculia urceolata J.E. Smith	24	230
Dysoxylum excelsum Bl.	21	170
Dysoxylum caulostachyum Miq.	21	200
Litsea noronhae Bl.	10	110
Cinnamomum iners Bl.	30	230
Bridelia minutiflora Hook	29	180
Acmena acuminatissima (Bl.) Merr. & Perry		
Syzygium lineatum (DC.) Merr. & Perry		
Diospyros aurea Teysm. & Binn.		
Blumeodendron tokbrai (Bl.) J.E. Smith		
Firmiana malayana Kosterm.		
Ficus magnoliaefolia Bl.		
Tarenna fragrans (Bl.) Kds. et Val.		
Artocarpus glauca Bl.		

*diameter at breast height

3. HYDROLOGY

3.1 Introduction

Under the humid tropical conditions prevailing in Central Java the pathways and fluxes of nutrients are intimately connected with the pathways and fluxes of water through the (catchment) ecosystem. The evaluation of the hydrologic cycle is therefore a prerequisite for establishing the chemical budget and in understanding the weathering mode of a certain area (BORMANN & LIKENS, 1967).

This third chapter constitutes the hydrologic framework for the next on the elemental and particulate budgets (ch. 4), the cycling of nutrients (ch. 5) and the chemical weathering of the volcanic ashes (ch. 6).

The general hydrological situation is described in section 3.2, whereas the water balance for the period of investigation is dealt with in section 3.3, with due attention being paid to the procedures followed and their accuracy. Hydrograph analysis makes up the final section (3.4).

3.2 General hydrological situation

The part of the catchment underlain by volcanic breccia (see section 2.3) is covered by Quaternary volcanic ashes of variable thickness, which act as the main *aquifer*. Generally, their depth ranges between six and twelves metres on the divides, becoming progressively thinner on some steep slopes.

In the lower reaches of the basin, where clayey bedrock is exposed, this ash cover is much thinner and sometimes even absent (Fig. 3.1), see also section 2.4.

Most of the *springs* feeding the stream are found at the contact between the volcanic ash deposits and the underlying (weathered) bedrock, indicating a significant change in permeability. The chemistry of these springs should thus reflect the overall effect of the (entire) ash cover on the percolating water. Part of the water, however, infiltrates into the breccias since a borehole in the breccia (crossing several joints) appeared to contain water way up in the dry season. Most springs disappear during the dry season. Only two of them were permanent and are believed to be associated with longer flow paths from greater depth along faults. The chemistry of both types of springs is reported upon in chapter 6.

A third type of spring occurs during extremely wet spells at various places along the stream, but especially in the bowl-shaped headwater area of the basin. Where the vertical transmitting capacity of the soil is exceeded the excess soil water drains laterally through a number of small pipings in the banks (*cf.* JONES, 1971; SCHOUTEN, 1976). This diffuse perched transitional "groundwater" system is tapped by the main channel at lower elevations within a few days. In an area as steeply dissected at the Mondo river basin, one does not expect the presence of an extended saturated water body supplying the *basal flow*. Rather, unsaturated drainage from the ash cover feeding inextensive saturated zones along the stream and in topographic hollows will be sufficient to account for the observed recessions (HEWLETT & HIBBERT; 1963; WEYMAN, 1973; ANDERSON & BURT, 1977a).

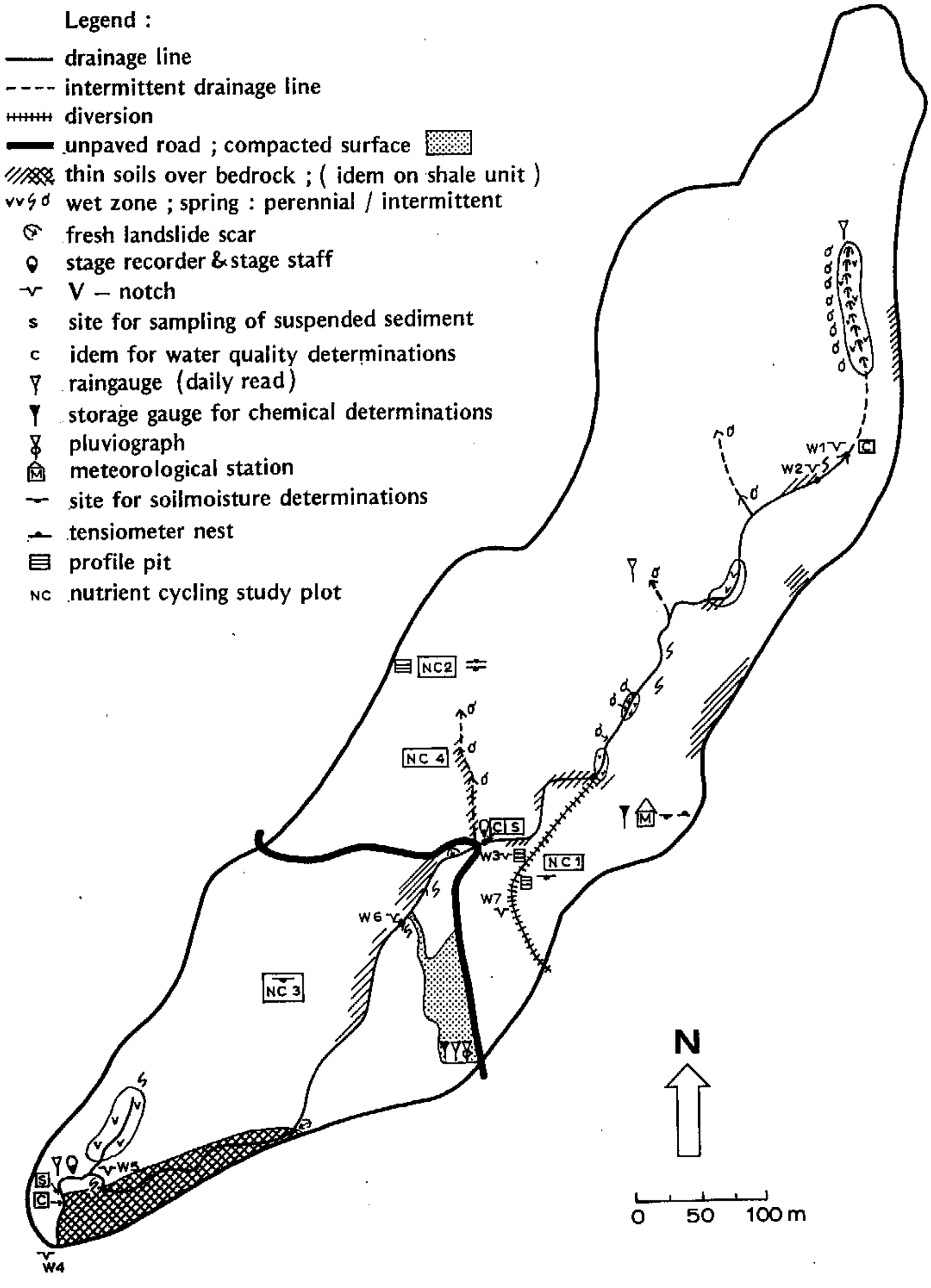


Fig. 3.1 Kali Mondo drainage basin : instrumentation and hydrological features

An analysis of recorded baseflow recessions is given in section 3.4.1. The Mondo river basin responds to the beginning or ending of rainfall almost instantaneously. *Stormflow* is produced by a variety of mechanisms : channel precipitation, Horton and saturation overland flow and subsurface stormflow. The latter is either occurring in strips at the base of the slopes or in areas with thin soils over more impermeable substrata.

Another form of subsurface stormflow is pipeflow as observed in the concave headwater area of the basin. The subject is treated in more detail in section 3.4.2.

3.3 The water budget for the Mondo river basin

3.3.1 *Introduction*

Climate, vegetation, soil type, geological substratum and topography each exert their specific influence upon the way water is moving through a catchment. Their combined influence is reflected in the timing and amount of water leaving the basin as streamflow. As such the continuous recording of rainfall and streamflow and the evaluation of the water flux through a particular catchment can reveal much about the internal functioning of that system (BORMANN & LIKENS, 1967).

Reliable data on precipitation and runoff from the Mondo river basin have been collected from 13 November, 1975 till 13 January, 1976 and from 1 December, 1976 till 1 February, 1978.

In the present chapter the water budget equation (WARD, 1975) for the latter period will be evaluated and compared with results obtained in other river basins. This equation reads

$$P = Q + E_a \pm \Delta S \pm \Delta G \qquad (3.1)$$

where P = precipitation
Q = streamflow
E_a = actual evapotranspiration
ΔS = change in soil moisture storage
ΔG = change in groundwater storage

All values are expressed in mm water.

3.3.2 *Procedures*

3.3.2.1 *Precipitation*

Precipitation was measured with three Hellmann-type raingauges (100 cm^2 orifice) and a Thiessen recording raingauge (float-type, 200 cm^{2}orifice) spaced about evenly over the area (Fig. 3.1). The standard gauges had their orifices at about 1.5 m above ground level to avoid splash-in. Care was taken that the gauges were not placed in the rainshadow of trees. All gauges were inspected daily and the arithmetic mean of all readings was used as the areal precipitation estimate.

By far the most important factor causing uncertainty about the *exactness of a point rainfall estimate* is the aerodynamic interaction between the falling precipitation, the wind and the raingauge plus its surroundings (WARD, 1975). Additional gauge errors may be leaks, splash out, inclination and adhesion, apart from any evaporation and condensation. Since winds in the Mondo river basin usually are very light (see section 2.2) the position of the gauges is not thought to result in a serious underestimation of the catch such as observed in the windier climates of, for instance, the Netherlands (BRAAK, 1945) or England (RODDA, 1967). Under similar tropical conditions (*i.e.* light winds and frequent heavy showers) KOOPMANS (1969) could not detect any significant differences between the amounts of rain measured by a ground-level gauge and a standard gauge at 1.5 m above groundlevel. On an annual basis the difference was less than 0.5 %, whereas the mean of the absolute differences was less than 2 %. The effect of the other factors mentioned above is considered to be very small in the present case.

An analysis applying methods described by RUSIN (1972) and DE BRUIN (1977) was performed with the rainfall data from the three gauges in the catchment to test the accuracy of the *areal rainfall estimate*. The standard error of this estimate proved to be very good : 1.38 % for all data (310 observations) and 1.19 % for wet-season data only (283 observations). It could further be shown that the variance of the areal estimate amounted to 0.97 that of the point observations (*cf*. RODRIGUES-ITURBE & MEJIA, 1974; BUISHAND, 1977).

3.3.2.2 *Streamflow*

Streamflow was monitored continuously at two 90° V-notch weirs by means of LEOPOLD & STEVENS "type-F" stage recorders (W3 and W4 on Fig. 3.1). Although the recording charts lasted one week the equipment was checked daily. Whereas Weir 4, situated at the basin outlet, had already been operative during the first phase of the investigation in 1975, Weir 3 was added in November, 1976 to provide data on that part of the catchment that remains unaffected by overland flow from compacted surfaces. In the dry season of 1977 a third V-notch (W6) was installed downstream of Weir 3 to estimate any leakage under the latter : small discharges (up till about 20 l sec^{-1}) were determined by volumetric measurements using bucket and stopwatch (usually in the early morning), higher flows generally were measured by means of the salt-dilution method (WATER RESEARCH ASSOCIATION, 1970) and occasionally (when available) with a Gurley No-622 "Teledyne" current meter. No consistent differences between these two approaches could be detected (BRUIJNZEEL, 1976).

Apart from the measurements at the above-mentioned structures discharges were determined at a handful of other locations within the catchment as well (also on a daily basis) : at W1 and W2 to monitor the discharge of a major spring; at W5 to study the behaviour of a marshy area and at W7 to measure the flow through a small diversion ditch leading-out of the catchment (for locations see Fig. 3.1). Only small flows were involved and the volumetric method proved adequate in all cases.

The frequent measuring of the flow revealed that the rating curve for the lowest station frequently shifted due to alterations in the configuration of the stream bed caused by the passage of flood waves ("banjirs"). To calculate the total amount of streamflow for a given period use was made of the appropriate rating curves. However, sometimes serious uncertainty arose as to the extrapolation of these ratings to high stages. In those cases refuge was taken to an empirical power curve relating the volume of quickflow to the amount of rainfall (based on two months of detailed observations in 1975 (see section 3.4.2.2 for further details). As to the *precision* of the streamflow measurements one can say that volumetric gaugings of the baseflow attain an accuracy of 2 % or better, the adopted values being the mean of at least three or four measurements at a time. Higher baseflow values are considered to have an accuracy of 5-10 %, whereas individual quickflow estimates sometimes may be seriously in error due to a mis-prediction of the quickflow formula referred to above. However, the contribution of quickflow to the total flow during the period of investigation amounted to *c.* 5 % only, and underestimates may be more or less cancelled by overestimates. To this should be added errors in staff-gauge readings (accurate up till 0.5 cm) and recorder performance. The latter errors are probably random.

A complicating factor is introduced by the presence of the small diversion ditch (gauged at Weir 7) leading out of the catchment (Fig. 3.1). Via a system of bamboo-pipes part of this water returns to the catchment and will eventually contribute to baseflow.

This proportion has been determined to be about 60 %, which means that the remainder (40 %) has been added to the recorded baseflow. An error of 20 % in the estimation of this proportion will increase the overall uncertainty about the total streamflow with slightly less than 2 %. In conclusion it seems fair to say that total streamflow is known with an accuracy of 6-10 %.

3.3.2.3 *Changes in soil moisture- and groundwater storages*

From February, 1977 onwards six tensiometers (manufactured by Soil-Moisture Ltd.), installed at 15, 45 and 70 cm depth at two locations with contrasting vegetation (viz. shrubs vs. short grass) were read daily (usually around 10 AM). The scale of the manometers could be read with an accuracy of 1 cbar at best, which means an observational error of 5-10 % during the wet season. These observations have been used as an indication of catchment wetness status rather than in an absolute sense.

The upper 100, respectively 225 cm of soil at the tensiometer plots and at three other locations in the basin (one on level ground, the other two midway on northwest- and southeast-facing slopes) were sampled once a month using an Edelman-type of auger. Stored in plastic bags the samples were transported to the UGM/NUFFIC laboratory in Yogyakarta the same day for the thermo-gravimetric determination of soil moisture (drying the samples for 24 hours at 105° C). The absolute values obtained in this way rarely differed more than 10 percent between locations, especially during the wet season, the accuracy of the laboratory determinations themselves being better than 5 %. The drybulk density (b.d.) of the soil near the sampling points was estimated by taking samples of known volume (100 cm^2) from the walls of soil pits. Since no replicas were taken the results may easily deviate 10-20 % due to variations in porosity (SCHEFFER & SCHACHTSCHABEL, 1973). The trends encountered in the vertical, however, were quite realistic and the fact that the weighted mean bulk densities for the two profiles investigated were equal puts some confidence in the values applied.

The weight-based percentages of moisture (wpm) as obtained in the laboratory can be converted to volume-based percentages of moisture (vpm) (STAKMAN, 1973), using the equation :

$$wpm = vpm \times bd \qquad (3.2)$$

Since vpm equals the amount of mm of water per 10 cm depth of soil, which ultimately is the required information, a reliable estimate of the dry bulk density is of obvious importance.

Despite the reasonable accuracy of *c.* 10 % that may be obtained in this way for at least the upper 200 cm of soil at a point it should be remembered that this makes up only a fraction of the total unsaturated zone, both in an areal sense and in the vertical. Although some major textural changes have been encountered between 2.5 and 5 m depth (representing older ash falls), each with their specific moisture retention capacity, the bulk of the water uptake by roots must be covered by the present sampling depth. Also, percolation to deeper layers must be fairly constant during at least the raining season. (BLACKIE, 1972) obtained good results when sampling homogeneous tropical soil to a depth of 3 m in Kenya under very seasonal circumstances.

As far as changes in *ground water storage* are concerned, these have been evaluated tentatively by considering the basal flowrates at the beginning and end of a given period taking into account the time needed to arrive from one base-flow level at the other (as derived from recession analysis). This approach was thought to be more representative for the behaviour of the catchment as a whole than observations from single sites, which might represent only local situations, not necessarily representative for the entire saturated zone of the basin. Direct information on any *groundwater leakage* from the Mondo river basin is absent. At the outlet of the basin the stream is incised into the weathered bedrock and there is very little valley fill. Leakage under the weir is therefore thought to be almost negligible. As far as deep seepage along the numerous faults in the area is concerned no direct estimates are available either. A water balance constructed for the period 20 November till 12 December, 1975 (which was assumed not to have significant changes in storage as baseflows at both occasions were equal) indicated that the observed difference between precipitation and runoff could entirely be accounted for by the potential evapotranspiration rate as calculated by the same combination-type formula as applied in the next section. Although such evidence is by no means conclusive, it gives some support to the idea that leakage from the catchment probably is of minor importance.

3.3.2.4 *Evapotranspiration*

Two approaches have been followed : the catchment water balance and a modified Penman formula. The first method gives an estimate of the actual evapotranspiration (E_a), whereas the second refers to the amount of water evaporating from an extended water body (E_o).

The weakness of the waterbudget method is, of course, that, even if the balance itself can be solved satisfactorily, errors in the assessment of the component may be much larger than suggested by the "fit" of the budget. In the present case P and Q are known with a fair to high degree of accuracy, whereas ΔG seems to be of minor importance. ΔS has been estimated for the upper 225 cm of the soil profile only and this is where the major uncertainty arises. Moreover, the samples taken to represent the moisture status of the area at the start of the investigation, suffered partial drying in the laboratory before the actual determination of moisture was performed and these estimates therefore are correspondingly low. Thus, unfortunately, no direct estimate of ΔS for the entire period of study is available, although some information on catchment wetness could be gained from the precipitation record over the foregoing two weeks. LEE (1970) concludes in general that "under the most rigorous research conditions observed water balances probably are accurate only to 13-30 % of yield". In the present case the error in E_a is estimated to amount to *c*. 20 %.

The major advantage of the catchment water balance approach is that the effects of many contrasting micro-situations existing over the basin are lumped together to one areal estimate of evatranspiration. Topography affects net radiation profoundly, whereas the combination of irregular vegetation (clearings, varying stand heights and tree densities) and topography produces an infinite array of aerodynamic profiles, not to speak of spatial differences in reflection coefficients and amounts of intercepted water which is known to be evaporating at much faster rates (RUTTER, 1967). Indeed, to obtain a spatially and temporally representative set of data, it would require a truly Herculean effort of computerized measurements. Or, as LEE (1970) puts it : "The use of the Penman method in estimating vaporization losses from forested watersheds is akin to felling trees with a surgeon's scalpel". However, in the absence of refined equipment to determine the actual values of the various extra parameters needed to account for biological factors (such as in the more sophisticated version of the combination formula as proposed by MONTEITH, 1965) and without wanting to resort to crude empirical formulae, one naturally arrives at the standard open-water evaporation (E_o) model (PENMAN, 1948, 1956). The biological parameters have been evaluated thusfar for a few temperate-zone vegetation types with data on tropical forests lacking almost entirely. The calculation of the canopy resistance to vapour transport in a Montane Rain forest in Kenya by SZEICZ & LONG (1969) is an example. A promising new technique - recently applied in the forests along the Amazone - is the use of radio-active tracers (JORDAN & KLINE, 1977).

The *combination formula* (PENMAN, 1948; 1956) is so well-known among hydrologists and foresters that it will not be repeated here *in extenso*. Rather, attention will be paid to the modifications applied in the present work, to the precision of the basic meteo-variables and the overall accuracy of the results.

The main modification is the use of an empirical (Angström-type of) formula to estimate incoming radiation. The equation reads

$$R_{sh} = R_o\ (0.18 + 0.49\ n/N) \qquad r^2 = 0.77 \qquad (3.3)$$

where R_{sh} = incoming short-wave radiation (cal cm^{-2} month^{-1}).

R_o = *ibidem* at the top of the atmosphere (cal cm^{-2} month^{-1}); to be read from tables, *e.g.* DE JONG, 1973,

and n/N = relative duration of sunshine between 7 AM and 5 PM.

Equation 3.3 has been derived from recent and pre-war data (BERLAGE, 1948; DEE & REESINCK, 1951; SCHMIDT, 1950) on the relative duration of sunshine and incoming radiation at five stations in West and

Central Java covering the entire elevational spectrum. As such it represents an (admittedly somewhat crude) estimate of the average Javanese situation. The use of this formula represents a reduction in calculated amounts of incoming global energy of 6 % as compared to the expression originally proposed by PENMAN, equivalent to a 5 % reduction in evaporation. The equations for estimating the net long-wave outgoing radiation and the vapour transfer by wind turbulence are the same as used by PENMAN in his later papers (*e.g.* on Kenya, PENMAN, 1967).

The basic data involved are : relative duration of sunshine (%), relative humidity (%), air temperature (° C) and wind speeds at 2 m height (msec^{-1}).

The *duration of sunshine* has not been measured in the river basin itself, but at the nearby meteorological station of Singomerto (about 5 km to the northeast, situated in the Serayu valley at an elevation of 310 m a.s.l.). For a few months no data were available due to instrument failure. In these cases values have been used obtained from regressions between sunshine duration at Singomerto and at Merden or Karang Kobar (situated about 15 km to the west and north of the catchment respectively). As a check the ratios between consecutive months were calculated as well. The readings themselves are believed to attain an accuracy of 5-10 percent, but larger errors may be associated with the conversion into radiation. According to data presented by SCHMIDT (1950) a reduction of 5 % should be applied to the Singomerto data to account for the difference in height between Singomerto and the catchment (300 m). Since radiation intensity increases with height (SCHMIDT, 1950) the reduction in incoming radiation will be less than 5 %. Since it is unknown how the two interact on a monthly basis no corrections have been applied to the Singomerto data. It should be added that the reduced sunshine figures resulted in evaporation estimates that were systematically lower than found by the water budget approach. It is particularly important to have reliable radiation data since radiation accounts for some 90 % of the evaporation. An error of 10 % in the former is reflected in an overall deviation of E_o of 7.8 %. Mainly because of this uncertainty in the radiation term the author felt that attempts to calculate the potential evapo*transpiration* (PE) on a monthly basis would not be justified and the standard open-water evaporation (E_o) has been preferred.

Temperature, humidity and wind were all measured at 200 cm above ground level at a site thought to represent a sort of mean condition for the study basin, *i.e.* a better exposure to air masses from the southeast than from the northwest. Shrubs and tall grasses ($\pm$ 1 m high) growing under a fairly open stand of *Agathis*, surrounded the place (Fig. 3.1).

Temperature and humidity were recorded continuously by a Thies thermo-hydrograph, which was checked daily around 9 AM. Agreement between the graph and the values actually determined by means of a standard thermometer and a Negretti pocket whirling psychrometer invariably was within 2 and 5 % respectively. A further check on the temperature record was provided by a "Six" maximum-minimum thermometer. Windrun was measured by a cup anemometer requiring a starting wind speed of 30 cm sec^{-1}. The precision of this instrument is not known, but this will not influence the results very much, since under the prevailing conditions the aerodynamic term in the combinatkon formula accounts for 10-11 % of the total evaporation only. Moreover, the Penman equation is not very sensitive to errors in the wind term : an error of 10 % will result in an overall error of about 2.5 %.

All in all most basic data are known with a fair degree of accuracy and although the spatial variations are not known precisely, they are probably not as important as in temperate climates. The overall precision of E_o cannot be predicted as it is not known to what extent the various errors are additive. Actually computed open-water evaporation over 1977, however, was virtually equal to the expected long-term value, viz. 1345 mm (*cf.* section 2.2), suggesting quite a good fit.

3.3.3 *Results and discussion*

Monthly and total values for rainfall, streamflow, changes in storage of soil moisture and ground water, together with estimates for the actual evapotranspiration (E_a) and the open-water evaporation (E_o) are presented in Table 3.1. In the following the various colums will be discussed in that order.

3.3.3.1 *Precipitation* (see also section 2.2.3)

The wet season of 1976/77 experienced a normal amount of precipitation, although April and June were distinctly wet and May considerably drier than on average.

The rains eventually started again in the last decade of November, rendering the dry season of 1977 one of the longest in the history of the rainfall station at Watubelah. The total quantity of rain falling during the investigation (December, 1976 - January, 1977) amounted to 4668 mm, fairly close to the long-term annual mean of 4768 mm, the rain having been distributed over 171 occasions, again close to the long-term estimate of 176 raindays yr^{-1}.

3.3.3.2 *Streamflow*

Monthly values of streamflow, together with rainfall and open-water evaporation, are depicted in Fig. 3.2. Normally rainfall (P) will exceed streamflow (Q), *i.e.* runoff ratios Q/P will be less than unity, at least in the rainy season. Heavy precipitation in one month, however, may cause high sustained flows in the next (drier) months and thus the pattern is reversed (*e.g.* May, July). The high runoff ratios observed for February and April can be explained by a significantly lower input of solar energy in February and by residual effects of large amounts of rainfall at the end of March, followed by another 400 mm burst during the first decade of April. However, errors in the measurements of peak discharges during the latter period may be partially debet as well.

The severity of the dry season is well-illustrated by the long period necessary to recharge the volcanic ashes and for the base flow to return to a normal level (some two months after the start of the northwest monsoon).

The overall runoff ratio for the Mondo river basin amounts to 0.74. It should be noted that this value applies to a period of fourteen months instead of twelve. If the same amount of precipitation would have been recorded in one year only the runoff ratio would rise to approx. 0.76 due to the elimination of two months of evaporative demand. The difference between these two estimates is not significant, however, and therefore the latter figure has been

Table 3.1 Water budget for the K. Mondo catchment between 1 December, 1976 and 1 February, 1978. Values in mm.

Month	Precipitation P (mm)	Runoff Q (mm)	Q/P	$\Delta S + \Delta G^*$ (mm)	E_a computed (mm)	E_o (mm)	E_a (0.8 E_o) (mm)
December 76	539.2	454.5	0.84	+ 72**	77.5	120.0	96.0
January 77	460.3	364.6	0.79	- 72**	102.9	123.4	98.7
February	444.1	415.7	0.94	+ 91.3$^+$	46.3	100.3	80.2
March	463.2	354.0	0.76			117.2	93.4
April	705.2	698.5	0.99	- 75.5	82.2	117.3	93.8
May	146.3	183.5	1.25	-138.5	101.3	108.8	87.0
June	455.9	323.1	0.71	+123.4	9.4	99.6	79.7
July	12.9	109.4	8.48	-176.3	79.8	103.2	82.6
August	2.5	27.3	10.92	-169.8	145.0	110.7	88.6
September	8.8	9.7	1.10	-103.3	102.4	116.4	93.1
October	38.7	4.3	0.11	- 70.9	105.3	135.2	105.3°
November	303.6	10.4	0.69	+217.8	75.4	108.6	75.4°
December	535.9	91.8	0.17	+173.5	271.8	103.5	82.8
January 78	551.3	413.3	0.75	- 12.3	150.3	107.9	86.3
Total	4667.9	3460.1	0.74	- 9.2**	1217^{++}	1572.1	1242.9

* changes in soil moisture (upper 225 cm of the soil profile) and groundwater storage respectively

** change in groundwater storage only

\+ soil moisture data from 10 February onwards

++ total P - total Q - ΔG, with $\Delta S = 0$

° Equal to E_a from water budget

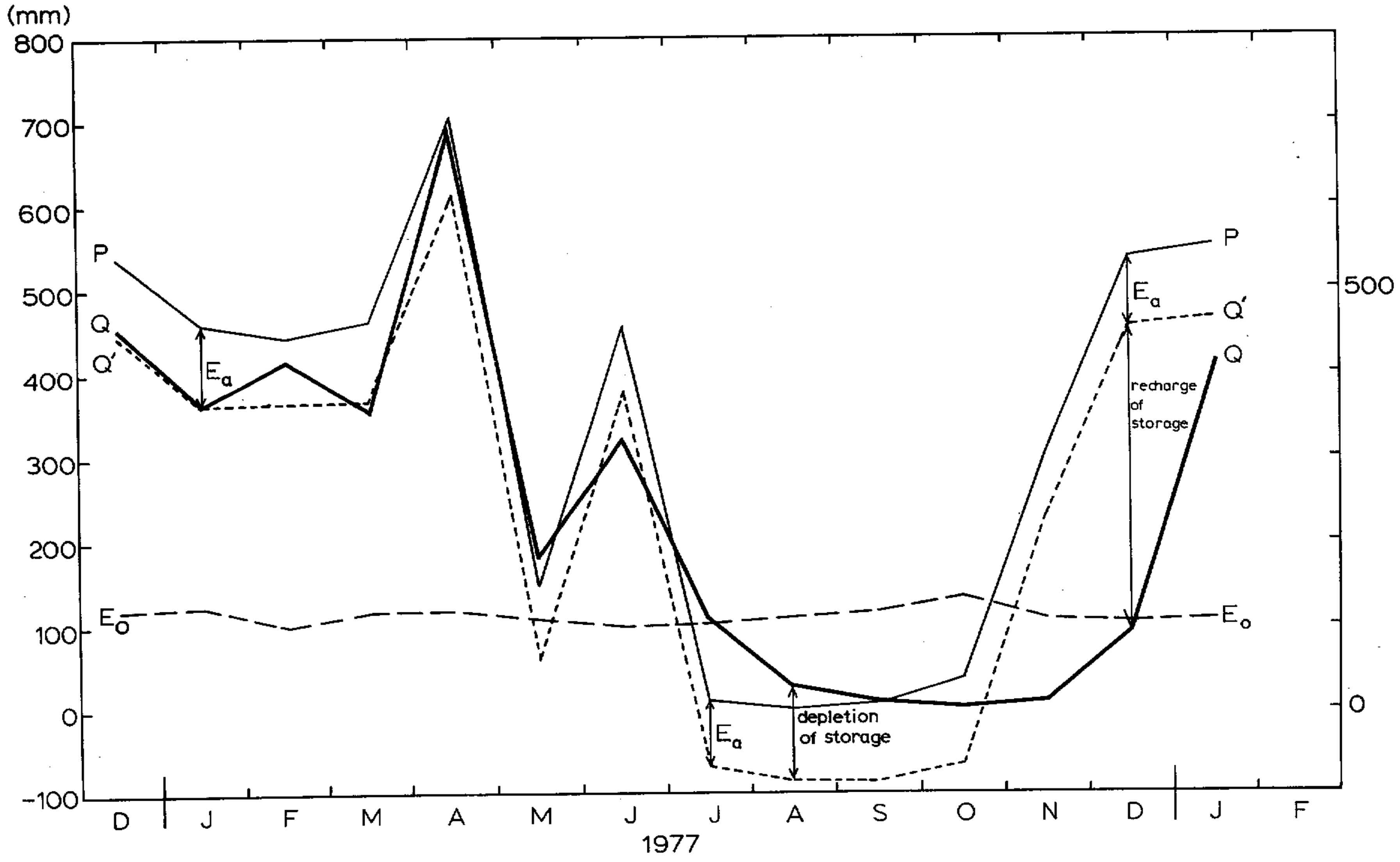


Fig. 3.2 Seasonal course of precipitation, streamflow, open-water evaporation and "ideal" streamflow for the Mondo drainage basin between 1 December, 1976 and 1 February, 1978

taken for more direct comparison with data from other tropical and extra-tropical catchments in Table 3.2.

3.3.3.3 *Changes in soil moisture-groundwater storages*

These largely exhibited the same recharge/drainage patterns. The decline in moisture - and ground-water storage, already starting as early as medio April, was offset partially by the recharge occurring in June, but then continued till the onset of the rains at 20 November. Considerable recharge of soil moisture and groundwater is seen to take place in November and December respectively, and here it is that the limitations of sampling the upper two metres only of a much deeper soil become manifest : the amount of (moisture) recharge for December is much too low (resulting in too high an estimate of the actual evapotranspiration E_a). Lack of representative soil sampling is also exemplified by the figures presented for June. Here the recharge of soil moisture is exaggerated as a result of a major storm falling on the day prior to sampling rendering the estimate of E_a in this case as low as 9.4 mm.

A similar situation occurs in January, 1978, which shows a decrease in storage of 15.6 mm caused by the high moisture status of the top soil at the time of sampling following heavy rains on the last three days of December, again resulting in an over-estimate of E_a. February and March combined shows a gain in moisture of 51 mm, but it should be noted that this value in reality applies to the period 10 February till 30 March and as such is not representative for the entire period. Negative values for the change in groundwater storage are observed for both February and April, despite substantial amounts of precipitation received. This is probably a corollary of the fact that in these months most of the precipitation fell during the first decade, whereafter the combined effect of continuing evapotranspiration and drainage caused the baseflow to fall below its initial level. The reverse can be seen for the month of March, which experienced most of its rainfall during the second half. Finally a word about the overall change in moisture storage. Since the overall change in groundwater storage is relatively small and the amounts of rainfall observed during the last ten days before the start and the termination of the field study differ by less than 10 mm, it is believed that the change in soil-moisture storage probably is of minor importance (note : a quantity of 20 mm being less than 2 % of total E_a).

3.3.3.4 *Actual evapotranspiration*

Values for E_a as determined from the foregoing quantities of rainfall, streamflow and changes in storage have been included in Table 3.1. Some individual months show quite realistic evapotranspiration levels (*e.g.* January, May, September), other estimates are definitely too high (December 1977, January 1978) or too low (June, March), for reasons explained in the previous section. Clearly the computation of E_a in this way presents major problems and refuge was taken to an alternative approach (Fig. 3.2). The average difference between precipitation and streamflow on the one hand and computed values of E_a on the other hand are virtually identical at 96.5 and 95.5 mm $month^{-1}$ respectively (during the wet season). It follows that E_a/E_o is close to 0.80 for this period. The ratio can probably be applied safely during most of the investigation period when soil water storage is not limiting evapotranspiration (*i.e.* E_a = PE). The only months when water stress may have occurred to some extent will be October and November, 1977. The calculated ratios for these months fall below 0.8 indeed at 0.78 (October, not significantly different) and 0.69 (November). Values of E_a thus obtained have been subtracted from precipitation figures for better comparison to actually observed streamflow levels (Fig. 3.2). Deviations are mainly interpreted in terms of recharge or depletion of storage. Total E_a over the entire period then amounts to 1243 mm, *i.e.* close to the 1217 mm computed from the actual overall waterbalance (difference 2.1 %). This certainly puts some confidence in the alternative approach. In the same way the normal annual value of E_a has been estimated as 1075 mm yr^{-1} (0.8 E_o).

3.3.3.5 *Open-water evaporation*

Monthly values of E_o almost exactly match the long-term average pattern as interpolated for an elevation of 625 m a.s.l. from the data compiled by ISNUGROHO (1975) : see also section 2.2.3. A minimum occurred in June, a maximum in October and a secondary minimum in February (Fig. 3.2), all of which can be explained in terms of incoming radiation and estimated windrun. The belated return of the west monsoon in 1977 and the associated high degree of cloudiness during November, and December, 1977 and January, 1978 is reflected in the lower evaporation values for these months as compared to the corresponding period in the preceding rainy season.

3.3.3.6 *Comparison with other locations*

Runoff ratios and water consumption figures for a number of selected forested catchments have been given in Table 3.2. The runoff ratio observed at the Mondo catchment is quite comparable to that of other wet tropical basins, such as Papua New Guinea and Sierra Leone. (It should be noted that the figure quoted for Ei Creek has been derived from data reported by the Papua Department of Works quoted by TURVEY.) When annual precipitation becomes substantially less than 3000 mm or is concentrated in a relatively short rainy season (Queensland) the runoff ratio drops accordingly as a result of continuing high evapotranspiration rates during the remainder of the year. Runoff ratios for the temperate-zone catchments appear to be between those observed for the humid and drier tropics in accordance with the lower evaporative demand of the temperate climate. The figure for E_a determined at Watubelah (1075 mm yr^{-1}) looks wholely realistic in view of the results obtained for Lowland Rainforest catchments. Estimates available for the Lower Montane Rainforest of Papua New Guinea are contrasting at 860 (Department of Works) and 1215 mm yr^{-1} (extrapolated value from TURVEY, 1974). Their average (1040 mm yr^{-1}) may well be a fair approximation as the elevated area (600 m a.s.l.) is reported to be fairly cloudy (TURVEY, 1974). The results reported for other drainage basins in Java agree less well with the present observations. BAKKER (1952) gives evaporation totals of 1280-1320 mm yr^{-1} corresponding to E_a/E_o values as high as 0.94-0.97. The amount of water claimed to be lost annually from the Montane Rainforest of West Java (1250 mm; GONGGRIJP, 1941) must be a considerable overestimate as well. It may well be that the figure quoted by COSTER (1937) for the same forest - 780 mm yr^{-1} - as determined from transpiration rates of cut-off leaves

Table 3.2 General hydrological data from selected catchments

Location	Runoff ratio Q/P	P*	E_a*	E_o*	E_a/E_o	Catchment lithology	Land use	Length of observation period (yrs)	Catchment area (km^2)	Reference
tropical catchments										
Ei Creek (Papua New Guinea)	0.75	3500	860 (1215)	1379°	0.75	basaltic agglomerates on phyllites	Lower Montane Rainforest	6	16.25	Turvey (1974)
West Malaysia (4 catchments)	0.51	2227 ±172	1103 ±110.5	1254 ±24.9	0.88 0.005	60% granite 40% schists	Lowland Rain forest, some rubber	1	52 ± 19	Low & Goh (1972)
Lagan (Western Kenya)	0.35 ±0.11	2053 ±414	1310 ±17.3	1658 ±99.8	0.79 ±0.04	phonolitic lava	Montane Rain forest	11	5.4	Blackie (1972)
Guma (Sierra Leone)	0.79 ±0.10	5795 ±112	1146** ±426	1010° ±78.2	1.13 ±0.35	gabbro	Lowland Rain forest, 13 % storage reservoir low-land	7	8.7	Ledger (1975)
Queensland	0.65	4037	1421**	-	0,87	metamorphic	Lowland Rain forest	6	0.26	Gilmour (1977)
Mondo river (Indonesia)	0.76	4768 ±1161	1075	1344	0.80	andesitic tuffs and breccias	*Agathis* plantations	1	0.19	present study
temperate-zone catchments										
Hubbard Brook N.H., USA	0.63	1322 ±68	489 ±10	-	-	till on gneiss	aggrading northern hardwood forest	11	0.12-0.43	Likens *et al.* (1977)
H.J. Andrews 10 Oregon, USA	0.66	2330	800	-	-	andesitic tuffs and breccias	mature Douglas Fir and Western Hemlock	2	0.10	Henderson *et al.* (1978)
Coweeta 18 N.C., USA	0.60	2080	830	-	-	gneiss and granodiorite	mature hardwoods	7	0.12	Henderson *et al.* (1978)

* mean annual precipitation, actual evapotranspiration and open-water evaporation respectively
**determined as precipitation minus streamflow
° pan estimate

and twigs, is closer to the truth. Especially when E_o for this high altitude (1750 m a.s.l.) is known to amount 975 mm yr^{-1}. (N.B. 0.8 x 975 = 780 also) The overestimations of E_a in the cited literature are probably due to an underestimation of annual streamflow resulting from calculation procedures applied in prewar times (VAN ENK, personal communication).

3.4 Hydrograph analysis

4.1 *Recession analysis*

The major pathway along which solutes are removed from a small headwater catchment like the Mondo river basin is the slow and continuous percolation of water through the soil mantle contributing to the baseflow. An analysis of the baseflow recession therefore is of relevance to the study of the chemical denudation rate.

During the rainy season non-storm streamflow levels in the catchment normally did not fall below 10-15 l sec^{-1}. In 1977, at the end of an abnormally severe dry season, the stream had been reduced to a mere trickle discharging only 0.015 l sec^{-1} (mid-November, 1977). The highest non-stormflow discharges were observed in the first week of April, 1977 (2-300 l sec^{-1}) when huge amounts of rainfall were received (*cf.* section 3.3). A master recession curve was constructed from data collected during the rainy seasons of 1975/76 and 1976/77 and the dry season of 1977. A semi-log representation of this curve is given in Fig. 3.3, whereas the log-log version constitutes Fig. 3.4. Both approaches, viz. 1) the superposition of linear reservoirs and 2) the use of empirical non-linear equations will now be discussed briefly.

Ad 1) A *reservoir* is called *linear* when the outflow is directly proportional to the dischargeable storage. Any hydrograph can be thought of as consisting of the discharge of a number of parallel linear reservoirs, each discharging according to a single exponential function (BARNES, 1939; DE ZEEUW, 1973). The drainage characteristics of such reservoirs are reflected in the so-called reservoir coefficients or "reaction factors", often denoted by the symbols k or α. They can be obtained from observed hydrographs by means of the well-known tail-recession analysis as originally devised by BARNES (1939).

Three parallel linear reservoirs were required for the description of the master recession curve of the Mondo river : see Fig. 3.3. The respective reservoir coefficients amounted to 0.031 day^{-1} for the slowest reservoir, 0.12 day^{-1} for an intermediate reservoir and 0.74 day $^{-1}$ for the fastest reservoir with definite breaks in the storage of the curve occurring after 6 and 36 days (Fig. 3.3). The exponential relationship between reservoir outflow and time finally breaks down after about 126 days (corresponding to the date of 20 October, 1977). Before interpreting these theoretical reservoirs in terms of hydrological processes, it may be illustrative to first inspect Fig. 3.4, the log-log representation of the recession curve.

Ad 2) *Empirical equations* have been used by a number of investigators to describe the free drainage of initially saturated soils under non-evaporating conditions (*e.g.* RICHARDS *et al.*,

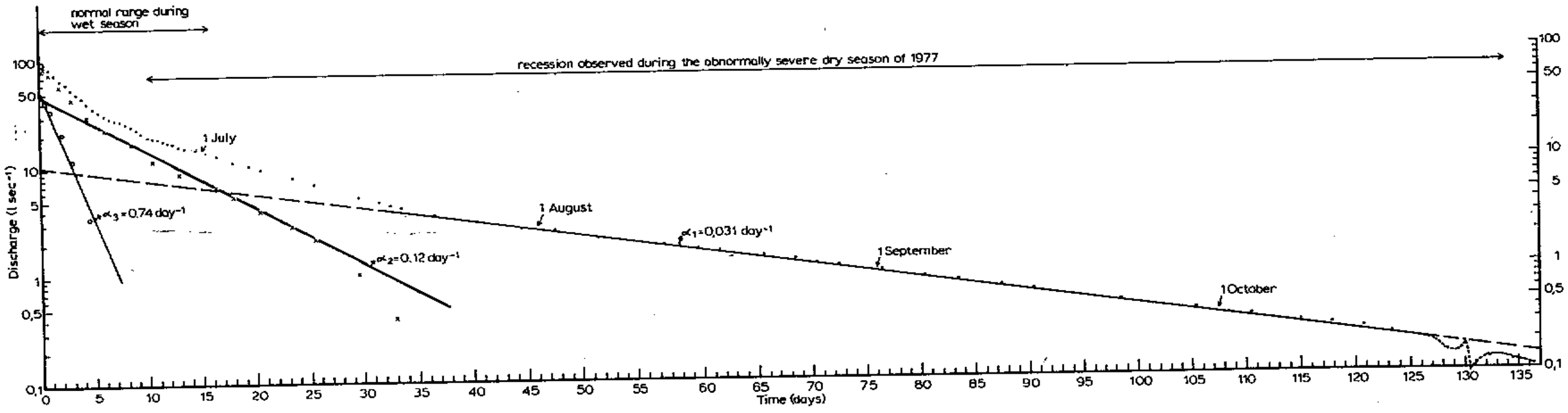
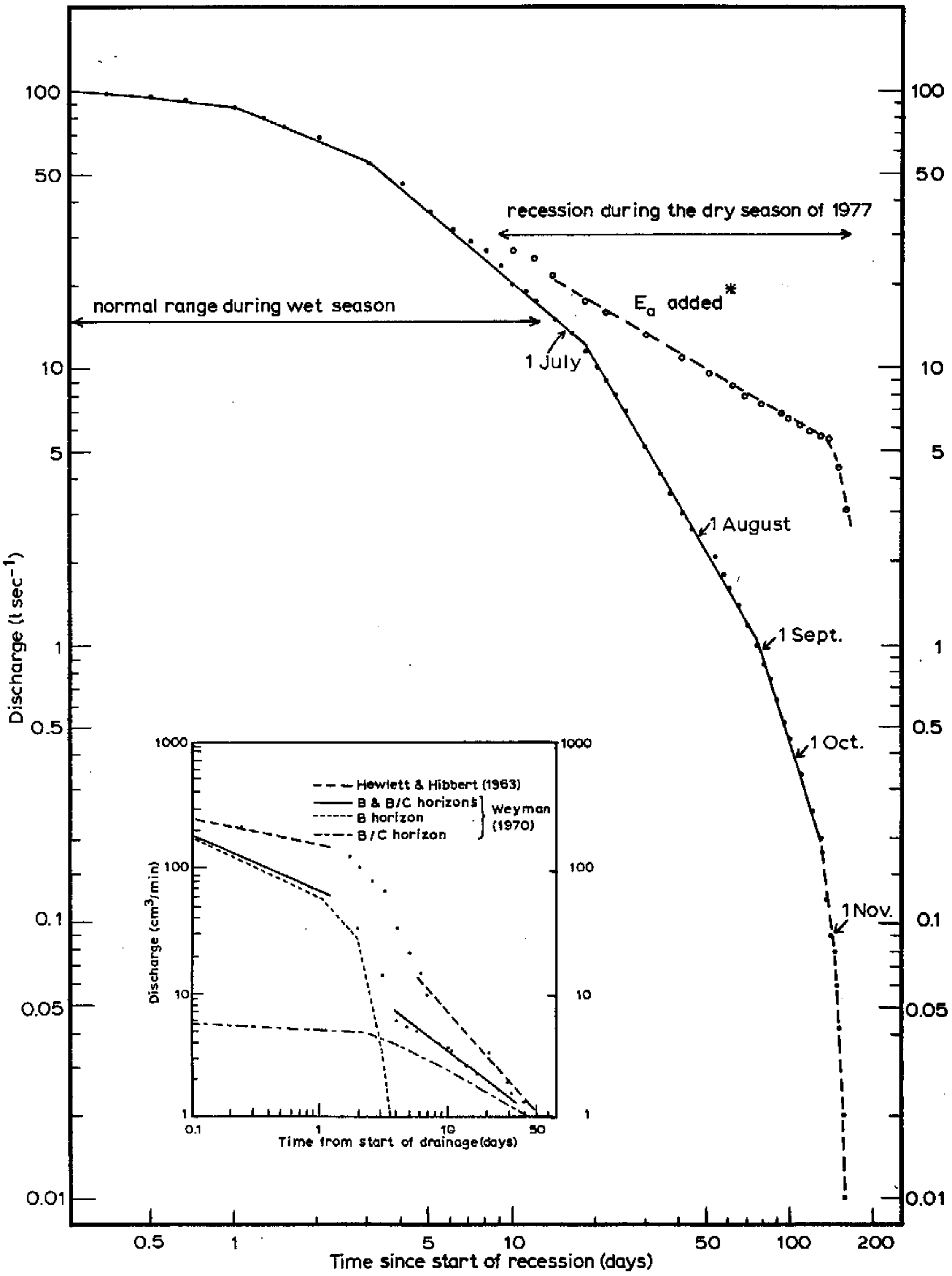


Fig. 3.3 Semi-log representation of the master recession curve of the Mondo river



* see text for explanation

Fig. 4.3 Log-log representation of the master recession curve of the Mondo river

1956; NIXON & LAWLESS, 1960; HEWLETT & HIBBERT, 1963) as well as under natural circumstances (WEYMAN, 1970; HARR, 1977). The general form of such equations reads

$$\frac{dM}{dt} = at^{-b} \qquad (3.4)$$

where M = moisture content (% or mm)
t = time since drainage started (days)
a = moisture loss after one day
b = slope of the regression line

Eq. 3.4 plots as a straight line on log-log paper.

Fig. 3.4 shows the results for the recession of the Kali Mondo and (in the inset) of WEYMAN's East Twin catchment (U.K.) and HEWLETT's sloping soil column (Coweeta, U.S.A.). The Indonesian data produce the same type of graph as does WEYMAN's B-horizon. Similarly, the *dry-season* decline in discharge of the Mondo river exhibits much the same pattern - when corrected for evapotranspiration demands - as HEWLETT's set-up (the values for E_a were derived from Table 3.1 and converted to lsec^{-1}) The uncorrected graph seems to indicate a decrease in discharge with time that is step-wise in character. As many as five breaks in slope can be distinguished before streamflow levels start to fall rapidly by the end of October. A comparison with Fig. 3.3 shows that none of these breaks coincides with changes in the slope of the semi-log representation of the same data. Also, the parameters a and b in eq. 3.4 are time-dependent. For example, plotting the dry-season part of Fig. 3.4 independently (again in log-log fashion, but starting with a flow rate of 25 instead of 100 lsec^{-1}) one obtains breaks at 19 l sec^{-1} (t = 7.5 days after the initial discharge), at 10 l sec^{-1} (t = 15), at 2.3 l sec^{-1} (t = 25) and at 0.35 l sec^{-1} (t = 105). None of these breaks returns in Fig. 3.4. In contrast, changes in slope are found to occur at flow rates of 12.5 l sec^{-1} (t' = 10 days, again taking a discharge of 25 l sec^{-1} as the starting point), at 1.2 l sec^{-1} (t' = 67) and 0.2 l sec^{-1} (t' = 122).

Similar contrasts as the ones described above brought ANDERSON & BURT (1980) to the supposition that the break they observed during the recession of a hillslope hollow in the U.K. was a consequence of the plotting technique rather than changes in hydrological processes. These investigators, could not identify a change from "rapid predominantly saturated drainage of large pores" to "slow predominantly unsaturated, drainage of the remaining voids" (as suggested by HEWLETT & HIBBERT (1963), WEYMAN (1970) and HARR (1977) to explain the break in the log-log recession curve, see inset Fig. 3.4, despite elaborate instrumentation such as recording tensiometer grids. Recession of this hillslope hollow appeared to be the result of outflow from a gradually shrinking small saturated lense in the bottom of the hollow, fed by unsaturated drainage from upslope (ANDERSON & BURT, 1977b; 1980).

Although the value of a semi-logarithmic presentation of recession data was also questioned by these authors, it would seem that the threefold division resulting from such a plot in the present case may have some interesting physical parallels (Fig. 3.3).

Streamflow decline between 20 and 0.2 l sec is quite smooth. This is interpreted as the gradual shrinking of a saturated zone of limited extent (found in the valley bottom and other topographic lows) fed by slow unsaturated drainage from upslope which diminishes as the dry season progresses (ANDERSON & BURT, 1977b).

As to the physical analogy of the two slowest reservoirs one could hypothesize distinct contributions from different parts of the volcanic ash-cover. Indeed, a horizon showing slight signs of temporary water logging (mottling) has been observed over most of the catchment slopes at about 200-250 cm below the surface. The intermediate reservoir might correspond with the ash layers above this pseudo-stagnation zone, whereas the slowest reservoir might represent the deeper and more clayey ashes.

At the top end of the recession curve (*i.e.* $\geq$ 30 l sec^{-1}) a third reservoir was hypothesized to account for the increased curvature. This may very well find its analogue in the catchment's headwater area, *i.e.* upstream of Weir 1 (Fig. 3.1). This bowl-shaped area starts to "overflow" as soon as the catchment wetness is such that a discharge of at least 25 l sec^{-1} is recorded at the basin outlet. Recession analysis for this perched groundwater table system (see also section 3.2) reveals a reservoir coefficient of 0.77 ± 0.10, *i.e.* very close to the postulated 0.74 day^{-1} in Fig. 3.3. During very high flows (> 100 l sec^{-1}) water was observed to drip from cracks in the banks as well and here one comes close to the item to be discussed in the next section.

Discharge rates start to deviate considerably from the exponential trend by the end of October, 1977. It seems as if soil moisture has reached a critical level. Other indications for severe moisture stress at this time of the year are the deviation of the E_a/E_o-ratio (becoming less than 0.8; see Table 3.1) and a peak in the production of litter by the catchment vegetation (Fig. 5.2). Comparable situations in temperate-latitude hardwood forests have been described by FEDERER (1973) and DUYSINGS *et al.*, 1983.

The detailed volumetric gauging of the streamflow during the dry season of 1977 revealed some interesting cyclic fluctuations (Fig. 3.5). Oscillations on a diurnal basis are well-known and usually interpreted in terms of transpiration by the vegetation (MEYBOOM, 1965; PARLANGE & AYLOR, 1975; BURT, 1979).

The present oscillations have a longer and more variable timebase however, and no correlation with either radiation input or temperature (taken as indices for evaporative demand) could be detected. HEWLETT & HIBBERT (1963) noted similar fluctuations during their Coweeta drainage experiment and ascribed the phenomenon to changes in temperature and barometric pressure (*cf.* STEVENSON & VAN SCHAIK, 1967).

Although the variations in barometric pressure in the region are reported to be quite small (BRAAK, 1919) it remains the only explanation that can be offered at this stage.

3.4.2 *Storm runoff*

3.4.2.1 *Introduction*

The process of stormflow generation in small catchments in the temperate zone has received considerable attention during the last

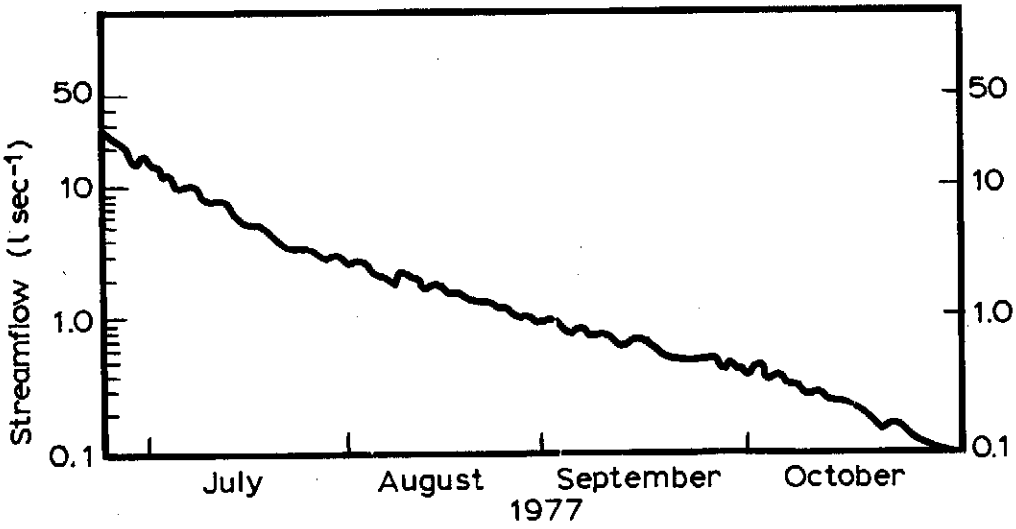
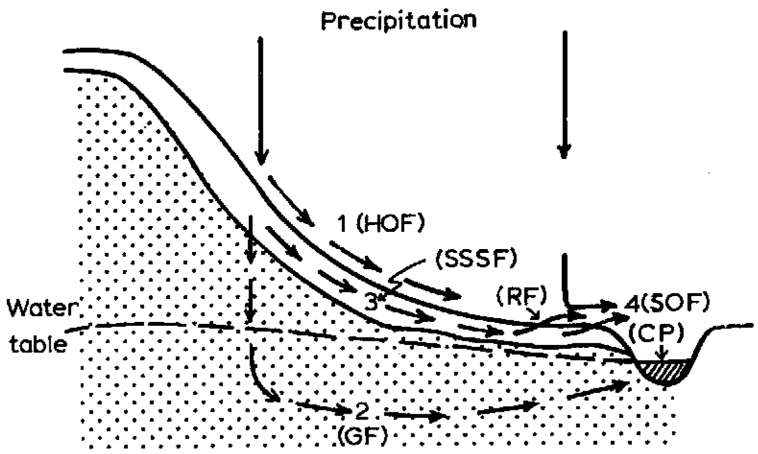


Fig. 3.5 Cyclic fluctuations in the Mondo river discharge during the dry season of 1977

decade (*e.g.* TISCHENDORF, 1969; DUNNE & BLACK, 1970ab; WEYMAN, 1970, 1973; FREEZE, 1972ab; DUNNE *et al.*, 1975; ANDERSON & BURT, 1977a, etc.) The state of the art has been discussed recently in review papers by DUNNE (1978) and FREEZE (1980).

Rain falling on a hillslope may move towards the stream channel along a variety of flow paths. The following general picture has emerged from the investigations quoted (Fig. 3.6). If the rainfall intensity is greater than the infiltration capacity of the soil the excess water runs off as overland flow (path no. 1, so-called *Horton overland flow*, HOF). This type of flow may reach high velocities on steep slopes and is a quick contributor to the storm hydrograph. As long as the infiltrated water meets no obstructions it moves vertically to the groundwater table and from there in a curved manner to the stream channel (path no. 2; groundwater flow, GF). Generally, the percolation rate of this deeper water is such that it does not contribute significantly to stormflow. Rather it maintains the catchment's baseflow. However, if the infiltrated water meets an impeding layer at least part of it will be diverted laterally (path no. 3, lateral flow, throughflow, interflow). The potential gradient and the lateral permeability of the layer in question will determine whether this water will reach the channel quickly enough to contribute to the storm hydrograph. Often it is then called subsurface stormflow (SSSF). A quick response may occur in wet soils via the mechanism of pressure translation. This sort of SSSF is called "translatory flow" (TF, HEWLETT & HIBBERT, 1967). Where the recharging of a soil by SSSF from upslope and rainfall infiltrating *in situ* exceeds the downslope discharge the soil profile may become fully saturated and the SSSF is forced to emerge and travel further along the surface as so-called return flow (RF). It is joined by the rain falling upon these saturated zones which cannot infiltrate anymore (so-called DPS : direct precipitation



HOF = Horton overland flow
GF = Groundwater flow
SSSF = Subsurface stormflow
RF = Return flow
SOF = Saturation overland flow
CP = Channel precipitation

Fig. 3.6 Possible flow paths of water moving downhill (after DUNNE, 1978)

onto saturated areas). Together RF and DPS make up the "saturation overland flow" (SOF; path no. 4 in Fig. 3.6). Where the latter type of runoff occurs it is often a major contribution to the storm hydrograph as it may attain appreciable velocities.

It will be clear from the above that the commonly practized separation of the hydrograph into "surface runoff" and "groundwater flow" is "little more than a convenient fiction" (FREEZE, 1972a).

It is now generally recognized that it is the speed of arrival of the water in the stream channel which is the most important factor determining the shape of the hydrograph. This is reflected in the use of the terms "quickflow" and "delayed flow" (WARD, 1975). Table 3.3 summarizes the terminology, whereas Fig. 3.7 illustrates the importance of the various flow types in relation to their major controls (climate, vegetation, soils, topography). DUNNE's scheme (Fig. 3.7) suggests SSSF to dominate the storm hydrographs of vegetated catchments in the humid tropics at least in a volumetric sense, whereas peaks would rather be produced by SOF. This type of hydrograph is observed in some cases indeed, see for example Fig. 3.8, which illustrates the behaviour of a Kenyan basin on deep permeable volcanic ashes. Work done in Malaysia (MORGAN, 1972), Amazonia (NORTCLIFF *et al.*, 1979) and Dominica (WALSH, 1980) suggest localized SOF and to a lesser extent SSSF to be the main suppliers of stormflow in most cases. Only in certain extreme situa-

Table 3.3 Types of flow in headwater areas of drainage basins

		Type of Flow	Character	Location
QUICKFLOW	SURFACE RUNOFF/FLOW	Overland flow (HOF)	Surface flow of water because rainfall intensity exceeds infiltration rate. Referred to as Horton overland flow or infiltration overland flow by some workers.	Semi-arid areas where rainfall intensities are high and vegetation cover sparse. In humid areas may occur adjacent to stream channels or in topograpphic hollows where water converges.
		Saturated overland flow (SOF)	Surface flow of water which occurs because soil is saturated and infiltration capacity has not been exceeded.	Locations usually close to stream channels or hollows where water table rises rapidly to surface during storm event.
	SUBSURFACE RUNOFF	Throughflow	Movement of water downslope in soil profile usually under unsaturated conditions. Referred to as unsaturated throughflow by some workers.	Slopes with well-drained soils and often encouraged by discontinuities in soil profile. Lateral flow will occur in soil if this meets less resistance than vertical.
		Saturated throughflow (may become return flow RF)	Lateral flow in soil under saturated conditions.	During storm a saturated wedge will extend upslope in soil profile and saturated throughflow occurs immediately above this.
		Translatory flow (TF)	Lateral flow in soil occurring by displacement of stored water due to addition of 'new' water.	Slope with soil with saturated zone.
		Interflow	May be used synonymously with throughflow. Some workers describe lateral flow above water table but below soil as interflow which could thus be through unsaturated rock or regolith	Slopes having permanent water table at depth and any lithological discontinuities may encourage lateral flow of water as interflow.
		Saturated interflow	Interflow occurring under saturated conditions.	Affected by extension of saturated wedge beneath surface in upslope direction.
		Pipeflow (PF)	Flow through subsurface network of interconnected, anastomosing pipes or tubes, larger than other soil voids and may be up to 1 m in diameter.	Variety of areas including steep slopes, where erodible layer lies above less permeable layer, or on flood plains marginal to channel banks.
DELAYED FLOW	GROUNDWATER FLOW	Groundwater flow (GF)	Water that has infiltrated into ground, has reached groundwater and is discharged to surface from spring or seepage at rate determined by hydraulic head.	Areas where groundwater storage is possible due to character of subsurface materials.

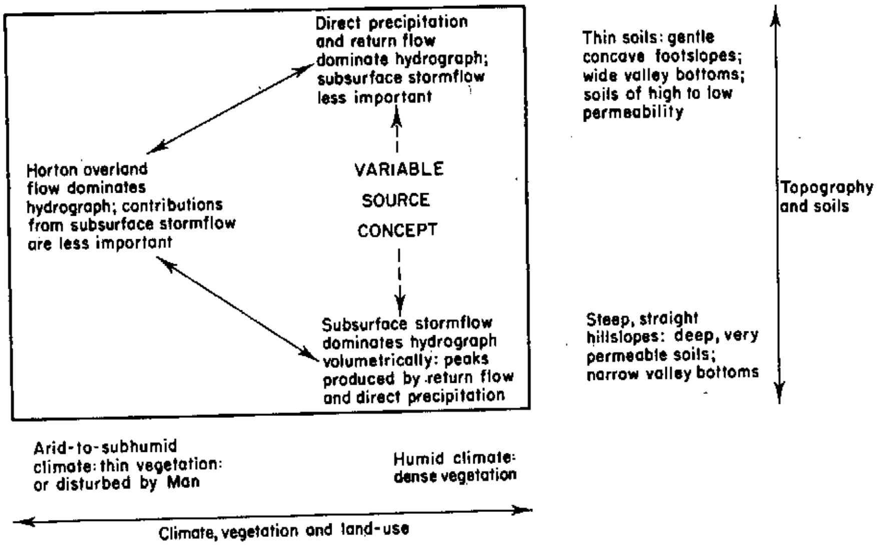


Fig. 3.7 Schematic illustration of the occurrence of various runoff processes in relation to their major controls (after DUNNE, 1978)

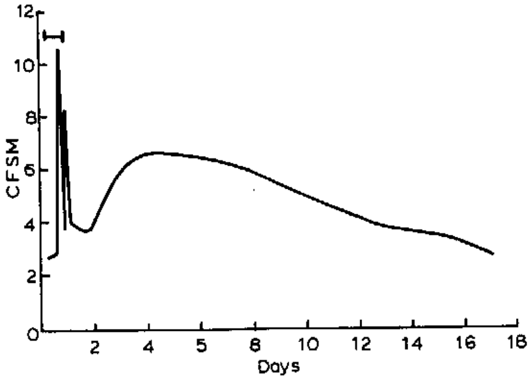


Fig. 3.8 Hydrograph from the Kimakia basin, Kenya, associated with a rainstorm of 61 mm in 24 hr (after HEWLETT & NUTTER, 1970)

tions, such as reported by BONELL & GILMOUR (1978) and GILMOUR *et al.* (1980) for northern Queensland (where rainfall intensities frequently exceed the transmission capacity of the B horizon) becomes SOF widespread. Interestingly enough WALSH (1980) mentions a case of storm runoff being dominated by SSSF in the superwet volcanic highlands of Dominica where hardpans also obstruct vertical percolation, but lateral conductivities were sufficient to discharge the water downslope without much generation of SOF.

The genetic separation of storm hydrograph components seems feasible for well-instrumented catchments or even hillslopes only. Yet, in the absence of extensive equipment the use of chemical parameters may prove quite enlightening in this respect (FRITZ *et al.*, 1976; DUYSINGS *et al.*, 1983). A more or less quantitative description of the storm runoff situation in the Mondo catchment will be attempted in the next section, based on direct hydrological evidence and the collected hydrochemical information.

.4.4.2 *Storm runoff in the investigated catchment*

General considerations

Since "quickflows" (*cf.* Table 3.3) constitute the main pathway along which sediment is removed from the Mondo river basin this section will be devoted to a better understanding of their nature in terms of contributing areas. In the present context "quickflow", or "stormflow" is defined as the amount of water leaving the catchment during and "immediately after" a rain storm minus the basal flow. The latter statement requires some explanation. For most storms the bulk of the quickflow is made up of some kind of overland flow (HOF and SOF) and "SSSF" (translatory flow, TF) from the immediate surroundings of the stream. The time required for this water to travel from the headwater area to the lowest gauging point exhibits a strong inverse relationship with the prevailing discharge level. Application of the travel times obtained with this formula (30-120 minutes) to the storm hydrographs indicated a coincidence of the end of overland flow and the second of two knickpoints on the recession (Fig. 3.9). The line between this point and the start of the hydrograph rise has been taken as the separation of quickflow and baseflow. In this way a consistent set of data was obtained. Other saturated lateral flow may or may not contribute to the actual stormflow but its effects are mainly visible on the recession limb of the storm hydrograph beyond the selected knickpoint. In fact it is a continuous process which may last for days and as such it has been included in the baseflow component from which it is hard to distinguish. Fig. 3.10 shows the relation between "quickflow" volumes according the above procedure and incident rainfall for a set of detailed measurements from the wet season of 1975/76 . During that season the water level recorder was equipped with a daily clock enabling a much more detailed registration of peakflow recessions. The inclusion of the study runoff events that were sampled (and monitored) in detail in the next period, in 1977 gave no reason to modify this relationship (Fig. 3.10), which reads :

$$Q_q = 0.009\ P^{1.415} \quad (n = 42 \quad r^2 = 0.90) \tag{3.5}$$

where Q_q = quickflow (mm)

and P = (gross) precipitation (mm)

An attempt has been made to improve the degree of correlation by making a distinction between "relatively wet" and "moderately dry" antecedent conditions. However, no improvement was found this way, suggesting that other factors - such as the intensity of the rainfall and therefore degree of interception are important as well. Despite the observed scattering equation 3.5 should be considered to be a fair means of predicting quickflow volumes for a certain rainfall during the wet season. It has been applied as such to estimate storm runoff volumes in those few cases when either stage registration was poor or reliable peakflow measurements were not available (*cf.* section 3.3.2.2).

On average quickflows in the Kali Mondo catchment normally make up

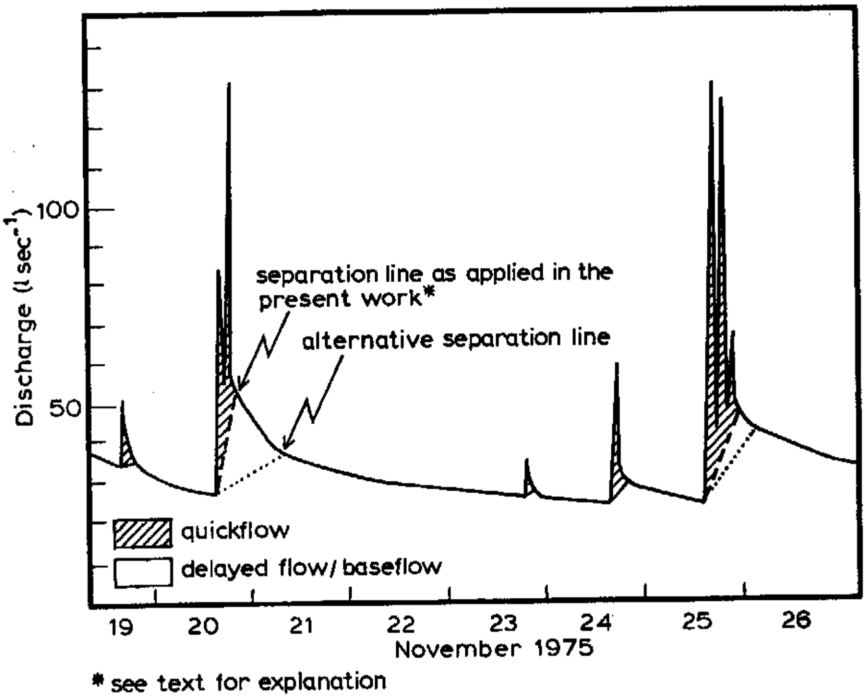


Fig. 3.9 Some typical storm hydrographs for the Kali Mondo catchment (wet season 1975/76)

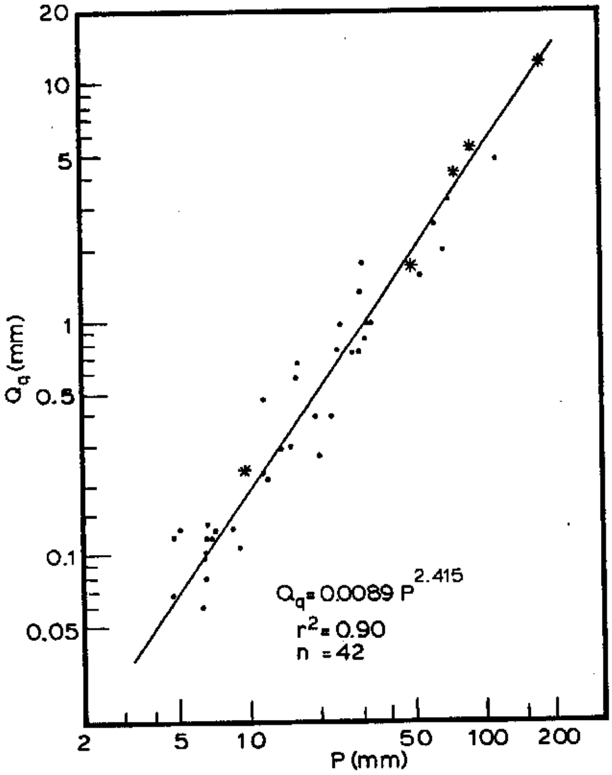


Fig. 3.10

Relationship between gross rainfall and quickflow for the Kali Mondo catchment only 5-7 % of the total monthly runoff during the wet season (Table 3.4). This figure rises in case of extremely low baseflow contributions (October, November 1977), even though the absolute values for quickflow are small. The figures indicate a direct response of the catchment in terms of stormflows after the return of the rains in November, in contrast to the time lag exhibited by the baseflow component. Monthly precipitation figures have been added to illustrate the seasonal relationship with stormflow amounts (*cf.* Fig. 3.2 on the seasonal course of total streamflow and precipitation).

The relative values for stormflows as presented in Table 3.4 are quite low when compared to values quoted normally for tropical catchments. WALSH (1980) for example, working in an environment which was very similar to that of the present work (the wet volcanic uplands of Dominica) reports stormflow amounts of 10-20 % of the monthly runoff. Also BONELL & GILMOUR (1978) quote a figure of 47 % (on an annual basis) for a basin covered with Rain forest in Queensland. It should be noted, however, that the latter estimate pertains to a special situation where rainfall intensities and subsoil intake capacities are such that SOF is a widespread phenomenon. The very steep nature and the deep soils of the present catchment prevent this phenomenon to become very extended (*cf.* Fig. 3.7). The definition of quickflow in the present study may be another explanation for the apparently low contribution of stormflows to total flow. However, if quickflow separations would have been made according to the dotted lines in Fig. 3.9 (connecting a third "knickpoint" and the start of the hydrograph ax) relative values would normally still be below 10 %.

Runoff sources : a hydrological approach

The cathment's storm hydrographs are typically single-peaked, unless they reflect more complex patterns of rainfall intensity (Fig. 3.9). Despite the presence of a deep and well-draining ash cover no secondary peaks have been observed, although major storms produce an increase in baseflow (Fig. 3.9).

Such secondary peaks have been described a.o. by HEWLETT & NUTTER (1970) for a Kenyan basin underlain by similar deposits (Fig. 3.8) and by WEYMAN (1974) and ANDERSON & BURT (1977A) for grass-covered hillsides on sandstones in the UK (Fig. 3.11, curve B).

Rather the storm hydrographs of the Mondo river basin resemble those produced by the concave head-water area of Weyman's basin (Fig. 3.11; curve A), which are known to result from a combination of HOF, SOF and occasionally pipeflow/SSSF. All these runoff types have been observed in the present case as well. The relative importance of the various flow types will now be discussed by an analysis of the runoff events of Fig. 3.10 in terms of the concept of "minimum contributing area" (MCA) - (DICKINSON & WHITELEY, 1970).

These authors defined the MCA as the minimum area, which, contributing 100 % of the effective rainfall, would yield the measured direct runoff. In the present case it can be evaluated as

$$MCA = \frac{0.1\ Q_q}{P} \qquad (3.6)$$

Table 3.4 Monthly amounts of quickflow (Q_q, mm and as % of total monthly runoff Q_t) in the Mondo catchment between 1 December, 1976 and 1 February, 1978. Figures for monthly precipitation (P) and total runoff (Q_t) have been added for comparison (mm) (see also Fig. 3.2).

	Dec.76	J	F	M	A	M	J	J	A	S	O	N	D	J 78	Total
P	539	460	444	463	705	146	456	13	2.5	9	39	304	536	551	4668
Q_t	454	365	416	354	698	183	323	109	27	10	4	10.5	92	413	3460
Q_q	35	23.5	20	19.5	37	6	22	0.3	-	-	0.5	7	24	26	221
$\frac{Q_q}{Q_t}x100$	7.7	6.4	4.8	5.5	5.3	3.2	6.9	0.2	-	-	16.3	91.0	26.1	6.4	6.4

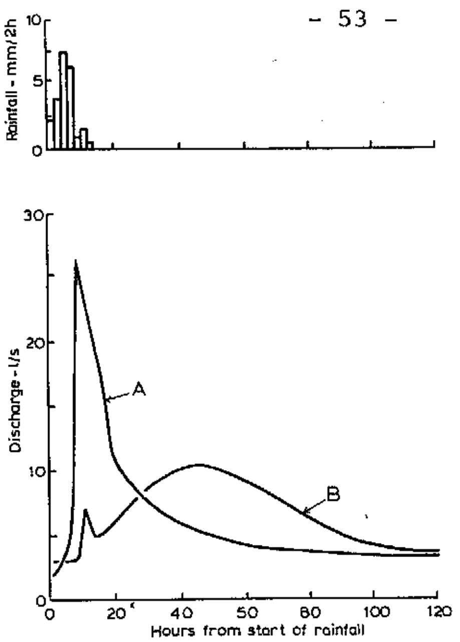


Fig. 3.11 Hydrographs from the East Twin catchment, U.K. (after WEYMAN, 1974)

where MCA = minimum contributing area (ha)
Q_q = quickflow volume (m^3)
and P = *gross* rainfall (mm)

Gross instead of net rainfall had to be used in the present case as figures for the canopy saturation value of the vegetation (LEYTON *et al.*, 1967) were not available. This will result in slightly lower values for the estimated MCAs, especially for low rainfalls.

As the term already suggests MCA is an underestimate of the real area that produces a certain volume of quickflow. One of the reasons is that part of the rainfall is "lost" in building up the moisture status of the soil thereby raising the unsaturated hydraulic conductivity (k_h) to such an extent that the soil can transmit the water at the rates applied (RUBIN, 1966). Another limitation of the concept is that it is two-dimensional whereas reality is of a three-dimensional nature. It can nevertheless be a useful tool in describing contributing areas.

The MCA's corresponding with the storm events of Fig. 3.10 are given in Fig. 3.12. It is seen that all of them exceed the minimum value of 0.22 ha, whereas MCA's of 0.90 ha (5 % of the total catchment area or more are only rarely attained. How do these total values of contributing area relate to the three types of storm runoff that were distinguished, viz.

1) SOF, 2) HOF and 3) SSSF ? The answer is found in Fig. 3.13 and discussed in the following.

Ad 1) Permanently wet zones are found along the principal drainage lines of the catchment, making up *c.* 0.09 ha. The channel area itself varies between 0.145 and 0.155 ha. Together this means a basic contributing area of 0.24 ha (1.3 % of the total catchment area), which agrees well with the minimum value of 0.22 ha in Fig. 3.12. This difference reflects the influence

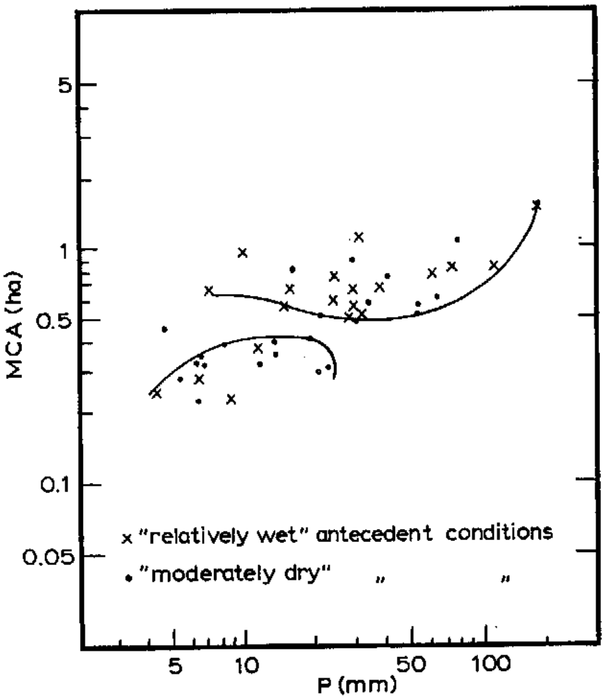


Fig. 3.12 Minimum contributing area vs. precipitation for the Kali Mondo basin (wet season values)

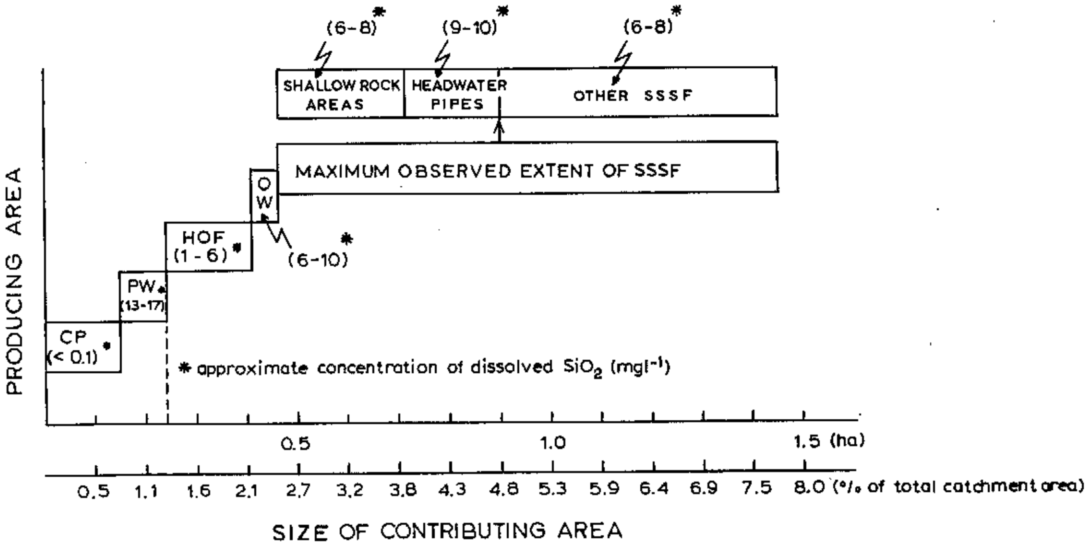


Fig. 3.13 Contributing area and runoff type (wet season situation)

of the use of P_{gross} in equation 3.6, since application of a canopy saturation value of 1 mm already resulted in minima of 0.25 ha in Fig. 3.12. Apart from SOF this area is also producing TF via a "push-through" mechanism (HORTON & HAWKINS, 1965).

Ad 2) *HOF* occurs on compacted trails and the yard of the Forestry station (Fig. 3.1), but was never observed on the forest floor. Even rainfall intensities as high as 200 $mmhr^{-1}$ (recorded on 25 November, 1975) were not sufficient to produce this type of overland flow in the forest. Trails and yards in the catchment occupy *c*. 0.165 ha (0.88 % of the catchment area).

Ad 3) Thus far the various flow categories could be linked to a certain areal extension by means of field-mapping. This approach is not directly possible in the ease of the third compact : *SSSF*. However, certain inferences are possible from Fig. 3.12 and field observations. Although perhaps a corollary of the limited size of the sample population Fig. 3.12 suggests a low frequency of MCA values between 0.4 and 0.5 ha. It may be argued that the former figure corresponds to the sum of the areas producing HOF and SOF as well as some TF (from the PW and OW areas) (Fig. 3.13) and that an MCA of 0.5 ha represents a threshold value for a significant occurrence of SSSF (*cf*. the critial moisture status of the catchment required for the overflow of the headwater area; section 3.4.1). The maximum MCA (1.45 ha or 7.7 % of the total catchment area) was observed on 2 April, 1977 when 169 mm of rain were recorded in about three hours. This would require an additional - *i.e.* on top of the basal 0.41 ha- area of *c*. 1 ha (contributing in the sense of eq. 3.6). Measurements of the vertical hydraulic conductivity (k_s) of the steeply sloping topsoils - as obtained with the cylinder infiltrometer technique (HILLS, 1970) - ranged from 630 to 1280 mm hr^{-1} with an arithmetic mean of 955 mm hr^{-1} (n=30). Applying the latter figure to a time base of four hours and a stream length of 1206 m one arrives at a contributing zone of 0.92 ha, which is in fair accordance (considering the large variability in values for k_s) with the 1.04 ha required for this particular storm.

In reality this contributing "zone" will not be evenly distributed along the stream, but will rather consist of mutually isolated saturated patches. The areal extent of these will be determined by the spatial (and vertical !) distribution of k_s (HARR, 1977; BONELL *et al.*, 1981) and local topography (ANDERSON & BURT, 1978). We will now try to locate this SSSF-producing "hectare" in the Mondo river basin. Attention will be focussed on areas with impeding layers close to the surface, major concavities and the lowermost parts of the hillslopes.

Areas where the underlying rock lies close (< 50 cm) to the surface are found at several points in the catchment (Fig. 3.1). The associated inflow lengths, however, are such that a contributing area of 0.25 ha at most can be assigned. This has been termed *"shallow rock area"* in Fig. 3.13.

In some *concavities* a perched water table may develop under wet conditions (*cf.* sections 3.2 and 3.4.1) discharging through pipes and cracks. At times peakflows of 22 l sec^{-1} were seen to persist for hours at the outlet point of the major concavity in the catchment (Weir 1; see Fig. 3.1). Comparing these rates to rainfall inputs yields a "sub-MCA" of 0.20 ha, termed *"head-water pipes"* in Fig. 3.13.

Another source of SSSF already mentioned in the foregoing will be *the lowermost parts of the slopes* where high moisture levels prevail and response to rainfall will be quickest. Since the catchment is steep and the stream deeply incised there is comparatively little opportunity for widespread extension of the saturated lenses in the valley bottom. Some 0.06 ha occasionally becomes saturated throughout and may produce SOF but more frequently it will provide TF. This area (derived from field mapping) has been called *occasionally wet - O.W.* - in Fig. 3.13. With respect to the rest of the riparian zone does the limited information available on "riparian k_s" suggest that the average of 760 ± 640 mm hr^{-1} (surface entry values, n = 10) is sufficient to account for the remaining 0.55 ha of SSSF-producing land* (*"other SSSF"* in Fig. 3.13). Data of subsoil permeability are restricted to one mid-slope location. There a value of 225 mm hr^{-1} was measured at a depth of 200 cm (mottled zone discussed in section 3.4.1) before dropping to 35-50 mm hr^{-1} in the underlying clays. Lateral flow is certainly induced along this lithological break (*cf.* Fig. 3.6 and Table 3.3), but the portion that reaches the stream as SSSF will depend on the depth of the impeding clays closer to the stream. Augerings were unsuccessful in this respect because of the presence of large rock boulders in the subsoil of the riparian zone (BRUIJNZEEL, 1976).

Thus far the various contributions to the storm hydrograph have been considered on a lumped basis. A description of their behaviour *during a storm* becomes possible to some extent by the inclusion of hydrochemical information (PINDER & JONES, 1969).

Runoff sources : a hydrochemical approach

General considerations

The principle underlying the separation of a runoff wave into a number of chemically contrasting components (1, 2, 3, ... n) by means of waterquality parameters can be stated in the form of a mass-balance equation (GREGORY & WALLING, 1974), *i.e.*

$$Q_tC_t = Q_1C_1 + Q_2C_2 \cdots + Q_nC_n \tag{3.7}$$

where Q_t = discharge of mixed water ("total runoff", l sec^{-1})

Q_n = discharge of a particular runoff component (l sec^{-1})

C_t = concentration of a selected chemical parameter in the mixed water (mg l^{-1})

---

*Calculated for a timebase of four hours and a stream length of 1000 m (total stream length minus stretches corresponding to the "shallow rock" and "headwater pipe" areas in Fig. 3.13).

C_n = concentration of a selected chemical parameter in a particular runoff component (mg l^{-1}).

The simplest case is that of a two-component system. Total runoff (Q_t) having a solute concentration C_t consists of baseflow, or "ground-water inflow" (Q_{bf} with solute concentration C_{bf}) and "quickflow" (Q_q with solute concentration C_q).

For this two-component system eq. 3.7 can be shown to have the following solution (PINDER & JONES, 1969) :

$$Q_{bf} = (\frac{C_t - C_q}{C_{bf} - C_q}) \cdot Q_t \qquad (3.8)$$

In case of a more complex system additional information on the discharge rates of the extra components is still needed.

Several investigators of runoff processes under humid temperate conditions applied equation 3.8 and found "groundwater inflow" to be an important contribution to peak flow rates (*e.g.* PINDER & JONES, 1969; NEWBURY *et al.*, 1969; FRITZ *et al.*, 1976). The mechanism at work was a rapid rise of the groundwater table in and around the valley bottoms during storms (*cf.* RAGAN, 1968).

Results

The question arises to what extent the complex patterns of stormflow generation prevailing in the Kali Mondo catchment (*i.e.* a mixture of CP, SOF, HOF and various sorts of SSSF) can be approximated by the two-component model of equation 3.8. Direct data on the discharge patterns of the various runoff components during a storm are not available, but their approximate chemical composition is known. The silica content of each flow type exhibits a characteristic value : rainfall contains virtually no silica (< 0.1 mg l^{-1}), concentrations in wet-season baseflow typically range between 13 and 17 mg l^{-1}, whereas HOF (1-6 mg l^{-1}), soil water (6-8 mg l^{-1}) and pipeflow in the headwater area (9-10 mg l^{-1}) show intermediate values. To overcome the lack of information on intra-storm behaviour of the various components a weighted mean silica concentration was assigned to the bulk quickflow (C_q), based on the approximate relative importance of each type in terms of contributing area (*cf.* Fig. 3.13) for each storm.

Information on the silica content of the streamwater during storms (C_t) was obtained by sampling. Nine runoff waves were sampled in detail during the wet seasons of 1975 and 1977 : five at the basin outlet (Weir 4) and four at Weir 3 (see Fig. 3.1 for locations). The former include HOF, the latter do not, since the second sampling site (W3) is located upstream of the HOF-producing zone (Fig. 3.1). Some examples of the variations in silica concentrations in the stream water during storms are given in Figs. 3.14-18a.

The strongest dilution of basal flow is observed on the rising limb of the hydrographs with a much slower return on the recession limb to pre-storm silica levels. The lowest silica concentrations may coincide with peak discharge (Figs. 3.14 & 3.17), but minima are observed both before (*e.g.* Fig. 3.16) and after the main peak (*e.g.* Figs. 3.15 & 3.18) as well. One storm produced a double-peaked runoff event (Figs. 3.15 & 3.18), the second of which was subjected to

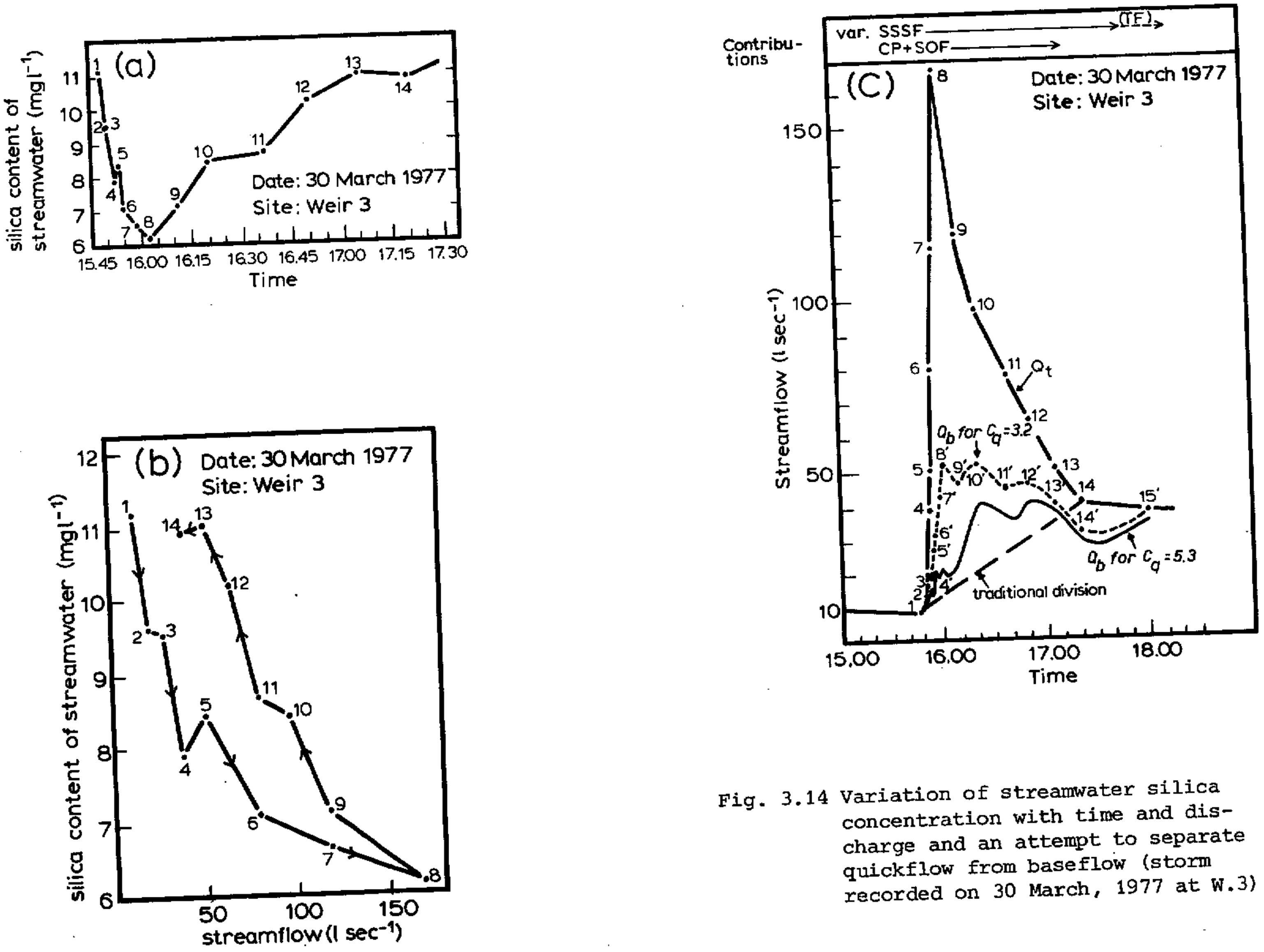


Fig. 3.14 Variation of streamwater silica concentration with time and discharge and an attempt to separate quickflow from baseflow (storm recorded on 30 March, 1977 at W.3)

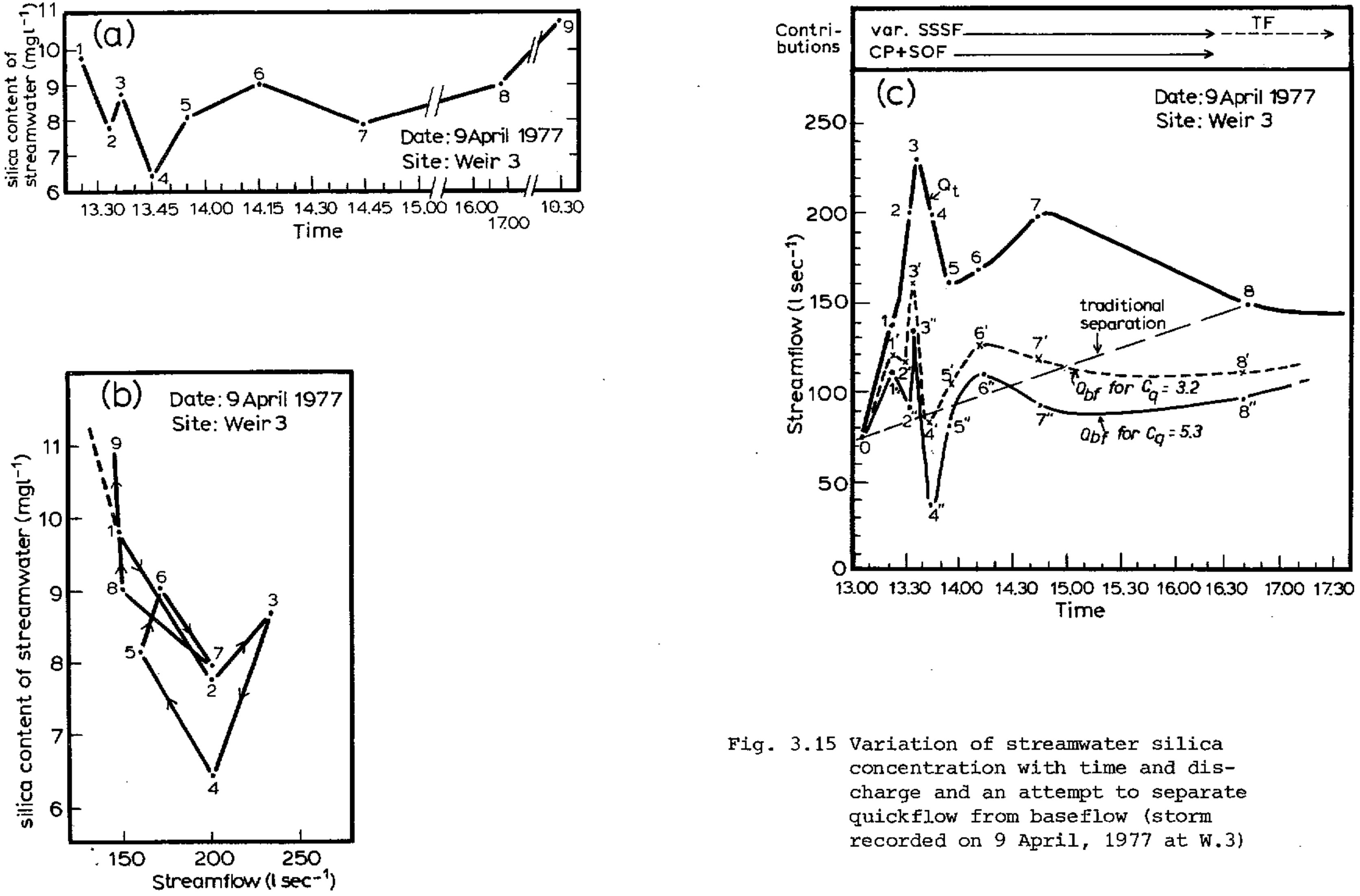


Fig. 3.15 Variation of streamwater silica concentration with time and discharge and an attempt to separate quickflow from baseflow (storm recorded on 9 April, 1977 at W.3)

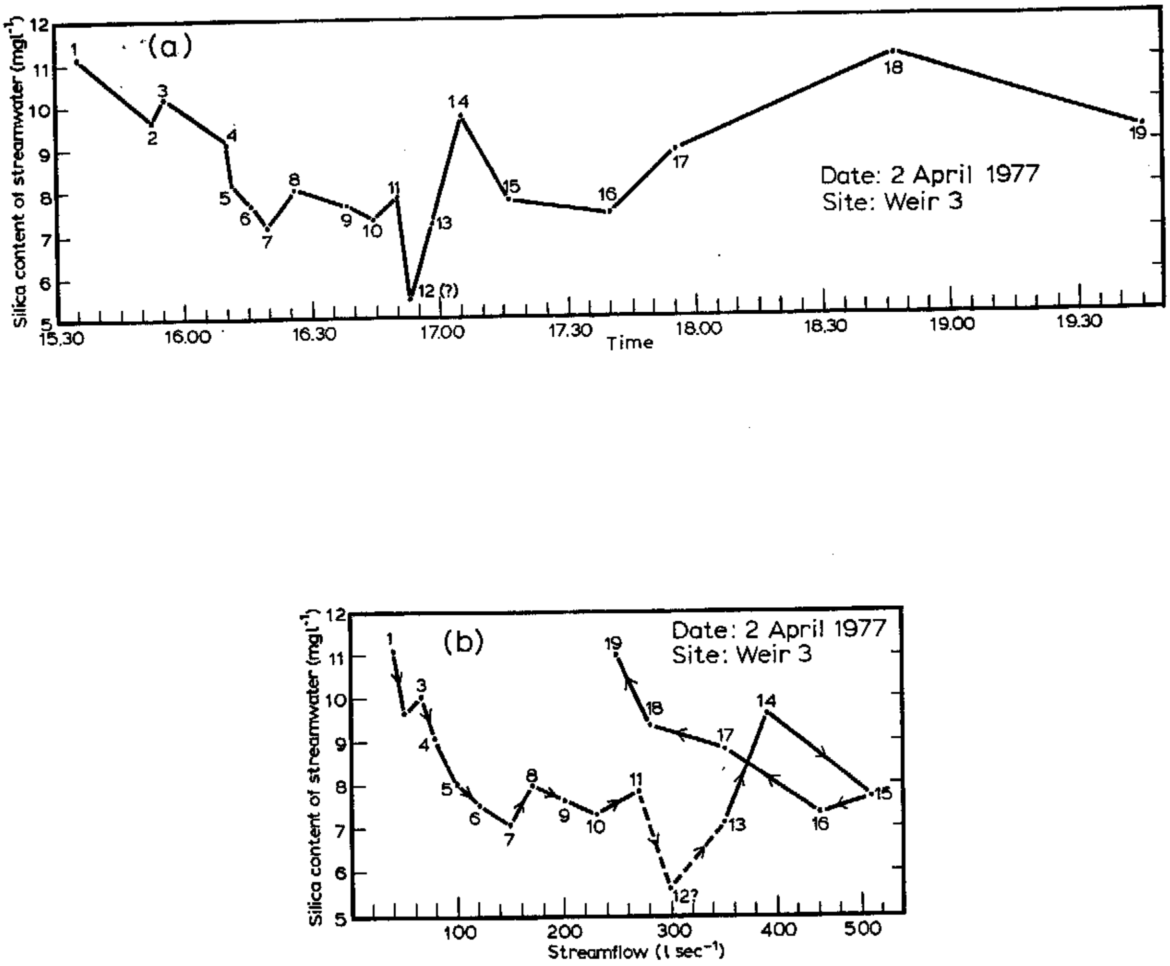
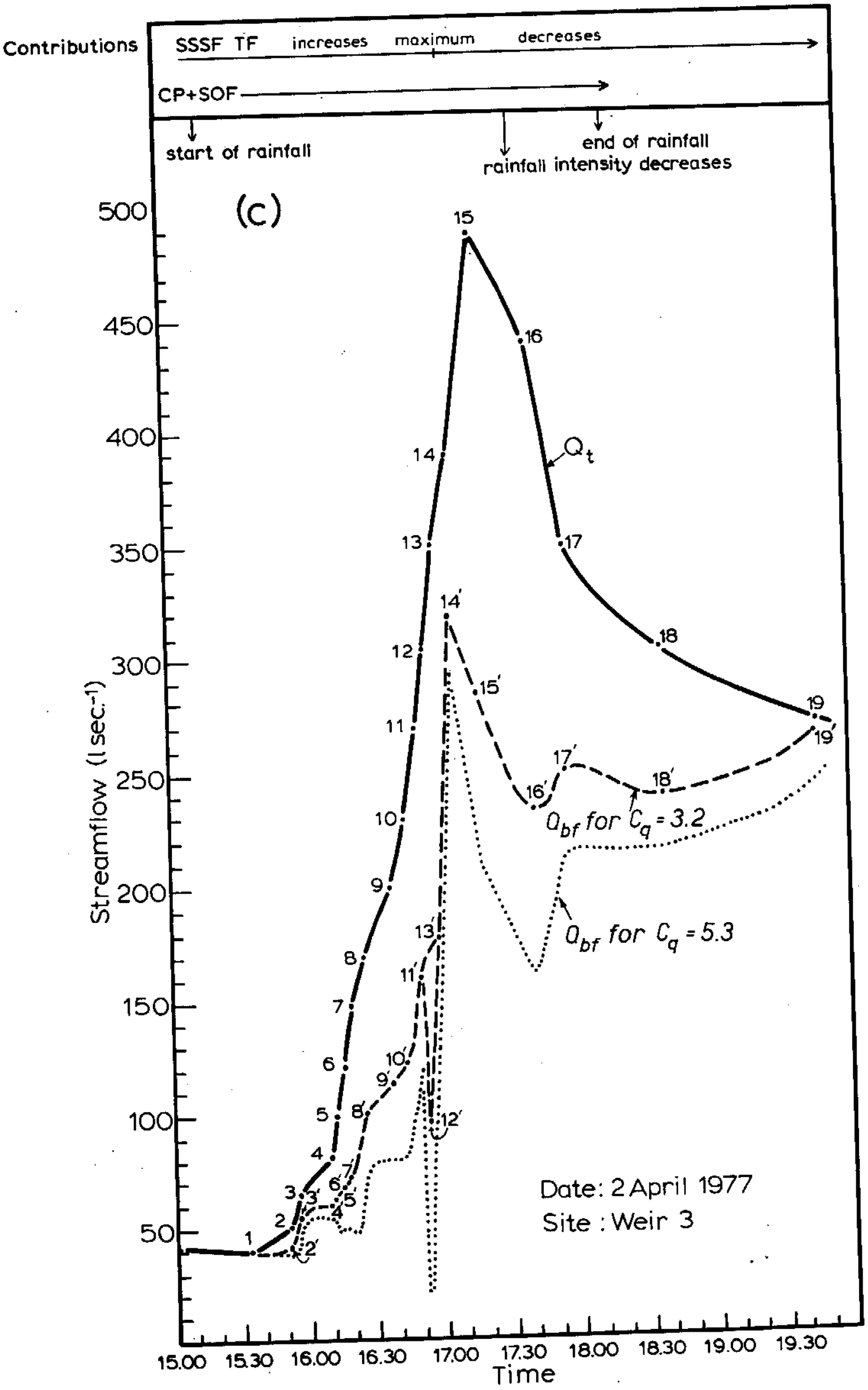
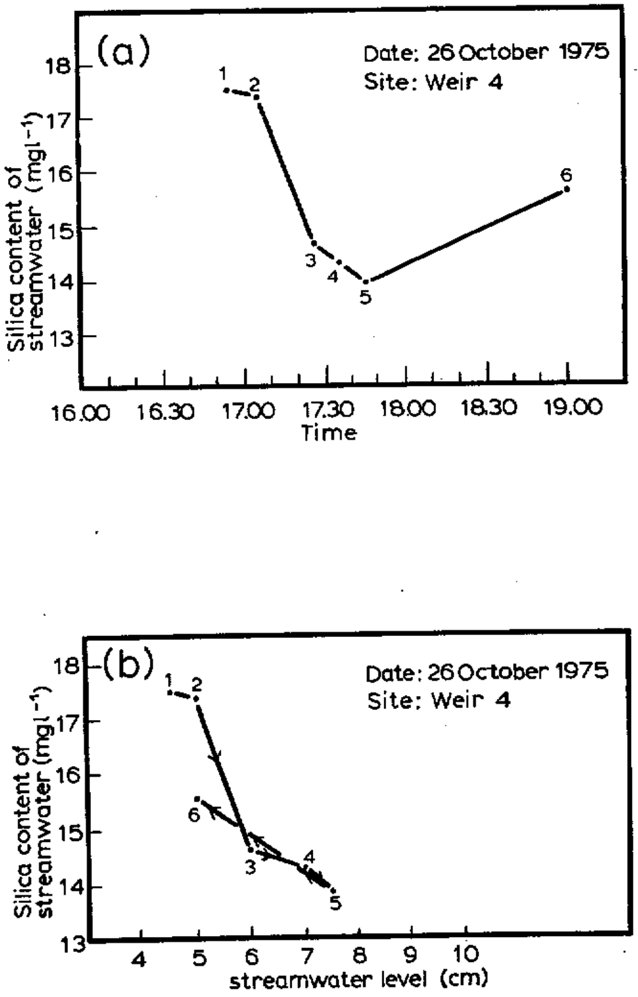


Fig. 3.16 Variation of streamwater silica concentration with time and discharge and an attempt to separate quickflow from baseflow (storm recorded on 2 April, 1977 at W.3)


Contributions
SSSF TF increases maximum decreases
CP+SOF
start of rainfall
end of rainfall
rainfall intensity decreases
(c)
Streamflow (l sec⁻¹)
500
450
400
350
300
250
200
150
100
50
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
2′
3′
4
5′
6′
7′
8′
9′
10′
11′
12′
13′
14′
15′
16′
17′
18′
19′
Q_t
Q_bf for C_q = 3.2
Q_bf for C_q = 5.3
Date: 2 April 1977
Site : Weir 3
15.00
15.30
16.00
16.30
17.00
17.30
18.00
18.30
19.00
19.30
Time



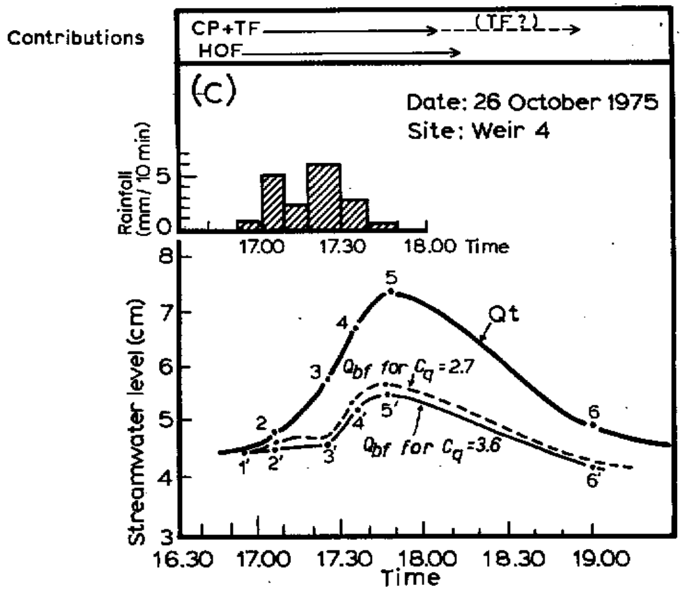


Fig. 3.17 Variation of streamwater silica concentration with time and discharge and an attempt to separate quickflow from baseflow (storm recorded on 26 October, 1975 at W.4)

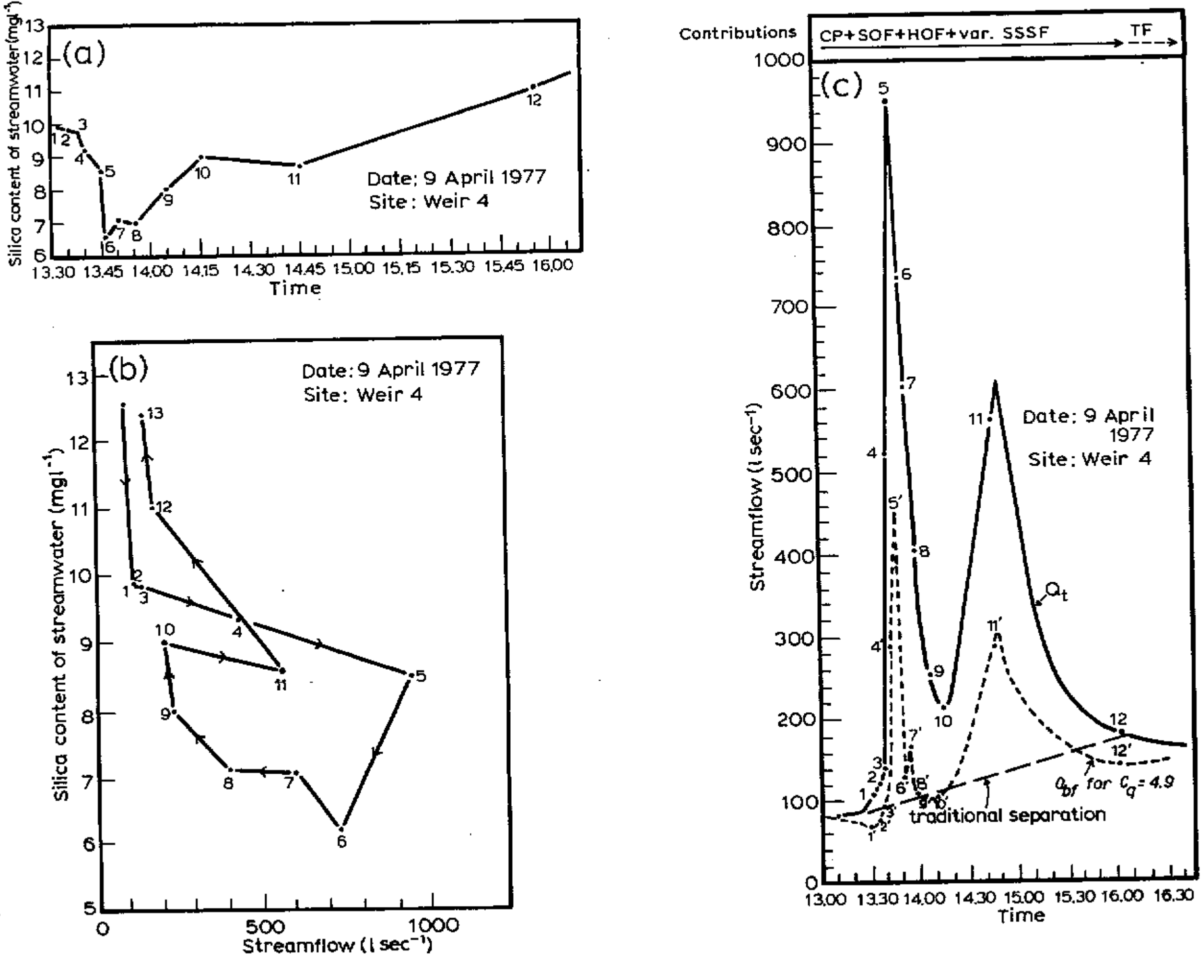


Fig. 3.18 Variation of streamwater silica concentration with time and discharge and an attempt to separate quickflow from baseflow (storm recorded on 9 April, 1977 at W.4)

a much weaker dilution than the first.

Naturally these patterns reflect the relative magnitude and timing of the various contributions. Very strong dilution must indicate the contributions of direct precipitation and HOF, whereas the apparent "stabilization" of silica levels on the recession limb of many a storm hydrograph (*e.g.* Figs. 3.15, 3.16 & 3.18) must represent a dominance of inflows with intermediate concentrations (*i.e.* all sorts of "soil water" or SSSF). Often "saw tooth" configurations occur on the rising limb (*e.g.* Figs. 3.14, 3.15 & 3.16) which sometimes can be traced back to variations in rainfall intensity (*i.e.* degree of dilution with water poor in silica). It should be borne in mind, however, that many of these fluctuations are within the precision limits of the analytical methods and therefore not "significant".

The contrasting behaviour of silica levels on the rising and falling limbs comes out clearly when concentrations are plotted against discharge. These "chemographs" often exhibit hysteretic loops that may be clockwise or anticlockwise (GREGORY & WALLING, 1974) and the present data are no exception to this (Figs. 3.14-18b).

An anticlockwise loop (*i.e.* higher concentrations on the falling limb) is usually observed at Weir 3 (upstream weir, see Fig. 3.1) for single-peaked storms (Figs. 3.14b; 3.16b). Double-peaked events display a more complex pattern (Fig. 3.15b). Since this gauging site is situated upstream of the HOF-producing zone these patterns should again be seen in terms of contributions of dilute water (direct precipitation) on the rising limb mainly and more concentrated "soil water" ("head-water pipes"; riparian water) on the falling limb mainly.

The "chemographs" for the downstream weir are generally somewhat irregular (Figs. 3.17b; 3.18b) but more clockwise than anticlockwise (BRUIJNZEEL, 1976). The influence of HOF now becomes manifest. It slows down the rate of dilution by rainfall on the rising stage, whereas it helps to dilute the relatively concentrated inputs occurring during the falling stage. Small storms producing only limited amounts of HOF and subsurface flows do not show much hysteresis in the loops (Fig. 3.17c) as could be expected.

An attempt at separating quickflows from "baseflows" was made by means of equation 3.8. In all cases (Figs. 3.14-18c) the mixing model indicates a rapid contribution to quickflow of water having pre-storm silica concentrations. In addition contributions follow the trends of total flow almost immediately. These patters are not contradictory to the above statement that "soil water" contributions mainly occur during the later parts of the storm hydrograph. It now appears that this type of flow happens during the whole event, becoming *dominant* in the later stages. The mechanism at work is suggested to be "displacement flow" (HORTON & HAWKINS, 1965) or "translatory flow" (HEWLETT & HIBBERT, 1967; *cf.* Table 3.3), as well as pipeflow. This would account both for the rapid reaction (wet soils !) and adequate silica levels.

A more complete description would require more detailed information on qualitative variations in the sources providing the direct runoff.

The data presented pertain to wet-season conditions (*i.e.* from November until March). Relative contributions to stormflow are likely to change during the transition periods, but data in this respect are lacking.

The following figure is an attempt to summarize the findings of the present study (Fig. 3.19). The temporal variations in the various contributions to storm runoff are given for a single-peaked event produced by a typical wet season rainstorm of *c.* 50 mm falling in one hour.

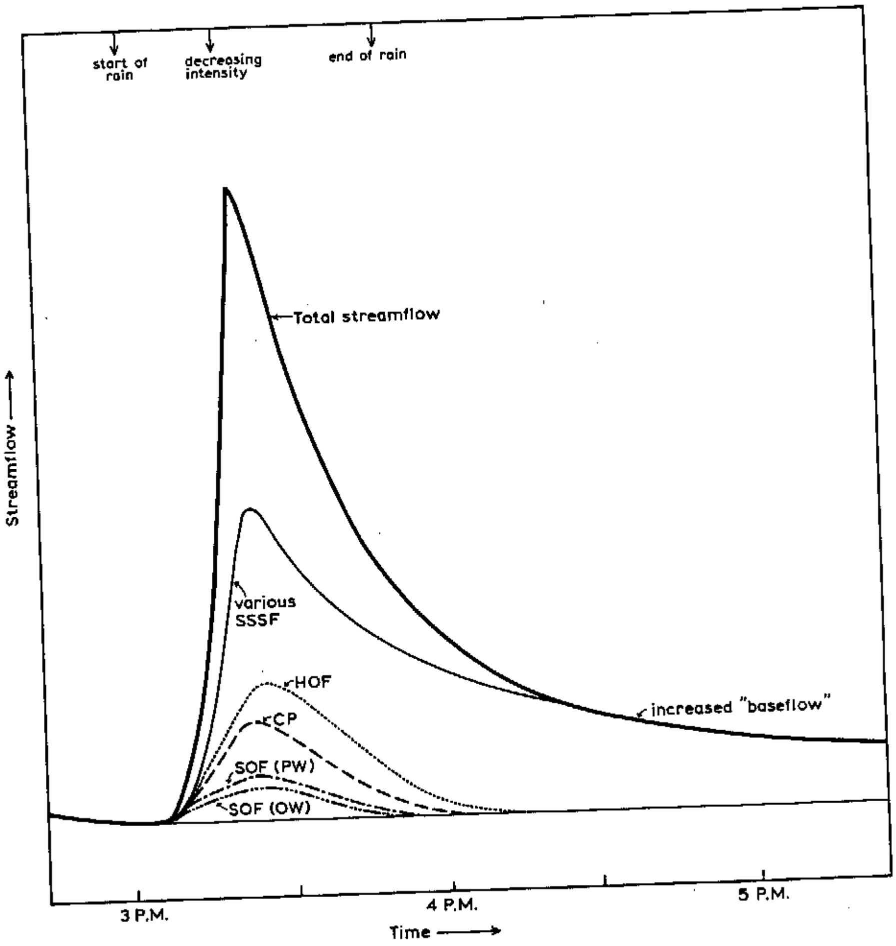


Fig. 3.19 Idealized diagram indicating timing and relative magnitude of runoff components for the "typical" wet season storm event

CP = Channel precipitation
HOF = Horton overland flow
SOF = Saturation overland flow < PW permanently wet zone
OW occasionally wet zone
SSSF = Subsurface stormflow

Subsurface stormflow makes up about 50 % of the total stormflow in Figure 3.19. This value may rise to *c.* 70 % under extreme conditions (*cf.* Fig. 3.16). Although the absolute magnitude of HOF, CP etc. increases with higher rainfalls, their relative contributions become smaller (*c.* 30 % in the extreme case of 170 mm of rain associated with Fig. 3.16).

4. DISSOLVED AND PARTICULATE MATTER BUDGETS

4.1 Introduction

Naturally a proper understanding and quantification of the hydrological cycle is a prerequisite for establishing the chemical flux through an ecosystem. Using the data on the water budget presented in the foregoing chapter it is now possible to evaluate the dissolved- and particulate matter budgets for the Kali Mondo drainage basin. When considering the flow of water and nutrients across the boundaries of an ecosystem it may be helpful to distinguish between meteorological, geological and biological carriers or "vehicles" (LIKENS *et al.*, 1977). Meteorological carriers include wet and dry deposition *i.e.* the input into the system of dissolved substances in precipitation and particulate matter (aerosols). Materials can also be blown out of the system (leaves, dust). Examples of geological "vehicles" are streams and subterranean movements of water (either into or out of the ecosystem), whereas biological flux mainly occurs through animals moving across the boundaries. In the case of a watertight catchment that is part of a larger and more or less homogeneous biotic unit the net biological flux tends to become zero, while inputs and outputs occur via meteorological (wet and dry deposition) and geological (streamflow) carriers respectively (BORMANN & LIKENS, 1967). Quantitative budgets for elements without a gaseous phase can thus be obtained by combining data on the amounts of precipitation and streamflow with the determination of their chemical composition. Because of the strong dependence of the chemical flux on the amount of rainfall (and therefore streamflow) it is of great importance that the observation period be characterized by a more or less "normal" precipitation regime. The year in which most of the present investigation took place - 1977 - experienced an extremely long dry season (see section 3.3.3). Therefore, the observation period was extended to a slightly longer period of fourteen months, viz. from 1 December, 1976 until 1 February, 1978.

In the following attention will be given to the flux of chemical elements through the catchment (section 4.2) and the export of particulate matter via the stream (section 4.3). The hydrochemical flux will only represent the ongoing rate of chemical denudation when the vegetation is in a steady state with respect to its uptake and return of nutrients (LIKENS *et al.*, 1977). Obviously the rapidly growing plantations in the catchment act as a sink of nutrients which renders the hydrochemical flux an underestimate of the chemical denudation rate. The apparent rate of total (chemical + mechanical) denudation will be dealt with in section 4.4, whereas the nutrient dynamics of the vegetation will be the subject of chapter 5. The implications of these for the estimation of the true weathering rate can be found in section 5.8.

4.2 The hydrochemical flux

4.2.1 *Introduction*

The elemental budget is of importance to both the earth scientist interested in an estimate of ongoing chemical denudation and the ecologist concerned with the overall functioning of ecosystems. The difference between the annual input and output of any given chemical parameter reveals whether there is a steady state (input equals output) or the presence of any accumulation *c.q.* net loss from the system for that parameter. As such it is a major tool in the comparison of the conservational efficiency of different ecosystems, whereas it also may provide the land-use planner with baseline data for evaluating the effects of human manipulations (*e.g.* LIKENS *et al.*, 1970).

4.2.2 *Sample collection and analytical methods*

Bulk precipitation (WHITEHEAD & FETH, 1964) was sampled on a weekly basis from a pluviograph, the siphon mechanism of which acted as a barrier against evaporation. Additional advantages of this apparatus were its height (preventing contamination from splash) and the sheltering of the collecting vessel against sunlight (preventing the growth of algae). Bulk-precipitation samples were also taken every other week from two containers (10 L) equipped with funnels of 20 cm diameter (all material polyethylene) that were placed close to each other at a slightly higher elevation than the pluviograph (see Fig. 3.1 for their locations). The plastic gauges had paper filters to hold back any coarse (organic) debris. These filters however appeared to give off Na and data presented for this element in the following derive from the pluviograph site only. Samples from the latter exhibited slightly higher concentrations for K, which may possibly be explained by the fact that the siphon system sometimes contained fine organic matter. Funnels and containers were rinsed with dilute chloric 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 that were exposed to the sun. This may constitute another explanation for the different K levels found in the two types of precipitation samples (*cf.* GALLOWAY & LIKENS, 1978). The mean of both estimates has been used.

Streamflow was sampled on a weekly basis as well. Numerous storm-runoff samples taken at the lower weir during five storms by immersing a 3-l can in the middle of the stream were stored until filtration the next morning.

All samples (both 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 filtre and the addition of 0.07 ml HNO_3 conc. plus two drops of CCl_4, for transport to the Netherlands.

Awaiting transport the samples were stored in the dark (20° C) for a period of one to three months, then flown to Amsterdam and stored again in the dark at 8° C until analysis. Ca, Mg, Na, Si, Fe, Al and Mn were determined by emission spectrometry. Storm runoff samples were analyzed separately using flame photometry (Na, K) and colorimetry (Ca, Mg, Si) according to the methods described by PEASLEY (1964), VAN SCHOUWENBURG (1965) and JACKSON (1958) respectively.

4.2.3 *Chemical composition of precipitation*

The weighted mean monthly composition of the bulk precipitation received at Watubelah during the period of study is presented in Table 4.1. The concentrations of Ca, Na and K generally do not

Table 4.1 Weighted mean chemical composition of bulk precipitation received at Watubelah between 1 December, 1976 and 1 February, 1978 (mg l^{-1})

	Ca	Mg	Na	K	SiO_2	Al	pH	amount of rain (mm)
December 1976	0.17	0.09	0.14	0.18	< (0.18)°	< (0.010)°	6.6	539.2
January 1977	0.15	0.06	0.14	0.18	< 0.20	< 0.009	7.0	460.3
February	0.08	0.05	0.17	0.16	< 0.15	< 0.012	6.7	444.1
March	0.12	0.06	0.12	0.14	< 0.19	< 0.019	6.7	463.2
April	0.14	0.08	0.15	0.16	< 0.38	< 0.026	6.7°	705.2
May	0.26	0.12	0.17	0.24	< 0.19	< 0.061	6.8	146.3
June	0.15	0.06	0.15	0.16	< 0.19	< 0.063	6.7	455.9
July	0.12	0.05	0.10	(0.18)°	< 0.44	< 0.50		
August	5.0	1.64	10.9	4.7	< 0.70		5.2	2.5
September								8.8
October								38.7
November	0.14	0.07	(0.25)°	0.16		< 0.042	6.0	303.6
December	0.19	0.06	0.19	0.12	< (0.20)°	< 0.025	6.3	535.9
January 1978	0.24	0.06	0.25	0.11		< 0.038	6.5	551.3
overall weighted means	0.21	0.09	0.28	0.20	< 0.23	< 0.034	6.4	4.668

differ much, but Mg levels are lower throughout. With such low concentrations it is difficult to say anything meaningful about the observed variations. The slightest contaminations - both in the field and in the laboratory - will immediately influence the overall composition significantly.

As to the origin of the various constituents in the bulk precipitation it seems that terrestrial rather than maritime influences are predominant in the present case. By comparing the precipitation composition with that of seawater the so-called "excess amounts" of the constituents can be computed (ERIKSSON, 1960). An excess for a particular element is the sample concentration found after subtracting the concentration of that element in seawater diluted to the chloride level (Cl^-) present in the sample. Such excesses are usually due to gaseous losses of Cl or to enrichment of the precipitation with material derived from terrestrial sources, such as dust, volcanoes and human activities. Unfortunately no reliable estimates of the Cl concentration of either rainfall or stream water could be obtained in the present case. Results obtained by titration indicated an average value of 4.6 ± 1.6 mg l^{-1}, which is far in excess of what is to be expected from the Na- and Mg concentrations. However, even when this high Cl concentration would be applied both Ca and K would still show excess values in the sense of ERIKSSON (1960), and must therefore be supplied by non-maritime sources mainly. During the rainy season the monsoon winds are coming from the north-west and have to cross the northern Serayu mountain range, one of the wettest parts of Java (*cf.* Fig. 2.3), before arriving at the study site. It is quite likely, therefore, that most of the seaspray will be washed out of the atmosphere in North Java already.

The situation is different in the dry season (July-September), when winds are coming from the southeast and the catchment is fully exposed to maritime influences. Concentrations of up to 70 mg l^{-1} of Cl were recorded for the plastic totalisators during the severe dry season of 1977. The excess values of Ca and K increased somewhat (from 40 to 50 %), but Mg and Na values still lagged behind considerably (230 and 350 % resp.) despite a clear increase in oceanic contributions. The latter is also reflected in the cationic sequences (equivalent basis) for the precipitation received in both seasons :

wet-season sequence : Ca > Na > Mg > K
dry-season sequence : Na > Ca > Mg > K

The relatively high Al concentration in the dry-season rainfall, however, points to a strong terrestrial component as well (splash effects being absent) and it can be concluded that precipitation chemistry for the study site is mainly governed by terrestrial influences except perhaps in the case of Na. In order to further investigate the various sources of the chemicals present in the bulk precipitation a correlation matrix was computed for the monthly data (Table 4.2)

Sodium exhibits poor correlations with the other elements, whereas Ca, Mg and K correlate fairly well with each other. All this suggests the latter three elements to have a common source with Na deriving from somewhere else. Silica, usually taken as an indicator of non-biological terrestral influence (dust) is not correlated with either Na or the other ions. Therefore - assuming Na is mainly

Table 4.2 Cross-correlation matrix (r^2) for the monthly bulk precipitation quality data at Watubelah during the wet season

	Ca	Na	Mg	K	SiO_2	Al	H
Ca	1.0	0.18	0.68**	0.72**	(0.03)	(0.13)	0.00
Na		1.0	0.07	0.01	(0.30)	(0.02)	0.30
Mg			1.0	0.48*	(0.04)	(0.05)	0.00
K				1.0	(0.00)	(0.15)	0.09
SiO_2					1.0	(0.11)	(0.03)
Al						1.0	(0.02)
H							1.0

*significant at $\alpha < 0.05$
**significant at $\alpha < 0.01$

provided by the sea - their origin may well be biologic. Indeed it has been recently maintained (CROZAT, 1979) that the high amounts of K observed in the bulk precipitation over the Rain forest region of Ivory Coast probably are produced by these forests themselves.

As far as a seasonal trend in precipitation quality is concerned it is clear that solute levels peak during the dry season when dry deposition is at a maximum (*cf.* the relatively dry month of May). Yet "normal" levels are again observed soon after the return of the rains in November. January 1978 on the other hand saw a different chemical composition : concentrations of Na and Ca were above normal and of K below normal. One can merely guess as to what causes such variations, but it should be mentioned here that clearing operations involving the burning of shrubs and grasses occurred in the immediate vicinity of the Mondo river basin at the time. The associated smoke particles might account for the observed increases in concentrations, but leave the low K levels unexplained. A possible cause for this might be the consumption of K by microorganisms in the collecting vessel of the main sampling station as well. A more likely explanation (at least for Na and Ca) is the occurrence of pollution in the laboratory during the processing of the December/January, 1978 samples of precipitation and streamflow. Some evidence for this was found when samples were analyzed a second time.

To put the present data in a broader perspective comparable data for a few other stations are given in Table 4.3.

Cation concentrations for the three Austral-Asian sites are very similar, although Na is low in the Javan case (approaching in fact the American values whose element input is claimed to be mainly of terrestrial origin; HENDERSON *et al.*, 1978). TURVEY (1974) also reports a value of .31 mg l^{-1} for Na in the rainfall over Papua New Guinea but concentrations for the other cations were exceedingly low. Data from the Caribbean are suggestive of somewhat higher solute levels comparable to those observed at Plynlimon, Wales (although Ca at the latter site was derived from agricultural sources; CRYER, 1976).

Table 4.3 Quality of bulk precipitation at selected stations (mg l^{-1})

Location	Ca	Mg	Na	K	Observation period	Reference
tropical regions						
Malaysia (Pasoh)	0.2	0.05	1.1	0.4	1-12/73	MANOKARAN, 1978
Australia (Queensland)	0.1	0.1	0.8	0.2	4/75-4/78 ?	BRASELL & GILMOUR, 1980
Java, Indonesia	0.2	0.1	0.3	0.2	12/76-1/78	present study
Puerto Rico*	0.6	0.15	1.5	0.5	2/67-2/68	JORDAN *et al.*; 1972
Trinidad°	2.1	0.4	2.3	1.5	8/72-7/73	DALAL, 1979
Ivory Coast	< 1.0	-< 0.1	< 0.5	< 0.5	63-68	MATHIEU, 1972
temperate latitudes						
U.S.A. (Coweeta)*	0.2	0.05	0.2	0.1	6/69-5/76	HENDERSON *et al.*, 1978
U.S.A. (Oregon)	0.15	0.05	0.25	0.04	5/72-5/75	SOLLINS *et al.*, 1980
U.K. (Plynlimon)	1.4	0.35	2.2	0.1	9/71-6/73	CRYER, 1976

*Calculated from data on precipitation amounts and nutrient input expressed as kg $ha^{-1}yr^{-1}$
°Station no. 3

4.2.4 *Input of chemical elements via bulk precipitation*

The magnitude of element accession into the catchment is obtained by multiplying the weekly amounts of rainfall by the corresponding element concentrations and summing to monthly values. Table 4.4 gives the monthly inputs of Ca, Mg, Na, K, SiO_2 and Al (expressed as $kgha^{-1}$) for the period December, 1976 until 1 February, 1978.

A total of 36.8 kg ha^{-1} of cations was supplied by the atmosphere during the fourteen months of observation. A comparison with the literature will be made later on in this chapter (section 4.2.7). Here it is sufficient to say that the above-mentioned amounts are considerable.

For a limited number of samples determinations of the ortho-P (n = 14) and NO_3^- (n = 22) concentrations were carried out in the NUFFIC/UGM Laboratory in Yogyakarta, Indonesia (by complexation with molybdate and by coloration of salicylic acid in an acid environment respectively). Average values were 0.06 ± 0.04 mg l^{-1} (PO_4^{3-}) and 0.25 ± 0.17 mg l^{-1} (NO_3^-), equivalent to a total input of 0.9 kg ha^{-1} ortho-P and 2.6 kg ha^{-1} N-NO_3. Adding these to the cation-, dissolved SiO_2- and Al accessions (Table 4.4) one arrives at a total input of 52.4 kg ha^{-1}.

4.2.5 *Chemical composition of stream water*

The chemical composition of the water leaving the Mondo river basin as baseflow appeared to be remarkably constant before the dry season of 1977 grew severe (Table 4.5). Similar constancies of streamwater chemistry have also been observed for forested catchments in the humid temperate zone (*e.g.* LIKENS *et al.*, 1977; SOLLINS *et al.*, 1980) and illustrate the ability of (undisturbed) ecosystems to regulate their nutrient outputs within rather narrow limits.

Wet-season stream water is about 4.5 times as concentrated as bulk precipitation (on an equivalent basis). Evapotranspiration would only account for a 1.4-fold increase in concentrations and therefore other processes must also be responsible for this difference. Comparing the concentrations of Si (expressed as mg l^{-1} SiO_2) in rainfall and stream water (viz. < 0.23 and 15 mg l^{-1} respectively) it will be clear that chemical weathering of the volcanic deposits supplies the remainder of the solutes. Stream water composition is entirely dominated by dissolved silica.

During the (climatologically-speaking quite normal) first half of the investigation (up to and including July 1977) over 83 % of the dissolved load consisted of dissolved SiO_2 with Ca, Mg and Na contributing 4.3 ± 0.3 % each, followed by K with 3.4 %. No clear relationships between monthly runoff and solute *concentrations* exist during this period, again illustrating the ecosystem's buffering capacity. Only after six weeks of continued recession, concentrations started to rise in August (Table 4.5). Unfortunately the natural increase in concentrations was interrupted by washing activities of the local population by the end of September (the Kali Mondo constituted one of the few places that still supplied water during the later phases of the drought). Concentrations of dissolved SiO_2 continued to increase until the return of the rains by the end of November. These increases were within the limits of analytical accuracy, however. Therefore, although the catchment vege-

Table 4.4 Input of chemical elements into the Mondo river basin via bulk precipitation (kg ha^{-1}) between December, 1976 and February, 1978.

	Ca	Mg	Na	K	Si*	Al
December '76	0.9	0.5	0.75	1.0	< 1.0	< 0.05
January '76	0.7	0.3	0.65	0.9	< 0.9	< 0.04
February	0.4	0.2	0.75	0.7	< 0.65	< 0.05
March	0.55	0.3	0.55	0.65	< 0.9	< 0.09
April	1.0	0.55	1.05	1.15	< 2.7	< 0.18
May	0.4	0.2	0.25	0.35	< 0.3	< 0.09
June	0.7	0.3	0.7	0.7	< 0.85	< 0.29
July	0.02	0.01	0.01	0.02	< 0.06	< 0.25
August September October	2.5	0.8	5.4	2.35	< 0.5	< 0.25
November	0.4	0.2	0.75	0.5	< 0.6	< 0.13
December	1.0	0.3	1.0	0.65	< 1.1	< 0.13
January '78	1.3	0.35	1.4	0.6	< 1.1	< 0.21
Total	9.9	4.0	13.3	9.6	< 10.6	< 1.51

*expressed as SiO_2

Table 4.5 Weighted mean concentrations (mg 1^{-1}) in the baseflow of the Mondo catchment between 1 December, 1976 and 1 February, 1978. Figures between parentheses denote range in concentration.

	Ca	Mg	Na	K	SiO_2	Al	Fe	Mn	total runoff (mm)
December '76	0.72 (0.69-0.80)	0.75 (0.67-0.85)	0.82 (0.80-0.89)	0.70 (0.66-0.79)	15.2 (14.9-16.0)	< 0.21	< 0.19	< 0.024	454.5
January '77	0.69 (0.64-0.73)	0.84 (0.75-0.91)	0.85 (0.71-0.93)	0.61 (0.54-0.71)	15.2 (14.2-15.8)	< 0.28	< 0.21	< 0.028	364.6
February	0.70 (0.65-0.80)	0.78 (0.75-0.84)	0.73 (0.68-0.79)	0.56 (0.53-0.63)	14.3 (13.8-14.9)				415.7
March	0.76 (0.68-0.87)	0.90 (0.80-1.06)	0.77 (0.66-0.85)	0.64 (0.60-0.68)	16.8 (14.9-18.0)	0.74	0.44	< 0.040	354.0
April	0.78 (0.75-0.91)	0.87 (0.83-0.91)	0.65 (0.60-0.75)	0.55 (0.53-0.59)	15.75 (15.2-15.9)	0.94	0.84	< 0.063	698.5
May	0.98 (0.90-1.17)	0.91 (0.84-1.07)	0.78 (0.76-0.80)	0.57 (0.54-0.66)	15.9 (15.0-16.9)	< 0.22	< 0.20	< 0.037	183.5
June	0.80 (0.73-1.04)	0.82 (0.74-1.00)	0.75 (0.69-0.80)	0.67 (0.63-0.69)	14.9 (14.6-15.6)				323.1
July	0.89 (0.84-1.07)	0.87 (0.83-1.10)	0.79 (0.77-0.89)	0.60 (0.57-0.63)	15.0 (14.6-15.1)				109.4
August	1.27 (1.19-1.37)	1.14 (1.09-1.24)	0.90 (0.84-0.92)	0.70 (0.66-0.73)	15.55 (14.7-16.1)				27.3
September	1.83 (1.47-2.08)	1.59 (1.36-1.73)	1.10 (1.03-1.15)	0.81 (0.70-0.87)	15.2 (14.8-15.4)				9.7
October*	2.7	2.4	1.6	1.2	15.5 (15.0-16.0)				4.3
November*	3.6	3.2	2.2	1.6	15.7 (13.0-16.2)				10.4
December	1.6*	1.3 (1.16-2.53)	1.0*	1.0 (0.85-1.66)	15.3 (14.5-15.6)				91.8
January '78	0.7*	0.78 (0.72-0.84)	0.75*	0.54 (0.51-0.55)	14.6 (14.0-15.5)				413.3

*estimated value (see text for explanation) tation experienced considerable moisture stress in October and November (see section 3.3.3.4 on actual evapotranspiration) this did not produce significant changes in the dissolved SiO_2 levels in the streamwater.

The natural composition of the streamwater during these two months, therefore must remain something of a problem. However, the estimates of the concentrations of dissolved SiO_2 are reliable and fortunately constitute the bulk of the total solute load. This load cannot be very large anyway as the amounts of baseflow involved are very small, viz. 4.3 and 2.8 mm for October and November respectively. Absolute errors therefore will be very small indeed (*c.* 1 %).

FREDRIKSEN (1972) also reported concentrations of dissolved SiO_2 to remain virtually constant during a dry period of about four months in Oregon, U.S.A. His catchment appears to be very similar to the Mondo drainage basin, as it is underlain by andesitic volcanic tuffs and breccias. It is forested and experiences high annual rainfall amounts under a very seasonal regime. Concentrations of Ca in the Oregon streamwater on the other hand rose sharply during the recession period (from 3.5 to 8 mg l^{-1}). No details were giving on the behaviour of other cations. FOSTER & WALLING (1978) discussed the effects of the 1976 drought and the subsequent rainfall on the solute concentrations in a small stream in the southwestern UK. Their results indicate similar responses to drought as reported by FREDRIKSEN (1972). A concentration factor of 2 in the present case was therefore applied to the cation concentrations observed for September to estimate those for November. Intermediate values were assigned to the October runoff. Since a substantial flushing effect may be expected to have occurred in the last decade of November (FOSTER & WALLING, 1978, ANDERSON & BURT, 1978b) baseflow concentrations were assigned to the November storm runoff as well.

In December heavy rains continued to flush the salts that had accumulated in the soils during the dry season. One of the processes involved will have been the gradual incorporation of new solute source areas during the headwater extension of the stream network as discharges increased (ANDERSON & BURT, 1978b). Measurements of the electrical conductivity (E.C.) of the streamwater indicated values comparable to those observed in August and September (50-60 µmho cm^{-1}), in accordance with the concentrations for Mg and K, which are similar also (Table 4.5). Both these elements and E.C. had returned to "normal" wet season values by the beginning of January, 1978 (*e.g.* 30 µmho cm^{-1} for E.C.). Calcium and Na, however, remained high throughout the post-drought period. Since this behaviour is not supported by the field E.C. readings it is suspected that these samples also suffered from contamination in the laboratory (*cf.* section 4.2.3). Based on measurements of E.C. the concentrations for Ca and Na in December, 1977 and January, 1978 were assumed to be similar to the average values found for August and September and February respectively.

Concentrations of NO_3^- were below the detection limit during the rainy season of 1976/77, but increased slowly during the drought (up till about 0.5 mg l^{-1}). The highest concentrations were observed during the first week after the return of the rains (1.1 mg l^{-1} on 24 November). FOSTER & WALLING (1978) reported a similar but much more extreme tendency for N-NO_3 after a severe drought.

They ascribed the phenomenon to an increased rate of mineralization of organic nitrogen after wetting of the soil, with subsequent nitrification. Post-drought concentrations in the Mondo basin were somewhat irregular but clearly much higher than normal. No attempt was made to make an estimate of the $N\text{-}NO_3$ losses from the catchment.

Concentrations of Al, Fe and Mn were determined for the period December, 1976 until May, 1977 only.

With respect to *solute concentrations during stormflows* the data collected suggest Ca, Na, and especially SiO_2 to be strongly diluted with increasing discharge, whilst K shows a rather irregular behaviour. Concentrations of Mg seem to be hardly affected by changes in discharge. Similar behaviour for the last four constituents is reported also for temperate-latitude streams draining forested catchments (*e.g.* LIKENS *et al.*, 1977). The nature of the underlying rocks may modify such trends, however. In the case of Mg-rich rocks Mg is frequently reported to be strongly diluted during stormflows, both in the tropics (TURVEY, 1974) and under temperate conditions (CLEAVES *et al.*, 1974).

Data on the behaviour of Fe, Al and Mn during storms are almost entirely lacking in the literature. It has been suggested that Al (LIKENS *et al.*, 1977) and Fe (BRUIJNZEEL, 1976) become more concentrated during floods, whilst Mn did not show any definite trends during the initial phase of the present study (BRUIJNZEEL, 1976). Later results (baseflow samples only) indicate increased concentrations during high discharges (*cf.* Table 4.5).

4.2.6 *Output of solutes via streamflow*

The export of solutes from the drainage basin was calculated in much the same way as the elemental input. Weekly amounts of baseflow were multiplied by the average of the concentrations observed at the beginning and end of that particular week and summed to monthly values. The amounts transported in quickflows were computed as follows : a number of runoff waves were sampled in detail and the weighted mean concentrations for the various constituents (Ca, Mg, Na, K and dissolved SiO_2) computed. These were multiplied by the quickflow volume to give the load of solutes transported in that particular stormflow. The individual loads were highly correlated to the quickflow volumes themselves (power curves having r^2-values > 0.98) and these equations were applied to estimate solute export via stormflows per storm and (by summation) per month.

Table 4.6 gives the monthly amounts of solutes leaving the catchment in the total streamflow. A total of 624 kg ha^{-1} of SiO_2, Ca, Mg, Na and K was removed from the Mondo basin during the period of investigation. Exported amounts of Al, Fe and Mn could be computed with fair precision for the first half of the study period only. Concentrations for the remaining wet months (June, December, 1977; January, 1978) were assigned a mean "wet season value" equal to the average of those observed for December, 1976 until February, 1977. Similarly concentrations for the dry season were estimated via those observed for May, whilst November concentrations were given a higher value to account for flushing effects. In this way total outputs of Al, Fe and Mn of 15, 12 and 1.2 kg ha^{-1} respectively could be computed. No attempts were undertaken to estimate the loads transported in stormflows for these elements.

Adding the exports of ortho-P (0.7 kg ha^{-1}) and the above-mentioned values for Al, Fe and Mn to the 624 kg ha^{-1} already found, one arrives at a grand total solute output of 653 kg ha^{-1} (*cf.* input via bulk precipitation for these constituents, viz. 50 kg ha^{-1}).

Storm runoff supplied 2.2 % of the total dissolved silica load. The corresponding figure for Ca, Mg, Na and K amounts to 4.1 ± 0.3 %.

The monthly solute loads again relate very well to the monthly runoff, reflecting the dominance of runoff volume over streamwater chemistry (Fig. 4.1). These regressions can be used to estimate solute output from the catchment from streamflow data alone.

4.6 Output of solutes from the Mondo river basin (kg ha^{-1}) between December, 1976 and February, 1978.

	Ca	Mg	Na	K	SiO_2	Total runoff (mm)
mber '76	3.3	3.3	3.65	3.1	66.8	454.5
ary '77	2.55	3.0	3.05	2.2	53.7	364.6
uary	2.95	3.2	3.0	2.3	58.2	415.7
h	2.7	3.3	2.7	2.3	57.8	354.0
l	5.8	6.3	4.7	4.0	113.0	698.5
	1.8	1.7	1.4	1.05	28.7	183.5
	2.6	2.6	2.4	2.1	46.45	232.1
	1.0	0.95	0.85	0.7	16.5	109.4
st	0.3	0.3	0.25	0.2	4.2	27.3
ember	0.2	0.15	0.1	< 0.1	1.4	9.7
ber	0.5*	0.4*	0.3*	0.2*	0.6	4.3
mber					1.6	10.4
mber	1.3*	1.0	0.8*	0.8	11.65	91.8
ary '78	3.0*	3.2	3.1*	2.2	58.5	413.3
al	28.0	29.4	26.4	21.2	519.1	3460

imated values (see text for explanation

4.2.7 *The hydrochemical flux*

Subtraction of the solute outputs from the corresponding inputs gives the flux of chemical elements through the drainage basin. Table 4.7 presents the results for the total investigation period.

le 4.7 Solute budget for the Mondo river basin (kg ha^{-1}) between December, 1976 and February, 1978.

	Ca	Mg	Na	K	SiO_2	ortho-P*	Al*	Fe*	Mn*
ut (I)	9.9	4.0	13.3	9.6	<10.6	0.9	<1.5	N.D.	N.D.
put (O)	28.0	29.4	26.4	21.2	519.1	0.7	<15	<12.2	<1.2
loss or in	-18.1	-25.4	-13.1	-11.6	-508.5	+0.2	-13.5	-12	-1
00 (%)	35.4	13.6	50.4	45.3	<2.0	132	10	-	-

ly limited data available

: not determined

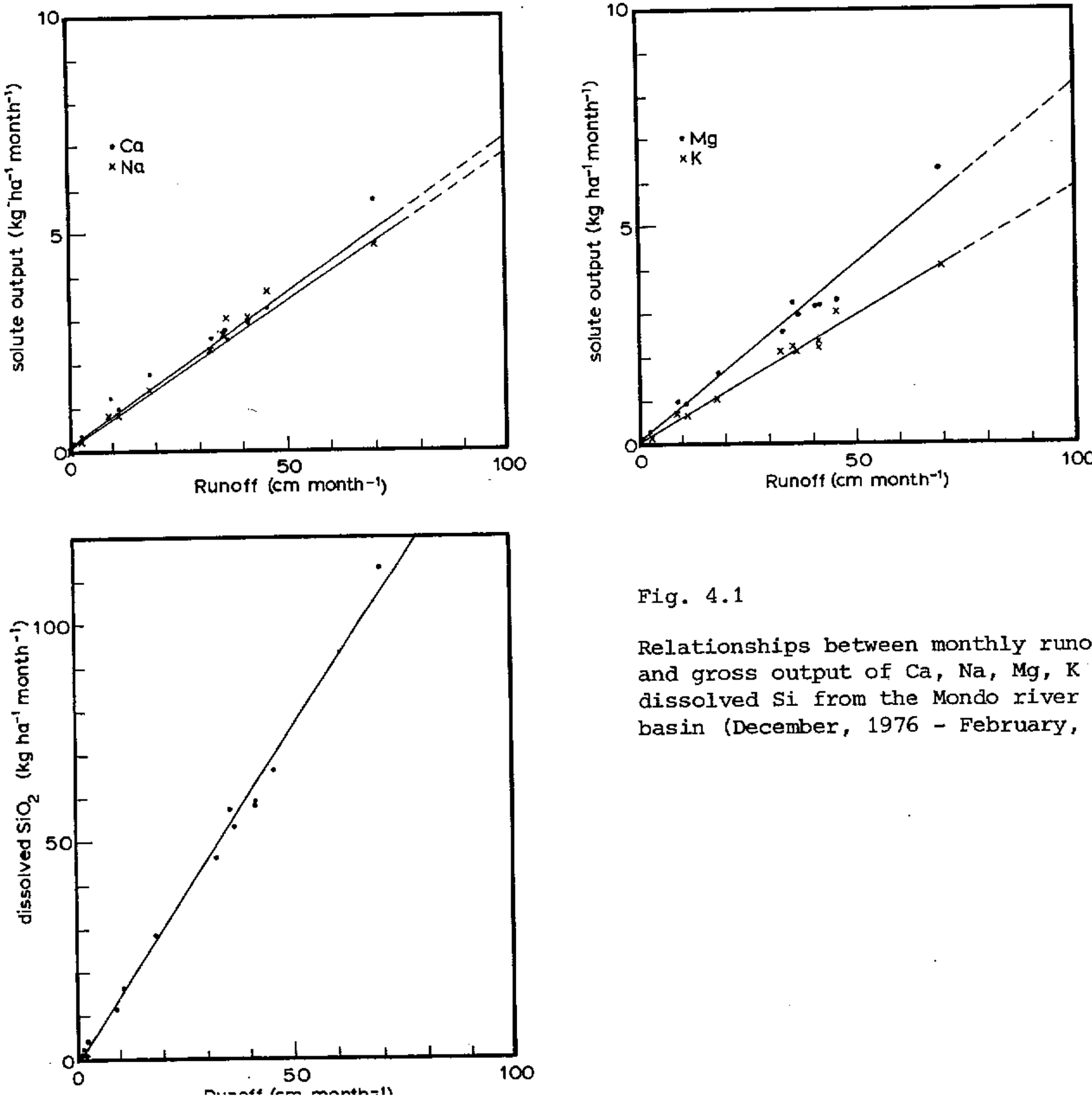


Fig. 4.1

Relationships between monthly runoff and gross output of Ca, Na, Mg, K and dissolved Si from the Mondo river basin (December, 1976 - February, 1978)

Solute outputs generally exceed solute inputs on a monthly basis except during the dry season (Tables 4.4 and 4.6). The only parameter which seems to accumulate in the catchment is ortho-P, but more data would be needed to substantiate this conclusion (see also section 5.8 on the implications of nutrient uptake by the vegetation).

Bulk precipitation appears to be an important contributor to the solute budget except for dissolved SiO_2 and perhaps Mg (Table 4.7) with relative contributions of 35 %, 45 % and 50 % provided in the case of Ca, Na and K respectively. Many other investigators come to the same conclusion, both for temperate-latitude ecosystems (*e.g.* CRYER, 1976; LIKENS *et al.*, 1977; HENDERSON *et al.*, 1978) and tropical regions (*e.g.* KENWORTHY, 1971; JORDAN *et al.*, 1972; MATHIEU, 1976).

The results obtained in the present study will now be compared with those of other forested basins (Table 4.8). To make such a comparison is far from easy. Numerous hydrological measurements and chemical determinations are needed for the computation of a catchment 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 normal during any year of investigation (LIKENS *et al.*, 1977). The latter remark is particularly relevant to the present study, which was conducted in a dry year. As related before, the investigation period was extended to fourteen months, receiving 4668 mm of rain, *i.e.* 100 mm less than the 50-yr average. If this amount would fall in one year the corresponding total runoff would be *c.* 3590 mm whilst 3460 mm were actually recorded. This difference in runoff corresponds to an "extra" export of 18.9 kg ha^{-1} of dissolved SiO_2 and 1.0 ± 0.1 kg ha^{-1} of Ca, Mg, Na and K, and these amounts have been added to the total values of Table 4.6 to obtain the figures for a "normal" year that are presented in Table 4.8. It should be noted that these are still minimum estimates due to the sink-effect of the vegetation in the catchment (see also section 5.8).

With respect to the 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 sometimes influence the results as well. For example, cation access rates reported by TURVEY (1974) for a Rain forest site in Papua New Guinea are noticeably low (except for Na) if one considers the corresponding amount of rainfall. BRASELL & GILMOUR (1980), working in a very similar environment in northern Queensland quoted values that seem more realistic : 2.3, 2.9, 20.8 and 4.5 kg ha^{-1} yr^{-1} for Ca, Mg, Na and K respectively (annual rainfall 2520 mm). TURVEY himself discussed the anomalous results obtained for Ca in terms of analytical procedures.

Outputs of solutes are generally determined by the nature of the geological substratum (MILLER, 1961; HEM, 1970) and the prevailing hydrological regime. With respect to the first factor it is clear that the relatively high amounts of cations removed from some drainage basins (*e.g.* H.J. Andrews forest; also, Mg from Ei Creek) reflect the weathering of feldspars (HENDERSON *et al.*, 1978) and chlorite-bearing phyllites (TURVEY, 1974) respectively. The effect of the hydrological regime is best illustrated by the example of

Table 4.8 Solute budgets for selected catchments (kg ha^{-1} yr^{-1})

Location	Input	Output	Net loss or gain	Annual precipi-tation (mm)	Annual runoff (mm)	Vegetation[a]	Geology[b]
			a) Calcium				
Jamieson Creek (B.C. Canada)[8]	7.2	41.7	-34.4	4540	3670	Df	till plut
Kali Mondo (Indonesia)[1*]	9.9	29	-19.1	4668	3590	*Agathis*	ava avb
H.J. Andrews (Oregon, U.S.A.)[6]	3.6	49.4	-45.9	2370	1545	Df	avb ava
Ei Creek (Papua New Guinea)[2*]	0[c]	24.8	-24.8[c]	2700	1480	LMRF	avb ph
El Verde (Puerto Rico)[3*]	21.8	43.1	-21.3	3760	(1350)	LMRF	and
Plynlimon (Wales, U.K.)[7]	25.1[d]	12.0	+13.1[d]	1850	1350	pg	till gw
Hubbard Brook (N.H., U.S.A.)[5]	2.2	13.9	-11.7	1320	830	Nh	till gn
Amitioro (Ivory Coast)[4*]	<13.1	6.1	< 7.0	1320	< 120	MSDF	sch
			b) Magnesium				
Jamieson Creek (B.C. Canada)[8]	2.2	8.8	- 6.6				
Kali Mondo (Indonesia)[1*]	4.0	30.5	-26.5				
H.J. Andrews (Oregon, U.S.A.)[6]	1.2	12.8	- 7.4				
Ei Creek (Papua)[2*]	0.3	51.0	-50.7				
El Verde (Puerto Rico)[3*]	4.9	15.0	-10.1				
Plynlimon (Wales, U.K.)[7]	4.4	8.7	- 4.3				
Hubbard Brook (N.H., U.S.A.)[5]	0.6	3.3	- 2.7				
Amitioro (Ivory Coast)[4*]	<1.3	3.3	- 2.0				
			c) Sodium				
Jamieson Creek (B.C. Canada)[8]	13.2	25.6	-12.4				
Kali Mondo (Indonesia)[1*]	13.3	27.4	-14.1				
H.J. Andrews (Oregon, U.S.A.)[6]	5.7	30.3	-24.6				
Ei Creek (Papua New Guinea)[2*]	8.4	66.0	-57.6				
El Verde (Puerto Rico)[3*]	57.2	64.5	- 7.3				
Plynlimon (Wales, U.K.)[7]	27.2	44.0	-16.8				
Hubbard Brook (N.H., U.S.A.)[5]	1.6	7.5	- 5.9				
Amitioro (Ivory Coast)[4*]	<6.6	4.2	< 2.2				
			d) Potassium				
Jamieson Creek (B.C. Canada)[8]	0.9	2.6	- 1.7				
Kali Mondo (Indonesia)[1*]	9.6	22.0	-12.4				
H.J. Andrews (Oregon, U.S.A.)[6]	0.95	5.25	- 4.3				
Ei Creek (Papua)[2*]	0.8	14.9	-14.1				
El Verde (Puerto Rico)[3*]	18.2	20.8	- 2.6				
Plynlimon (Wales, U.K.)[7]	1.6	2.6	- 1.0				
	0.9	2.4	- 1.5				

Table 4.8 Solute budgets for selected catchments (kg ha^{-1} yr^{-1}) (continued)

e) Dissolved SiO_2

Location	Input	Output	Net loss or gain	Annual rainfall (mm)	Annual runoff (mm)	Vegetation[a]	Geology[b]
Jamieson Creek (B.C., 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 Ck. (Queensland)[10*]	-	279		4000	2325	L(M)RF	gran
H.J. Andrews (Oregon, U.S.A.)[12]	tr.	113.6	-113.5	2370	1545	Df	avb ava
Ei Creek (Papua New Guinea)[2*]	0	288	-288	2700	1480	LMRF	avb ph
Davies Ck. (Queensland)[11*]	-	180		1400	900	L(M)RF	gran
Sungai Gombak (Malaya)[10*]	-	128		2360	856	LMRF	gran
Hubbard Brook (N.H., U.S.A.)[5]	0	23.8	- 23.8	1322	833	Nhw	till gw
Rio Tanama (Puerto Rico)[9*]	-	165		2000	630	L(M)RF	and
East Twin (Somerset, U.K.)[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 (N.I., 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 (1967b; 1973)
[12] Fredriksen (1972)
[13] Waylen (1979)
[14] Verstraten (1977)
[15] Knight & Will (1977)

[a] vegetation abbreviations : be =beech; df = douglas fir; gh = grass & heathland; LMRF = Lower Montane Rain forest; MSDF = Moist semi-deciduous 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

the Amitioro basin in Ivory Coast, where the annual runoff is extremely small. There, most elements in fact accumulate in the system (MATHIEU, 1976). Also, the solute loads from the superwet Jamieson Creek catchment (Canada) are much larger than those of the Hubbard Brook area (U.S.A.) as a result of the high annual runoff volumes observed in 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° C) are greater than observed for the Ivory Coast catchment which experiences on average the same amount of rainfall but a much higher mean annual temperature (> 20° C).

The data in Table 4.8 therefore suggest that catchment lithology and hydrological regime are the dominant factors in determining net solute losses from (undisturbed) catchments, 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 the (sub)tropical streams presented in Table 4.8 are generally higher than those for the temperate-latitude catchments. Average values for the "tropical" and "temperate" groups amount to 18.1 ± 4.7 and 5.0 ± 2.3 mg l^{-1} SiO_2 respectively. This difference is significant at the 1 %-level (*t*-test). More data will be needed to test the above conjecture, however. Factors as catchment rock type, degree of disturbance, catchment size, climatological conditions (including leaching intensity), etc. should be included in such a study.

With respect to the annual losses of Al, Fe and Mn data are exceedingly scarce. The only information on *Al* that could be found was that for the Hubbard Brook forest (1.87 kg ha^{-1} yr^{-1}; LIKENS *et al.*, 1977) and for a cloud forest ecosystem in Venezuela (1.1 kg ha^{-1} yr^{-1}; STEINHARDT, 1979). The latter value is much too low according to STEINHARDT himself and was obtained from tension lysimetry at 90 cm depth. Taking the Al concentration of the soil water at a depth of 20 cm one obtains a figure of 9.9 kg ha^{-1} yr^{-1} which is comparable to the 15 kg ha^{-1} removed from the Mondo catchment.

Estimates of the export of *Mn* and *Fe* were also given by STEINHARDT (1979), but suffer from the same limitation. Adapted figures (*i.e.* again based on soil water concentrations) read .5 and 2.1 kg ha^{-1} yr^{-1} for Mn and Fe respectively (*cf.* 1.2 and 12.2 kg ha^{-1} in the present case). Another estimate was published by JORDAN *et al.* (1972) for the Lower Montane Rain forest of Puerto Rico. There annual losses of Mn and Fe amounted to 0.1 and 0.04 kg ha^{-1} yr^{-1} respectively. It would seem, however, that "runoff" in this case consisted of very shallow (and overland) flow from a very small (< 1 ha) plot only, which would account for the minor amounts reported.

4.3 Particulate matter output

4.3.1 *Introduction*

Apart from the material carried away by the stream in dissolved form there is the output of particulate matter leaving the drainage basin either in suspension ("suspended sediment load") or rolling and sliding along the stream bed ("bed load"). Whether chemical or mechanical denudation processes dominate the removal of matter from an ecosystem depends on a number of factors such as rainfall characteristics, the occurrence of frost, soil stability, bedrock lithology, land-use/ecosystem disturbance, etc.

Undisturbed forested catchments in the *temperate zone* are frequently exporting material mainly in dissolved form (*e.g.* CLEAVES *et al.*, 1970; JOHNSON & SWANK, 1973; LIKENS *et al.*, 1977), but mechanical erosion becomes much more important after disturbance of the delicate ecological balance (*e.g.* WOLMAN & SCHICK, 1967; IMESON, 1974; HARR *et al.*, 1975) or in the case of easily eroding bedrock (DUYSINGS, 1979) and extensive mass wasting (BROWN & KRYGIER, 1971).

Work done in the *tropics* on a fairly large scale (*e.g.* CORBEL, 1957; GIBBS, 1967; GROVE, 1972) suggests that suspended sediment loads frequently exceed solute loads, but it should be noted that these data pertain to disturbed systems. Studies comparing the mechanical and chemical denudation rates for smaller tropical catchments still covered with (more or less unaltered) Rain forest are scarce and virtually restricted to Australasia. The investigations of DOUGLAS in Malaysia and North Queensland should be mentioned in particular (DOUGLAS, 1967ab; 1969; 1973), whilst similar work has been carried out by VAN DIJK & EHRENCRON (1949) in Java and by TURVEY (1974) in Papua New Guinea.

Although the relative contribution of solute transport to the total output of matter appeared to vary widely from basin to basin, DOUGLAS (1969; 1973) was able to show that the precipitation regime was a most important factor in this regard. For example, in the high rainfall area of Queensland over half of the suspended sediment loads of streams is carried in less than 7 days of the year. Under the more evenly distributed rainfall of West Malaya 50 % of the annual load was carried in 24 days of the year, indicating the importance of extreme events. Sediment loads frequently exceeded solute loads in the wetter catchments and the results of VAN DIJK & EHRENCRON (1949) and TURVEY (1974) support these findings. When these wet tropical forests are cleared and the land is converted to agricultural use, the suspended sediment production usually increases dramatically and the problem is now widespread over the humid tropical zone (ECKHOLM, 1976; GREENLAND & LAL, 1977). Examples of the contrasting sediment loads exported from well-vegetated and more or less seriously disturbed locations in South-east Asia are presented by several investigators, *e.g.* COSTER (1938) and VAN DIJK & VOGELZANG (1948) for Java, by KELLMAN (1969) for Mindanao, by SHALLOW (1956) for peninsular Malaysia and by GILMOUR (1971) for northern Queensland.

In the present case a number of runoff events were sampled in detail at the outlet of the Mondo river basin (Weir 4) and upstream of the HOF-producing zone (Weir 3, see Fig. 3.1 for locations. In total thirteen storms were sampled including a few extreme cases.

4.3.2 *Procedures*

In the absence of more sophisticated instrumentation and laboratory facilities simple methods of sample collection and filtration had to be used. Samples for the estimation of *suspended sediment* concentrations were taken in the middle of the stream by immersing a 3-l can. Although this may have resulted in an underestimate of the suspended sediment concentration as compared to depth-integrated sampling this deviation is believed to be only minor as the water usually becomes quite turbulent during floods and the actual water depths rarely exceeded 30 cm. The samples thus collected were filtered through pre-weighed paper filters.

This again caused a slight underestimation as some of the finest material was not retained by these non-professional filters and some leaching from the filters may have occurred as well (*cf.* HINRICH, 1965). Reweighing was done at the laboratory in Yogyakarta. The observed suspended sediment concentrations were combined with the corresponding momentous discharge rates to compute the amount of sediment (kg) removed from the catchment by a particular runoff event (VAN ENK, in preparation). This procedure has been preferred over the use of sediment rating curves and flow duration curves (MILLER, 1951) because of the considerable scatter commonly associated with such rating curves (*e.g.* WALLING, 1977; FINLAYSON, 1978). Sediment concentrations associated with a particular discharge rate varied widely in the present case also and the application of rating curves might have produced serious errors.

The sediment loads for each flood (Ind. "Banjir") were then related to quick-flow volume and/or rainfall and, after inserting the observed daily rainfalls in the latter equation monthly sediment outputs were obtained by summation. These again correlated very well with the monthly rainfall totals and were summed to estimate annual totals.

Bedload transport has been estimated by means of an empirical formula and by occasionally measuring the amount of material deposited behind the weir (see section 4.3.3.2).

During the last months of the field investigation *floating material* which accumulated behind a gauze (1-mm mesh width) installed upstream of the upper weir was collected occasionally as well. This location was chosen to minimize the risk of damage by floods. Yet it would trap about 90 % of the total floating load, since only few trees have been planted in the riparian zone in the downstream reaches of the catchment.

4.3.3 *Results*

4.3.3.1 *Suspended sediment output*

The equations referred to in the foregoing section on procedures read :

Weir 4 : $SY = 5.02 \times 10^{-4}\ P^{3.32}$ $r^2 = 0.96$ $n = 4$ S.E. = 13 % (4.1)

Weir 3 : $SY = 0.11 \times 10^{-2} (Q_q+20)^{1.84}$ $r^2 = 0.97$ $n=9$ S.E. = 26 % (4.2

where SY = suspended-sediment load carried per runoff event (kg)
P = precipitation (mm)
and Q_q = quickflow volume (m^3) (see section 4.2.2). (See also Fig. 4.2)..

Monthly sediment export appeared to relate to monthly rainfall totals according to

$SY_m = 0.13 \times 10^{-2}\ P_m^{2.44}$ $r^2 = 0.97$ $n = 13$ S.E. = 10.5 % (4.3)

where SY_m = suspended sediment load (kg $month^{-1}$) and P_m = rainfall (mm $month^{-1}$).

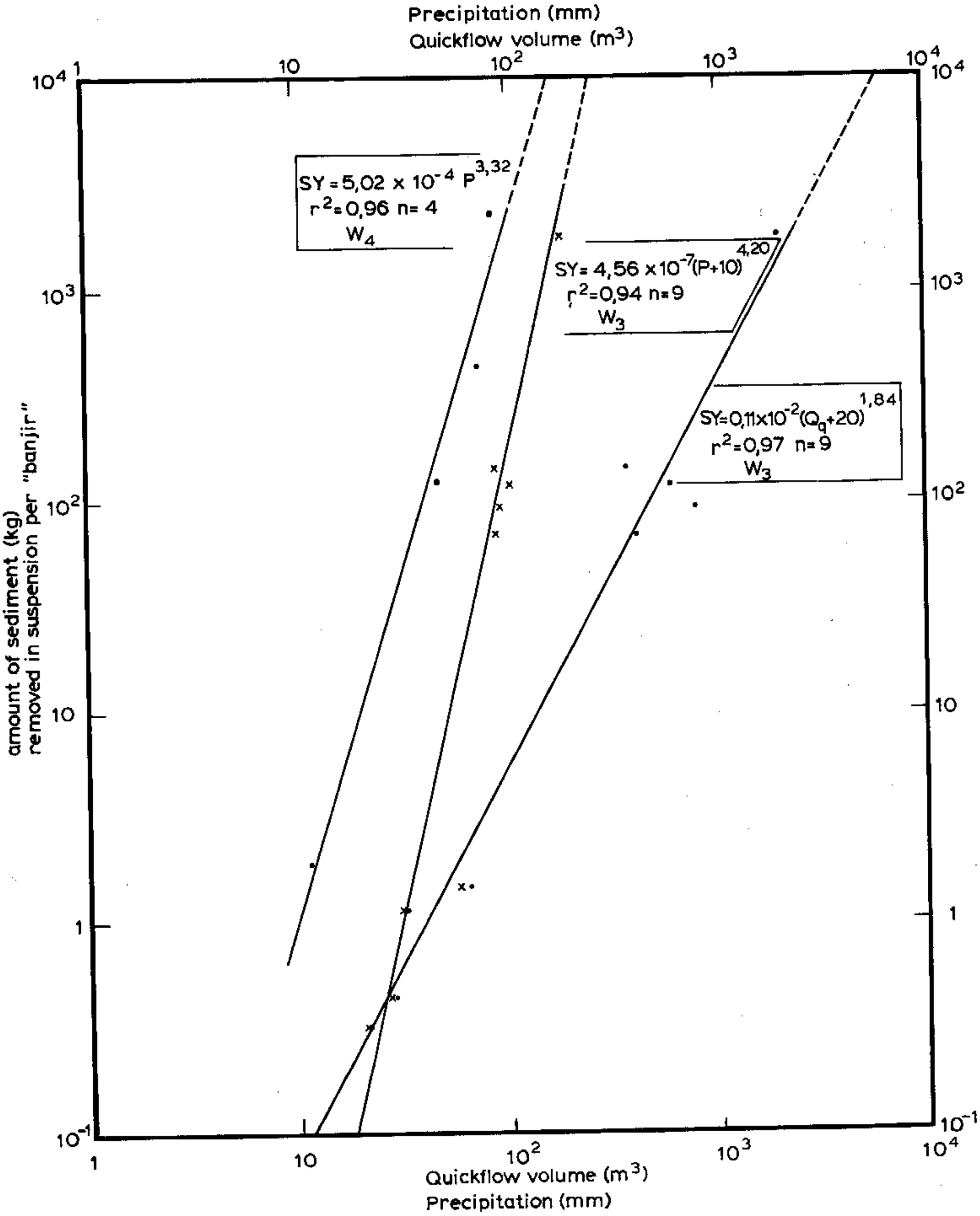


Fig. 4.2 Amounts of sediment carried in suspension per storm vs. precipitation and quickflow

By summation of the monthly amounts obtained in this way and adding small extra loads to account for the contribution supplied by non-storm flow (15 and 2 tkm^{-2} respectively as estimated from baseflow samples) total sediment outputs of 306 and 27 tkm^{-2} were computed for the entire basin and the subbasin respectively (December, 1976 - February, 1978). This difference well illustrates the impact of the greater stormflow volumes recorded at the basin outlet due to the contribution of HOF from compacted surfaces and two landslides occurring downstream of the upper weir. Greater stormflows result in a more intense bank erosion whereas additional sediment is supplied by the landslips and other areas producing HOF (*cf.* section 3.4.2).

To what extent the easily erodible shales outcropping in the lower part of the catchment are contributing is not known. In an attempt to estimate the "long-term" rate of sediment removal from the Mondo river basin the monthly rainfall figures recorded at the forestry station between 1950 and 1977 were inserted in equation 4.3 to give a "long-term" estimate of 313 tkm^{-2}, which differs hardly from the total output during the period of investigation (viz. 306 tkm^{-2}). Table 4.9 brings together some suspended sediment yields from various tropical catchments, some of them relatively undisturbed, others already seriously affected by accelerated erosion.

It appears that erosion rates in undisturbed catchments underlain by volcanic ashes are much higher than those reported for most other forested basins (Papua, Malaysia, Kenya). It should be noted, however, that annual rainfall figures for Central Java are distinctly higher as well. The estimate for the Mondo watershed compares favourably with the yields obtained at the Kali Pelus and Rambut drainage basins. The protective value of undisturbed vegetation cover is also illustrated by these data (Kali Sanggreman and Bengawan Solo being seriously affected by accelerated erosion).

4.3.3.2 *Bedload*

Due to the difficulties associated with obtaining reliable estimates of the amounts of sediment transported by natural streams along their beds very few direct measurements have been published in this regard. After comparing the results obtained with a large number of computation formulas with bedload values actually measured for Northamerican streams a study group (TASK COMITTEE, 1971) concluded: "In view of the results... one must assume that the probable error in sediment discharge calculations under the most favorable circumstances is large. Errors as large as 50 to 100 % can be expected. When calculations are based on average values of slope, bed material characteristics and estimated flow, depth and velocity, larger errors can be expected".

In the present case data on hydraulic radius, gradients, as collected during four runoff events, as well as granulometric information on bed material (Fig. 4.3) were inserted in various bedload computation formulas (ILRI, 1972). Bedload discharges obtained in this way proved to be enormous, viz. 70 m^3 (Frijlink formula) for the investigation period, or 4 kg per m^3 of quickflow. The latter value should be considered to be completely unrealistic and another approach was followed.

Bedload output has recently been estimated in the Kali Desel basin, a small (17.8 ha) catchment under agricultural land use and situat-

Table 4.9 Suspended sediment yields ($m^3\ km^{-2}\ yr^{-1}$) for tropical catchments

Location	Suspended sediment yield ($m^3\ km^{-2}\ yr^{-1}$)	Annual rainfall (mm)	Catchment area (km^2)	Land-use	Geology	Reference
Indonesian catchments						
K. Mondo (C. Java)	209** - 313*	4668	0.187	*Agathis* forest, some gardening	young volcanics	This study
ibidem (subbasin)	185** - 27.5*	4668	0.122	*Agathis* forest		*ibidem*
K. Pelus (C. Java)	270** - 400*	5-6000	13.2	Rain forest°		Van Enk (in prep.)
K. Rambut (C. Java)	420** - 630*	3620	45.0			
K. Sanggreman (C. Java)	>2600 (730***)	3220	0.629	indigenous agriculture		
K. Serayu (C. Java) (headwater area)	410** - 615*	~3800	666			
Bengawan Solo (E.C. Java)	>>4000	2-3000	2890		*ibidem*; old volcanics	McComb & Zakaria (1972)
Other catchments						
Ei Creek (Papua)	36.3	2700	16.25	Rain forest°	phyllites	Turvey (1975)
Cameron hills (Malaysia)	21.1	2000	-		-	Shallow (1956) quoted by Douglas (1967)
ibidem	103.1	2000	-	rubber plantations	-	
Sungai Gombak (Malaysia)	24.9	2455	26.5	Rain forest°	schists/granite	Douglas (1972
ibidem	67.3	2360	140	various	*ibidem*; alluvium	Douglas (1967a)
Kenyan catchments	13 - 20**	1000	-	Rain forest	old volcanics	Dunne (1979)
Amazone headwaters	186**-279*	2500	811.000	various	young volcanics, sedimentary rocks	Gibbs (1967)

*original data ($tkm^{-2}\ yr^{-1}$) converted to $m^3km^{-2}\ yr^{-1}$ by applying a density of 1.0 gcm^{-3} (volcanic ash soils)
**idem using a density of 1.5 gcm^{-3}
***original estimate (Van der Linden, 1978)
°slight disturbance

ed 15 km to the north of the present site (VAN DER LINDEN, 1979). It is underlain by volcanic ashes and shales that are very similar to those present in the lower reaches of the Mondo river basin. Bedload output per storm event in the Desel basin appears to be related to quickflow volume by the equation :

$$BL = 11.6 \times 10^{-3} \cdot Q_q{}^{1.5} \quad r^2 = 0.80 \quad n = 9 \quad S.E.E. = \tag{4.4}$$

with BL = bedload transport (kg)
and Q_q = quickflow (m^3).

Insertion of the stormflows observed in the present catchment gave a bedload estimate of 8300 kg for the study period, or 44.3 tkm^{-2} (12.6 % of the total sediment output of 350 tkm^{-2}). This estimate was adopted in the computation of the total denudation (section 4.4).

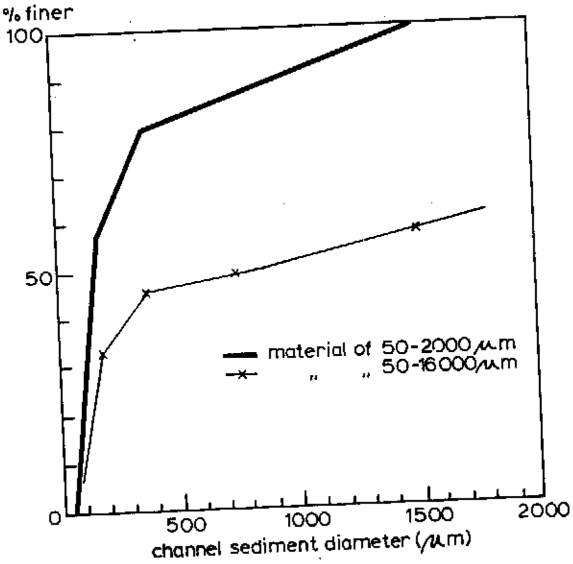


Fig. 4.3 Granulometric analysis of stream bed material at Weir 4 (basin outlet)

Table 4.10 gives the chemical composition of stream bed material and the river banks of the Mondo catchment to enable calculation of chemical element removal via mechanical erosion (note that the data are presented as oxides).

Table 4.10 : Chemical composition (percent by weight) of river bed material and stream banks

	SiO_2	Al_2O_3	Fe_2O_3	FeO	MgO	CaO	K_2O	Na_2O	LOI	TiO_2	P_2O_5	MnO
bed material	50.6	17.0	10.5	3.9	2.4	1.1	1.4	0.65	6.9	1.0	0.15	0.1
stream bank	33.3	32.5	10.6	2.8	0.6	0.4	0.15	0.15	15.3	1.3	0.2	0.3

LOI = Loss on ignition

Concentrations of Mg, Ca and K appear to be higher in the bed material ("suspended material"). This reflects the different nature of the two : bank material consits of volcanic ashes and bed material is made up of shale particles (having much higher Mg, Ca and K-concentrations) and to a lesser extent of heavy mineral grains that are derived from the ashes.

.3.3.3 *Floating load*

Only minor amounts were trapped. The bulk (74.2 %) consisted of *Agathis* leaves with the remainder almost equally being made up by *Agathis* twigs (12.5 %) and leaves of riverine vegetation (13.3 %). During the months of December 1977, January 1978 and May 1978 44.6, 106.4 and 33.2 g of oven-dry organic material was collected representing a total export of 750-900 gyr^{-1}.

This amount is negligible in terms of nutrient losses if one takes into account the, concentrations of nutrients in *Agathis* litter (section 5.3).

4.4 Total export of material

Converting the solute export data (Table 4.6) to oxides (for ready comparison with the sediment outputs) one obtains a total(*i.e.* including P, Al, Fe and Mn) solute load of 80.7 tkm^{-2} over the study period, or 83.6 tkm^{-2} for a "normal" year (*cf.* section 4.2.7). Adding the amounts transported in suspension (313 tkm^{-2} yr^{-1}) and along the stream bed (45 tkm^{-2} yr^{-1}) one arrives at a grand total output of 442 tkm^{-2} yr^{-1}. Table 4.11 summarizes the results.

Table 4.11 Total export of material from the Mondo river basin (tkm^{-2} yr^{-1}) for an "average" year.

Type of load	Absolute amount (tkm^{-2} yr^{-1}		Relative amount (%)
Solutes	84	442	19
Suspended sediment	313		71
Bed transport	45		10

VAN DIJK & EHRENCRON (1949) reported solute and suspended loads of 158 and 532 tkm^{-2} yr^{-1} respectively for a larger (4500 ha) catchment covered with Rain forest on nearby Mount Slamet. Their dissolved load therefore made up 14.2 % of the total material output, a figure which is lower than found for the Mondo river basin (21 %, excluding bedload which was not estimated by VAN DIJK & EHRENCRON). This difference may be partly explained by the immobilization of nutrients by the vigorously growing vegetation in the present catchment in contrast to the steady-state situation in the Rain forest of the other catchment. Also, the present estimate is not truly representative of the total solute export since only few anionic species were determined. Thirdly, there may be slight lithological differences between the two drainage basins which also differ greatly in size (19 vs. 4500 ha).

A still higher relative proportion (*c.* 30 %) of solute load was reported by DOUGLAS (1973) for areas in Queensland with annual precipitation values over 4000 mm. This may reflect the greater stability of the Queensland soils as compared to the vulnerable volcanic ash deposits in Java, especially if one knows that 40-50 % of the annual runoff in the former area consists of quickflow (BONELL & GILMOUR, 1978).

5. BIOGEOCHEMICAL CYCLING: THE INTRA-SYSTEM CYCLE

5.1 Introduction

A forest (or any other) ecosystem is an open system: chemical elements may move into and out of it, thus constituting the link with the larger global cycles. Superposed on these larger cycles there is the tendency exhibited by a number of chemical elements to cycle continuously *within* the ecosystem. This has been referred to by LIKENS *et al.* (1977) as the *intra-system cycle*. The term *biogeochemical cycling* is often used to denote these processes as the elements tend to move from non-living components ("geo") to living organisms ("bio") and back (ODUM, 1971).

The forest biogeochemical cycle consists of a series of interdependent processes, which can be conceived of as *transfers of nutrients* between a number of nutrient *storage pools* or *compartments*. Figure 5.1 illustrates the major compartments and transfer pathways for non-gaseous elements *in a very simplified form.*

The following nutrient accumulating/supplying compartments can be distinguished :

- *atmosphere* (aerosols, rainfall)
- *living biomass* both above and below ground and including (dead) structural matter
- *forest floor* or *litter layer*
- *clay-humus exchange complex* or *available nutrients in the soil*
- mineral soil and rock (both fresh and weathered)

The second and third compartments are sometimes put together and termed the "organic compartment". In the present work the forest floor has been retained as a specific compartment in view of its central position in the ecosystem ("dead organic matter" in Fig. 5.1; *cf.* GOSZ *et al.*, 1976).

Nutrients are transferred or exchanged between compartments in many ways (see for a concise account LIKENS *et al.*, 1977), of which only the most important ones can be touched upon in the present study.

In order to describe the intricate web of processes constituting the forest nutrient cycle it is convenient to take the forest floor as a focal point (Fig. 5.1). Nutrients found in this compartment are derived directly from the atmosphere (wet and dry deposition), from the soil (weathering) and from the vegetation, either directly (decomposing litter; root exudates) or indirectly (leaching of exudates and dust/aerosols from the canopy via drip and stemflow). Removal of nutrients from the forest floor is through the uptake of mineralized organic matter by the vegetation, by leaching of nutrients to the sub-soil and in some cases by erosion (overland flow).

The *measurement* of a number of nutrient transfers, such as bulk precipitation input, hydrological export, litterfall and crown drip is comparatively easy, whilst a determination of nutrient contents in the various compartments is equally well possible. Procedures applied in the present case will be dealt with in section 5.2.

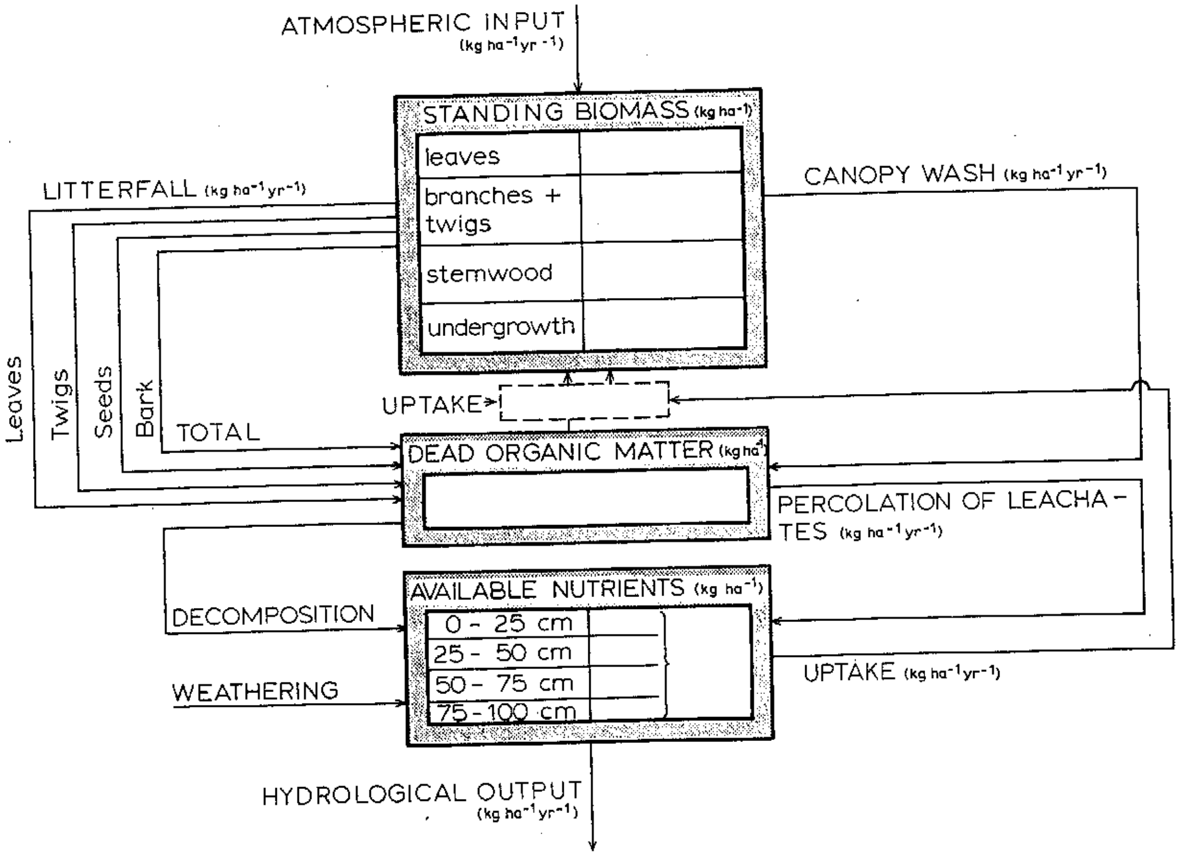
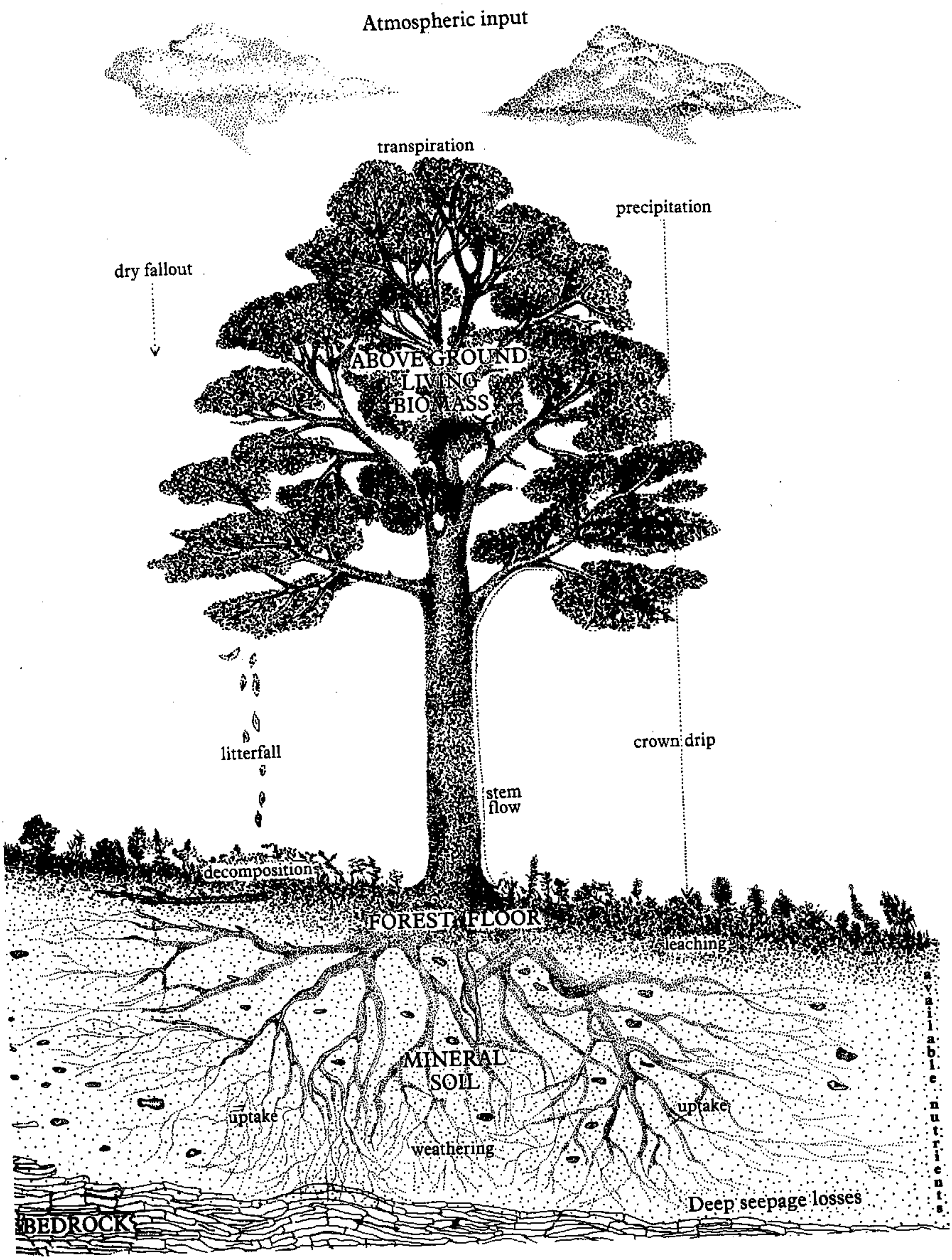


Fig. 5.1 Simplified representation of the forest biogeochemical cycle for non-gaseous elements (modified from STEINHARDT, 1979 (a))


Atmospheric input
transpiration
precipitation
dry fallout
ABOVE GROUND
LIVING
BIOMASS
litterfall
crown drip
stem
flow
decomposition
FOREST FLOOR
leaching
available nutrients
MINERAL
SOIL
uptake
uptake
weathering
Deep seepage losses
BEDROCKS

Other processes, such as the excretion of root exudates (SMITH, 1976) or the impaction of aerosols upon forest vegetation (SCHLESINGER & REINERS, 1974; ELIAS *et al.*, 1976; MILLER *et al.*, 1976) are exceedingly difficult to quantify, whereas estimates of the annual nutrient uptake by the vegetation, the net mineralization of dead organic matter and the rate of supply of nutrients by chemical transformation of minerals have to be evaluated indirectly.

For instance, under steady-state conditions, *the uptake of nutrients by the living biomass* equals the sum of the nutrients incorporated in the vegetation and those returning to the soil via litterfall and crown drip (the latter corrected for bulk precipitation, the so-called "net canopy wash").

Similarly can the actual rate of chemical weathering be found by establishing the chemical mass balance for a catchment (*cf.* chapter 4), adding the appropriate amounts of nutrients accumulating annually in the living biomass.

The *rate of net mineralization of organic matter* on the forest floor can be evaluated theoretically by comparing the various inputs and outputs for this compartment (in kg ha^{-1} yr^{-1}; LIKENS *et al.*, 1977).

This chapter is an attempt to describe the (or some) biogeochemical circulation patterns for a number of chemical elements in plantation forests of *Agathis loranthifolia* (7-35 yr old), *Tectona grandis* (25 yr old) and *Pinus merkusii* (12 yr old) as well as for *Eupatorium* shrubs and the local climax forest, the Lower Montane Rain forest. Descriptions will follow the lines indicated in Figure 5.1 as much as possible in the following order :

- *litterfall* and the associated accession of nutrients to the forest floor (section 5.3)
- *crowndrip* and associated nutrient accession (section 5.4)
- *uptake of nutrients* by the vegetation (section 5.5)
- *nutrient dynamics of the forest floor* (section 5.6), based on items 1-3 and data on leaching of nutrients out of this compartment
- *available nutrients in the soil* in relation to the amounts stored in the organic compartment (section 5.7).

All this naturally leads to an evaluation of the data in terms of *consequences for forest management* (section 5.9) and the *actual rate of chemical weathering* (section 5.8). *Major contrasts in chemical-element behaviour* (*e.g.* their mobility) *and ecosystems* (shrubs *vs.* young plantation forest; mature plantation forest *vs.* climax forest) constitute the subject of the final section (5.10).

In order to minimize the effort required to digest the present (bulky) chapter a distinction has been made between "essential" and "less essential" text. The former is set in normal typescript, whereas the latter (containing discussions of results presented in the numerous tables and figures or comparisons with the literature, etc.) is set in the present format.

5.2 Field and laboratory procedures

Transfers

Bulk precipitation input

The measurement of precipitation has been treated in detail in section 3.3.2.1, whereas the chemical aspects have been discussed in section 4.2.2.

Total throughfall, i.e. crowndrip and direct throughfall, has been estimated using essentially the same plastic collectors as used for determination of bulk-precipitation input (section 4.2.2). A roving approach (WILM, 1943) together with a sampling frequency of about once every two weeks has been applied for four gauges per site. Although non professional, these collectors compared very well with the standard raingauges. Results have been adjusted only for the dry season when sampling frequency was low and prolonged evaporation resulted in high concentrations. Treatment of collectors and samples are as described in section 4.2.2 for bulk precipitation. No attempts have been made to measure *stemflow*. The only case where stemflow is important is that of *Tectona grandis*. Amounts have been estimated from relevant literature (section 5.4.1).

Litter-leachate has been sampled from March 1977 onwards. Rainwater/canopy drip was allowed to percolate through raised litter trays (0.25 m^2; two devices per plot except for *Tectona* which had none) and was collected in a 10 litre can (*cf.* KENWORTHY, 1971). Treatment of these water samples is as specified for precipitation and throughfall samples.

The output of nutrients on a catchment basis has been dealt with in detail in chapters 3 and 4 (see sections 3.3.2.2 and 4.2.2).

Litterfall plots consisted of five collection trays (1 m^2; bottoms of 1.6 mm screen) that were sampled on a monthly basis. A roving gauge procedure (WILM, 1943) was applied in order to sample as many sites as possible. For the *Eupatorium* plot smaller trays (0.25 m^2) were used. After two months these were sampled every week since the leaves of this species appeared to break down easily under the prevailing heavy rains. Root litter measurements have not been attempted. Litter samples were separated in the laboratory (Yogyakarta) in three categories initially: leaves / needles; branches / twigs / bark / seeds; and other material (mainly derived from the undergrowth storey). They were then dried for 24 hours in an oven at 70° C and re-weighed. From September 1977 onwards the second category has been sorted in more detail: twigs / branches, bark, and seeds /fruits. All samples were flown to the Netherlands, ground in a Culatti DFH-48 mill to pass a 1 mm sieve and were subsequently analyzed for Ca, Mg (applying a 1% $LaNO_3$ solution), Mn, Fe (atomic absorption flame photometry), Na, K (emission flame photometry) and total P (colorimetrically according to CHEN *et al.*, 1956) after wet ashing with $HNO_3/HCLO_4$ at the Biology Department of the Free University, Amsterdam. Total N for a limited number of samples was analyzed by burning in a pure oxygen stream with a N-micro-rapid azotometer (MERZ, 1970). Silica (SiO_2) and Al were determined for a number of samples by emission spectrometry (Argon arc using a 0.1 N $LiNO_3$ solution) after dry (450° C) and wet ashing with $HNO_3/HCL/HF$ (BUCKLEY & CRANSTON, 1971) at the Institute of Earth Sciences of the Free University, Amsterdam.

An estimation of the *rate of litter decomposition* has been attempted for three species *(Agathis, Pinus, Eupatorium)* by means of the meshbag technique (*e.g.* EWEL, 1976). Fresh plant material (leaves) was gathered in the first week of March 1977 and allowed to dry for one week at the laboratory in Yogyakarta. In total three sets of twelve bags (30 x 20 cm; 1.6 mm screen stapled along the sides) were filled with ± 7.5, ± 35 and ± 30 grams of *Eupatorium, Agathis* and *Pinus* litter respectively and weighed. Two samples of each group were retained for the determination of initial dry weight, the remainder was installed in the field on 26 March anchoring the bags with steel nails. Unfortunately not only the nails, but also most of the litter bags soon disappeared. Only in the case of *Agathis* a few bags remained in position. These were recovered, dried and reweighed in May 1978. The experiment has not been repeated for the other species.

Compartments

Litter on the forest floor has been sampled in three 1 m^2 quadrats for each plot in late August 1977. Wet weights were converted to oven-dry values by conversion factors obtained in the laboratory. Analysis of the samples as described for litterfall.

The *above-ground living biomass* has been estimated for all plots. First a general structural vegetation description was made, indicating height, cover and dominating life form of each stratum. Dominant species were noted as well (section 2.6).

In each plot the diameter at breast height (DBH) and height of all trees in a sample plot of 0.12 or 0.25 ha were measured. From these data the dimensions of an "average" tree were computed as follows: the DBH of each tree was transferred to basal area (BA) and the mean BA of the plot (MBA) was calculated. This again was transferred to diameter to arrive at the diameter (DBA) of the "average" tree. By inserting this value in the diameter/height curve of each plot the height of the "average" tree was obtained.

This part of the work was carried out by a team from the Ecological Institute of the Padjadjaran University in Bandung, Indonesia (assisted by two observers from the WOTRO and 'Serayu Valley' projects respectively) between 27 August and 3 September 1977 and is reported upon in TEAM VEGETATION & EROSION (1979b).

After permission had been obtained from the State Forest Enterprise Perum Perhutani two sample trees having dimensions as close as possible to these "average" trees in each plot were cut during the second half of September. Branches, leaves and smaller stems were weighed directly in the field (wet weight). Dry-weight biomass was calculated by applying conversion factors found in the laboratory from drying samples of known wet weight (24 or 48 hours at 70° C; all determinations in duplo). Stemwood volume (diameter > 7 cm including bark) was estimated in the field by dividing the trunk in 1-m sections and determining the diameter of each sample at midpoint; volumes of each section were calculated and summed to give total stem volume. These volumes were converted into oven-dry weights again by means of conversion factors established in the laboratory by weighing oven-dry samples of known volume. Total above-ground tree biomass was found by adding oven-dry weights of stemwood, branches and leaves.

No such determinations could be made in the teak plantation as no permission to cut sample trees was obtained. Here plot biomass was estimated by inserting the average DBH and height of the stand in local yield tables (SUHARLAN *et al.*, 1975) and converting the stem volume into weight via a specific gravity factor of 0.67 g cm^{-3} (WERKGROEP TROPISCHE HOUTTEELT, 1973). As the species is a deciduous one the foliage mass was assumed to be equal to the annual leaf fall (SETH *et al.*, 1963). The amount of branches and twigs was calculated roughly from foliage biomass by applying a ratio factor obtained from the other investigated stands.

Due to the time and manpower available for the UNPAD team, the small size of the plots and the need to leave these undisturbed as much as possible, not enough replicates of sample trees could be taken for a statistical analysis of the biomass data. The present results therefore cannot be more than a general estimate of the above-ground biomass of the plots (TEAM VEGETATION AND EROSION, 1979b). The biomass of the *forest undergrowth* was estimated by harvesting all biomass from three random plots (1 m^2) per site. Wet weights were determined in the field and converted to oven-dry weights by conversion factors again. Samples were taken from the branches, twigs, stemwood (slice) and leaves from all sample trees. No distinction was made between sun-lit or shaded leaves, or between 1-yr old and 2-yr old leaves. Samples were taken after mixing thoroughly large volumes of leaves or twigs. They were then dried, treated and analyzed as described for litterfall. *Tectona* stemwood could be sampled in another plantation where a regular logging operation had taken place recently; branches and leaves could be obtained both from the original plot and the additional site.

Available nutrients in the soil were estimated for the upper two metres of the soil profile under *Agathis*, *Eupatorium*, *Pinus* and *Tectona*. Analysis was performed at the Soil Research Institute in Bogor, Indonesia. The analysis comprised the availability of soil P and K by extraction with citric acid and the determination of the cation exchange characteristics of the soil (both the cation exchange capacity NH_4-acetate at pH=7) and the amounts of adsorbed cations (by analyzing the extract for Na, K, Ca and Mg by means of emission and atomic absorption flame photometry, applying a $LaCl_3$ solution in the latter case. Furthermore an extraction with NH_4-acetate/acetic acid at pH = 4.8 was performed. This extract was analyzed for Ca, Mg, Na, K, total P, Al, Mn, Fe, SO_4 and NO_3, and, after addition of KCl, for NH_4 by means of atomic absorption (Ca, Mg, Mn), emission-flame photometric (Na, K) and colorimetric techniques (P, Al, Fe, SO_4, NO_3, NH_4) (SUDJADI *et al.*, 1971).

Total chemical content of the soil profiles has been determined at the Laboratory for Physical Geography and Soil Science of the University of Amsterdam. Analytical methods will be given in the chapter on soil geochemistry (section 6.2).

5.3 Litterfall

5.3.1 *Production of litter by Agathis loranthifolia and Eupatorium sp.*.

The production of litter by *Agathis* was estimated in four stands, the youngest of which (planted in 1970) was situated outside the study catchment. The plantations were established in 1942, 1956 and 1966 respectively (see also Fig. 2.6). Observations started in January 1977 in the 1942 and 1966 stands as well as in *Eupatorium* thicket. Measurements in the remaining plantations commenced in March 1977. All observations lasted until February 1978.

The seasonal course of the litter production is illustrated in Figures 5.2a (total litter) and 5.2b (leaf litter only). Standard deviations have been omitted in these figures for reasons of clarity, but have been included in Tables 5.2a (leaf litter) and 5.2b (woody litter). Results of statistical testing are summarized in Table 5.1. Total and woody litter appear to exhibit some differentiation. The amounts of leaf litter produced by the shrub community and the various stands of *Agathis* do not differ significantly. Differences do exist with regards to the amounts observed in the teak, pine and Rainforest plots (*cf.* sections 5.3.4 and 5.3.7).

Both total and leaf litterfall show a distinct minimum around July/August, *i.e.* in the first half of the dry season. *Agathis* seems to respond more intensely to the subsequent drought than *Eupatorium*. The pattern of leaf shedding for *Eupatorium* differs from that of *Agathis*. (Fig. 5.2b).

> *Similar responses to seasonal dry spells in an otherwise humid climate have been reported for a number of natural tropical forests (*e.g.* FÖLSTER & DE LAS SALAS, 1976; EDWARDS, 1977; LIM, 1978).*

Table 5.1 Statistical testing (student's t) of the amounts of total and woody litter produced by plantations of *Agathis loranthifolia* and *Eupatorium*.

total litter	*Agathis* 1942	*Agathis* 1956	*Agathis* 1966	*Agathis* 1970	*Eupatorium*
Agathis 1942	-	N.S.	$\alpha = 0.05$	$\alpha = 0.01$	$\alpha = 0.05$
Agathis 1956		-	$\alpha = 0.05$	$\alpha = 0.01$	$\alpha = 0.05$
Agathis 1966			-	N.S.	N.S.
Agathis 1970				-	N.S.

woody litter	*Agathis* 1942	*Agathis* 1956	*Agathis* 1966	*Agathis* 1970
Agathis 1942	-	N.S.	$\alpha = 0.01$*	$\alpha = 0.01$*
Agathis 1956		-	$\alpha = 0.01$	$\alpha = 0.01$*
Agathis 1966			-	$\alpha = 0.05$
Agathis 1970				-

N.S.: not significant at $\alpha < 0.05$

* : Mann & Whitney test

Fig. 5.2 Monthly litter production in plantations of *Agathis loranthifolia* & *Eupatorium* thicket

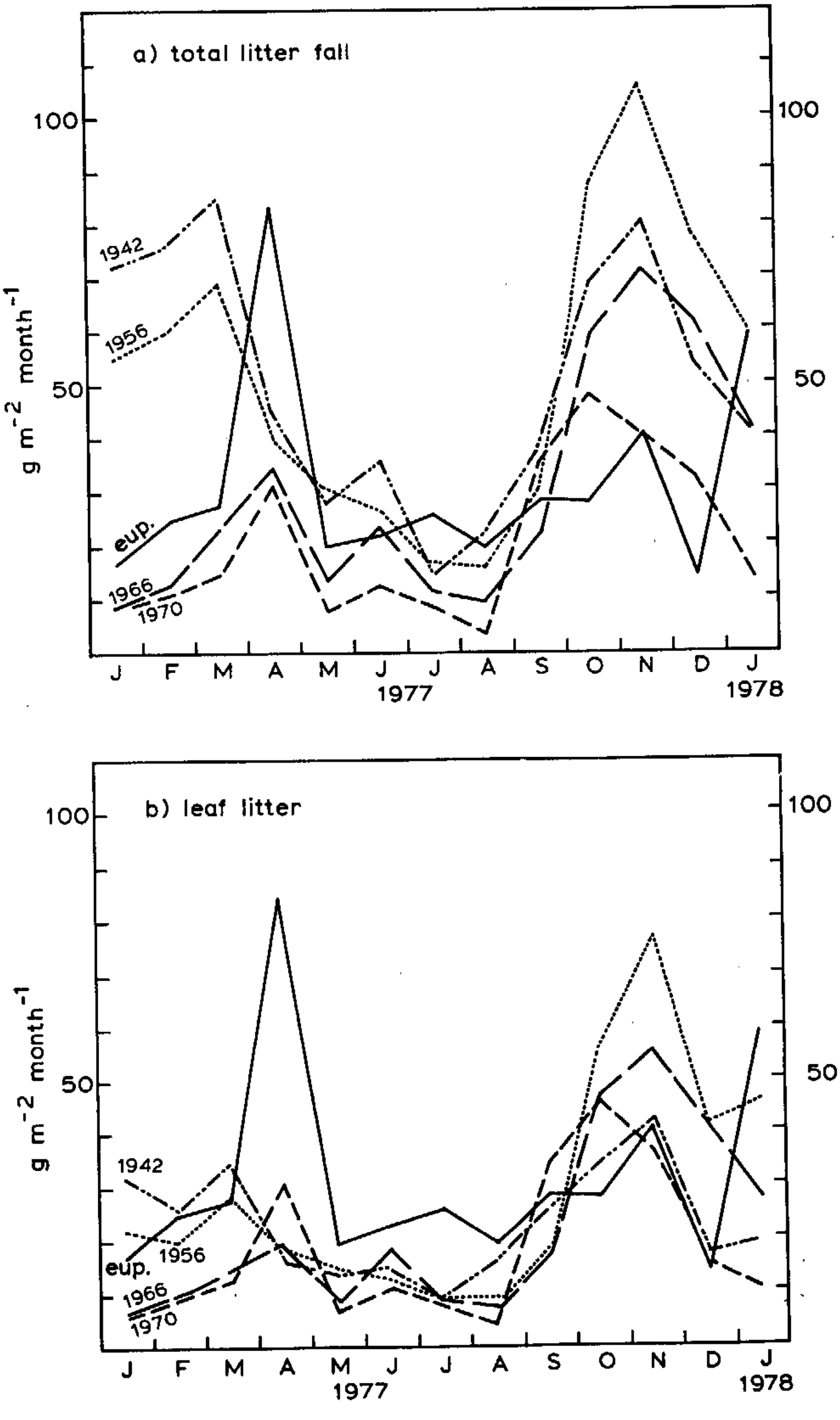


Table 5.2a Production of leaf litter (g m^{-2} $month^{-1}$) in plantations of *Agathis loranthifolia* of varying age* and *Eupatorium* thicket. Stand densities 160, 450, 580 and 2110 trees ha^{-1} respectively.

	Agathis 1942	*Agathis* 1956	*Agathis* 1966	*Agathis* 1970	*Eupatorium* incl. herb layer
January '77	31.7 ± 6.1	22°	6.2 ± 2.3	(6)°°	16.8 ± 6.0
February	25.6 ± 3.8	20°	9.8 ± 3.9	(9)°°	24.9 ± 5.9
March	34.2 ± 7.9	28°	15.1 ± 8.6	(13)°°	27.3 ± 7.3
April	16.2 ± 6.0	18.8 ± 4.2	19.2 ± 8.0	31.0 ± 12.5	83.4 ± 20.3
May	13.2 ± 4.3	14.8 ± 2.5	8.9 ± 4.2	7.7 ± 5.3	19.0 ± 7.1
June	14.3 ± 7.8	13.1 ± 2.3	10.8 ± 9.0	10.7 ± 7.6	22.6 ± 6.3
July	9.3 ± 1.9	9.0 ± 1.3	9.1 ± 1.7	7.6 ± 1.7	25.4 ± 7.2
August	16.2 ± 2.8	8.8**	7.2 ± 5.3	3.6 ± 0.8	19.0 ± 8.5
September	25.6 ± 2.9	18.4 ± 4.8	17.4 ± 9.0	33.6**	28.1 ± 12.4
October	34.3 ± 7.3	56.8 ± 11.6	47.0 ± 22.7	45.3 ± 25.0	27.8 ± 12.3
November	42.6 ± 14.2	77.2 ± 6.4	55.8 ± 11.5	35.8 ± 13.4	41.1 ± 6.1
December	17.2 ± 7.4	41.8 ± 7.6	40.8 ± 12.5	15.6 ± 8.4	13.8 ± 6.0
January '78	19.4 ± 9.9	46.1 ± 11.3	27.2 ± 16.3	10.8 ± 7.9	59.0 ± 30.4
Estimated total (g m^{-2})	300	375	282	230	408

°estimated via regression analysis

°°arbitrarily estimated value

*excluding litter produced by undergrowth which was either scarcely developed due to cuttings (*Agathis* 1942; 1970 or consisted mainly of tall grasses whose litter was not trapped (*Agathis*, 1966)

**one sample available only

Table 5.2b Production of woody litter (gm^{-2} $month^{-1}$) in plantations of *Agathis loranthifolia* of varying age.

	Agathis 1942				*Agathis* 1956				*Agathis* 1966				*Agathis* 1970
	twigs	bark	seeds	total	twigs	bark	seeds	total	twigs	bark	seeds	total	
January '77	40.2 ± 26.5				33°				3.1 2.2 ± 1.2 1.3				n.m.
February	50.0 ± 26.8				40°				2.6 ± 2.9				n.m.
March	51.2 ± 40.1				41°				7.0 ± 4.2				n.m.
April	28.5 ± 13.3				21.2 ± 6.4				14.7 ± 11.0				0.7 ± 0.9
May	14.1 ± 8.5				15.8 ± 3.1				4.2 ± 3.9				–
June	21.0 ± 15.7				13.3 ± 3.9				4.6 ± 4.3				1.9
July	5.1 ± 2.9				7.6 ± 3.5				1.9 ± 1.0				0.5 ± 0.7
August	5.8 ± 3.6				7.0*				2.4 ± 1.0				–
September	1.5	7.1	3.4	12.1 ± 5.7	7.0	3.3	2.2	12.6 ± 6.2	3.2	0.5	0.1	3.8 ± 2.5	1.2 ± 0.8
October	13.1	17.9	3.4	34.4 ± 14.2	15.4	7.6	6.8	29.9** ± 15.3	10.1	1.5	0.4	11.9 ± 6.5	2.3 ± 1.7
November	11.9	19.2	7.0	38.1 ± 22.8	13.3	12.6	3.4	29.4 ± 9.4	11.9	1.9	2.1	16.0 ± 9.8	3.8 ± 2.9
December	14.3	15.9	5.6	35.9 ± 19.1	25.6	7.7	2.1	35.4 ± 17.2	15.2	2.5	1.7	19.4 ± 10.7	15.8 ± 7.4
January '78	3.6	17.1	0.4	21.2 ± 22.5	4.8 ± 2.5	5.2 ± 1.5	2.2 ± 2.3***	12.2 ± 5.0	12.7	1.1	0.1	13.9 ± 20.4	2.6 ± 2.5
Total	44.4	358			66.1		298		53.1		105		31

12.6 better ±6.0

° estimated via regression analysis
n.m. not measured
* one sample available only
** including one outlier
***excluding one outlier but including an immature cone

Apart from site-specific, species-determined and climatic influences a major factor determining the amount of litter returning to the forest floor is the degree of canopy closure (BRAY & GORHAM, 1964). In plantations both stand age and degree of thinning are important in this respect. The absolute and relative amounts of woody litter produced by the four *Agathis* stands increase with stand age (Table 5.2b) but such a trend is less obvious for the leaf litter component. If the production of leaf litter is expressed on a per-tree basis, however, a clear trend does emerge: there is a strong increase both in leaf- and in total litter production with age as would be expected from the increase in tree biomass with age (Table 5.3). Also, the relative amounts of leaf litter decrease markedly with age, viz. from 88% in the 7-yr old stand to 46% in the oldest plantation.

To avoid effects of tree density, values of annual litterfall in various tropical woodlands, both plantations and natural forests, have been expressed on an areal (kgha^{-1}) and on a per-tree (kg tree^{-1} yr^{-1}) basis in Table 5.3.

> *The data presented in this table suggest high production rates of (leaf) litter by Terminalia ivorensis (a deciduous species) and Mora excelsa and on the whole much lower amounts of litter returning to the forest floor in plantations of Araucariaceae, be it Araucaria or Agathis. In fact, seen on a per-tree basis, only the oldest Agathis stand produces significant quantities of litter. Under normal stocking conditions this would mean values of about 5.7 and 12.4 t ha^{-1} for leaf- and total litter respectively, i.e. higher than produced by the local Rain Forests (Table 5.3). Litter production per tree in 42-yr old plantations of Hoop pine in Queensland is remarkably low and similar to that of 21-yr old Agathis in Java. In contrast to Terminalia ivorensis which does not show very large differences in production with age (Table 5.3). The amounts shed annually by Agathis loranthifolia increase dramatically with age, especially after about 20 years. This is in accordance with the occurrence of maximum growth rates after about 30 years (SUHARLAN et al., 1975). It is somewhat difficult to tell to what extent the relatively low production of litter by Agathis is due to site characteristics (soils) or a characteristic of the species. The fact that also the natural forests in the region remain on the low side of the production range (cf. Tables 5.3 and 5.13) points to the first factor.*
>
> *Nearby plantations of Tectona (25 yr) and Pinus merkusii (12 yr) on the other hand produced about two times as much leaf litter per tree than 21- and 11-yr old Agathis specimens. Also a very young plantation of Acacia auriculiformis in West Java was reported to return at least six times the amounts of leaf litter observed in the youngest Agathis stand (TEAM VEGETATION & EROSION, 1979a). It should be added, however, that this plantation was growing on a soil derived from clayey sedimentary rock rich in bases.*

The fairly low production of litter by *Agathis* may therefore well be characteristic for the species. In its natural habitat it is usually found on poor sites, *e.g.* on the bleached sands of Serawak (BRUNIG, 1971).

Eupatorium odoratum appeared to produce similar amounts of litter as observed in the dry zone of Nigeria (OLAOYE, 1974).

Table 5.3 Litter production in selected tropical forests

Location	Forest type	Age (yr)	Total litterfall		Leaf litterfall		Annual rainfall (mm)	Elevation (m a.s.l.)
			t ha^{-1} yr^{-1}	kg tree^{-1} yr^{-1}	t ha^{-1} yr^{-1}	kg tree^{-1}yr^{-1}		
Indonesia[1] °30' S	*Agathis loranthifolia***	35	5.9	36.6	2.7	16.8	4760	*c.* 600
	ibidem	21	6.2	13.7	3.5	7.8		
	ibidem	11	3.8	6.5	2.8	4.8		
	ibidem	7	2.5	1.2	2.2	1.1		
	Eupatorium sp.	5 ?	3.9	-	-	-		
Nigeria[2] 7° N	*E. odoratum*	5	4.3	-	-	-	1100	200
Ivory Coast[3], 6° N, 2 sites	*Terminalia ivorensis*	22	8.6	18.1	7.2 (3.3)*	15.1 (20.1)*	2100	50-100
Trinidad[4], 10° S	*Mora excelsa*	natural forest	-	-	7.0 ± 1.3	23.3	3300	200
Australia[5]. 17° S 2 sites	*Araucaria cunninghamii*	42	8.2 ± 1.6	12.4	*c.* 6.3	*c.* 8.8	2100	700
		41	9.9 ± 4.1	13.0				
India[6], 30° N	*ibidem*	30	-	-	6.1	15.4	2000	> 500
Indonesia[7], 6°30' S	*Acacia auriculiformis*	4-5	10.7	10.6	6.4	6.3		
	LMRF***[1]	natural forest	6.8	-	5.4	-	4570	800
	ibidem	*ibidem*	6.0	-	4.5	-	3380	1550
Papua[8], 6° S	*ibidem*	*ibidem*	7.6	7.6-8.9	6.4+	6.5-7.5	4000	2500
Malaysia[9], 3° N	LRF****	*ibidem*	9.4		6.4	-	2050	120

**Terminalia* only;

**Values for January, 1977 and 1978 averaged;

***Lower Montane Rain Forest;

****Lowland Rain Forest;

+"non-woody" material

[1] present study
[2] Olaoye, 1974
[3] Bernhard-Reversat, 1976
[4] Cornforth, 1970ab
[5] Brasell *et al.*, 1980
[6] Seth *et al.*, 1963
[7] Team Vegetation and Erosion 1979a
[8] Yamada, 1976
[9] Edwards, 1977
[10] Lim, 1978

5.3.2 *Nutrient concentration of Agathis and Eupatorium litter*

Average concentrations of nutrients found in the litter of *Agathis* and *Eupatorium* are presented in Table 5.4.

Concentrations of most elements are distinctly higher in the leaf litter component as is commonly found (*e.g.* BERNHARD, 1970; GOLLEY *et al.*, 1975). Aluminium, Fe and P are exceptions in this regard.

In one case (*Agathis* 1942) the woody litter has been divided into three components which have been analyzed separately (Table 5.4b).

Leaves shed by *Eupatorium* are considerably richer in Ca, P, Si, Al and Fe than *Agathis* litter, but they contain less Na and K. Magnesium and Mn concentrations are similar for both species.

> *(Undergrowth is often found to exhibit higher concentrations than the tree stratum (OVINGTON, 1968), and as such the observed pattern is as expected. The low Na (and K ?) concentrations found in Eupatorium litter may reflect a smaller catch of aerosols associated with the species' smaller leaf area surface or simply leaching in the collection trays).*
>
> *The chemical composition of the litter produced by the various stands of Agathis exhibits only minor differences. The 11-yr old stand is remarkably rich in Ca, but relatively poor in Na, whilst the youngest plantation is quite rich in Mg and Fe and poor in K. The differences can be explained in terms of soil and rock.*
>
> *No significant differences were observed for the mixed woody litter of the eleven-and 21-yr old stands. No average values were calculated for the youngest plantation as only two samples (June 1977 and a composite sample over the period September until January) were available. A comparison of overall weighted mean concentrations was possible, however, and showed the woody litter of the Agathis 1970 stand to be relatively rich in Mg and P and rather poor in Mn. This again compares favourably with the low Mn content of the underlying rock (cf. the fairly low - but not significantly so-value for Mn in the leaf litter of this stand).*

Twigs from 35-yr old *Agathis* specimens appear to contain more Ca, Mg and Na than either bark or seed litter, whereas seeds are richest in K, P and N. Bark litter often attains intermediate values but is relatively poor in P and K. No significant differences between the components were observed for Si, Al or Fe.

The seasonal course of macro-element concentrations in leaf litter produced by *Eupatorium* and the three oldest stands of *Agathis* is depicted in Fig. 5.3. The magnitude of the oscillations of these "chemographs" clearly differs between species and elements. Calcium for example exhibits quite irregular patterns both for *Eupatorium* and *Agathis* with no direct relation to the rainfall pattern.

Sodium and K on the other hand attain their highest values during the dry season due to the accumulation of aerosols from the Indian Ocean and the absence of leaching rains. The seasonal trend for Mg, and to a lesser extent that of P, resembles that of Na in the case of *Eupatorium*. Fluctuations in the Mg and P concentrations in the *Agathis* litter are only minor, except for the oldest stand which exhibits a somewhat more irregular pattern in this regard.

Table 5.5 puts the present observations into a broader perspective.

Table 5.4a Average nutrient concentration (mg g^{-1} dry wt) of leaf litter from *Agathis* and *Eupatorium*

	Ca	Mg	Na	K	P	SiO$_2$	Al	Fe	Mn
Agathis '42	$26.4^{a*} \pm 3.6$	$4.8^{a} \pm 0.8$	$1.0^{a} + 0.5$	$4.8^{a} \pm 2.2$	$0.4^{a} \pm 0.1$	8.1 ± 3.7	$0.27^{a} \pm 0.10$	$0.27^{a} \pm 0.11$	$0.31^{a} \pm 0.14$
Agathis '56	$29.5^{ab} \pm 6.6$	$4.5^{a} \pm 0.4$	$0.8^{a} \pm 0.4$	2.8 ± 1.1	$0.3^{a} \pm 0.04$	4.2 ± 1.2	$0.21^{a} \pm 0.07$	$0.23^{a} \pm 0.10$	$0.33^{a} \pm 0.06$
Agathis '66	$40.2^{c} \pm 7.9$	$4.6^{a} \pm 0.5$	0.5 ± 0.1	$4.0^{a} \pm 1.1$	$0.4^{a} \pm 0.05$	3.9 ± 0.8	$0.75^{a} \pm 0.18$	$0.31^{ac} \pm 0.15$	$0.44^{a} \pm 0.20$
Agathis '70	$30.4^{b} \pm 4.5$	5.9 ± 0.6	$1.0^{a} \pm 0.4$	$1.9^{b} \pm 0.8$	$0.3^{a} \pm 0.04$	-	-	$0.39^{c} \pm 0.08$	$0.26^{a} \pm 0.11$
Eupatorium	$39.0^{c} \pm 7.5$	$4.9^{a} \pm 1.1$	0.2 ± 0.1	$1.6^{b} \pm 1.1$	1.1 ± 0.2	28.1 ± 5.9	2.0 ± 0.8	1.75 ± 0.59	0.26 ± 0.08

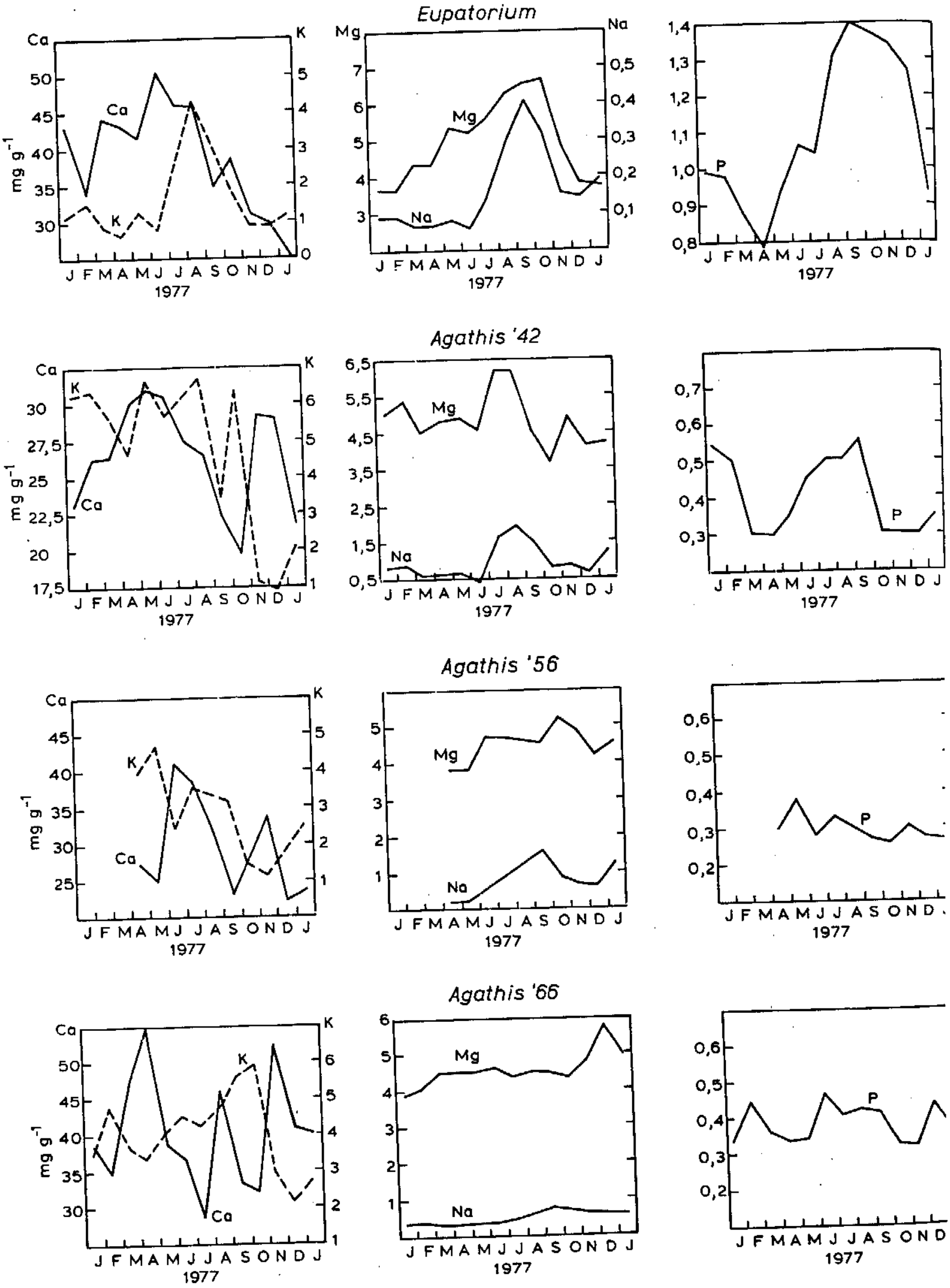
*Columns sharing the same letter are not statistically different at $\alpha < 0.05$

Table 5.4b Average nutrient concentration (mg g^{-1} dry wt) of woody litter from *Agathis*

	Ca	Mg	Na	K	P	SiO$_2$	Al	Fe	Mn
Agathis '42									
twigs	15.2 ± 2.5	3.1 ± 0.9	0.9 ± 0.3	$3.2^{bc} \pm 1.8$	$0.23^{b} \pm 0.16$	$6.8^{b} \pm 2.4$	$0.20^{b} \pm 0.09$	0.17 ± 0.08	$0.09^{b} \pm 0.03$
bark	11.2 ± 2.5	$0.8^{b} \pm 0.1$	0.2 ± 0.1	$1.6^{c} \pm 0.4$	$0.08^{b} \pm 0.05$	$4.7^{b} \pm 0.8$	$0.47^{b} \pm 0.39$	0.27 ± 0.17	$0.08^{bc} \pm 0.07$
seed	1.8 ± 1.2	$0.7^{b} \pm 0.3$	0.2 ± 0.1	$5.7^{b} \pm 4.2$	0.50 ± 0.21	$6.2^{b} \pm 2.9$	$0.10^{b} \pm 0.08$	0.57 ± 0.33	$0.05^{c} \pm 0.03$
Agathis '56*	$9.5^{a} \pm 5.5$	$2.6^{a} \pm 1.5$	0.5 ± 0.3	2.9 ± 1.0	$0.34^{a} \pm 0.09$	$3.5^{a} \pm 0.8$	$0.21^{a} \pm 0.11$	0.30 ± 0.18	$0.09^{a} \pm 0.05$
Agathis '66*	$16.8^{a} \pm 2.7$	$3.0^{a} \pm 0.6$	0.4 ± 0.1	1.7 ± 0.6	$0.39^{a} \pm 0.16$	$4.3^{a} \pm 1.2$	$0.61^{a} \pm 0.56$	0.35 ± 0.24	$0.11^{a} \pm 0.05$

*mixed woody litter

Fig. 5.3 Seasonal course in nutrient concentration in leaf litterfall from *Eupatorium* (a) and *Agathis* (b, c, d). All values in mg g^{-1} dry wt.



e 5.5 Nutrient concentrations in leaf litterfall (mg g^{-1} dry wt) of selected (sub)tropical woodlands

n	Forest type	Ca	Mg	Na	K	P	N	SiO_2	soil/rock
ia[1] S	*Agathis loranthifolia* (1942)	26.4	4.3	0.9	4.8	0.4	7.4	7.7	andesitic volcanic ashes
	Lower Montane Rain forest	21.6	3.9	0.5	4.8	0.6	-	40.8	*ibidem*
oast[2]	*Terminalia ivorensis*								
	site 1 (Yapo)	6.3	4.3	-	2.7	1.2	12.3	-	arkose/schists
	site 2 (Banco)	11.0	2.7	-	3.4	0.4	16.6	-	sands
d[3]	*Mora excelsa*								
	site 1 (Valencia)	10.0	2.2	-	1.7	0.5	9.0	-	sands/gravel
	site 2 (Matura)	8.2	2.1	-	1.5	0.3	8.0	-	phyllite/schists
ia[4]*	*Araucaria cunninghamii*								
	site 1	20.2	2.4	0.35	5.5	1.1	9.3	-	basalts & pyroclasts
	site 2	16.2	3.3	0.38	3.8	0.9	8.8	-	pyroclasts
30° N	*ibidem*	28.5	2.9	-	4.2	2.8	5.6	7.3	alluvium
[5], 25°N	*Shorea robusta*	15.8	4.8	0.5	4.9	4.4	8.1	8	sandstones

ted mean concentration;
nt study
ard-Reversat, 1976;
orth, 1970a;
ll *et al* ., 1980;
et *al*., 1963;
, 1968;

Compared to other locations the *Agathis* litter is quite rich in Ca and Na and somewhat low in N and perhaps P. Other constituents fall well within the published range.

Average concentrations of K and P in litter from *Eupatorium odoratum* in Nigeria (OLAOYE, 1974) did not differ significantly from the concentrations found in the present study.

5.3.3 *Nutrient accession via litterfall from Agathis and Eupatorium*

Combining the amounts of litter produced per month with the respective chemical concentrations yields the accession of chemical elements to the forest floor via litterfall. Rates are usually expressed as kg $ha^{-1}yr^{-1}$. Table 5.6 gives the total amounts of nutrients returning annually to the soil in this way for the *Agathis* and *Eupatorium* plots whilst a comparison is made with other tropical locations in Table 5.7. As related before (Table 5.2a) the present estimates do not include the amounts of nutrients involved with litterfall produced by the herb- and shrublayers of the forest. As such the figures presented for the *Agathis* sites in Table 5.6 are underestimates, although it is difficult to assign an order of magnitude to the errors involved.

Table 5.6 Total nutrient return via litterfall (kg ha^{-1} yr^{-1}) from *Agathis* and *Eupatorium* between 1 February, 1977 and 1 February, 1978

Leaves	Ca	Mg	Na	K	P	N*	SiO_2	Al	Fe	Mn	Amount of litter
Eupatorium	148	19.0	0.6	5.6	4.1	-	110.5	7.0	6.1	0.95	3910
Agathis 1942	70	12.6	2.5	11.7	1.0	20	22	0.7	0.7	0.80	2680
Agathis 1966	115	13.1	1.5	10.5	1.0	-	11	0.7	0.9	0.93	2760
Woody											
Agathis 1942	30	4.6	1.1	8.9	0.8	18	20	0.6	0.9	0.23	3180
Agathis 1966	24	1.1	0.6	2.6	0.5	-	4.5	0.6	0.6	0.12	1030
Total litter											
Agathis 1942	100	17.2	3.6	20.6	1.8	38	41	1.4	1.6	1.0	5860
Agathis 1966	139	14.2	2.0	13.1	1.5	-	15.5	1.3	1.5	1.0	3790

*see Appendix 4 for a summary of nitrogen data

Table 5.7 Annual rate of nutrient return to the forest floor via litter in selected tropical forests*

a) leaf fall only, b) total litterfall

	Location	Forest type	Litter fall	Accession rate (kg ha^{-1} yr^{-1})						
			(t ha^{-1} yr^{-1})^1	Ca	Mg	Na	K	P	N	SiO_2
(a)	Ivory Coast[1] 6° N	*Terminalia ivorensis*								
		site 1 (Yapo)	3.3	36	9	-	11	1	40	-
		site 2 (Banco)	3.0	19	13	-	8	4	50	-
	Trinidad[2] 10° S	*Mora excelsa*								
		site 1 (Valencia)	6.8	68	15	-	11.5	3.3	61	-
		site 2 (Matura)	7.0	57	15	-	10.5	2.4	56	-
	India[3] 25° N	*Shorea robusta*	2.0	31.5	9.5	1	10	9	16	16
	"[4] 30° N	*Araucaria cunninghamii*	5.9	168	17	-	25	16.5	33	43
	Indonesia[5] 6°30' S	Lower Montane Rain forest	5.4	128	22.5	2.5	27.5	3	*c.* 62	219
(b)	Ivory Coast[1]	*T. ivorensis*								
		site 1 (Yapo)	8.6	120	26	-	42	3.8	112	-
		site 2 (Banco)	8.3	65	35	-	33	8.5	156	-
	Australia[6] 17° S	*Araucaria cunninghamii*								
		site 1	8.2	177	21.5	3	50	10	82	-
		site 2	9.9	200	40	4.5	46	11	108	-
	Indonesia[5] 6°30' S	Lower Montane Rain forest	6.8	154	27	3	37	4	-	238

[1] Bernhard-Reversat 1976;
[2] Cornforth, 1970a;
[3] Singh, 1968, 1969;
[4] Seth *et al.*; 1963
[5] present study;
[6] Brasell *et al.*, 1980.
*for additional data on these forests see Table 5.3

> *Nutrient accession via leaf fall in the Agathis plantations is quite comparable to that of the natural Mora excelsa forests of Trinidad, despite the fact that the latter forests produce more than twice as much leaf litter (CORNFORTH, 1970a). The Terminalia ivorensis plantations in Ivory Coast are also quite similar, although Agathis is much lower in N. Transfer rates of N and* SiO_2 *with Agathis are about the same as for Shorea robusta in India (SINGH, 1968; 1969).*

The local climax forest (see also section 5.3.7) exhibits much greater transfer rates than the *Agathis* plantations, a feature also noted by BERNHARD REVERSAT (1976) who compared *Terminalia* and natural forests in Ivory Coast. Conversely, *Eupatorium* shrubs have accession rates for Ca, Mg and P and probably N (OLAOYE, 1974) matching those for the climax forest, illustrating its pioneering nature (*cf.* EWEL, 1976).

As far as *total litter* is concerned the return of nutrients by *Agathis* appears to be somewhat low for Mg and K and definitely poor for P and N in contrast to the other forests cited in Table 5.7.

5.3.4 *Production of litter by Tectona grandis and Pinus merkusii*

Litterfall in a 12 yr-old stand of *P. merkusii* and in a *Tectona* plantation dating from 1952 was estimated from 1 February, 1977 until 1 February, 1978. From May 1977 onwards additional measurements were made in a better-stocked teak forest (1946) as well. Sites have been described in section 2.6.2.

Results of the litter study are presented in Fig. 5.4 and Table 5.8 in the same manner as for *Agathis* (Fig. 5.2 and Table 5.2). The deciduous habit of *Tectona* is clearly illustrated for both sites, with the seasonal amplitude being less extreme in the older and more wind-protected stand. Litter returns between May 1977 and February 1978 were quite similar for both sites (viz. 470 and 458 gm^{-2} for the 1952 and 1946 plantations respectively). The overall total produced by the youngest teak stand was significantly less than that of the pine plantation (Table 5.9). The return of seed litter was quite seasonal in the case of *P. Merkusii*, with a definite peak in August and September. The shedding of needles appears to react rapidly to decreasing soil moisture levels.

> *Production increased markedly in the relatively dry month of May as well as during the dry season, whereas a quick return to normal levels was observed after the return of the rains in November. Similar responses of needle fall to dry periods are reported for pine trees in tropical Africa, viz. P. caribaea in Nigeria (EGUNJOBI & ONWELUZO, 1979) and P. patula in Tanzania (LUNDGREN, 1978). In fact, the latter author noted a bimodal distribution in the litterfall. The second (but smaller) peak coincided with a top production of cones and a secondary peak in rainfall.*

Results of statistical testing of data from the 1952 *Tectona*, 1956-*Agathis*, 1965 *Pinus* and 1966 *Agathis* stands are given in Table 5.9, whereas a comparison with other teak and pine forests from (sub)-tropical latitudes is presented in Table 5.10.

Fig. 5.4 : Monthly production of litter in plantations of *Pinus merkusii* & *Tectona grandis* (gm^{-2})

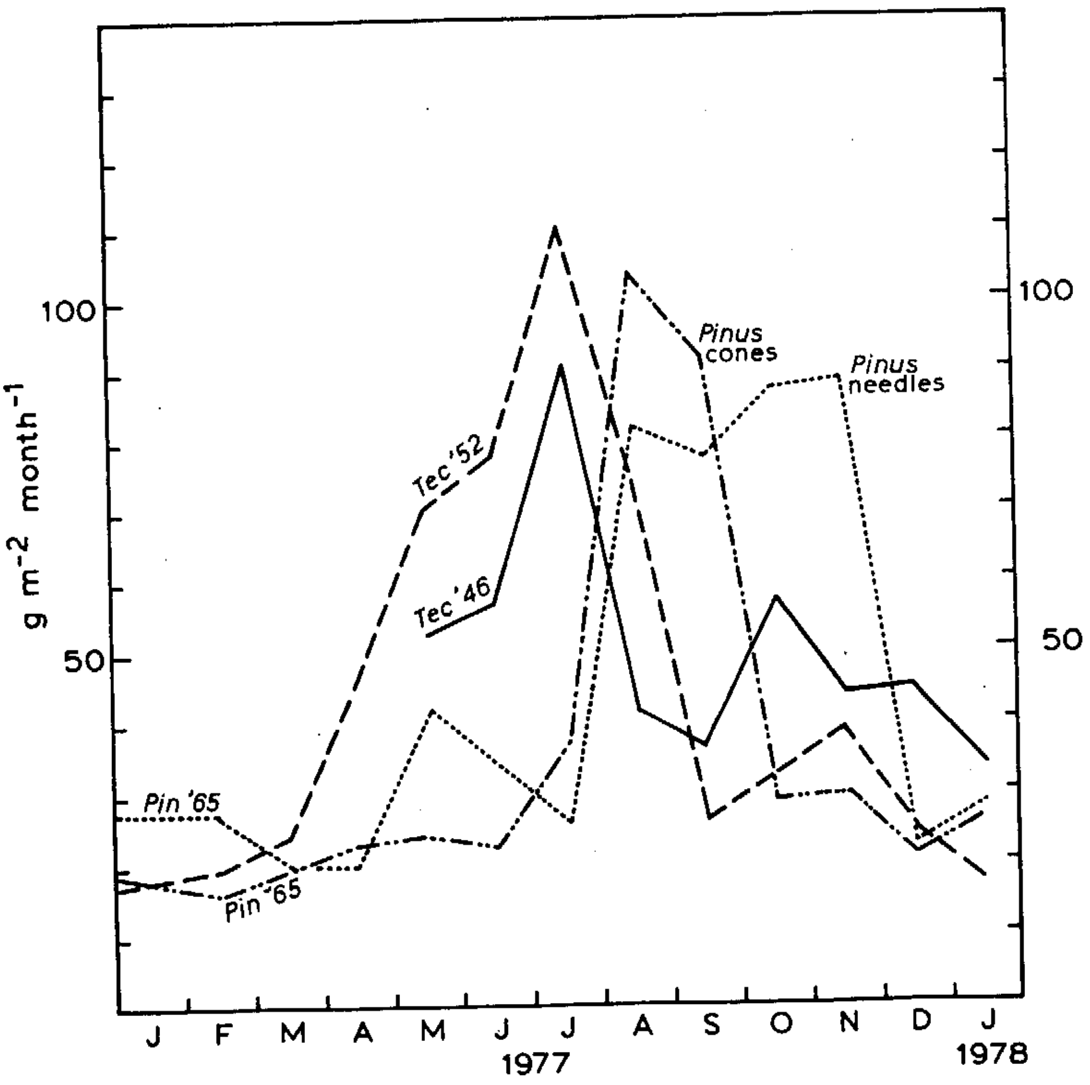


Table 5.8 Production of leaf litter* ($gm^{-2} month^{-2}$) in plantations of *P. merkusii* (1965) and *Tectona grandis* (1952 & 1946); stand densities 720, 342 and *c.* 500 trees ha^{-1} respectively.

	Litter production (gm^{-2} $month^{-1}$)			
	Pinus merkusii (1965)		*Tectona grandis*	
	needles	woody litter	(1952)	(1946)
February '77	27.4 ± 10.0	16.0 ± 10.0	19.1 ± 5.8	-
March	20.4 ± 6.6	19.0 ± 18.3	24.2 ± 6.7	-
April	19.7 ± 5.3	23.0 ± 16.3	46.0 ± 19.9	-
May	41.1 ± 10.3	24.3 ± 15.8	70.5 ± 17.8	52.4 ± 15.5
June	34.6 ± 8.2	22.8 ± 18.2	78.5**± 7.7	57.0 ± 8.2
July	26.2 ± 2.8	36.8 ± 14.4	110.0 ± 29.4	90.6 ± 17.4
August	81.7 ± 32.0	103.1 ± 71.2	73.3 ± 34.6	45.4 ± 4.0
September	77.3 ± 23.2	91.3 ± 75.4 {s 90.7 {t 0.6	25.9 ± 8.1 {l 22.7 {t 0.7 {s 1.7	36.2 ± 7.7
October	87.2 ± 26.9	28.5 ± 8.3 {s 28.1 {t 0.4	32.2 ± 6.0 {l 29.3 {t 0.1 {s 4.0	57.3 ± 15.9
November	88.7 ± 26.0	29.9 ± 35.4 {s 29.3 {t 0.6	38.8 ± 23.2 {l 35.4 {t 0.1 {s 3.2	43.9 ± 4.5
December	22.6 ± 7.6	20.7 ± 15.6 {s 20.4 {t 0.3	24.5 ± 11.9 {l 23.9 {t - {s 0.6	45.0 ± 14.2
January '78	28.0 ± 8.3	26.6 ± 12.6 {s 24.6 {t 2.0	16.5 ± 9.2 {l 15.8 {t 0.3 {s 0.4	33.7 ± 1.4 {l 28.9 {t - {s 4.8
Total production (gm^{-2} yr^{-1})	555	442	560	(545)

*excluding litter produced by undergrowth which is poorly developed in both the *Tectona* '52 stand (cuttings) and the pine forest (densely stocked)

**mean of two samples

l = leaves; t = twigs; s = seeds

Table 5.9 Statistical testing (student's *t*) of amounts of litter produced by plantations of *Tectona* (1952), *Agathis* (1956), *Pinus* (1965) and *Agathis* (1966)

Total litter	*Tec* '52	*Ag* '56	*Pin* '65	*Ag* '66
Tectona '52	-	N.S.	$\alpha = 0.05$	
Agathis '56		-	$\alpha = 0.10$	$\alpha = 0.05$
Pinus '65			-	$\alpha = 0.01$
Agathis '66				-
Leaf litter	*Tec* '52	*Ag* '56	*Pin* '65	*Ag* '66
Tectona '52	-	$\alpha = 0.05$	$\alpha = 0.05$	$\alpha = 0.05$
Agathis '56		-	$\alpha = 0.05$	N.S.
Pinus '65			-	$\alpha = 0.05$
Agathis '66				-
Woody litter	*Tec* '52	*Ag* '56	*Pin* '65	*Ag* '66
Tectona '52	-	$\alpha = 0.01$*	$\alpha = 0.01$	
Agathis '56			N.S.	$\alpha = 0.05$
Pinus '65			-	$\alpha = 0.01$
Agathis '66				$\alpha = 0.01$

N.S. not significant at $\alpha < 0.05$
* Mann & Whitney test

It is evident from Table 5.10 that the Javan teak plantation is quite comparable to the other stands, at least on an areal basis. Litter production per tree is much higher in Java than elsewhere, either as a result of age (as compared to the African stands) or climate (the Indian plantations growing under less favourable circumstances). Woody litter seems to be slightly less important in the present case.

The Indonesian conifers rank high in total litter production per tree (mainly as a result of a high seed cone component). They are followed closely by P. roxburghii and P. patula and are even surpassed at a later stage by P. radiata growing under warm temperate conditions in New Zealand (WILL, 1959). Leaf litterfall on an areal basis does not show great variations. The relatively young P. merkusii trees lag somewhat behind most other species cited although they produced more than twice as much needles as 10-yr old P. caribaea in Nigeria (EGUNJOBI & ONWELUZO, 1979).

5.3.5 *Nutrient concentration of litter from Tectona and Pinus*

The weighted mean composition of the leaf- and seed litterfall produced by the *Tectona* (1952) and *Pinus* (1965) plantations is presented in Tables 5.11a and b respectively, along with data from similar woodlands in the tropics.

Most of the Indonesian data have been tested statistically and results are indicated in Table 5.11 as well.

For all the Indonesian stands (*Tectona, Agathis* and *Pinus merkusii*) leaf litter contains more Ca, Mg and Mn than seed litter, whilst the reverse is true for K, P and Fe.

There are significant differences between the three species for Ca and Mg, with *Pinus merkusii* leaf litter containing the smallest and *Agathis* leaf litter the greatest amounts. *Tectona* and *Pinus* do not differ significantly in their Na, K, Al- and Fe concentrations, but *Agathis* again is richer in Na and K. Finally, the high SiO_2 and low Mn levels of *Tectona* litter are striking.

Table 5.10 Production of litter in selected (sub)tropical teak and pine plantations ($t\ ha^{-1}\ yr^{-1}$). Values between brackets : $kg\ tree^{-1}\ yr^{-1}$.

Location	Total litter $t\ ha^{-1}\ yr^{-1}$	Leaf litter $t\ ha^{-1}\ yr^{-1}$	Annual rainfall (mm)	Stand age (yr)	Reference
Indonesia, 6°30' S *Tectona grandis*	5.6 (16.4)	5.2* (15.1)	4760	25	present study
Nigeria, 7° N	9.0 (5.4)	8.2 (4.9)	1140	6-8	Egunjobi, 1974
Senegal, 15° N	-	5.0 ± 1.1 4.2 ± 0.2	1600	4 8	Maheut & Dommergues, 1960
India, 25° N	5.0 (9.2)	4.7 (8.6)	1100	old	Singh, 1968
ibidem, 30° N	5.9**(9.4)	5.3** (8.5)	2080	33	Seth *et al.*, 1963
	-	4.5***(9.0)		36	Dabral & Sagar, 1967
	7.8 (11.7)	-		39-43	Subba Rao *et al.*, 1972
Indonesia, 6° 30' S *Pinus merkusii*	10.0 (13.8)	5.6 (7.7)	3750	12	present study
ibidem, 1300 m.a.s.l.	2.8 (15.0)**	-	3300	21	Sutjahjo, 1975 quoted by
	3.6 (18.7)**	-		29	Thojib, 1981
Nigeria, 7° N	-	1.9 (0.6)	1180	4-5	Egunjobi & Fasehun, 1972
Pinus caribaea	-	5.8 (2.2)$^{+}$ 6.0 (3.1)$^{++}$		7-10	Egunjobi & Onweluzo, 1979
Tanzania, 5° S *P. patula*	6.2 (12.7)$^{+++}$	5.4 (10.9)$^{+++}$	1060	19	Lundgren, 1978
India, 30° N *P. roxburghii*	7.5**(14.1)	7.0**(13.2)	2080	30	Seth *et al.*, 1963
	-	4.8***(4.2)		26	Dabral & Sagar, 1967
	7.8 (14.0)	-		40-44	Subba Rao *et al.*, 1972
New Zealand, 38° S *P. radiata*	4.4 (1.2)	-	1520	5-8	Will, 1959
	6.3 (21.1)	4.3 (14.4)		26-29	*ibidem*

*calculated as 92 % of total based on observations between September, 1977 and January, 1978

**observation period of 7 months only

***air-dry material including some fine woody litter

$^{+}$unthinned stand

$^{++}$thinned stand

$^{+++}$assuming a tree density of 490 trees ha^{-1}

Table 5.11a Mean weighted composition of leaf litter in selected teak and conifer plantations in the (sub)tropics ($mg\ g^{-1}$ dry wt)

Location	Species	Age	Ca	Mg	Na	K	P	N	SiO_2	Al	Fe	Mn	substratum	reference
Indonesia, 6°30' S	*Tectona grandis*	25	20.8	2.8	0.2^{a}*	2.9^a	0.6	-	48.4	0.7^b	0.42^a	0.007	andesitic tuffs	present study
Nigeria, 7° N		6-8	22.1	2.5	0.23	7.7	1.0	10.1	-	-	-	-	granite, gneiss	Egunjobi, 1974
Senegal, 15° N		4	22.8	2.6	-	6.7	1.0	6.6	-	-	-	-	"grey soils"	Maheut & Dommergues, 1960
		8	11.6	3.8	-	6.6	0.6	9.4	-	-	-	-	-	
India, 25° N		natural	25.4	2.5	2.0	2.4	1.8	7.8	112	-	-	-	sandstones	Singh, 1968; 1969
ibidem 30° N		33	24.6	1.1	-	3.7	2.1	9.8	31	-	-	-	alluvium on	Seth *et al.*, 1963
		39-41	20.2	1.2	-	4.1	1.4	9.1	-	-	-	-	conglomerates	Srivastara *et al.*, 1972
Indonesia, 6°30' S	*P. merkusii*	12	9.2	1.9	0.4^a	2.5^a	0.4^a	-	6.1^a	0.62^{2b}	0.22^a	0.31^a	andesitic tuffs	present study
	Agathis	11	40.2	4.6	0.5^a	4.0^a	0.4^a	-	3.9^a	0.26	0.31^a	0.44^a	*ibidem*	
Tanzania, 5° S	*P. patula*	18-20	8.1	2.4	-	1.4	0.3	6.4	-	-	-	-	gneiss	Lundgren, 1978
Nigeria, 7° N	*P. caribaea*	7-10	6.0	1.7	0.85**	2.2	0.1	4.5	-	-	-	-	sandy	Egunjobi & Onweluzo, 1979
India, 30° N	*P. roxburghii*	30	6.6	1.3	-	5.6	1.9	10.5	3.4	-	-	-	alluvium	Seth *et al.*, 1963
		40-42	9.9	1.2	-	5.2	1.3	7.7	-	-	-	-		Srivastara *et al.*, 1972
New Zealand, 38° S	*P. radiata*	27-29	3.7	0.9	0.6	3.1	0.9	6.9	-	-	-	-	rhyolitic tuffs	Will, 1959

*columns sharing the same letter are not statistically different ($\alpha < 0.05$)

**litter produced by same stand when 5 yrs old (Egunjobi & Fasehun, 1972)

Table 5.11b Mean weighted composition of seed litter in selected teak and conifer plantations in the (sub)tropics ($mg\ g^{-1}$ dry wt)

Location	Species	Age	Ca	Mg	Na	K	P	N	SiO_2	Al	Fe	Mn	Reference
Indonesia, 6°30' S	*Tectona*** *grandis*	25	5.9	2.3	0.8	5.0^{a}*	1.4	-	21.5	1.3	0.9	0.01	present study
Nigeria, 7° N	*ibidem*	6-8	7.3	1.7	0.25	9.9	1.2	12.7	-	-	-	-	Egunjobi, 1974
Indonesia, 6°30' S	*Pinus merkusii*	12	1.4^a	0.6^a	0.2^a	3.5^a	0.4^a	-	10.6^a	0.8	0.4^a	0.008^a	present study
	Agathis	35	1.8^a	0.7^a	0.2^a	5.7^a	0.5^a	6.5	6.2^a	0.1	0.6^a	0.05^a	
Tanzania, 5° S	*P. patula*	18-20	2.3	1.2	-	2.0	0.7	11.0	-	-	-	-	Lundgren, 1978
Queensland, 17° S	*Araucaria*	40	1.4	1.0	0.3	7.0	1.2	8.8	-	-	-	-	Brasell *et al.*, 1980

*columns sharing the same letter are not statistically different ($\alpha < 0.05$)

**September, 1977 - February, 1978

> *Indeed Si is known to influence the uptake of Mn by certain plants (TANAKA & PARK, 1966; PEASLEE & FRINK, 1969).*
>
> *The observed differences can only partly be explained in terms of soil chemistry and must therefore in some cases be considered as characteristic for these species as well. For example, the soils at the teak and pine plots are richer in SiO_2 than those of the Agathis and Eupatorium sites. Yet Eupatorium litter shows a much higher concentration than either that of Agathis or Pinus. A glance at the data from India on the chemistry of litter in plantations of Tectona and Pinus roxburghii (SETH et al., 1963) leads to the same conclusion : teak litter is much richer in SiO_2 than pine litter. Apart from the above-mentioned interaction between Si and Mn there is evidence that the soil profile of the teak plantation is low in Mn as well, in accordance with the low Mn concentration of the litter. No such indications are available for Ca and Mg. In fact, the soil of the Agathis (1942) experimental plot exhibits a much lower base saturation than either that of the teak or the pine plantation, which do not differ greatly from each other (although the Tectona site is more fertile than the Pinus site).*

Seed litter from *Agathis* and *P. merkusii* is chemically very much alike, the only significant difference being the Al concentration, which is high in the case of pine seeds. The composition of *Tectona* seed (Table 5.11b) is represented by a bulked sample for the period September, 1977 till February, 1978 only and as such no average value is available for statistical testing. The available data seems to indicate higher concentrations (compared to *Agathis* and pine seed litter) of all elements except for Mn.

The nutrient concentration of the Indonesian *leaf* litter (*Tectona*, *P. merkusii*) is in many respects similar to that observed elsewhere in the (sub)tropics for teak and pine litter.

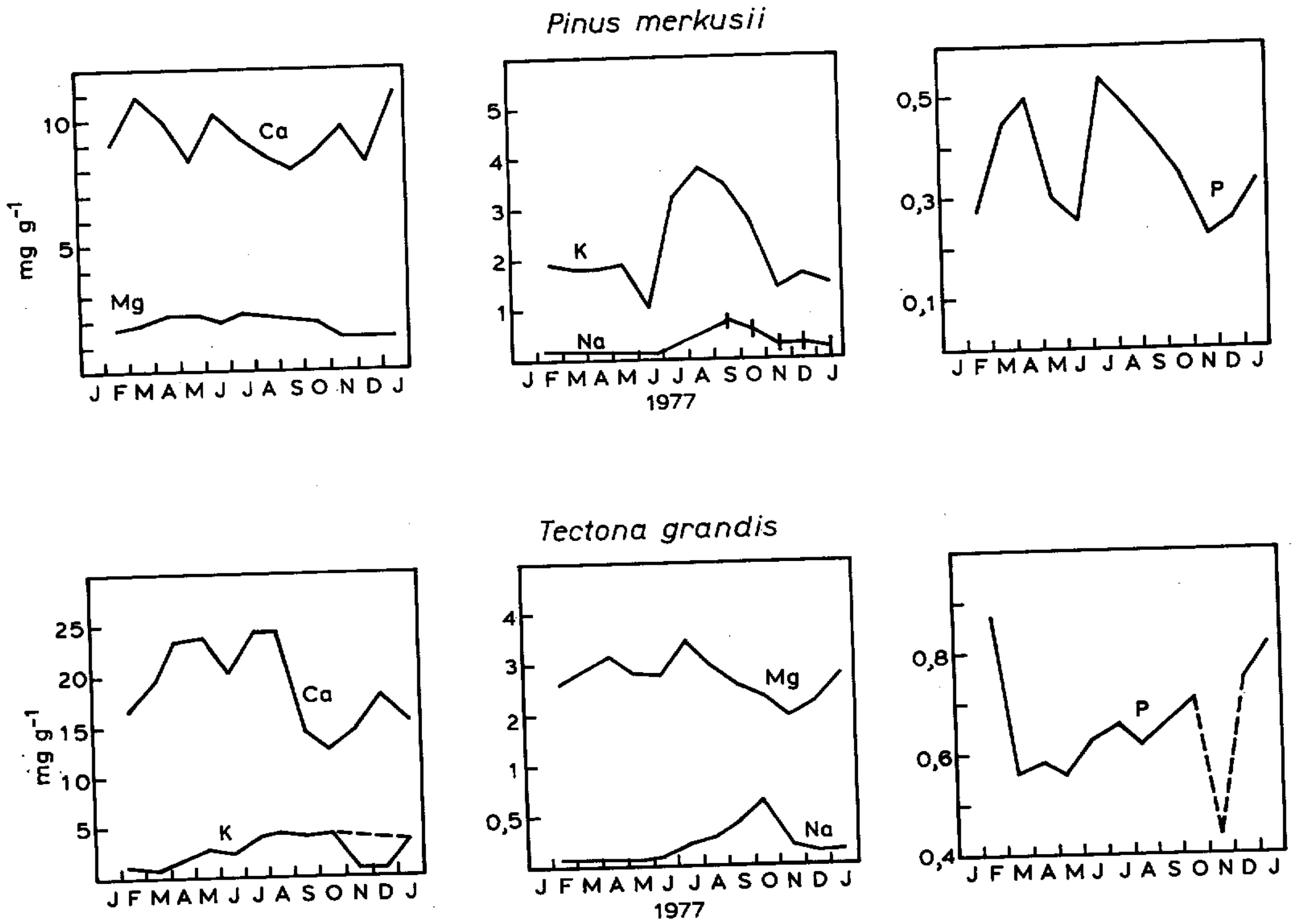
> *Java teak seems to be somewhat richer in Mg than reported for Indian samples, but poorer in K and P. The young African stands all exhibit high K levels in their litter (Table 5.11a). Pine needle litter from Java falls within the published range (Table 5.11) and is fairly poor in K and P (cf. P. patula and P. caribaea in Africa).*
>
> *Needles falling from Radiata pine are quite poor in Ca and Mg (WILL, 1959). Aluminium concentrations in Merkusii pine litter are very close to the mean value reported for P. radiata foliage in eastern Australia (viz. 0.74 mg g^{-1}, HUMPHREYS & TRUMAN, 1964).*

The scarce data on the chemical composition of seed litter in plantations in the tropics have been put together in Table 5.11b.

> *Seed litter from Nigeria is much richer in K and poorer in Na than Tectona seeds from Java. Cones of Tanzanian P. patula contain about twice as much Mg and P as those of P. merkusii, but have about half the K concentration of the latter. A comparison of seeds from Agathis and Araucaria shows the former to be poorer in the major nutrients N, P and K (Brasell et al., 1980).*

The seasonal course of macro-element concentrations in leaf litter from the Indonesian plantations is portrayed in Fig. 5.5. As with *Agathis* and *Eupatorium* the seasonal pattern differs between species

Fig. 5.5 Seasonal course of nutrient concentrations (mg g^{-1} dry wt) in leaf fall from *Tectona* and *Pinus*



and elements. Both for teak and pine the pattern of P is irregular without any distinct relationship with rainfall regime. Sodium and K show patterns that are similar to that observed for the other species, *i.e.* a maximum occurs in the dry season. Magnesium fluctuates within narrow limits (*cf.* SRIVASTAVA *et al.*, 1972). Calcium concentrations show more variation, although not as much as in the case of *Agathis* or *Eupatorium*. As was observed in India (SRIVASTAVA *et al.*, 1972) this seasonal variation for Ca was least in the case of pine litter (as compared to teak).

The above results indicate that (for most elements) a monthly sampling scheme is required to arrive at a reasonably accurate estimate of the amounts of nutrients returning annually to the forest floor via litterfall. Bulking weekly collections to monthly samples will also decrease effects of leaching and decomposition and is probably the most practical approach.

5.3.6 *Nutrient accession via litterfall from Tectona and Pinus*

Estimates of nutrient accession to the forest floor via litterfall are given in Table 5.12 together with data from other locations.

Amounts returning in the Indonesian teak plantation are quite comparable to those found elsewhere (India, West Africa), except for P and perhaps K, which are low. The Nigerian stand returns quite a lot of K (EGUNJOBI, 1974), whereas the Indian plantations exhibit a fairly slow cycling rate for Mg (Table 5.12a). Calcium and P transfers via needlefall in the Javan pine plantation are lagging behind the other coniferous forests. Quite large quantities of K, P and N seem to be involved in the litterfall from P. roxburghii. (SETH et al., 1972). Seedfall and therefore nutrient transfer in the P. merkusii stand was considerable.

Naturally the accession rates as given in Table 5.12 are influenced by stand density. It appears, if data are expressed on a per-tree basis, that 11-yr old Agathis produces far less litter, but returns more nutrients to the forest floor than 12-yr old specimens of P. merkusii. Similarly 21-yr old Agathis produces less litter than 25-yr old Tectona, although this pattern will be reversed within a few years. It is tentatively concluded therefore that Agathis, although naturally found on poor sites, compares favourably with the other species frequently planted in the region.

Dynamics of the forest floor compartment (receiving the litter input) will be discussed in section 5.6.

5.3.7 *Production of litter by the Lower Montane Rain forest*

The monthly amounts of litter collected in the Rain forest of Pringombo (see section 2.6.4) between June, 1977 and February, 1978 are given in Fig. 5.6. The production of leaf litter during three months of considerable rainfall (viz. June, December and January) was quite constant (39 gm^{-2}). More leaves were shed during the rainless period in between, with a peak occurring in October. Standard errors of the mean (S.E.) ranged from 5.2 % (July) to 19.2 % (June) with an overall value of 11.2 %. Standard deviations (S.D.) for the nonleaf litter category were much larger. The number of collectors needed to arrive at an S.E. of 10 % would become unpractical, however (*cf.* WILM, 1943). The total dry weight of litter reaching the

Table 5.12a Annual rate of nutrient return to the forest floor leaf-fall in selected teak and conifer plantations in the (sub)tropics (kg ha^{-1} yr^{-1})

Location	Species	Age (yrs)	Leaf fall t ha^{-1} yr^{-1}	Element accession (kg ha^{-1}yr^{-1})										
				Ca	Mg	Na	K	P	N	SiO$_2$	Al	Fe	Mn	
Indonesia* 6°30' S	*Tectona grandis*	25	5.2	114	16	1	16	3.4	-	266	3.8	2.3	0.36	present study
Nigeria, 7° N		6-8	7.8	108	20	2	63	8	82	-	-	-	-	Egunjobi, 1974
Senegal, 15° N		4	5.8	132	15	-	39	6	38	-	-	-	-	Maheut & Dommergues, 1960
		8	4.7	55	18	-	31	3	44	-	-	-	-	Singh, 1968; 1969
		natural	5.0	120	11	-	20	8	36	560	-	-	-	Seth *et al.*, 1972
India 25° N		33	5.3	131	6	-	20	11	52	165	-	-	-	Srivastara *et al.*, 1972
ibidem 30° N		39-41	4.7	155	9	-	32	11	70	-	-	-	-	
Indonesia* 6°30' S	*Pinus merkusii*	12	5.6	23	10	2	13.5	2.0	-	34	9.4	1.2	1.7	present study
	Agathis	35	2.7	70	13	2.5	12	1	20	22	0.7	0.7	0.8	
		11	2.8	115	13	1.5	10.5	1	-	11	0.7	0.9	0.9	
Tanzania 5° S	*Pinus patula*	18-20	5.4	46	13	-	7.3	1.3	33	-	-	-	-	Lundgren, 1978
Nigeria, 7° N	*P. caribaea*	7-10	5.9	35	11	5	14	0.6	26	-	-	-	-	Egunjobi & Onweluzo, 1979
India 30° N	*P. roxburghii*	30	7.0	46	9	-	39	13.4	74	24	-	-	-	Seth *et al.*, 1963
		40-44	8.5	84	11	-	45	11.4	65	-	-	-	-	Srivastara *et al.*, 1972
New Zealand, 38° S	*P. radiata*	26-29	4.3	16	4	2.3	13	4	29	-	-	-	-	Will, 1959
Indonesia, 6°30' S	Lower Montane Rain forest		5.4	128	23	2.5	27	3	-	219	4	3.5	0.5	present study

*excluding undergrowth

Table 5.12b Annual rate of nutrient return to the forest floor as seedfall in selected teak and conifer plantations in the (sub)tropics (kg ha^{-1} yr^{-1})

Location	Species	Seed fall (tha^{-1}yr^{-1})	Ca	Mg	Na	K	P	N	SiO$_2$	Al	Fe	Mn	Reference
Indonesia, 6°30' S	*Tectona grandis*	0.38	2.4	1	0.3	2	0.6	-	9	0.5	0.35	0.00^4	present study
Nigeria, 7°	*ibidem*	0.52	3.8	0.9	0.1^3	5.2	0.6	6.7	-	-	-	-	Egunjobi, 1974
Indonesia, 6°30' S	*P. merkusii*	4.4	6	2.6	0.9	15	1.8	-	46	3.4	1.8	0.36	present study
	Agathis '42	0.44	0.8	0.3	0.9	2.5	0.2	2.9	2.7	0.4	0.25	0.02	
Tanzania, 5° S	*P. patula*	1.3	0.7	-	1.5	0.4	5.7	-	-	-	-	-	Lundgren, 1978

forest floor during the eight months of observation amounted to 500 gm^{-2}, 77.4 % of which consisted of leaf litter. About 13.4 % was made up of branches and twigs, whilst seeds, fruits, flowers and pieces of bark (as well as minor amounts of unidentified material) constituted the remaining 9.2 %.

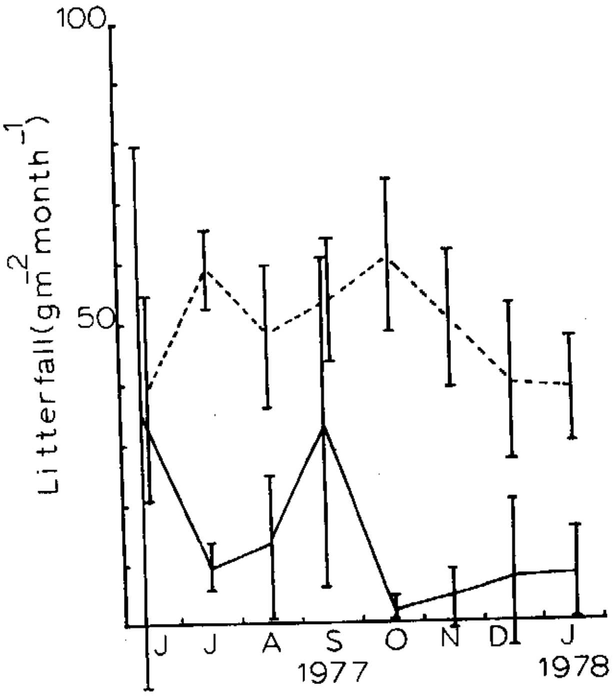


Fig. 5.6 Monthly litterfall (gm^{-2} dry wt) at Pringombo Lower Montane Rain forest

In order to arrive at an estimate of the annual litter production, monthly values for the rest of the rainy period (February till May) were assumed to amount to 39, 10 and 2 gm^{-2} for leaves, branches and "seeds" respectively (uncorrected for decay in traps and based on observations obtained during the remainder of the period). Adding these to the above-mentioned figure one obtains an annual total of 682 gm^{-2} yr^{-1}.

Data on total- and leaf litterfall for a number of forests in the humid tropics experiencing high amounts of annual rainfall are presented in Table 5.13.

> *Comparisons of total litterfall are a bit hazardous in that widely different methods for estimating the branchfall component may have been applied. Although leaffall is usually determined according to more readily comparable procedures there are still a couple of complicating factors. First, there is the annual variation in litter production. KUNKEL-WESTPHAL & KUNKEL (1979) and BRASELL, et al. (1980) for example state that data from different sites which differ by less than 20 % may fall within the range of variation at either site as caused by climatic fluctuations. A further complicating factor is constituted by the fact that litter*

Table 5.13 Annual (leaf) litter production in selected natural forests of the humid tropics (kg ha^{-1})

	Litter production Total	Litter production Leaves	Altitude (m.a.s.l.)	Annual precipitation (mm)	Author
Lower Montane Rain forest					
Central Java, Indonesia	6815 (7380)*	5410 (5750)*	800	4570	This study
West Java, Indonesia		4490	1550	3380	Yamada (1976)
Malaya	6300	-	600	2000	Mitchell, quoted by Bray & Gorham (1964)
Papua New Guinea	7430	6270	2500	3985	Edwards (1977)
Puerto Rico	9660*	5050*	510	3500	Odum (1970)
Guatemala	9680 (11040)*	7020 (8385)*	1000	3000	Kunkel-Westphal & Kunkel (1979)
North Panama	11800	10480	500	2500	Golley *et al.* (1975)
Zaîre	-	8500	1650	2000	Brynaert, quoted by Bray & Gorham (1964)
Jamaica (Gap forest)	6470	5500	1550	2500	Tanner (1980)
Lowland Rain forest					
Malaysia	9375 ±1385**	6365 ± 1008**	75-150	2054	Lim (1978)
Colombia	8370	6645	10	3000	Fölster & de las Salas (1976)

*corrected for decay in traps

**variation between years

confined in traps for periods longer than a week tends to lose weight (e.g. KIRITA & HOZUMI 1969). Often no correlation for this has been made.

Taking the above considerations into account it will be clear that the annual production of leaf litter by the forests presented in Table 5.13 has to be regarded as fairly uniform. For example, there is no clear distinction between Lowland Rain forests and Lower Montane Rain forests or any clear effect of altitude within the latter category. Mount Panggerango (Java) and Darien (Panama) represent the lowest and the highest values encountered so far, producing 449 and 1048 $gm^{-2}yr^{-1}$ respectively. The estimated annual production of the Pringombo forest falls within the lower part of the presented range as do the other upland studies in Malesia. The periodicity of leaffall observed at Pringombo is similar to that of most other tropical forests : a continuous and somewhat irregular fall with a main peak at the end of the dry season (*cf.* YAMADA 1976; LIM 1978; KUNKEL-WESTPHAL & KUNKEL 1979).

Branchfall is usually more associated with events of intense precipitation (e.g. YAMADA, 1976: LIM 1978) but this component of the litterfall could not be evaluated properly by the use of a limited number of trays. The ratio between branch- and leaffall varies considerably between studies, mainly because of the sampling technique followed. The low values found at Pringombo (0.19), New Guinea (0.18) or Malaysia (0.24; LIM, 1978) stand in strong contrast to that of El Verde (0.81), where 1256 m^2 of forest floor were cleared. Similarly in Guatemala KUNKEL-WESTPHAL & KUNKEL (1979) reported an increase in branchfall estimate from 178 $gm^{-2}yr^{-1}$ (as obtained by the use of 10 trays with a total surface area of 10 m^2) to 472 $gm^{-2}yr^{-1}$ in the case of forest-floor clearance (two plots of 25 m^2). On the other hand, an extremely low value (0.13) was observed by GOLLEY et al. (1975) for a lower Montane Rain forest in Panama although ten plots of 4 m^2 had been cleared of all branch litter. The rate of branchfall obtained in this way (132 $gm^{-2}yr$) appears to be even lower than that observed in Guatemala by means of ordinary collectors.

5.3.8 *Nutrient concentration of Rain forest litter*

Average concentrations of nutrients in the three categories of litter are given in Table 5.14.

No significant differences in composition existed between leaf- and woody litter (apart from SiO_2 and Al ($\alpha < 0.01$). This is thought to indicate a re-translocation of nutrients from the leaves to the twigs before leaf abscission in an attempt to conserve them or at least retard their return to the forest floor. "Seed" litter contained less Ca and Mg than either leaf- or branch litter ($\alpha < 0.01$). Also, leaves were richer in SiO_2 ($P < 0.01$), Al and Na.

Seasonal trends in concentrations in leaf fall are given in Fig. 5.7. Calcium, Fe, Mn and (probably) Cu concentrations show a minimum in September, whereas Na and K then attain their maximum values. SiO_2 and Al peak a little later in November, whilst both Mg and P concentrations increased fairly regularly from June till February. These variations are thought to be the result of interactions between climatic, chemical and biotic factors.

The occurrence of increased deposition of terrestrial dust (containing much Si and Al and lesser amounts of K plus ocean-

Table 5.14 Average nutrient concentration in litterfall at Pringombo (mg g^{-1} dry weight) between 1 June, 1977 and 1 February, 1978

	Ca	Mg	Na	K	P	SiO_2	Al	Fe	Mn	Cu*
Leaf litter	21.56 ± 3.84	3.92 ± 0.60	0.49 ± 0.23	4.77 ± 1.41	0.55 ± 0.09	40.80 ± 7.84	0.74 ± 0.18	0.46 ± 0.13	0.08^5 ± 0.029	0.011 ± 0.001
Branch litter	22.53 ± 6.25	3.32 ± 0.84	0.30 ± 0.15	4.85 ± 2.31	0.46 ± 0.08	15.80 ± 9.22	0.29 ± 0.13	0.31 ± 0.15	0.059 ± 0.030	0.013 ± 0.004
"Seed" litter	0.48 ± 3.54	2.37 ± 1.01	0.24 ± 0.19	6.28 ± 4.24	0.65 ± 0.43	8.47 ± 4.95	0.37 ± 0.30	0.49 ± 0.50	0.031 ± 0.020	0.013 ± 0.006

*September till January

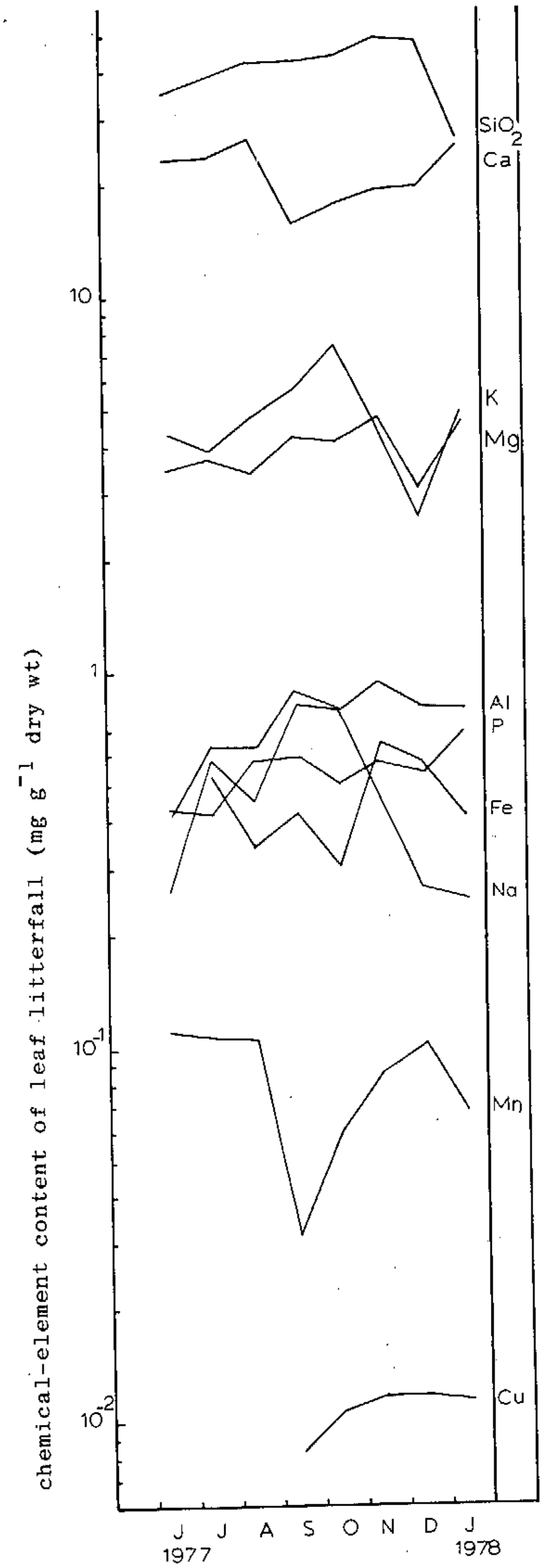
Table 5.15 Average nutrient concentrations of leaf litter in selected natural tropical forests (mg g^{-1} dry wt)

	Ca	Mg	Na	K	P	SiO_2	Al	Fe	Mn	Cu
Central Java[1]*	22.3	3.9	0.45	4.8	0.45	3.81	0.71	0.6	0.08	0.011
Puerto Rico[2]	7.6	1.7	(1.0)	1.9**	0.2			0.2**	0.28	
Panama[3]	10.2	2.3	1.1	1.2	0.8			0.13	0.24	0.005
Malaya[4]	7.0	2.2		3.8	0.3					
Colombia[5]	13.6	1.3		3.3	0.4	24.9	0.13	0.09	0.52	
Amazonia, Brazil[6]	2.0	2.0	0.8	2.0	0.3			0.18	0.11	0.003
Ivory Coast, Plateau[7]	5.6	4.6		2.2	0.7					
Ivory Coast, Valley[7]	9.5	4.1		9.1	1.6					
Tanzania	12.7	3.0		4.3	1.0					

[1]present study; [2]**Odum (1970); Jordan (1970b); [3]Golley *et al.* (1975); [4]Lim (1978); [5]Fölster & de las Salas (1976); [6]Klinge & Rodrigues (1968); [7]Bernhard (1970); [8]Lundgren (1978)

*calculated values for twelve-month period, corrected for decay in traps

Fig. 5.7 Seasonal variations in leaffall nutrient concentrations at the Pringombo Lower Montane Rain forest (mgg^{-1} dry wt)



derived aerosols (rich in Na and Mg) on the canopy and forest floor during the dry season causes these constituents to increase as the drought progresses. Depending on their ionic mobility or presence in soil particles splashed into the collectors these elements see their concentrations drop sharply (Na, K) or somewhat less abruptly (SiO_2, Al, Mg(with the onset of the rains in November. Iron concentrations are irregular, but show a slight tendency to be higher after rainy spells, which would suggest the effect of soil splash. No significant correlation exists, however, with either Al- or SiO_2 concentrations. Calcium, Mn and Cu (?) all have a minimum in September and do not exhibit any clear trend in relation to rainfall. As in the case of P, which increases more or less regularly throughout the observation period, this may reflect the timing of leaf fall of different species. No specific data have been collected in this regard, however.

The overall weighted mean concentrations of the leaf litter as calculated for a twelve-month period are compared with data from other tropical forests in Table 5.15. It appears that the Pringombo forest leaf litter (as well as its branch litter) is relatively rich in Ca, Mg, Cu, Al and Fe, whereas Na and Mn are relatively low in comparison to most other forests. Unfortunately, very little data exist on Si, Al and Cu levels in litterfall rendering definite conclusions in this regard somewhat difficult.

The high SiO_2 concentration of the fallen leaves is in accordance with the findings of FÖLSTER & DE LAS SALAS (1976) in Colombia and VAN SCHUYLENBORGH (1958), who analyzed the litter of a Rain forest of comparable elevation in West Java. Similarly TURVEY (1974) observed high concentrations of dissolved SiO_2 in leachates from litter collected in the Rain forest of Papua New Guinea. RONDIN & BASILEVICH (1967) even stated : "The preponderance of silica in the cycle of elements distinguishes tropical rain forest from the forest formations of other zones, in which calcium or hydrogen occupy the first place.

5.3.9 *Nutrient accession via litterfall in the Lower Montane Rain forest*

The return of chemical elements to the forest floor via litterfall (canopy leaching has not been studied at this site) was calculated for the three categories of litter for the period of study (eight months) and for a hypothetical year (Table 5.16). Concentrations for the remaining months (February until May) were estimated by taking the average of the values observed in June and January (leaves, seed litter) or the overall mean (branch litter). In addition correction factors for decay in the collectors were applied.

Leaf litter clearly provides the bulk of nutrients returning to the forest floor as litterfall. Calcium and SiO_2 together make up 85 % of the total, a figure which is increased to 96 % when Mg and K are added. These figures become 82 and 95 % respectively (1 June, 1977 - 1 February, 1978) in the case of total litterfall.

Annual nutrient returns in total- and leaf litter for a number of tropical forests are given in Table 5.17 in order to compare the nutrient transfer at Pringombo with that at other locations. It appears from Table 5.17 that the chemical-element access to the forest floor in the present case is quite comparable to most other forests, even though the amount of litter produced at Pringombo is on the low side of the spectrum (Table 5.13).

Table 5.16 Return of nutrients to the forest floor as litterfall (kg ha^{-1}) during the study period (eight months) and for a hypothetical year* at Pringombo

		Ca	Mg	Na	K	P	SiO_2	Al	Fe	Mn
Eight months	Leaf litter	82.4	15.2	2.0	18.9	2.10	159.3	2.9	2.40	0.32
	Branch litter	12.7	1.7	0.2	2.7	0.27	8.0	0.16	0.14	0.01
	"Seed" litter	3.3	1.0	0.2	4.3	0.18	4.1	0.18	0.25	0.02
	Total litter	98.4	17.9	2.4	25.9	5.0	171.4	3.25	2.79	0.37
Twelve months	Leaf litter	128.3	22.7	2.6	27.4	3.1	219.1	4.1	3.4	0.5
	Branch litter	21.7	3.0	0.3	4.7	0.4	14.3	0.3	0.3	0.05
	"Seed" litter	4.0	1.2	0.2	4.6	0.2	4.7	0.2	0.3	0.02
	Total litter	154.0	26.9	3.1	36.7	3.8	238.1	4.5	3.9	0.6

*see text for explanation

Table 5.17 Annual return of nutrients (kg ha^{-1}) via total and leaf litterfall in selected natural tropical forests

Total litterfall	Ca	Mg	Na	K	P	SiO_2	Al	Fe	Mn
Central Java[1]	154	27	3	37	4	238	4.5	4	0.5
Puerto Rico[2]	50	12	4	(2)				1.1	2.^{3}
Panama[3]	115	26	13	20	8.5			1.5	3
Malaya[4]	69.5	18		31.5	3				
Colombia[5]	124	12		29.5	3.5	182	1.2	0.8	4.4
Queensland[6], site 2	158.5	33.0	5.0	51.4	10.2				
Tanzania[7]	104	23		35	8				
Leaf litterfall	**Ca**	**Mg**	**Na**	**K**	**P**	**SiO_2**	**Al**	**Fe**	**Mn**
Central Java[1]	128	22.5	2.5	27.5	3	219	4	3.5	0.5
Puerto Rico[2]	42	9	2*	10.5*	1			1*	1.6
Panama[3]	107.5	24.5	11.5	12.5	8.5			1.5	2.5
Malaya[4]	45	14		31.5	2.8				
Colombia[5]	90.5	8.5		22	2.7	165.5	0.9	0.6	3.4
Tanzania[7]	70	15.5		22.4	5.2				

[1]present study; [2]*Odum (1970), Jordan (1970b); [3]Golley *et al.* (1975); [4]Lim (1978); [5]Fölster & de las Salas (1976); [6]Brasell *et al.* (1980); [7]Lundgren (1978).

5.4 Canopy leaching

5.4.1 *Quantitative aspects*

The second major pathway for nutrient transfer from forest canopy to forest floor (litterfall being the first) is that of *canopy-* or *crown-drip*. Closely related, but often considered of minor importance in tropical forests (*e.g.* JACKSON, 1971; HUTTEL, 1975; STEINHARDT, 1979) is the flow along trunks, known as *stemflow*.

Amounts of canopy drip have been estimated for two stands of *Agathis* (35- and 11-yr old), the *Tectona-* and *Pinus* plantations and *Eupatorium* thicket. Observations commenced by the end of December, 1976 at some of these locations, but full comparisons became possible from 1 February, 1977 onwards only (*cf.* section 5.2 for procedures). Totals for the year February, 1977 till February, 1978 are given in Table 5.18. Individual amounts per sampling occasion are presented in Appendix 1.

It should be noted that these totals correspond with an amount of rainfall in the open of 3715 $mmyr^{-1}$, which is considerably below average. Taking the 4668 mm of rain recorded over the entire observation period (section 3.3) as a more representative estimate one arrives at drip totals of *c.* 25 % greater magnitude.

able 5.18 Total amounts of rainfall ($mmyr^{-1}$) collected under different vegetation covers between 1 February, 1977 and 1 February, 1978

	Agathis '42	*Agathis* '66	*Eupatorium*	*Tectona* '52	*Pinus* '65
ughfall	3300^{a*}	2935^{bc}	3414^{a}	3212^{ab}	2547^{c}
fall	3715	3715	3715	3715	3715
	$0.86^{d} \pm 0.11$	$0.77^{ef} \pm 0.09$	$0.91^{d} \pm 0.13$	$0.87^{de} \pm 0.15$	$0.70^{f} \pm 0.17$

*figures sharing the same letters are not statistically different at $\alpha < 0.05$.

The standard errors of the mean appeared to be quite large for some sampling data (Appendix 1) due to the variable nature of the canopy in space or time.

This problem is well-known in the literature, both for temperate-latitude woodlands (e.g. HELVEY & PATRIC, 1965) and - more recently - equatorial forests (e.g. JACKSON, 1971: HUTTEL, 1975). A considerable number of gauges is often required to obtain a pre-set precision c of say 10 % of the mean (i.e. $c = 0.1 \cdot \bar{x}$). *The widely-used formula :*

$$n = \frac{t^2 . s^2}{c^2} \qquad \text{(TOEBES \& OURYVAEV, 1970)} \qquad (5.1)$$

where n = *number of gauges required to obtain the permissible difference of* c

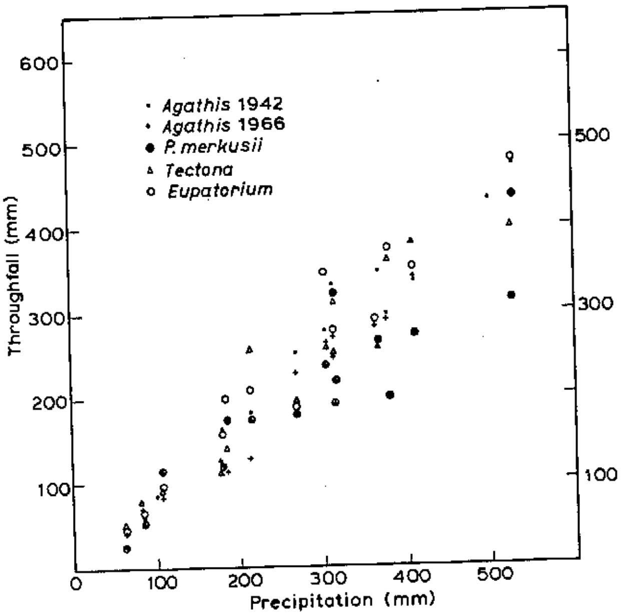
s = *standard deviation of sample group*

and t = *standard normal variable of a normal distribution, was applied in the present case with* c *set at 10 %* ($\alpha = 0.10$)
On average 9, 18, 6, 8 and 5 gauges would have been required for the Agathis 1942, Agathis 1966, Eupatorium, teak and pine sites respec-

tively. For some individual sampling occasions, however, much larger amounts of equipment would have been required.

It can be concluded that the studied plots have not been sampled adequately with the present set-up. Taking into account the fairly large variance of the data it will be no surprise that only a few significant differences between the investigated forests emerged (Table 5.18; Fig. 5.8). However, *total amounts* caught by individual gauges did not differ more than 3 % within a site, (Appendix 1).

Fig. 5.8 Relationships between incident rainfall and crown drip.



Interception of rain by 11-yr old Agathis trees was unexpectedly greater than for most other sites which showed only minor differences. The rather high percentage of rain falling through Agathis (1942) and Tectona is thought to reflect the open character of these stands. The crowns of the former species are quite narrow leaving the raingauges relatively exposed, whereas the Tectona started to shed its leaves in April already. Rainfall interception by Eupatorium shrubs was lowest as would be expected for undergrowth vegetation, although the chemical composition of the collected throughfall (section 5.4.2) suggested another source of the water (guttation) as well. The relatively low throughfall value for P. merkusii is somewhat an underestimate as rainfall data for Watubelah had to be used instead of on-site figures, which are probably lower.

It is difficult to say to what extent since the record showed important gaps due to gauge disturbance. Reference can be made to occasional observations on P. merkusii by SOEKOTJO et al. (1974) in Central Java and the more continuous work of SUPRIYO AMBAR (in press) in West Java. Slopes of regression lines (drip vs. rainfall in the open) given by these authors for 5 to 11-yr old trees ranged from 0.70 (62 showers; SUPRIYO) to 0.75 (5 showers;SOEKOTJO et al.), i.e. higher than found in the present study, viz. 0.58 (Fig. 5.8). It should be noted, however, that *the latter figure pertains to fortnightly or monthly totals, rather than individual storms, i.e. the quantities of rain involved are much larger. Depending on the storm regimes of the various observation periods interception values may vary considerably even when total incident rainfalls are of similar magnitude (JACKSON, 1971).*

Despite their high coefficients of determination the capacity of the regression equations of Fig. 5.8 to predict rainfall interception is poor (note the high values for $S_{y.x}$). Amounts of rainfall and canopy drip are of the same order of magnitude, whereas intercepted amounts are much smaller. This explains the high values of r^2 when the former parameters are related and the almost total absence of correlation when interception is related to gross rainfall (JACKSON, 1975). (The lower correlation observed for P. merkusii is probably a result of the use of rainfall data not pertaining to the site itself).

Table 5.19 puts the present data in perspective. Both studies dealing with natural forests and plantations have been quoted. Considering the general scarcity of data on tropical plantations work conducted in warm temperate regions has been included as well.

The relative amount of water collected under the canopy of natural forest in the humid tropics is close to 80 %. Slightly higher values are observed in somewhat drier areas (e.g. NYE, 1961; HUTTEL, 1975) and lower values at locations where rain falls predominantly as rather light showers (e.g. CLEMENTS & COLON, 1975). Apart from the youngstands investigated by WIERSUM (in press) the magnitude of crowndrip in plantations is less than observed for natural tropical forests.

Values for pine lie around 70 ± 3 %, close to the observations for P. merkusii in Java. The work conducted in India suggests that amounts of throughfall for Tectona (fully developed foliage) and P. roxburghii are about equal, whereas evidence from New Zealand (BLAKE, 1972; 1975) indicates very high amounts of interception by 60-m tall virgin forest of Agathis australis (indeed the same forest for which WHITMORE (1977) quoted a very high tree biomass, see section 5.5.1).

Despite their large trunks these trees exhibit only minor amounts of stemflow, viz. 1 % of gross rain fall (BLAKE, 1975). This is probably a corollary of the drooping habit of the species' branches and perhaps the flakey nature of the bark (section 2.6.1). This suggests that no large errors are involved in omitting stemflow measurements in the present investigations, at least for Agathis. To what extent this is also true for the other species remains to be seen. The literature on stemflow in plantations under warm-temperate (rather than humid tropical) conditions reports values ranging between 1 and 15 % for teak, with an overall value of 6 % (DABRAL & SUBBA RAO, 1968). Teak trees having the same diameter at breast height as the ones studied by the present writer exhibited a mean value of 4.6 %. (According to DABRAL & SUBB RAO (1968) there is no distinct relationship between stemflow volumes and tree diameter. This is explained by them by strongly different branching patterns for the individual trees that are mostly independent of trunk diameter.)

Table 5.19 Proportion of incident rainfall collected under natural and plantation forest in the (sub) tropics.

Location and	Forest type	Crown drip C ($mm\ yr^{-1}$)	Precipitation P ($mm\ yr^{-1}$)	$\frac{C \times 100}{P}$ (%)	Observation period (yr)
Natural forest					
Ivory Coast[1] (Banco)	Lowland Rain forest	1585 ± 42	1800	88 ± 3	3
ibidem[1] (Yapo)		1510	1950	77	2
Ghana[2]	semi-deciduous	1562	1847	85	1
Malaysia[3]	Lower Montane Rain forest	2024	2500	81	½
Papua[4]		2155	2694	80	0,83
Puerto Rico[5]		1956	2810	70	1
ibidem[6]				72	1
Mauritius[7]		2152 ± 353 2356 ± 28*	3094	70 ± 10 76 ± 1	
Tanzania[8]		815 ± 166	1051	78 ± 16	2½
West Java[9]		2394 ± 119	3007	80 ± 4	1
Venezuela[10]		1260	1576	80	1
Mean of natural forests				79 ± 5	
Plantations					
Indonesia[11]	*Acacia auriculiformis* *Albizzia falcata* *Anthocephalus chinensis*			80 80 80	2
Tanzania[12]	*Cupressus macrocarpa*	862 1085	1042 1529	83** 71***	6
India[13]	*Tectona grandis* *Pinus roxburghii*			73 74	½
New Zealand[14]	*Agathis australis*			35	-
	Pinus radiata	-	-	67	1
ibidem[15]	*ibidem*	1073	1511	71	2

*2 gauges only
**20-yr old stand
***25-yr old stand

[1] Huttel (1975); [2] Nye (1961); [3] Kenworthy (1971); [4] Turvey (1974); [5] Kline & Jordan (1968); [6] Clements & Colon (1975); [7] Vaughan & Wiehe (1947); [8] Lundgren & Lundgren (1979); [9] Gonggrijp (1941); [10] Steinhardt (1979); [11] Wiersum (in press); [12] Pereira (1952); [13] Dabral & Subba Rao (1968); [14] Blake (1975); [15] Will (1959).

Stemflow for P. roxburghii described by the same authors varied within rather narrow limits (2.8-4.7 %) with an average value of 3.6 %. These measurements took place in the summer-monsoon and included storms as large as 51 mm. BLAKE (1975) gives regression equations for stemflow in c. 23-yr old plantations of Radiata pines in northern New Zealand representing less extreme rainfall conditions. Computations suggest relative stemflow contributions (expressed as percentage of gross rainfall) of 2 % for falls of 10 mm up to 5 à 6 % for showers of 30 mm. FAHEY (1964) mentions 3 % for stemflow for a dense stand of P. radiata in the same country. Occasional measurements of stemflow from P. merkusii have been described by SOEKOTJO et al. (1974) for a stand of unknown age in East-Central Java. Results indicated stemflow percentages of c. 14% for gross rainfalls of 10-30 mm, i.e. substantially higher than reported for either P. roxburghii or P. radiata. Again, more work is necessary in this regard.

Since the throughfall data for *Tectona* in the present work seem to be on the high side already, no attempts have been made to add stemflow. In the absence of actual data values of 6 % for *Tectona* and 4 % for *P. merkusii* would seem to be the best approximations.

5.4.2 *Nutrient concentrations of canopy drip*

Rainwater collected under a forest canopy often exhibits much higher chemical concentrations than rainfall in the open, as has been noted by many investigators in deciduous (MADGWICK & OVINGTON, 1959; EATON *et al.*, 1973) and coniferous (WILL, 1959) forests of temperate latitudes as well as in tropical forests (NYE 1961; KENWORTHY 1971; TURVEY 1974; CLEMENTS & COLON, 1975). Upon hitting the canopy precipitation may pick up leaf exudates and dry fallout already present on the foliage. Some nutrients may be leached out of the leaves themselves as well (ZAMIEROWSKY, 1975) or, conversely, be absorbed by the canopy (UNESCO, 1978, discussing results from Pasoh, Malaya). Since the relative contributions of the various processes can be evaluated by means of tracer studies only, generally no distinction is made and "leaching" is defined as "the loss of metabolites - both organic and inorganic - from above ground plant parts by the action of aqueous solutions, including rain, mist and dew" (TUKEY & TUKEY, 1962).

The Javan plantations and shrubs are no exception to the above and show significant increases of nutrient concentrations in crown drip as compared to the incident precipitation. Table 5.20 presents the weighted mean concentrations of canopy drip for the investigated species as well as for a number of tropical forests. Since the chemical composition of the incident rainfall is likely to vary from place to place a table showing the relative enrichment factors has been prepared as well (Table 5.21).

The weighted mean concentrations of the water dripping from *Agathis*, *Tectona* and *Pinus* do not differ much between species. Especially Na and Mg vary within narrow ranges. Variations in Ca and K concentrations are somewhat greater but not significantly so. Young *Agathis* trees seem to give off somewhat more Ca (as in their litter, see Table 5.4) and less K (not so in the litter) than their older relatives. The similarity of the canopy drip composition for the tree species returns naturally in a comparison on a milli-equivalent basis. Potassium is highest and Mg lowest in all cases (including

Table 5.20 Weighted mean concentrations (mg l^{-1}) of canopy drip in the study plots (February, 1977 - February, 1978) and selected natural and man-made forests in (sub)tropical regions

Location	Vegetation	Ca	Mg	Na	K	"SiO_2"	Al
Plantations							
Indonesia[1]	*Agathis* 1942	0.34^{a+}	0.22^{b}	0.61^{c}	1.45^{d}	$< 0.3^{e}$	$< 0.07^{f}$
	Agathis 1966	0.48^{a}	0.21^{b}	0.64^{c}	0.77^{d}	$< 0.5^{e}$	$< 0.13^{f}$
	Eupatorium sp.	3.10	1.21	0.52^{c}	3.12	2.44	$< 0.07^{f}$
	Tectona grandis	0.68^{a}	0.26^{b}	0.58^{c}	1.36^{d}	$< 0.9^{e}$	$< 0.15^{f}$
	P. merkusii	0.50^{a}	0.27^{b}	0.87^{c}	2.0^{d}	$< 0.6^{e}$	$< 0.08^{f}$
	ibidem[2]	0.6	0.5	-	-	-	-
	ibidem[3] (11-yr)	0.6*	0.13	-	-	-	-
		0.3**	0.21				
New Zealand[4]	*P. radiata*	0.29	-	2.40	1.63	-	-

[+]columns sharing the same lettering do not differ significantly at $\alpha < 0.05$ (parametric tests and MANOVA (Seyhan, 1981);
*start of wet season;
**mid of wet season

Location	Vegetation	Ca	Mg	Na	K	"SiO_2"	Al
Natural forests							
Ivory Coast[5]	LRF* Banco	2.5	2.8	-	4.0	-	-
	Yapo	2.5	1.6	-	5.1	-	-
Malaysia[6]	*ibidem* (Dipterocarp)	0.26	0.13	1.24	2.08	-	-
ibidem[7]	LMRF**	1.38	0.25	-	2.5	-	-
Papua[8]		1.08	0.30	3.96	1.62	0	-
Puerto Rico[9+]		1.6 - 2.1	0.8 - 1.7	11.6 - 14.1		-	-
ibidem[10++]		1.10	2.02	10.6	3.36	-	-
Venezuela[11]		0.76	0.45	0.47	7.83	-	0.19
Ghana[12]	semi-deciduous	1.86	1.15	-	14.1	-	-

*Lowland Rain forest;
**Lower Montane Rain forest;
+October, 1965 - July, 1966;
++1 yr (1970[9]);

[1] present study;
[2] Soekotjo *et al.* (1974);
[3] Soekotjo (p.c.);
[4] Will (1959);
[5] Bernhard-Reversat (1975);
[6] Manokaran (1978);
[7] Kenworthy (1971);
[8] Turvey (1974);
[9] Sollins & Drewry (1970);
[10] Clements & Colon (1975);
[11] Steinhardt (1979);
[12] Nye (1961)

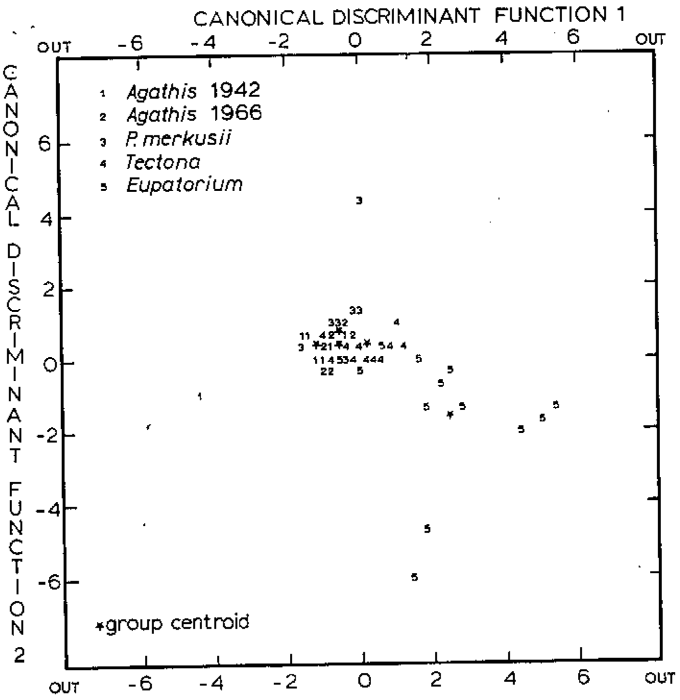
Table 5.21 Relative enrichment of the nutrient concentration of incident rainfall after hitting the canopy

Location	Vegetation	Ca	Mg	Na	K	"SiO_2"*	Al*
Plantations							
Indonesia[2]	*Agathis* 1942	2.0	2.7	1.9	10.4	1.3	2
	Agathis 1966	2.8	2.6	2.0	5.5	2.2	4
	Eupatorium	18.2	14.9	1.6	22.3	10.6	2.2
	Tectona 1952	4.0	3.2	1.8	9.7	3.9	5
	P. merkusii 1965	2.3	4.2	1.7	12.5	2.6	3
	ibidem[3]	1.7 - 2.6	1.1 - 1.2	-	-	-	-
New Zealand[4]	*P. radiata*	1.7	-	1.5	7.8	-	-
Natural forests							
Ivory Coast[5]	Lowland Rain Banco	1.7	10.4	-	11.1	-	-
	Yapo	1.5	5.9	-	14.2	-	-
Malaysia[6]	Dipterocarp Rain	1.3	2.6	1.1	5.0	-	-
ibidem[7]	Lower Montane Rain	2.5	1.9	-	5.0	-	-
Papua[8]		?	30	12.4	54	-	-
Puerto Rico[9]		∿ 2	∿ 1.8	∿ 3.6		-	-
ibidem[10]		4.4	2.6	1.8	9.6	-	-
Venezuela[11]		2.0	0.9	1.7	37.3	-	1.2
Ghana[12]	Moist Semi-deciduous	1.3	4.3	-	39.2	-	-

1-12 : for references see Table 5.21

*values represent the ratio of two *maximum* estimates

Fig. 5.9 Scatter plot of canopy drip quality data following discriminant analysis (DIRECT SOLUTION)



Eupatorium) except for young *Agathis*. The sequence observed is : K > Na > Ca > Mg (*Eupatorium*, *Pinus*, older *Agathis*) with Ca and Na exchanging places in the case of *Tectona* (throughfall relatively rich in Ca). For young *Agathis* the sequence reads Na = Ca > K > Mg.

> *The latter sequence is similar to that observed for Lower Montane Rain forest in Papua (TURVEY, 1974), whilst the former sequence seems to be somewhat special. None of the studies listed in Table 5.20 reports this particular sequence. McCOLL (1970), however, observed it for a Rain forest in Costa Rica. Since his investigations lasted for two weeks only and were conducted under extremely wet conditions these have not been included in Table 5.20.*

The absolute nutrient concentrations in tree canopy drip seem to be rather low in the Indonesian case. Table 5.21, however, shows this to be the result of incident rainfall composition mainly, as the enrichment factors are quite comparable to those for other localities. This again supports the notion that a direct comparison of concentrations in canopy drip can be misleading.

The water collected under *Eupatorium* thicket appears to contain significantly higher amounts of nutrients (Table 5.20; see also Fig. 5.9, where the group centroid of *Eupatorium* data has a position different from the others). Discriminant analysis (RAO solution - SEYHAN, 1981) indicated especially "SiO_2" and K concentrations in *Eupatorium* drip to be strongly different. An as yet unproven explanation may be the occurrence of guttation (the exudation of nutrient-rich liquid from leaf margins and apices during the night).

A first explanation for the observed concentrations would be the leaching of leaves trapped in the collectors as dead Eupatorium leaves wither very easily away. These were picked from the funnels almost daily, however, and cannot be regarded as the main source of nutrients. Calculations show that even the release of the total contents of Mg, K and Na in the maximum amount of litter that could possibly be caught in the collectors would not be sufficient to explain the observed concentrations. It would, however, in the case of Ca, SiO_2 and Al. Since the nutrient concentration of the litter itself may be an underestimate due to leaching similar computations were performed using concentrations for living foliage as well. Although according to these calculations significant contributions to drip composition are possible theoretically it will be clear that other factors must be important as well.

The humid tropics are often considered as particularly favorable for rapid guttation (STOCKING, 1956; KRAMER, 1959). The volume of water involved in the process and the composition of the liquid are extremely variable (KRAMER, 1959). The latter quotes rates of 100 ml day^{-1} and SLATYER (1967) even reports a value of 1 l day^{-1} per plant.

In the absence of data on tropical forest species some indication of the order of magnitude of nutrient concentrations in guttation fluid can be obtained from data presented by CURTIS (1944) on vegetables and GOATLEY & LEWIS (1966) on cereals. Calcium was found to be the main ion in the vegetable exudate (100-125 mg l^{-1} in contrast to the 1.5-4.8 mg l^{-1} reported for the grain crops). Potassium dominated the liquid from the cereals (18-30 mg l^{-1}, cf. 15-40 mg l^{-1} reported for vegetables), whereas Na concentrations were low. Magnesium exhibited intermediate concentrations (vegetables 5-8 mg l^{-1};grains 1.5-2.4 mg l^{-1}) and Al was either similar to the drip from Eupatorium (0.06-0.09 mg l^{-1} in the case of cereals) or higher (0.3 ppm, vegetables). It has been impossible to trace any evidence of guttation by Eupatorium sp. in the literature. The only explanation for the observed phenomenon that can be offered at present is the above hypothesis which is not directly refuted by the limited data available. Further experimental work is needed and intended.

There is no distinct seasonal trend in throughfall composition apart from an enrichment during drier spells as noted for precipitation and litterfall (sections 4.2 and 5.3). This is thought to reflect the continuous accumulation of aerosols and exudates on the foliage as well as the smaller volume of rainfall available for dilution.

5.4.3 *Nutrient accession via canopy drip*

As with litterfall the combination of nutrient concentrations and volume of water enables the computation of the amounts transferred from canopy to forest floor via canopy wash. Subtraction of the corresponding amounts brought into the ecosystem by incident rainfall (Table 4.4) yields the contribution of the canopy itself, the "net canopy wash". Results for the study plots and various other (sub) tropical locations are given in table 5.22.

Table 5.22 Nutrient returns to the forest floor via "gross" and "net " canopy wash (kg ha^{-1} yr^{-1}) in selected natural and man-made forests in the (sub)-tropics

Location	Vegetation	Ca		Mg		Na		K		"SiO_2"		Al	
		gross	net	gross	net	gross	net	gross	net	gross	net+	gross	net+
plantations													
Indonesia[1]*	*Agathis* 1942	11.3	*3.0*	7.3	*4.1*	20.4	*8.5*	48.2	*40.5*	< 11.3	2.6	< 2.2	0.8
	Agathis 1966	14.1	*5.8*	6.1	*2.9*	18.6	*6.7*	22.5	*14.8*	< 15.7	7.0	< 3.7	2.3
	Eupatorium sp.	106.5	*98.2*	41.5	*38.3*	18.2	*6.3*	106.9	*99.2*	83.6	74.9	2.35	0.9
	Tectona 1952	21.8	*13.5*	8.2	*5.0*	18.8	*6.9*	43.6	*35.9*	< 28.4	19.7	< 4.8	3.4
	P. merkusii 1965	12.8	*4.5*	6.8	*3.6*	22.2	*10.2*	51.9	*44.2*	< 15.8	7.1	< 1.9	0.5
New Zealand[4]	*P. radiata*	3.2	*0.6*			25.8	*1.8*	17.5	*14.4*				
Ivory Coast[5]	*Terminalia ivorensis*	4.1	*25*	21	*14*			80.5	*75*				
	(Banco & Yapo)	40	*24*	13	*6*			86.5	*81*				
Natural forests													
Ivory Coast	Lowland Rain												
	Banco	39	*23*	41	*34*			65.5	*60*				
	Yapo	35	*19*	23	*16*			87.5	*82*				
Malaysia[6]	*ibidem***	4.3	*0.2*	2.2	*1.2*	20.7	*-2.3*	34.6	*26*				
ibidem[7]	Lower Montane Rain	28	*14*	5	*2*			5	*38*				
Papua[8]		23.3	*(23.3)*	6.5	*6.2*	83	*75*	35	*34*				
Puerto Rico[9]		34.8	*13.0*	9.2	*4.3*	61	*26*	155	*137*				
ibidem[10]***		25.8	*19.4*	47.5	*28*	249	*97*	79	*71*				
Venezuela[11]		6.9	*1.3*	3.3	*1.9*	4.4	*1.1*	69.7	*67.1*			2.3	0.1
Ghana[12]	Semi-deciduous	29	*16.4*	18	*6.6*			219.5	*202*				

1-12 see for references Table 5.20, except 5 (now Bernhard-Reversat, 1977) and 9 (now Jordan *et al.*, 1972; values including stemflow)

*1 February, 1977 - 1 February, 1978

**assuming throughfall amount of 1664 mm yr^{-1} (Kenworthy, 1971)

***assuming an annual rainfall of 2540 mm

+figures result from subtracting two maximum values

Since the amounts of rainfall withheld on the canopy by the various species do not differ greatly (Table 5.18) any differences in nutrient returns reflect the chemical composition of the canopy wash mainly (for example, the high Ca and low K values for Tectona and young Agathis respectively).

The Javan plantations fall in the lower range of the spectrum in accordance with their relatively low nutrient concentrations of the crown drip. Similarly Eupatorium ranks high as a result of its low interception percentage and high nutrient concentrations. In fact only the Radiata pine plantations in New Zealand (WILL, 1959) and the Rain forests of Venezuela (STEINHARDT, 1979) and Malaya (constructed data applying an interception figure of 20 %, KENWORTHY, 1971) have lower transfer rates than the Indonesian trees; values reported for West Africa (NYE, 1961; BERNHARD-REVERSAT, 1977; also MATHIEU, 1976) seem to be higher than for most other locations.

Now that the nutrient accession rates via incident rainfall (Table 4.4), litterfall (Tables 5.6 & 5.12) and net canopy wash (Table 5.22) have been determined we can evaluate the relative contributions of these pathways to the total input of nutrients into the central compartment : the forest floor. Results are presented in Table 5.23.

Patterns for the tree plantations appear to be quite similar, *e.g.* Ca and Mg inputs to the forest floor happen mainly via litterfall, whereas K is predominantly provided by canopy wash, followed by litterfall. Sodium finds its way to the soil mainly through rainfall (50-60 %) and canopy drip (another third). Only minor amounts of this constituent are transported as litterfall, even in the case of *Eupatorium* where canopy wash is important. The relative contributions observed in Java recur in most other studies on nutrient cycling in the tropics (apart from the Lower Montane Rain Forest of Puerto Rico for which sometimes contradictory sets of data exist).

5.5 Uptake of nutrients

5.5.1 *Introduction*

As related in section 5.1 the annual uptake of chemical elements by the vegetation equals the amounts contained in the annual increase in biomass plus the transfers of nutrients via litterfall and (net) canopy wash.

Having determined the latter aspects in foregoing sections we will now deal with the first-mentioned aspect : the uptake of nutrients. In order to evaluate the magnitude of nutrient immobilization associated with annual increase in plantation biomass (section 5.5.4) knowledge is needed of this increase (section 5.5.2) as well as the chemical composition of the forest (section 5.5.3).

5.5.2 *Above-ground living biomass*

The above-ground living biomass of the study plots has been estimated along the lines described in section 5.2 (field and laboratory procedures). Results of these measurements (both on an areal and on an individual basis) are given in Table 5.24 and (for *Agathis* only) Figure 5.10.

Table 5.23 Total input (*t*) of Ca, Mg, Na and K to the forest floor (kg ha^{-1} yr^{-1}) and relative contributions of rainfall (*r*), net canopy wash (*n*) and litterfall (*l*) in selected natural and man-made forests in the (sub)tropics

Location	Vegetation	Total input (kg ha^{-1} yr^{-1}) and relative contributions (%)															
		Ca				Mg				Na				K			
		t	r	n	l	t	r	n	l	t	r	n	l	t	r	n	l
plantations																	
Indonesia[1]*	*Agathis* 1942	*111*	7	3	90	*24.5*	13	17	70	*24.0*	50	35	15	*69*	11	59	30
	Agathis 1966	*153*	6	4	90	*20*	16	14	70	*20.6*	58	32	10	*36*	22	41	37
	Eupatorium	*254.5*	3	39	58	*60.5*	6	63	31	*18.8*	63	34	3	*112.5*	7	88	5
	Tectona	*138*	6	10	84	*25*	13	20	67	*20.1*	59	34	7	*62*	13	58	29
	P. merkusii	*42*	20	11	69	*19*	16	19	65	*25.0*	48	41	12	*80*	10	55	35
Ivory Coast[2]	*Terminalia* 1)	*106*	16	25	65	*56*	12	25	63					*113.*	5	66	29
(Banco & Yapo)	*ivorensis* 2)	*160*	10	15	75	*39*	18	15	67					*128.5*	4	63	33
New Zealand[3]	*P. radiata*	*24.4*	11	2.5	87					*28.8*	83	6	10	*32.7*	10	44	46
natural forests																	
Ivory Coast[2]	Lowland Rain	*100*	16	23	61	*92*	8	37	55					*93.5*	6	64	30
	(Banco & Yapo)	*140*	11	14	75	*46*	15	35	50					*113.5*	5	72	23
Puerto Rico[4]	Lower Montane Rain	*115*	6	23	71	*79*	25	62	13	*416*	37	62	1	*99*	9	84	7
ibidem[5]		*85*	26	15	59	*21*	23	20	57	*87*	65	30	5	*157*	12	87	1
Venezuela[6]		*50*	11	3	86	*21.5*	24	9	67	*4.6*	70	24	6	*103*	2.5	65.5	32
Ghana[7]	Moist semi-deciduous	*235*	5.5	7	87.5	*62.8*	18	10.5	71.5					*288*	6	70	24

[1] present study
[2] Bernhard-Reversat (1977);
[3] Will (1959);
[4] Clements & Colon (1975);
[5] Jordan *et al.* (1972);
[6] Steinhardt (1979);
[7] Nye (1961)

1977 until 1 February, 1978; insertion of rainfall and drip data for a "normal" year (4670 mm rainfall) would

Looking at *Agathis* first, it becomes obvious that the mass of all components increases regularly with age of the trees (Fig. 5.10). On a relative basis, however, stemwood becomes more important with age : it makes up 66 % of the total weight in the youngest and 82 % in the oldest stand. There are no major differences in relative weights between the plantations established in 1942 and 1956, despite a difference in age of 14 years. Conversely, much greater differences are observed between the 1956- and 1966 stands. Apparently the *Agathis* trees begin to distribute their annual increase in biomass more evenly after about twenty years.

The following quadratic functions (valid for *Agathis* only) relate tree-component (leaves, wood, etc.) biomass to age. They were derived from data determined for 11-, 21- and 35-yr old sample trees (see Fig. 5.10).

$$\text{leaf biomass}^{*} = -\ 0.68 + 0.58\ t^{**} + 0.03\ t^2 \tag{5.2}$$

$$\text{branch biomass} = -\ 10.65 + 1.46\ t + 0.05\ t^2 \tag{5.3}$$

$$\text{twig biomass} = 7.55 - 0.42\ t + 0.04\ t^2 \tag{5.4}$$

$$\text{stemwood biomass} = -141.7 + 14.43\ t + 0.42\ t^2 \tag{5.5}$$

$$\text{bark biomass} = -\ 8.0 + 0.81\ t + 0.02\ t^2 \tag{5.6}$$

$$\text{stemwood + bark biomass} = -149.7 + 15.24\ t + 0.44\ t^2 \tag{5.7}$$

---

*kg o.d. wt per tree

**age in years

These equations give very good results for *Agathis* trees between 10 and 40 years of age. Further extrapolation gives results of unknown quality. They underestimate the biomass of 5-yr old specimens considerably, however, and this had to be estimated via the available observations on 7-yr old sample trees.

The general production of leaf-, branch-, twig-, bark- and stemwood biomass in time by *Agathis* as computed by the above formulae is given in Appendix 2, both for standing crop and thinnings (site class III;standard management).

Such a regular increase in biomass with age is not equally clear on a plantation basis as a result of the fact that the stands planted in 1942 and 1966 are understocked by almost 40 %. According to local standard yield tables (SUHARLAN *et al.*, 1975) the *Agathis* plantations of the Mondo River basin should ideally contain 330, 490, 1040 and 1830 trees ha^{-1} (*cf.* Table 5.25), representing stemwood volumes (without bark) of 427, 280, 123 and 76 $m^3\ ha^{-1}$ respectively. The plots are actually estimated to contain 262, 300, 68 and 70 $m^3\ ha^{-1}$ of stemwood (without bark) according to TEAM VEGETATION & EROSION (1979b) with the first figure pertaining to the oldest plantation.

The *Tectona* site is quite understocked too : actual tree density amounts to 342 trees ha^{-1} as opposed to the optimum stocking of 545 (SUHARLAN *et al.*, 1975). The *Pinus* plantation on the other hand is quite dense : 720 trees ha^{-1} *vs.* only 370 in a normal stand. When comparing pine and teak trees with *Agathis* of similar age the (initially) rapid growth rate of *Pinus merkusii*, which is about twice that of *Agathis*, is striking. *Agathis* on its turn grows *c.* twice as fast as *Tectona* (Table 5.24).

Fig. 5.10 Cumulative production of biomass by *Agathis loranthifolia* (site class III) over 40 years

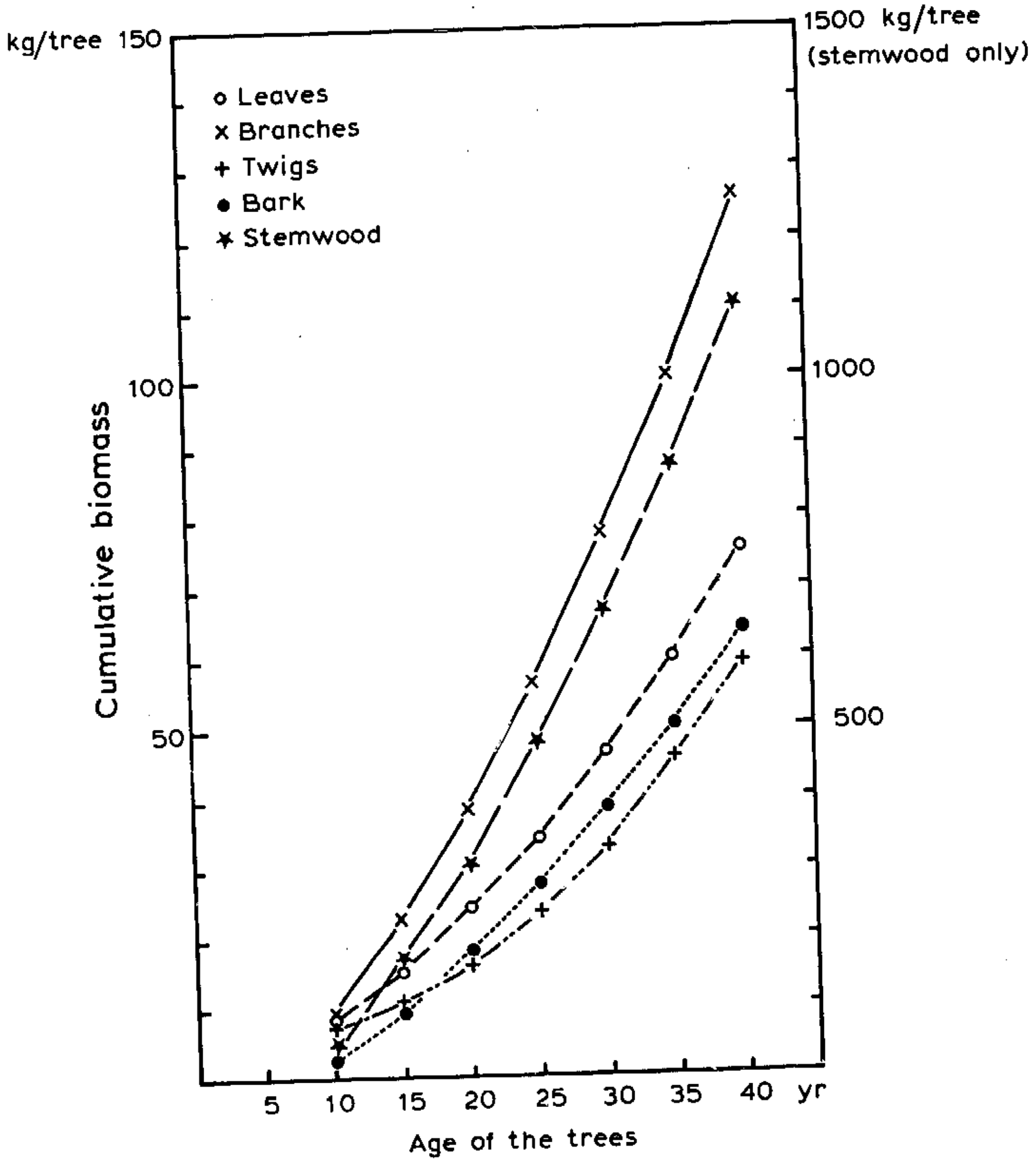


Table 5.24 Above-ground living biomass of the study plots (kg per tree *c.q.* kg ha^{-1} dry wt)

Site	Above-ground living biomass*											Tree density ha^{-1}
	kg $tree^{-1}$ (dry wt)					kg ha^{-1} (dry wt)						
	Leaves	Branches	Twigs	Stemwood incl. bark	Total	Leaves	Branches	Twigs	Stemwood incl. bark	Under-growth	Total	
Agathis 1942	60.0 ± 2.1 (5.3)***	100.4 ± 0.8 (8.9)	45.1 ± 8.3 (4.0)	922 ± 61.4 (81.8)	1127.6 ± 66.8	9600	16064	7216	147536	3100**	183520	160
Agathis 1956	26.0 ± 8.0 (5.8)	41.6 ± 4.7 (9.3)	17.6 ± 2.3 (3.9)	364 ± 46.3 (81.0)	449.4 ± 61.3	11700	18720	7920	163890	4100	206300	450
Agathis 1966	9.7 ± 0.1 (9.7)	11.4 ± 0.9 (11.4)	8.1 ± 3.5 (8.1)	71 ± 3.7 (71.0)	100.3 ± 8.0	5626	6612	4693	41238	5000	63170	580
Agathis 1970	2.8 ± 0.4 (12.3)	5.0 ± 0.1 (21.9)		15.0 ± 3.0 (65.8)	22.8 ± 3.5	5908	10550		31650	3000**	51108	2110
Eupatorium											10500	
Pinus 1965	16.6 ± 0.3	38.8 ± 2.5 (16.2)	7.2 ± 1.2 (3.0)	176.9 ± 3.4 (73.9)	239.5 ± 6.9	11952	27936	5184	127368	1490	173940	720
*Tectona***** '52	15.1(5)	38 (13)		241 (82)	294	5150	12900		82400	1950	100500	342

*accuracy not to the last integer

**under-estimate due to cuttings

***expressed as percentage of total weight

****see text for explanation (section 5.2)

Most of the investigated stands belong to site classes II to III which indicates average growth under the prevailing forestry practices. The youngest plantation of *Agathis* exhibits better than normal growth (site class IV) whilst the *Pinus* site has excellent growth (site class V).

It is somewhat difficult to put the above observations into perspective. Until very recently detailed data on the biomass of man-made forests in the humid tropics was very scarce indeed (UNESCO, 1978). Most of the older material available is in the form of yield tables showing average stemwood volumes (excluding bark) as a function of stand age, density and site quality. No mention is made in such tables of the mass of branches, twigs and leaves involved. Table 5.25 summarizes the available information on tree biomass in (sub)tropical plantation forests.

Table 5.25 Above-ground tree biomass in the (sub)tropics in selected monoculture plantations (kg per tree)

			Tree biomass (kg dry wt)				
Species	Location	Age (yr)	Bole	Branches	Leaves	Total	Reference
P. caribaea	Brazil	5-6	54.7	5.2	7.3	67.3	CHIJIOKE, 1980
	Nigeria	6	16.6	3.1	3.7	23.5	EGUNJOBI & BADA, 1979
		10	34.0	5.8	7.1	46.9	
P. oocarpa	Brazil	8	37.2	4.4	2.6	44.2	CASTRO *et al.*, 198
		14	150.7	15.4	7.4	173.4	
		18	281.3	28.9	12.4	322.6	
P. patula	Tanzania	10	157.7	46.8	19.8	224.3	LUNDGREN, 1978
		20	689.0	189.8	67.4	947.0	
P. roxburghii	India	30	115.8	-	13.3	-	SETH *et al.*, 1963
P. radiata	New Zealand	10	45.3	5.7*	3.1	54.1	WILL, 1964
		28	748.2	39.0	15.0	802	ORMAN & WILL, 1960
Tectona grandis	India	33	128.9	-	8.5	-	SETH *et al.*, 1963
Araucaria cunninghamii		30	441.0	-	15.0	-	*ibidem*

*including dead branches

A comparison of biomass figures for the Javan trees (Table 5.24) and those presented in Table 5.25 reveals the excellent growth of *P. merkusii* in the present case.

Only P. patula growing at high altitudes on andosols in Tanzania and perhaps P. oocarpa (18 yrs) in Brazil, show equally vigorous growth. Teak, Roxburghii pine and Hoop's pine in northern India all have a much smaller biomass than their Indonesian counterparts (despite their older age) which probably reflects differences in climate. The biomass accretion of P. radiata in New Zealand during the later stages of its growth is remarkable and seems to be associated with the roots breaking through a gravel layer and extending into deeper layers (WILL, 1964).

Some scattered data do exist on the biomass of natural forests of Agathis in Australasia. DILMY (1971) for example gives a stembiomass of 232.5 t ha^{-1} for a forest in Kalimantan dominated by Agathis borneensis. Agathis trees constituted 76 %, i.e. 177 t ha^{-1} (377 m^3 ha^{-1}), which is quite comparable to the figure obtained for the well-managed 21-yr old stand of Agathis loranthifolia of the study catchment. A much higher amount of timber is quoted by WHITMORE (1977) for the 50 m high virgin forest of Agathis australis in New Zealand, viz. 2300 t ha^{-1} ! Such values are not even attained in the Lowland Rain forest of Southeast Asia, whose biomass ranges from 325 t ha^{-1} in southern Thailand to 493 t ha^{-1} at Sabah, Malaysia (KIRA & OGAWA, 1971).

A final word on the accuracy of the biomass estimations of the present study before proceeding to a description of the nutrient content of the vegetation. Two kinds of errors may occur : 1) The method to define the "average" tree (section 5.2) is wrong, and 2) the sample trees deviate from the "average" trees. In order to evaluate such errors use was made of volume tables published by MURSAID (1956) and SUKMANA *et al.*, (1976). Field procedures appeared to produce only minor deviations, but biomass estimations may be 5-10 % too high due to differences in dimensions of sample trees (only two per location !) and theoretical "average" trees (TEAM VEGETATION AND EROSION, 1979b). Precision of biomass estimates for the *Tectona* stand is naturally less than for sites where sample trees could be felled. Undergrowth biomass is probably on the low side as harvesting took place in the middle of the dry season and cuttings for cattle fodder were obvious in some cases.

5.5.3 *Nutrient content of the living biomass*

The elemental concentrations of the foliage, branches, twigs, bark and stemwood of the sampled trees in each study plot are presented in Table 5.26a-h. Most analyses are based on only two composite samples for each category and a statistical analysis of the data would not be justified.

Conclusions drawn from Table 5.26 should therefore be regarded with caution. Even more so since nutrient concentrations in especially leaves tend to depend on their position in the crown (WILL, 1957; ATTIWILL, 1980). Similar variations in composition have been observed by these authors for stemwood and bark, but are ruled out in the present case as samples for these categories were taken at 50 cm height.

The multitude of data in Table 5.26 will now be discussed in the following order :
1) differences between tree components
2) differences between species
3) trends with age (*Agathis* only)
and 4) foliage composition *vs.* forest floor litter composition.

Ad 1) With Agathis the highest concentrations of nutrients are observed in the leaves, followed by twigs and bark (which usually contain about equal amounts), branches and stemwood. Calcium (and to a lesser extent Mn) tend to accumulate in the bark rather than in the twigs. The data on silica concentrations are contradictory in that some stands do not show any variation amongst components whereas others do.

Table 5.26 a-h Nutrient concentrations of the organic compartment (mg g^{-1} dry wt) of the study plots

(a)

Agathis (1942)	Ca	Mg	Na	K	P	SiO_2	Al	Fe	Mn
Leaves	16.1 ± 2.7	5.0 ± 0.3	0.8 ± 0.2	8.4 ± 2.5	1.3 ± 0.4	5.7*	0.5*	0.3*	0.37*
Branches*	3.6	0.8	0.2	1.6	0.5	5.8	< 0.08	0.17	< 0.12
Twigs	12.2 ± 2.5	3.5 ± 0.1	0.7 ± 0.1	7.0 ± 1.3	2.2 ± 0.4	5.6*	0.13 ± 0.07	< 0.16 ± 0.01	< 0.12 ± 0.01
Stemwood	1.0	0.25 ± 0.07	0.1 ± 0.3	0.8 ± 0.3	0.05± 0.07	5.6 ± 0.1	< 0.08 ± 0.005	(0.2 ± 0.1)	(< 0.12 ± 0.01)
Bark	13.5 ± 4.7	2.8 ± 0.9	0.7 ± 0.1	4.7 ± 1.1	2.0 ± 0.9	5.9 ± 1.0	< 0.14 ± 0.04	< 0.18 ± 0.05	< 0.13 ± 0.03
Undergrowth**	7.9	2.7	0.4	6.4	0.6	5.1	1.8	0.6	0.18
Litter**	15.6	2.5	0.25	2.4	0.4	27.0	-	-	0.5

(b)

Agathis (1956)	Ca	Mg	Na	K	P	SiO_2	Al	Fe	Mn
Leaves	19.5 ± 4.3	3.2 ± 0.0	0.5 ± 0.0	6.4 ± 1.0	0.9 ± 0.2	1.6 ± 0.6	0.32 ± 0.04	0.22 ± 0.06	0.52 ± 0.11
Branches	5.9 ± 0.7	1.3 ± 0.3	0.2 ± 0.0	1.9 ± 0.2	0.5 ± 0.1	2.8 ± 3.0	0.08 ± 0.02	0.05 ± 0.01	0.05 ± 0.02
Twigs	10.8 ± 0.8	2.7 ± 0.1	0.5 ± 0.1	6.1 ± 1.8	1.3 ± 0.0	2.5 ± 2.8	0.15 ± 0.04	0.07 ± 0.00	0.12 ± 0.01
Stemwood	1.2 ± 0.2	0.2 ± 0.0	0.07 ± 0.03	0.5 ± 0.1	0.2 ± 0.0	4.1 ± 1.2	0.08 ± 0.00	0.08 ± 0.00	0.02 ± 0.00
Bark	17.8 ± 3.5	2.2 ± 0.4	0.1 ± 0.0	2.1 ± 0.1	0.6 ± 0.2	5.9*	0.18 ± 0.03	0.09 ± 0.02	0.14 ± 0.00
Undergrowth**	7.7	2.6	0.3	8.0	0.6	5.4	1.1	0.44	0.14
Litter**	16.9	2.6	0.3	2.3	0.5	18.6	2.5	0.65	0.4

(c)

Agathis (1966)	Ca	Mg	Na	K	P	SiO_2	Al	Fe	Mn
Leaves	20.8 ± 2.8	3.7 ± 0.7	0.25 ± 0.0	8.0 ± 2.1	1.2 ± 0.0	11.1 ± 1.1	0.43 ± 0.01	0.16 ± 0.01	0.35 ± 0.04
Branches*	3.3	0.8	0.11	4.9	0.8	9.9	0.16	0.06	0.04
Twigs	7.9 ± 0.7	2.6 ± 0.0	0.3 ± 0.1	6.9 ± 1.3	1.5 ± 0.5	9.6*	0.19 ± 0.04	0.07 ± 0.00	0.10 ± 0.03
Stemwood	0.8 ± 0.1	0.2 ± 0.0	0.12 ± 0.18	0.6 ± 0.3	0.17± 0.06	9.8*	0.15 ± 0.00	0.04 ± 0.01	0.02 ± 0.00
Bark	13.8 ± 2.6	2.2 ± 0.3	0.5 ± 0.2	3.0 ± 1.1	0.6 ± 0.1	9.8 ± 0.6	0.23 ± 0.03	0.08 ± 0.01	0.12 ± 0.08
Undergrowth**	8.0	2.6	0.4	6.2	0.7	6.5	2.3	0.83	0.17
Litter**	14.9	2.6	0.2	2.8	0.6	16.1	-	-	0.4

(d)

Agathis (1970)	Ca	Mg	Na	K	P	SiO_2	Al	Fe	Mn
Leaves*	20.8	5.3	1.0	5.5	0.9	> 7.7	0.5	0.73	0.36
Branches } Twigs }	8.0 ± 0.8	2.6 ± 0.3	0.4 ± 0.2	5.9 ± 7.7	1.3 ± 0.7	2.0 ± 2.2	<0.09 ± 0.03	0.08 ± 0.02	0.07 ± 0.02
Stemwood	0.8 ± 0.3	0.24±0.15	0.11 ± 0.08	0.6 ± 0.2	0.16±0.07	2.9 ± 3.4	< 0.10*	0.07 ± 0.01	0.01 ± 0.00
Bark	18.7 ± 6.3	2.5 ± 1.3	0.5 ± 0.1	3.1 ± 1.6	0.7 ± 0.2	4.1 ± 3.0	0.36*	0.12 ± 0.00	0.11 ± 0.00
Undergrowth**	6.1	3.1	0.3	6.1	0.6	5.9	2.3	1.3	0.27
Litter**	17.8	4.0	0.4	2.2	0.4	10.9	-	3.7	0.4

*one sample only

Table 5.26 a-h Nutrient concentrations of the organic compartment (mg g^{-1} dry wt) of the study plots (continued)

(e)

Tectona 1946	Ca	Mg	Na	K	P	SiO_2	Al	Fe	Mn
Leaves	8.8 ± 0.1	2.8 ± 0.1	0.055 ± 0.007	12.8 ± 0.5	1.2 ± 0.2	16.7 ± 3.3	0.35 ± 0.01	0.20 ± 0.02	0.06 ± 0.02
Branches	1.8 ± 0.2	0.9 ± 0.0	0.07 ± 0.01	4.7 ± 0.3	0.9 ± 0.3	}3.3 ± 1.8	< 0.08 ± 0.01	0.05 ± 0.02	0.004 ± 0.00
Twigs	3.4 ± 1.1	0.8 ± 0.05	0.06 ± 0.02	4.7 ± 0.6	0.8 ± 0.3			0.05 ± 0.00	0.01 ± 0.01
Bark of branches & twigs***	24.0 ± 5.2	2.4 ± 0.7	0.09 ± 0.02	7.2 ± 2.0	1.1 ± 0.4	1.2 ± 0.1	0.14 ± 0.03	0.12 ± 0.11	0.06 ± 0.01
Sapwood*	1.5	0.9	0.03	3.8	1.6	13.2	< 0.08	0.02	0.007
Heartwood*	6.9	0.75	0.04	1.3	0.9	3.1	< 0.08	0.05	0.007
Bark*	61.7	3.2	0.05	5.3	0.5	2.0	0.64	0.30	0.035
Total stemwood incl. bark*	8.5	0.9	0.045	2.7	0.95	3.7	< 0.09	0.08	0.010

(f)

Tectona 1952	Ca	Mg	Na	K	P	SiO_2	Al	Fe	Mn
Leaves	9.4 ± 0.9	2.6 ± 0.5	0.1 ± 0.0	14.3 ± 2.0	1.3 ± 0.7	14.5 ± 1.4	0.46 ± 0.08	0.29 ± 0.009	0.03 ± 0.00
Branches	2.7 ± 0.3	0.8 ± 0.0	0.1 ± 0.0	3.2 ± 0.1	0.4 ± 0.0	}6.3 ± 0.6	}<0.11 ± 0.01	0.06 ± 0.03	0.002 ± 0.000
Twigs	4.3 ± 1.0	0.8 ± 1.0	0.1 ± 0.0	3.9 ± 0.1	0.3 ± 0.1			0.05 ± 0.00	0.006 ± 0.001
Bark of branches & twigs	51.8 ± 8.2	2.7 ± 0.4	0.2 ± 0.1	5.4 ± 0.8	0.6 ± 0.3	3.0 ± 0.0	0.41 ± 0.05	0.13 ± 0.04	0.07 ± 0.01
Undergrowth**	8.8	2.6	0.4	7.2	0.5	(5.9)°	(2.3)°	0.8	0.33
Litter**	22.6	3.0	0.25	2.5	0.5	*c.* 50°°	3.2	1.3	0.3

*one sample only
**3 samples bulked for analysis
***arithmetic mean of 4 samples
°estimated value
°°*ibidem*, via litterfall

(g)

Pinus merkusii 1965	Ca	Mg	Na	K	P	SiO_2	Al	Fe	Mn
Needles	10.6 ± 5.4	2.3 ± 0.6	0.4 ± 0.1	7.2 ± 0.1	0.7 ± 0.2	2.0 ± 0.6	0.32*	0.23 ± 0.02	0.62 ± 0.11
Branches	2.6 ± 0.6	0.3 ± 0.1	0.03 ± 0.01	0.55 ± 0.1	0.1 ± 0.0	}3.0 ± 0.1	< 0.10 ± 0.00	0.12 ± 0.04	0.06 ± 0.01
Twigs	5.1 ± 0.3	0.55 ± 0.0	0.1 ± 0.04	1.4 ± 0.3	0.2 ± 0.0			0.09 ± 0.05	0.14 ± 0.03
Stemwood	0.85 ± 0.07	0.2 ± 0.05	0.03 ± 0.01	0.45 ± 0.1	0.15 ± 0.1	-	-	0.05 ± 0.01	0.04 ± 0.00
Bark	2.8 ± 2.2	0.3 ± 0.05	0.04 ± 0.01	0.55 ± 0.2	0.2 ± 0.1	6.2*	0.21*	0.08*	0.07 ± 0.01
Undergrowth**	8.9	2.7	0.5	10.3	0.7	5.9	2.7	0.5	0.5
Litter**	8.2	1.8	0.2	2.1	0.3	3.7	3.1	1.6	0.5

(h)

Eupatorium sp.	Ca	Mg	Na	K	P	SiO_2	Al	Fe	Mn
Live shrub**	12.1	3.7	0.7	5.4	0.6	6.4	2.66	0.94	0.16
Litter**	14.6	3.4	0.3	2.8	0.7	17.3	8.8	5***	0.4

*one estimate available only
**3 samples bulked for analysis
***estimated from litterfall

With the Merkusii pine the sequence is more or less the same, be it that twigs are richer in nutrients than bark or branches which show about equal concentrations. The few data available for SiO_2 suggest an accumulation in the bark.

Patterns for Tectona are quite different from the softwood species. Here, leaves rank first in SiO_2, P, and K concentrations only, whilst the bark contains the highest amounts of Ca, Mg, Al and Mn. Sodium is indifferent in both stands that were investigated.

Sapwood of Tectona usually contained more nutrients than heartwood, with the exception of Ca. A similar trend was observed by ORMAN & WILL (1960) for P. radiata in New Zealand on leached rhyolitic tuffs and (for Ca and Mg) in Terminalia alata trees in Thailand (STONE & BOONKIRD, 1963).

Ad 2) Leaves of Agathis are notably rich in Ca, Mg and Na as compared to Tectona or P. merkusii. Teak leaves exhibit the highest K and SiO_2 levels, but are quite low in Na and Mn. Pine needles contain low to intermediate amounts of most elements, except of Mn, for which it ranks first. Eupatorium exhibits very high concentrations of Al (as does the undergrowth component in general), but Mn is fairly low.

Foliar concentrations observed for the Javan trees are compared to those of similar or related species investigated elsewhere in the (sub)tropics in Table 5.27a.

Leaves of Agathis loranthifolia have a composition quite similar to that of A. australis in New Zealand, although the latter is poorer in Ca. The teak trees from northern India probably differ from their Javan counterparts in that their leaves are richer in Ca and P, but poorer in K. Thirty-year old P. roxburghii trees growing at the same location showed concentrations very identical to those observed for needles of P. merkusii, although the latter's foliage was much poorer in P (data not included in Table 5.27). The Javan pine generally exhibits quite high concentrations compared to most other Pinus species (Ca, Mg, Mn), but is intermediate in P concentration. The range in concentrations reported for P. caribaea needles is substantial, even when growing on a similar substratum (CHIJIOKE, 1980 and STARK, 1970). Similarly large differences in the K, Ca and Mg concentrations of P. patula needles are found in the literature (LUNDGREN, 1978). These examples indicate the limited value of direct comparisons between species without taking into account the natural variation due to site characteristics.

Fairly little information has been published on concentrations of non-essential nutrients in tropical plantations. Merkusii pine needles seem to contain relatively little Al, fair amounts of SiO_2 and Fe and quite much Mn. HUMPHREYS & TRUMAN (1974) report a range in Al concentrations in Australian P. radiata needles of 0.32-1.41 mg g^{-1}, i.e. more than twice that of P. merkusii (Table 5.26). SETH et al. (1963) mention a foliar SiO_2 concentration 0f 1.4 mg g^{-1}

Table 5.27 a Nutrient concentration of foliage of selected monoculture plantations in the (sub)tropics

Species and location	Age (yr)	Element concentration mg g^{-1} dry wt								
		Ca	Mg	Na	K	P	N	SiO$_2$	Fe	Mn
Agathis loranthifolia^{1}, Indonesia, 6°30' S	7-35	16.1-20.8	3.2-5.3	0.2-1.0	5.5-8.4	0.9-1.4	12.7*	1.6-11.1	0.2-0.7	0.35-0.52
A. australis^{2}, New Zealand, 36° S, rhyolitic tuffs	28	7.8-13.3	-	0.9-1.0	3.9-9.0	1.8-1.4	7.6-9.1	-	0.15-0.17	0.07-0.08
ibidem^{2}, natural growth basalts 36° S	80	10.3-17.5	-	0.7-1.1	4.5-6.2	0.4-0.5	5.3-6.7	-	0.27-0.37	0.36-0.44
Araucaria cunninghamii^{3} India, 30° N	30	17.3	3.7	-	11.7	2.1	9.9	0.6	-	-
Tectona grandis^{1}, Indonesia, 6°30' S	25-31	8.8-9.4	2.6-2.8	0.1	12.8-14.4	1.2-1.3	15.9**	14.5-16.7	0.2-0.3	0.03-0.06
ibidem^{3}, India 30° N	33	23.4	2.9	-	7.6	2.7	19.3	9.4	-	-
Pinus merkusii^{1}, Indonesia, 6°30' S	12	10.6	2.4	0.4	7.2	0.7	14.0**	2.0	0.23	0.62
P. caribaea^{4}, Nigeria, 8° N	10	3.5	1.8	-	7.5	0.3	8.7	-	-	-
ibidem^{5}, Surinam, 5° N	8-16	5.0	1.1	-	4.8	0.6	10.2	-	-	-
ibidem^{6}	7	10.0	3.0	0.2	2.4	0.9	11.6	-	0.04	0.01
P. patula^{7}, Tanzania, 5° S	various	6.1	1.7	-	7.2	1.4	15.9	-	-	-
P. oocarpa^{8}, Brazil, 22° S	14	2.1	0.7	-	5.0	0.8	15.3	-	0.30	0.22
P. radiata^{9}, N. Zealand, 38° S	12^{9,10}	3.3	1.2	(0.5)	9.9	1.5	14.7	-	(0.05)^{10}	(0.23)^{10}

*Agathis 1942 only;
[1] present study;
[2] Peterson (1962);
[3] Seth *et al*. (1963);
[4] Egunjobi & Bada (1979;
[5] Chijioke (1980);
[6] Stark (1970);
[7] Lundgren (1978);
[8] Castro *et al*. (1980;
[9] Will (1964);
[10] Askew, 1937.

Subscripts maintained throughout Table 5.27.
*35-yr old trees only
**see also Appendix 4

for Roxburgh pine in India, which is quite comparable to the Indonesian value of 2 mg g^{-1}. P. radiata and P. caribaea needles seem low in Fe, whereas the P. oocarpa stand from Brazil shows an Fe concentration in its foliage very similar to that found for P. merkusii (Table 5.27a).

Branches of *Agathis* trees contain more Ca, Mg and Na than those of *Tectona* or *Pinus* (Table 5.26). Reference material with respect to other locations is restricted to pine plantations (Table 5.27b).

Table 5.27b Nutrient concentration of branches and twigs in selected monoculture pine plantations in the (sub) tropics (mg g^{-1} dry wt)

Species and location	Age (yr)	Element concentration mg g^{-1}						
		Ca	Mg	K	P	N	Fe	Mn
P. merkusii[1], Indonesia	12	3.0	0.4	0.7	0.1	1.1	0.11	0.07
P. caribaea[2], Nigeria	10	1.9	0.5	1.8	0.1	3.1	-	-
P. caribaea[5], Surinam	8-16	2.4	0.6	1.2	0.2	2.7	-	-
P. Patula[7], Tanzania	-	3.0	0.7	2.0	0.4	3.0	-	-
P. oocarpa[8], Brazil	14	1.2	0.3	1.6	0.2	2.4	0.06	0.11
P. radiata[9], New Zealand	12	1.9	0.8	3.9	0.5	5.0	-	-

Merkusii pine exhibits the lowest concentrations for most clements, except Ca (comparable to teak), Fe (comparable to Agathis 1942) and Mn (lowest in teak). Tectona and Agathis have similar concentrations of K, P and Fe in their branches.

Twigs of Agathis show the highest concentrations of all elements except Mn, which is highest for P. merkusii. Levels in pine twigs are generally low (K, P) sometimes comparable (Na, Mg) or even higher (Ca) than observed for teak.

Chemical-element concentrations found in the *bark* differ greatly between species (Table 5.27c). That of *Tectona* is quite rich in Ca, Mg, K, Al and Fe as compared to *Agathis* (which contains fairly much P and Na) or pine bark, which ranks lowest for most elements.

Agathis bark appears to be of comparable composition as that of its relative Araucaria cunninghamii (Hoop pine), although the former contains more Mg and the latter more K. Although teak grown in India contained large amounts of Ca in its bark, the amounts involved were probably not as great as encountered in Java. On the other hand, trees of Terminalia alata growing under the same conditions as natural teak forests in Thailand exhibited excessively high concentrations of Ca in their bark (STONE & BOONKIRD, 1963). Values of 165 mg g^{-1} were reported. Magnesium levels were low : between 0.20 and 0.4 mg g^{-1}, i.e. comparable to pine trees (Table 5.27c).

P. merkusii bark contains a fair amount of Ca as compared to most other pines, but still little in comparison to P. roxburghii. Potassium-, Mg and P concentrations are quite similar to those for P. caribaea and lower than found for P. roxburghii and (except for Mg) P. patula.

Stemwood chemical compositions are given in Table 5.27d.

Table 5.27c Nutrient concentrations of bark in selected monoculture plantations in the (sub)tropics (mg g^{-1} dry wt)

Species and location	Age	Element concentration mg g^{-1} dry wt							
		Ca	Mg	K	P	N	SiO_2	Fe	Mn
Agathis loranthifolia[1] Indonesia	7-35	13.5-18.7	2.2-2.8	2.1-4.7	0.6-2.3	(3.1*)	4.1-9.8	0.08-0.12	0.11-0.14
Araucaria cunninghamii[3] northern India	33	14.9	1.3	6.8	0.8	3.9	4.2	-	-
Tectona grandis[1], Indonesia	31	61.7	3.2	5.3	0.5	-	2.0	0.3	0.04
ibidem[3], northern India	33	42.6	1.8	7.4	1.5	4.0	2.6	-	-
P. merkusii[1], Indonesia	12	2.8	0.3	0.55	0.2	-	6.2	0.08	0.07
P. caribaea[4], Nigeria	10	1.1	0.3	0.7	0.1	2.8	-	-	-
ibidem[5], Surinam	8-16	0.9	0.35	0.55	0.1	1.6	-	-	-
P. patula[7], Tanzania	-	0.9	0.2	1.2	0.15	2.3	-	0.08	0.03
P. oocarpa[8], Brazil	14	0.7	0.2	3.8	0.7	7.5	-	-	-
P. roxburghii[3], India	30	10.0	0.5	2.5	0.6	3.3	3.0	-	-

**Agathis* 1942 only

Table 5.27d Nutrient concentrations of stemwood of selected monoculture plantations in the (sub)tropics (mg g^{-1} dry wt)

Species and location	Age	Element concentration (mg g^{-1} dry wt)							
		Ca	Mg	K	P	N	SiO_2	Fe	Mn
Agathis loranthifolia[1], Java	7-35	0.8-1.2	0.2	0.5-0.8	0.05-0.2	1.7*	2.9-9.9	0.04-0.08	0.01-0.02
Araucaria cunninghamii[3], northern India	30	1.6	0.2	1.4	0.9	1.0	0.4	-	-
Tectona grandis[1], Indonesia**	31	1.5 6.9	0.9 0.8	3.8 1.3	1.6 0.9	1.6 2.0*** 0.9	13.2 3.1	0.02 0.05	0.007 0.007
ibidem[3], India	33	2.3	1.0	1.3	1.3	1.3	1.3	-	-
Pinus merkusii[1], Indonesia	12	0.8	0.2	0.45	0.2	1.25°	3.3	0.05	0.04
P. caribaea[4], Nigeria	10	0.8	0.3	0.8	0.1	1.8	-	-	-
ibidem[5], Surinam	8-16	1.5	0.4	1.5	0.15	1.9	-	-	-
P. patula[7], Tanzania	-	0.6	0.2	0.8	0.1	1.0	-	-	-
P. oocarpa[8], Brazil	14	0.7	0.2	0.7	0.1	1.0	-	0.01	0.06
P. roxburghii[3], India	30	1.5	0.1	1.0	0.4	1.1	0.7	-	-

**Agathis* 1942 only

**first line : sapwood; 2nd line heartwood

***both sap- and heartwood } see also Appendix 4

°including bark }

Stemwood exhibits the same trend as bark in that teak heartwood again is richest in bases and lowest in Mn. Differences between Agathis and *P. merkusii are only minor. Wood from Agathis and Indian Araucaria are similar in some respects. Araucaria wood (as was its bark) is richer in P and K (the P concentration of the wood is in fact reported to be even higher than that of the bark) but much poorer in* SiO_2*. The heartwood of Tectona in Java does not differ much from that produced in northern India, apart from Ca and* SiO_2 *which are higher in the Indonesian case (Table 5.27d).*

Merkusii pine shows relatively low concentrations for Ca, Mg and especially K. Silica and Fe levels on the other hand seem to be fairly high, whereas P and perhaps Mn concentrations are more or less "normal".

Ad 3) *Trends with age* emerging from the data on *Agathis* in Table 5.26a-d are an increase in Ca, Mg, and Na concentration in twigs plus and increase in Na and a decrease in P and K concentrations of the branches. Aluminium levels seem to decrease with age, although actual differences are quite small.

Reference material is restricted to data on P. oocarpa in Brazil (CASTRO et al., 1980), P. caribaea in Surinam (CHIJIOKE, 1980) and P. radiata in New Zealand (ASKEW, 1937, ORMAN & WILL, 1960;WILL, 1964). No material has been encountered on either Agathis or Tectona in this regard. The results of the above-mentioned studies are contradictory in many respects. For example, P and K decrease with age in the branches of P. oocarpa and P. radiata (as in the case of Agathis), but the reverse takes place with P. caribaea. ASKEW (1937) found Ca concentrations in Monterey pine needles to rise with age, whereas WILL noted a decrease, etc.

Ad 4) Comparison of nutrient concentrations in the living foliage, (Table 5.26), "freshly" fallen leaves (Tables 5.4a - *Agathis* & *Eupatorium* and 5.11a - *Tectona /Pinus*) and mature forest floor litter may give information on re-translocation of nutrients before leaf-abscission and on chemical changes occurring in the litter layer. Nitrogen, P (except *Eupatorium*) and K appear to be retranslocated into the trees before leaffall in all cases. Similar findings have been reported elsewhere and are in fact quite characteristic for sites of limited nutrient supplies (*e.g.* for *P. patula* (LUNDGREN, 1978), *P. caribaea* (EGUNJOBI & BADA, 1979; GUNJOBI & ONWELUZO, 1979), *Tectona* (SETH *et al.*, 1963) and montane forest in Venezuela (STEINHARDT, 1979). In addition, Al may be retained by the foliage of *Agathis*, Na possibly by *Eupatorium* and Ca, Mg (perhaps) and Mn by *P. merkusii*.

Pine needle fall usually contains more Ca and at least as much Mg as living needles (SETH et al., 1963; ORMANN & WILL, 1960; WILL, 1967;LUNDGREN, 1978;EGUNJOBI & BADA, 1979). With the exception of P. merkusii all species had the highest concentrations of Ca, Mg, Na and SiO_2 *in the leaffall component.*

Silica (except for pine) together with the micro-nutrients Fe and Mn and the non-essential Al (except for *Agathis*) seemed to accumulate in the floor litter. Bases were usually leached from the forest floor layers. The latter observations agree with those of GOLLEY *et al.* (1975) and STEINHARDT (1979) for natural forests in Panama and Venezuela with the exception of Mn.

Agathis twig- and bark litter (Table 5.4b): K and P are retained by the trees in both cases (as with leaffall), whilst Mg, Na and possibly N show re-translocation in the case of "bark-fall".

A combination of the data on above-ground living biomass (Table 5.24) with chemical-element concentrations (Table 5.26) enables the computation of the standing crop of nutrients : Table 5.28. The living biomass is one of the main compartments in which nutrients are held, the forest floor (section 5.6) and the soil (section 5.7) being the other two (*cf.* Fig. 5.1). When the figures of Table 5.28 are expressed as percentages of the total tree/plot biomass (italics in Table 5.28) the distribution of nutrients over the organic compartment becomes more distinct. Any consequences for harvesting practices are discussed in section 5.9 on implications for forest management.

With *Agathis* the relative contributions of the leaf- and twig fractions are much higher for all elements (except for Si and Fe respectively) than would appear from their biomass alone. For young *Agathis* trees the amounts contained in the leaves even exceed those present in the stemwood and bark (except again for Si). From 11-yr old trees onwards the wood fraction starts to take over, perhaps except for Mn.

Leaf contributions in *P. merkusii* resemble those of *Agathis* 1966 whereas in the case of *Tectona* most of the nutrients are stored in stemwood and bark (on average 76 % *vs.* 13 % in the leaves). This is even more than in the oldest *Agathis* plantation which holds 66 % of the nutrients in the wood and 18 % in the leaves. Nevertheless the relative amounts held in *Tectona* leaves are larger again than would be expected from their relative biomass alone.

Undergrowth represent some 2 % of the total living biomass in the older stands (*Agathis*, *Tectona*), a figure that rises to 8 % in the young *Agathis* (1966) plantation. In contrast a very low value (0.9 %) is found for the densely stacked *P. merkusi* site. The relative contribution of the shrub- and herblayers to the total nutrient inventory of the living vegetation is greater than expected from organic matter data alone, reflecting the relatively high concentrations in the undergrowth. Relative contributions naturally increase as tree biomass decreases (younger stands), whereas undergrowth biomass (except for the *P. merkusii* plot) varies within fairly narrow limits. The high proportions of Fe and Al brought in by the shrublayer are striking.

Although the nutrient dynamics of the *forest floor litter* will be dealt with in more detail in a later section (5.6), some remarks on its importance are appropriate in the present context.

Table 5.28a-g Standing crop of nutrients in the organic compartment of the study plots (kg ha^{-1})*. Figures in italics represent percentage of total tree biomass (tree item), of total living biomass (undergrowth component) and of total organic compartment (litter layer)

a

Agathis (1942)	Organic matter*	Ca	Mg	Na	K	P	SiO_2	Al	Fe	Mn	N
Leaves	9600 *(5.3)*	154.6 *(21.2)*	48.5 *(27.7)*	8.2 *(15.3)*	80.8 *(18.6)*	13.0 *(16.7)*	54.7 *(5.4)*	4.7 *(25.1)*	2.8 *(6.9)*	3.6 *(15.4)*	121.9 *(22.1)*
Branches	16064 *(8.9)*	57.8 *(7.9)*	12.8 *(7.3)*	3.2 *(6.0)*	25.7 *(5.9)*	8.0 *(10.3)*	93.5 *(9.2)*	1.3 *(6.9)*	2.7 *(6.6)*	1.9 *(8.1)*	38.6 *(7.0)*
Twigs	7216 *(4.0)*	88.0 *(12.1)*	25.3 *(14.4)*	5.4 *(10.0)*	50.9 *(11.7)*	16.2 *(20.8)*	40.5 *(4.0)*	0.9 *(5.0)*	1.2 *(2.8)*	0.9 *(3.8)*	37.2 *(6.7)*
Stemwood including bark	147536 *(81.8)*	427.8 *(58.7)*	88.5 *(50.5)*	36.9 *(68.7)*	276.6 *(63.7)*	40.6 *(52.2)*	829.2 *(81.5)*	11.8 *(63.0)*	34 *(83.6)*	17 *(72.6)*	354.1 *(64.2)*
Undergrowth	3100***(1.7)*	24.5 *(3)*	8.5 *(5)*	1.2 *(2)*	19.8 *(4)*	1.8 *(2)*	15.9 *(1.5)*	5.5 *(23)*	1.9 *(4)*	0.5^5 *(2)*	20.6 *(36)*
Total Living Biomass	183516	753	184	55	454	80	1034	24.2	42.6	24.0	572
Litter layer	4700 *(2.5)*	73.3 *(9)*	11.8*(6)*	1.2 *(2)*	11.3 *(2.4)*	1.9 *(2.3)*	127 *(11)*	11.5°*(32)*	3° *(7)*	2.4 *(9)*	35.2 *(6)*
Total Organic mass	188216	826	195	56	465	81.5	1161	36	46	26	608

*accuracy not to the last integer; for biomass determinations see sections 5.2 and 5.5.2

°estimated via 1956-stand concentrations

**biomass somewhat underestimated due to cutting for fodder

b

Eupatorium sp.	Organic matter	Ca	Mg	Na	K	P	SiO_2	Al	Fe	Mn	N
Living material	10500 *(64)*	127.2 *(59)*	39.3 *(66)*	74 *(80)*	56.5 *(77)*	6.6 *(61)*	67.4 *(39)*	27.9 *(35)*	9.9	1.6 *(40)*	104.0 *(60)*
Litter layer	5970 *(36)*	87.2 *(41)*	20.3 *(34)*	1.8 *(20)*	16.7 *(23)*	4.2 *(39)*	103.3 *(61)*	52.5 *(65)*	?	2.4 *(60)*	68.7 *(40)*
Total organic mass	16470	214	60	9	73	11	171	80.4	?	4.0	173

Table 5.28 continued

(c)

Agathis (1956)	Organic matter	Ca	Mg	Na	K	P	SiO$_2$	Al	Fe	Mn
Leaves	11700 *(5.8)*	228.7 *(28.2)*	36.9 *(26.5)*	6.1 *(21.0)*	74.9 *(29.4)*	10.3 *(16.0)*	18.7 *(2.3)*	0.4 *(2.2)*	2.6 *(15.2)*	6.1 *(47.3)*
Branches	18720 *(9.3)*	110.4 *(13.6)*	24.0 *(17.2)*	4.1 *(14.1)*	36.5 *(14.3)*	9.2 *(14.3)*	56.1 *(6.9)*	1.5 *(8.4)*	0.9 *(5.3)*	1.0 *(7.8)*
Twigs	7920 *(3.9)*	85.1 *(10.5)*	21.0 *(15.1)*	4.1 *(14.1)*	48.7 *(19.1)*	10.6 *(16.4)*	47.0 *(5.8)*	2.8 *(15.7)*	0.5 *(3.2)*	0.9 *(7.0)*
Stemwood incl. bark	163890 *(81.0)*	387.6 *(47.7)*	57.4 *(41.2)*	14.8 *(51.0)*	95.0 *(37.2)*	34.4 *(53.3)*	688.3 *(85.0)*	13.1 *(73.6)*	13.1 *(76.6)*	4.9 *(38.0)*
Undergrowth	4100 *(2.0)*	32.8 *(4)*	10.7 *(7)*	1.6 *(5)*	25.4 *(9)*	2.8 *(4)*	26.8 *(3.2)*	9.5 *(35)*	3.4 *(16)*	0.7 *(5)*
Total living biomass	206303	845	150	31	281	67	837	27.3	20.6	13.6
Litter Layer	5300 *(2.5)*	89.6 *(10)*	13.8 *(8)*	1.6 *(5)*	12.1 *(4)*	2.6 *(4)*	98.6 *(11)*	13.2 *(32)*	3.4 *(14)*	2.1 *(13)*
Total organic mass	211603	934	164	32	293	70	909	40.5	24	16

(d)

Agathis (1966)	Organic matter	Ca	Mg	Na	K	P	SiO$_2$	Al	Fe	Mn
Leaves	5626 *(9.7)*	117 *(41.9)*	20.8 *(36.6)*	1.4 *(16.7)*	45.0 *(27.8)*	6.6 *(20.8)*	62.2 *(10.8)*	2.4 *(22.2)*	0.9 *(18.4)*	2.0 *(54.0)*
Branches	6612 *(11.4)*	21.8 *(7.8)*	5.2 *(9.1)*	0.7 *(8.3)*	32.4 *(20.0)*	5.2 *(16.4)*	65.4 *(11.3)*	1.1 *(10.2)*	0.4 *(8.2)*	0.2 *(5.4)*
Twigs	4698 *(8.1)*	37.1 *(13.3)*	12.1 *(2.1)*	1.3 *(15.5)*	32.6 *(20.2)*	7.2 *(22.7)*	45.1 *(7.8)*	0.9 *(8.3)*	0.3 *(6.1)*	0.5 *(13.5)*
Stemwood incl. bark	41238 *(71.0)*	103.1 *(37.0)*	18.8 *(33.0)*	5.0 *(59.5)*	51.6 *(31.9)*	12.7 *(40.1)*	404.1 *(70.1)*	6.4 *(59.2)*	3.3 *(67.3)*	1.0 *(27.0)*
Undergrowth	5000 *(7.9)*	38.5 *(12)*	13.0 *(18.5)*	1.4 *(14)*	40.0 *(20)*	3.1 *(9)*	27.2 *(4.5)*	5.6 *(35)*	2.2 *(31)*	0.7 *(16)*
Total living biomass	63174	317.5	70	10	202	35	604	16.4	7.1	4.4
Litter layer	4000 *(6)*	59.6 *(16)*	10.4 *(13)*	0.8 *(7.5)*	11.2 *(5)*	2.4 *(6.5)*	64.4 *(10)*	10° *(38)*	2.6° *(27)*	1.6 *(27)*
Total organic mass	67174	377	80	11	213	37	668	26	10	6.0

Table 5.28 continued

(e)

Agathis (1970)	Organic matter	Ca	Mg	Na	K	P	SiO_2	Al	Fe	Mn
Leaves	5908 *(12.3)*	122.9 *(42.6)*	31.6 *(43.3)*	5.7 *(40.1)*	52.5 *(26.5)*	5.1 *(20.7)*	45.5 *(28.1)*	3.0 *(54.5)*	4.3 *(56.6)*	2.1 *(55.3)*
Branches } Twigs }	10550 *(21.9)*	84.4 *(29.2)*	28.0 *(38.4)*	4.4 *(31.0)*	61.8 *(50.3)*	13.5 *(54.9)*	21.1 *(13.0)*	0.9 *(16.4)*	0.8 *(10.5)*	0.8 *(21.0)*
Stemwood incl. bark	31650 *(65.8)*	81.3 *(28.2)*	13.3 *(18.2)*	4.1 *(28.9)*	28.5 *(23.2)*	6.0 *(24.4)*	95.4 *(58.8)*	2.5 *(47.3)*	2.5 *(32.9)*	0.9 *(23.7)*
Undergrowth	3000***(5.9)*	18.3 *(6)*	9.4 *(11.5)*	0.9 *(6)*	18.3 *(13)*	1.1 *(7)*	17.7 *(10)*	6.9 *(53)*	4. *(34)*	0.8 *(17)*
Total living biomass	51108	307	82	15	141	26.5	180	13.4	11.6	4.6
Litter layer	3100 *(5.7)*	55.2 *(15)*	12.4 *(13)*	1.2 *(7)*	6.8 *(5)*	1.2 *(4)*	> 24 (> 12)	7.8° *(37)*	11.5 *(50)*	1.2 *(21)*
Total organic matter	54208	362	95	16	148	28	> 204	21	23	5.8

Table 5.28 continued

	Tectona (1952)	Organic matter	Ca	Mg	Na	K	P	SiO_2	Al	Fe	Mn
(f)	Leaves	5150 *(5.1)*	47.1 *(6.0)*	14.0 *(14.1)*	0.46 *(8.7)*	70.0 *(20.2)*	6.7 *(7.5)*	74.7 *(13.1)*	2.4 *(19.7)*	1.3 *(14.9)*	0.14 *(13.1)*
	Branches / Twigs	12900 *(12.8)*	39.0 *(5.0)*	10.4 *(10.5)*	1.1 *(20.9)*	53.2 *(15.4)*	4.4 *(4.9)*	81.3 *(14.3)*	≤ 1.4 *(11.5)*	0.7 *(8.3)*	0.07 *(6.5)*
	Stemwood incl. Bark	82400 *(82.0)*	700.4 *(89.0)*	75.0 *(75.4)*	3.7 *(70.3)*	22.5 *(64.4)*	78.7 *(87.6)*	413 + 106 *(72.6)*	8.4 + 0.7 *(68.8)*	6.6 *(76.7)*	0.86 *(80.4)*
	Undergrowth	1950 *(1.9)*	17.2 *(2)*	5.0 *(5)*	0.7 *(1)*	14.0 *(4)*	1.0 *(1)*	11.5 *(1-2)*	4.5 *(27)*	1.5 *(15)*	0.65 *(38)*
	Total living biomass	102400	804	104	51.5	360	91	474.5 -886.5	16.0 -17.4	10.0	1.7
	Litter layer	4700 *(4.4)*	106.2 *(12)*	14.1 *(12)*	1.2 *(2)*	11.8 *(3)*	2.4 *(3)*	235 *(21-33)*	15.0 *(48)*	6.1 *(38)*	1.4 *(45)*
	Total organic matter	107100	910	118	53	362	93	709-1121	31.5	16	3

	P. merkusii (1965)	Organic matter	Ca	Mg	Na	K	P	SiO_2	Al	Fe	Mn
(g)	Needles	11952 *(6.9)*	126.1 *(31.8)*	28.1 *(37.0)*	4.9 *(42.6)*	86.6 *(50.0)*	8.0 *(22.9)*	24.0 *(4.5)*	3.8 *(19.2)*	2.8 *(18.9)*	7.4 *(44.3)*
	Branches	27936 *(16.2)*	72.6 *(18.3)*	9.2 *(12.1)*	1.0 *(8.7)*	15.4 *(8.9)*	3.1 *(8.9)*	97.7 *(18.2)*	3.3 *(16.7)*	3.3 *(22.3)*	1.7 *(10.2)*
	Twigs	5184 *(3.0)*	26.4 *(6.6)*	2.9 *(3.8)*	0.5 *(4.3)*	7.3 *(4.2)*	0.9 *(2.6)*			0.4 *(2.7)*	0.7 *(4.2)*
	Stemwood incl. bark	127368 *(73.9)*	172.0 *(43.3)*	31.8 *(41.8)*	5.1 *(44.3)*	63.7 *(36.8)*	22.9 *(65.6)*	415 *(77.3)*	12.7 *(64.1)*	8.3 *(56.1)*	6.9 *(41.3)*
	Undergrowth	1490 *(0.9)*	13.2 *(3)*	4.0 *(5)*	0.7 *(6)*	15.3 *(8)*	1.0 *(3)*	8.8 *(2)*	4.0 *(1.7)*	0.7 *(4)*	0.7 *(4)*
	Total living biomass	173930	410	76	12	18.8	36	545	24	15.5	17.4
	Litter layer	8200 *(4.5)*	67.2 *(14)*	14.8 *(16)*	1.6 *(12)*	17.2 *(8)*	2.5 *(6)*	30.3 *(5)*	25.4 *(52)*	13.1 *(46)*	4.1 *(19)*
	Total organic matter	182130	477	91	14	205	38.5	576	49	28.6	21.5

The litter layer represents some 2.5 % and 6 % of the total organic matter in the older and younger *Agathis* plantations resp., with inventories of K, P and Na being similar. Calcium and Mg contributions by the litter layer are somewhat higher than this (6-10 %) as are those by SiO_2 and the non-essential nutrient Al.

The litter layer under *Eupatorium* makes up quite a substantial part of the total organic mass (36 %). Sodium and K are leached from the forest floor; Ca, Mg and P are indifferent (no accumulation or leaching) whilst SiO_2 and the non-essential nutrients constitute major portions of the total store for these elements (> 60 %).

The *Tectona* and *P. merkusii* plantations have similar relative weights of litter. Relative contributions of the litter to the total Ca and Mg stores in the organic compartment are similar for both species and fall within the range observed for *Agathis*. Silica in *Tectona* litter is an important constituent in contrast to *P. merkusii* litter. "Micro-nutrient" contributions of the litter are high again (over 40 %), although Mn is somewhat low for needle litter. The latter contains surprisingly enough a higher relative amount of K, Na and P than *Tectona* litter, which resembles that of the older *Agathis* plantations in this respect.

The information given in this and the foregoing section on vegetation biomass will now be used to evaluate the annual uptake of nutrients by the living vegetation.

5.5.4 *Rate of nutrient uptake*

The total amount of nutrients taken up annually by trees ("gross uptake") is much larger than required for increase in biomass alone ("net uptake"). As we have seen a substantial part of the uptake naturally returns to the topsoil as litterfall (section 5.3) and rain-washed exudates (section 5.4). Strictly speaking only the net uptake of nutrients has to be determined for an evaluation of the true weathering rate of the *substratum*. It is of interest, however, to investigate how different species (in this case hard-wooded *Tectona*, shrubs and softwood conifers) distribute their nutrients.

The data on biomass (Table 5.24) and element concentration (Table 5.26) of *Agathis* trees ranging in age between seven and thirty-five years enabled the computation of their annual nutrient uptake in more detail than was possible for the remaining plots, for which only one age class was available *(Tectona, Pinus)* or no information at all *(Eupatorium* shrubs). Dividing the current biomass by the number of years elapsed since the planting of the trees results in an estimate of growth rate that is far too low, as a result of slow initial growth and removal of thinnings. Therefore, use has been made of local yield tables (SUHARLAN *et al.*, 1975) to estimate the *current* increment in stemwood volume. It was assumed that both *Tectona grandis* and *Pinus merkusii* would distribute their increase in biomass over the various categories (branches, stemwood, etc.) in the same proportion as these categories contributed to the total mass of the trees at the time of sampling. The wood volumes obtained from the tables were multiplied with 0.63 and 0.47 in the cases of teak and pine respectively to obtain oven-dry stem weights. Bark densities of 0.73 (SETH *et al.*, 1963) and 0.69 respectively were applied. Table 52.9 presents the results. In the case of *Eupatorium* an age of 5 ± 1 years was assumed to be the most reasonable estimate, suggesting a growth rate of 0.21 kg m^{-2} yr^{-1}.

Table 5.29 Actual annual increment in biomass of the "average" tree in the study plots (kg yr^{-1} dry wt)

	Leaves	Branches + twigs	Stemwood	Total
Agathis 1970	0.8	1.5	6.8	9.1
Agathis 1966	1.7	3.7	19.1	24.5
Agathis 1956	2.0	5.1	34.9	42.0
Agathis 1942	2.4	6.2	39.8	47.4
Pinus 1965	5.0	14.0	53.8	72.8
Tectona 1952	0.7	1.8	11.6	14.1

Agathis increases its biomass accretion with age, in accordance with the observation of SUHARLAN *et al.* (1975) that maximum growth occurs when the trees are about 30-35 years old. The contrasting growth rates of old *Tectona* trees and young Merkusii pines is also well-reflected.

> *Figures for the latter seem exceptionally high at first sight when compared to the Agathis trees of similar age. It should be borne in mind, however, that the pines showed excellent growth (siteclass V). Also P. radiata (site class II, New Zealand) was observed to produce c. 44 kg* yr^{-1} *of stemwood only (as computed from data on 12 and 26-yr old trees given by ORMAN & WILL (1960) and WILL (1964).*

Insertion of data on chemical-element concentrations (Table 5.26) into Table 5.29 yielded estimates of the quantities of nutrients involved (Table 5.30). These estimates are bound to be somewhat conservative as a result of the sampling procedure.

Table 5.30 Net annual uptake of nutrients by the tree component of the study plots (g per tree yr^{-1})

	Net annual uptake (g $tree^{-1}$ yr^{-1})									
Agathis 1942	Ca	Mg	Na	K	P	SiO_2	Al	Fe	Mn	N
Leaves	38.6	12.1	2.0	20.2	3.2	13.7	1.2	0.7	0.9	30.5
Branches + twigs	23.4	10.2	2.3	20.4	6.4	35.7	0.6	1.0	0.7	20.2
Stemwood	115.4	23.9	10.0	74.4	11.1	223.7	3.2	9.2	4.6	95.5
Total	*177.4*	*46.2*	*14.3*	*115.0*	*20.7*	*273.1*	*5.0*	*10.9*	*6.2*	*146.2*
Agathis 1956	Ca	Mg	Na	K	P	SiO_2	Al	Fe	Mn	
Leaves	39.1	6.3	1.0	12.8	1.8	3.2	0.6	0.4	1.0	
Branches + twigs	37.4	8.6	1.6	16.3	3.8	(19.7)	0.8	0.3	0.4	
Stemwood	82.7	12.2	3.1	20.2	7.3	(146.6)	2.8	2.8	1.0	
Total	*159.2*	*27.1*	*5.7*	*49.3*	*12.9*	*(169.5)*	*4.2*	*3.5*	*2.4*	
Agathis 1966	Ca	Mg	Na	K	P	SiO_2	Al	Fe	Mn	
Leaves	35.4	6.3	0.4	13.6	2.0	18.8	0.7	0.3	0.6	
Branches + twigs	19.3	5.7	0.7	21.3	4.7	36.1	0.7	0.2	0.3	
Stemwood	47.8	8.7	2.3	23.9	5.9	187.2	3.0	1.5	0.5	
Total	*102.5*	*20.7*	*3.4*	*58.8*	*12.6*	*242.1*	*4.4*	*2.0*	*1.4*	
Agathis 1970	Ca	Mg	Na	K	P	SiO_2	Al	Fe	Mn	
Leaves	16.6	4.3	0.8	4.4	0.7	6.2	0.4	0.6	0.3	
Branches + twigs	12.0	4.0	0.6	8.8	1.9	3.0	< 0.13	0.1	0.1	
Stemwood	17.5	2.9	0.9	6.1	1.3	20.4	0.6	0.5	0.2	
Total	*46.1*	*11.2*	*2.3*	*19.3*	*3.9*	*29.6*	*1.1*	*1.2*	*0.6*	
Tectona 1952	Ca	Mg	Na	K	P	SiO_2	Al	Fe	Mn	
Leaves	6.6	1.8	< 0.1	9.9	0.9	10.0	0.3	0.2	0.02	
Branches + twigs	5.4	1.4	0.2	7.4	0.6	11.3	0.2	0.1	0.01	
Stemwood	98.6	10.6	0.5	31.3	11.1	42.9-73.1	1.2	0.9	0.1[2]	
Total	*110.6*	*13.8*	*< 0.8*	*48.6*	*12.6*	*64.2-94.4*	*1.7*	*1.2*	*0.15*	
Pinus 1965	Ca	Mg	Na	K	P	SiO_2	Al	Fe	Mn	
Needles	52.8	11.8	2.0	36.2	3.4	10.0	1.6	1.2	3.1	
Branches + twigs	42.0	5.1	0.6	9.6	1.7	41.3	1.4	1.5	1.0	
Stemwood	72.6	13.4	2.2	26.9	9.7	175.4	5.4	3.5	2.9	
Total	*167.4*	*30.2*	*4.8*	*72.7*	*14.8*	*226.7*	*8.4*	*6.2*	*7.0*	

Leaf samples were composed of leaves of varying age and therefore likely to contain lower nutrient concentrations than freshly-formed leaves (PETERSON, 1962; WILL, 1957). Also stemwood samples have been taken from the base of the stem only, whereas concentrations higher up in the stem are often a bit higher (ORMAN & WILL, 1960; MILLER, 1963; ATTIWILL, 1980). Moreover, these samples represent the overall composition of the stemwood disc rather than the outer ring only where growth actually occurs and where concentrations are often higher as well (ORMAN & WILL, 1960; STONE & BOONKIRD, 1963).

Annual uptake of nutrients increases quite regularly with age for Agathis in most cases. Twenty-five year old trees of Tectona consume less than 21-yr old Agathis trees, whereas uptake by the young pines is only exceeded by the oldest specimens of Agathis. Table 5.30 represents uptake by the tree component only.

Undergrowth cycling rates should be added to obtain total uptake for each plot. Several difficulties exist in this respect : first of all the age of the undergrowth is difficult to assess and secondly biomass figures for this component can be expressed on an areal basis only. This does not permit the direct comparison of total uptake of sites with large differences in tree density unless the immobilization rate of the trees is expressed on an areal basis as well. Assuming ages of two to five years for the shrubs in the fairly open stands (depending on the observed intensity with which local inhabitants are cutting for fodder) a growth rate of 0.1 ± 0.02 kg m^{-2} yr^{-1} is obtained. For the denser *Agathis* 1956 and *Pinus* 1965 stands figures of 0.08 and 0.025 kg m^{-2} yr^{-1} were estimated. Insertion of mean chemical concentrations (Table 5.26) again yields approximate annual nutrient uptake by the undergrowth component (Table 5.31).

Table 5.31 Approximate nutrient uptake by the undergrowth component (gm^{-2} yr^{-1})

	Ca	Mg	Na	K	P	SiO2	Al	Fe	Mn
Agathis 1942, 1966, 1970, *Tectona*	0.8	0.3	0.04	0.6	0.06	0.6	0.2	0.1	0.02
Agathis 1956	0.6	0.2	0.02	0.7	0.05	0.4	0.1	0.04	0.01
Pinus 1965	0.2	0.1	0.01	0.3	0.02	0.15	0.1	0.01	0.01

Expressing the data of Tables 5.30 and 31 as kg ha^{-1} yr^{-1} enables the computation of the relative importance of nutrient uptake by the undergrowth (Table 5.32).

Depending on stand density and growth rates of both trees and undergrowth the proportion of total nutrient uptake accounted by the shrub- and herb layer varies between two (*Pinus*, densely planted, fast growing trees, little undergrowth) and 20 % (older understocked stands of *Agathis* and *Tectona*). Sodium, K, Al, Fe, and Mn are elements that are taken up in relatively large quantities by the undergrowth (Table 5.32).

Nutrient uptake by forest trees is often reported as the amounts incorporated in the stand (*e.g.* SETH *et al.*, 1963 for *Tectona*, *Araucaria* and *P. roxburghii*; WILL (1964) for *P. radiata*; CHIJIOKE (1980) for *P. caribaea*; CASTRO *et al.*, 1980 for *P. oocarpa*, etc.) rather than as current annual increase.

Table 5.32 Total net uptake of nutrients (kg ha^{-1} yr^{-1}) at the study plots and relative importance of the undergrowth (%)

	Uptake kg ha^{-1} yr^{-1}									Total
	Ca	Mg	Na	K	P	SiO_2	Al	Fe	Mn	
Agathis '42	36	10	3	25	*4*	50	3.0	2.6	1.2	134
Undergrowth (%)	21	27	14	26	15	12	73	35	19	20
Agathis '56	78	14	3	*29*	*6*	*(81)*	*(2.8)*	2.0	1.2	217
Undergrowth (%)	8	15	9	23	8	5	32	18	9	10
Agathis '66	67	15	2	41	8	146	4.8	2.1	1.0	287
Undergrowth (%)	11	19	16	16	8	4	46	43	23	10
Agathis '70	105	26	5	47	9	68	4.5	3.4	1.5	269
Undergrowth (%)	7	11	7	14	7	9	49	26	16	10
Tectona '52	45	7.5	0.6	23	5	33 + 5	2.8	1.3	0.3	11.8
Undergrowth (%)	17	37	60	28	12	18	79	69	80	23
Pinus '65	*123*	*22*	*4*	*55*	*11*	*165*	*6.7*	*4.6*	*5.1*	396
Undergrowth (%)	2	3	4	5	1.5	1	10	3	2.5	2
Eupatorium	25	8	*1.5*	*11*	1.3	13.5	5.6	2.0	0.3	68

In Table 5.33 the Indonesian tree growth is compared with that of a number of other species growing in monoculture plantations in the (sub)tropics. Figures are given on a per-tree basis to avoid effects of stand density.

Table 5.33 Immobilization of nutrients in the stemwood of trees in selected mono-culture plantations in the (sub)tropics (g $tree^{-1}$)

Species, Location,	Age (yrs)	Immobilization (g $tree^{-1}$)							Stemweight (kg)
		Ca	Mg	Na	K	P	SiO_2	N	
Agathis (Indonesia)[1]	35	2674	553	231	1729	254	5182	2213	922
ibidem[1]	21	861	128	33	211	76	1530	-	364
ibidem[1]	11	178	32	9	89	22	697	-	71
ibidem[1]	7	12	4	2	9	2	(43)	-	15
Araucaria (India)[2]	30	1800	179	-	1061	389	489	680	441
Tectona[1] (Indonesia)	25	2048	219	11	650	230	898-1518	482	241
ibidem[2] (India)	33	1173	146	-	300	172	196	226	129
P. *patula*[3] (Tanzania)*	10*	194	67	-	162	30	-	290	158
ibidem	20*	700	257	-	643	116	-	1112	690
P. *caribaea*[4] (Nigeria)	10	29	10	-	26	3	-	68.5	34
ibidem[5] (Brazil)	5-6	25	17	-	31	21	-	9.9	55
P. *oocarpa*[6] (Brazil)	14	92	22	-	94	11.5	-	134	151
P. *merkusii*[4] (Indonesia)	12	239	44	7	88.5	32	576	256	177
P. *radiata*[7] (New Zealand)	12	229	94	-	311	25	-	283	279.5
ibidem[8]	26-29	338	-	-	585	65	-	487	748
P *roxburghii*[2] (India)	30	163	20.5	-	149	51	132	176	116

*assuming stand densities of 1110 & 490 trees ha^{-1} respectively : probably underestimates

[1] present study; [2] Seth *et al.* (1963); [3] Lundgren (1978); [4] Egunjobi & Bada (1979); [5] Chijioke (1980); [6] Castro *et al.* (1980); [7] Will (1964); [8] Orman & Will (1960).

The trees of the Indonesian plantations appear to grow about twice as fast as their counterparts from India. They have also incorporated more SiO_2 and P (all species), Mg, (Agathis, Pinus) or K (Tectona) (all on a relative basis). Agathis seems to need considerable amounts of N. There is a dramatic increase in nutrient immobilization by Agathis between its 20th and 35th year of age. The nutrient requirements of P. patula and P. radiata are remarkable and exceed those of P. merkusii (of similar age) considerably for some elements (Mg, K). Comparatively little nutrients have been incorporated in the 10-yr old stand of P. caribaea in Nigeria reported upon by EGUNJOBI & BADA (1979). These differences reflect different climatic conditions (Indonesia vs. India for example), nutrient status of the soils (e.g. poor "latosols" in Nigeria and Brazil) and species characteristics (e.g. the high K content of P. radiata as compared to P. merkusii whose substratum is richer in K).

It is of interest to compare the total net uptake of nutrients (Table 5.32) with the various other transfers into, within and out of the eco-system : rainfall input (Table 4.4), canopy leaching (Table 5.22), litterfall (Tables 5.6 & 12) and streamflow output (Table 4.6).

Here the information will be restricted to a comparison of the relative contributions of immobilization, litterfall and net canopy wash to gross uptake (Table 5.34).

Table 5.34 Relative proportions of gross nutrient uptake accounted for by
a) net uptake (immobilization) (upper rows)
b) litterfall (middle rows) and
c) net canopy wash (lower rows). All values in percentages

Site	Ca	Mg	Na	K	SiO_2	Al	
Agathis 1942	26	32	20	29	53	58	*immo*
	72	55	24	24	44	27	*litter*
	2	13	56	47	3	15	*wash*
Agathis 1966	32	47	19	59	87	57	*immo*
	66	44	18	19	9	16	*litter*
	3	9	63	21	4	27	*wash*
Tectona 1952	26	25	7	30	10	27	*immo*
	60	58	14	23	84	41	*litter*
	8	17	78	47	6	32	*wash*
Pinus 1965	79	58	23	43	65	33	*immo*
	18	33	17	22	32	64	*litter*
	3	9	59	35	3	3	*wash*
Eupatorium	9	12	18	9	7	41	*immo*
	55	29	7	5	55	52	*litter*
	36	59	75	86	38	7	*wash*

Calcium and Mg appear to be transported mostly via litterfall (except for *Pinus* where uptake is paramount or *Eupatorium* where leaching becomes dominant in the case of Mg). Sodium transfers take place mainly via canopy wash. Potassium behaves differently in that canopy leaching is dominant in the case of old trees and shrubs whereas uptake takes over in the case of the younger trees (*Agathis*, *Pinus*). Similarly SiO_2 is taken up strongly by the young trees, whereas canopy wash gains some importance only with *Eupatorium* (see also section 5.4.2). Aluminium is taken up in relatively large quantities by *Agathis* (and to a lesser extent by *Eupatorium*) and transferred preferentially via litterfall with the other species.

The absolute figures for net canopy washare known to be underestimates (see section 5.4.2), but their relative importance (as presented in Table 5.34) deviates by 2-3 % only from trends observed in a year with normal precipitation.

The data on nutrient immobilization (Table 5.32) indicate rates of net uptake that cannot be covered by the annual input via precipitation (Table 4.4). The investigated stands therefore place a demand on the soil nutrient reserves. This will be discussed in more detail in sections 5.7 (available nutrients in the soil) and 5.9 (implications for forest management).

We will now take a closer look at the central compartment of the eco-system, the litter layer or forest floor compartment (section 5.6).

5.6 Forest floor dynamics

5.6.1 *Quantitative aspects*

The humic layers of the forest floor constitute a major and centrally located reservoir of organic matter and nutrients in the forest eco-system (Fig. 5.1). Its role in erosion control, moisture retention, nutrient cycling and regulation of baseflow composition is widely recognized (LIKENS *et al.*, 1977; PRITCHETT, 1979). The study of the dynamics of nutrients in the forest floor compartment involves the measurement of the various inputs (litterfall, precipitation, canopy wash, stemflow, root exudation) and outputs (uptake by roots, leaching by percolating water, erosion by overland flow), whereas internal biological processes (decomposition, etc.) have to be evaluated as well (Fig. 5.1). Only a few studies of this nature are available for the tropics and virtually all of them deal with natural forests.

The rapid replacement of tropical forest and agricultural wasteland by (mostly coniferous) monoculture tree plantations, however, indicates the urgent need for similar studies in plantation forest (LUNDGREN, 1978; CHIJIOKE, 1980). In the climax forest ecosystem there exists a balance between uptake and return of nutrients. Upon removal of the forest this balance will be disturbed and the ensuing nutrient cycling pattern will depend on the species planted as well as the reserves of the soil. Most of the species used are fast growers and make heavy demands on the generally poor soils. The change in nutrient balance of the soil will eventually have a detrimental effect on tree crop production (*e.g.* WILL, 1964; CHIJIOKE, 1980).

The present section brings together some data on the standing crop of organic matter and nutrients in the ground litter of the plantations considered as well as a rough indication of the residence times of the various elements and organic matter in the litter layer (Tables 5.35 & 36) and the nutrient concentrations of the water percolating through the litter layer (Table 5.37).

An index which is frequently used to estimate the rate of decay of ground litter is the so-called fractional loss rate k, defined as

$$k = \frac{A_t}{L} \ (\mathrm{yr}^{-1}) \qquad (5.8)$$

where A_t = annual litterfall (kg ha^{-1} yr^{-1})

and L = standing crop of litter (kg ha^{-1})

Equation 5.8 is supposed to be valid under equilibrium conditions in non-seasonal climates and implies an exponential rate of litter decay (JENNY *et al.*, 1949) according to

$$\frac{x}{x_o} = e^{-kt} \qquad (5.9)$$

where x_o = amount of litter at start of observation period (kg ha^{-1})
and x^o = idem after time t (kg ha^{-1})

According to this approach 95 % of x_o will be converted after a time $t = 3\ k^{-1}$. Such figures have mainly relative value, however, since most climates in the tropics are more or less seasonal and decomposition is often reported to proceed in a linear rather than exponential fashion (BERNHARD-REVERSAT, 1972; EDWARDS, 1977; STEINHARDT, 1979).

Table 5.35 (last column) shows the average residence time (calculated as standing crop divided by annual input of *Agathis* litter to decrease with the age of the plantations reflecting the moister conditions in the older stands. Teak and pine litter seem to decompose at a rate about equal to that of the older *Agathis* plantation's litter, whereas it is suggested that *Eupatorium* leaves decompose much slower. In reality it was seen that the litter of *Tectona* and *Eupatorium* decayed more rapidly than that of the coniferous species. These figures have to be treated with caution since sampling of the forest floor was performed only once, in August, 1977. A glance on Figs. 5.2 and 5.4 (portraying the seasonal course of litterfall from *Agathis* & *Eupatorium* and *Tectona* & *Pinus* respectively) shows that in the case of the former litter production during the preceding three months was minimal. Litterfall was above average in the *Tectona* and pine stands during this time, whereas decomposition slowed down as well during the dry season. It can be concluded that the average standing crop of ground litter is over-estimated in the *P. merkusii* and *Tectona* plantations (resulting in too low a k-value !), but is rather under-estimated for *Agathis* (*i.e.* the estimated fractional loss rate is too high). If the amounts of ground litter observed at the *Tectona* and *Pinus* sites of the present study are corrected for seasonal variations in litterfall (multiplying the standing crop by a ratio of monthly dry season leaf fall over the overall mean) one obtains loss rates of 2.3 yr^{-1} (*Tectona*; equal to the result found in Nigeria) and 1.8 (*P. merkusii*). Values calculated in this way for the *Agathis* stands become very low (< 0.5), although not wholely unrealistic. Results for *P. merkusii* on the other hand seem somewhat improbable.

The overall decay rate of Agathis leaves (1966 plantation) has been calculated from weight losses of litter in mesh bags as well (cf. section 5.2). A low value of k = 0.43 was the result. The technique is known to underestimate the decomposition rate (WILL, 1967; TEAM VEGETATION & EROSION, 1979b) and the latter authors

Table 5.35 Standing crop of ground litter (kg ha^{-1}) as compared to litterfall (kg ha^{-1} yr^{-1}) and mass of foliage (kg ha^{-1}) for selected natural and man-made forests in the (sub)tropics

Location	Vegetation type and age (yr)		Standing crop of litter (L*) kg ha^{-1}	%	Litterfall Leaves (A$_L$) (kg ha^{-1} yr^{-1})	Total (A$_t$)	Mass of foliage (M)* (kg ha^{-1})	(k**) (yr^{-1})	3/k*** (yr)	MA$_1^{-1}$° (yr)	LA$_1^{-1}$°° (yr)
Plantations											
Indonesia	*Agathis*^{1}	35	4700	2.5	2680	5860	9600	1.25	2.4	3.6	0.80
	Agathis^1	21	5300	2.5	3530	6180	11700	1.17	2.6	3.3	0.85
	Agathis^1	11	4000	6.0	2760	3790	5630	0.95	3.2	2.0	1.06
	Agathis^1	7	3100	5.7	2240	2550	5910	0.82	3.6	2.6	1.22
	Tectona^1	25	4700	4.4	5150	5580	5150$^+$	1.19	2.5	1$^+$	0.84
	P. merkusii^1	12	8200	4.5	5550	9970	11950	1.22	2.5	22	0.82
	Eupatorium^1		5970	36.2	-	3910	10500••	0.65	4.6	2.7	1.54
	Acacia auriculiformis^2	5	4825	6.0	6400	10690	6850	2.22 *(1.3)*$^{++}$	1.4	1.1	0.45
	Tectona^3	7	4436	-	9028	10034	-	2.26	1.3	-	0.5
Nigeria	*P. caribaea*^{4}	10	19710	12.0	-	6123	20233	0.31	9.7	3.3•••	3.2
Tanzania^5	*P. patula*	20	31700	6.4	5360	6215	33000	0.20	15	6.2	5.0
Australia^6 (N.S.W.)	*P. radiata*	12	17000 *(4900)*•	12.6	3930	5000?	9500	0.29	10.3	2.4	3.4
Natural forests											
Malaya^7	LRF		4370 (1750)•	0.9	6300	10550	8000	2.4	1.2	1.3	0.41
Puerto Rico^8	LMRF		5980 *(5110)*•	3.0	5040	9670	9370	1.6 *(1.0)*•	3.0 *(1.85)*•	1.9	0.63
Panama^9	LMRF		4820	1.8	9160	10480	10580	2.2	1.4	1.15	0.46
Papua^{10}	LMRF		6460 *(5520)*•	2.0	6350	7550	8900	1.2	2.6	1.5	0.86

*sampled late August, 1977; **fractional loss rate, see text; ***time elapsed when 95 % of original litter has decomposed;
°residence time in foliage; °°residence time of litter; $^+$equated with annual leaf litterfall; $^{++}$mesh-bag technique;

•leaves only; ••total biomass; •••total litterfall;

^{1}present study; ^{2}Team Vegetation and Erosion (1979a); ^{3}Egunjobi (1974); ^{4}Egunjobi & Bada (1979); Egunjobi & Onweluzo (1979);
^{5}Lundgren (1978); ^{6}Forrest & Ovington (1970); ^{7}Ogawa (1978); ^{8}Odum (1970); ^{9}Golley *et al.* (1975); ^{10}Edwards (1977).

found the actual rate of decay to be 1.7 times that predicted from the mesh-bag technique in a plantation of Acacia in western Java. Applying this factor to the k value obtained for Agathis yields k ≑ 0.73. The absence of rain prior to the sampling date will certainly have had some influence on the high value found for Eupatorium ground litter and accordingly on its residence time. However, even if the litter production of the preceding eight weeks is subtracted from the standing crop and the annual litterfall is increased by 25 % the corresponding k value remains below 0.9. This high value may indicate a tendency to improve site quality as is often seen with pioneer species (e.g. EWEL, 1976; TEAM VEGETATION & EROSION, 1979b). Again, more work is necessary on decomposition rates of litter produced by the species studied.

Pine litter in Java (Table 5.35) seems to decompose more rapidly than either the needles shed by P. caribaea in Nigeria (EGUNJOBI & ONWELUZO, 1979; EGUNJOBI & BADA, 1979) or P. patula in Tanzania (LUNDGREN, 1978). Also, THOJIB (1981) quoted a fractional loss rate of 0.66 for needle litter contained in mesh bags at an elevation of 1300 m a.s.l. (East Central Java). These differences are thought to reflect climatic conditions rather than species characteristics. Especially the Nigerian site experiences a long dry season during which virtually no decomposition takes place (EGUNJOBI & ONWELUZO, 1979), whereas the Tanzanian forest is located at a much higher elevation (1500-2000 m a.s.l.).

On the other hand, teak litter as produced under conditions similar to that experienced by the P. caribaea stand appeared to decay in less than half a year (on the whole) or even in one month (wet season) ! (EGUNJOBI, 1974). The fractional loss rates for ground litter in natural tropical forests decrease with elevation. The forests quoted in Table 5.35 range between 50 (Malaya) and 2450 m a.s.l. (Papua) with k-values of 2.4 and 1.2 respectively. More extreme figures have been reported for lowland Rain Forest in Ivory Coast (Yapo site; BERNHARD-REVERSAT, 1974) and Venezolan Montane forest (STEINHARDT, 1979), viz. k = 4.66 and 0.18 resp. These rates are not merely dictated by climatic conditions but also by the type of litter (EDWARDS, 1977). As such the coniferous litter in Java appears to be more resistant to decay than the litter naturally found at this elevation in Southeast Asia (as inferred from observations in Malaya and Papua New Guinea).

5.6.2 *Nutrient concentrations of ground litter and leachates*

Most of the differences in the standing crops of nutrients in ground litter as presented in Table 5.36 (August, 1977) are a reflection of littermass mainly as the chemical composition does not differ greatly between species (Table 5.26). *Tectona* litter (still fairly fresh) exhibits the highest concentrations of Ca and Si, whereas pine litter contains the lowest amounts of most of the nutrients. *Eupatorium* litter is characterized by a high Al (and probably Fe) concentration. The only trend in litter composition with plantation age (*Agathis*) is an increase in Si.

Amounts of nutrients held in the ground litter of pine plantations and natural forests in the tropics vary widely (Table 5.36) with some indications for an increase with elevation. On the whole the Javan sites seem to be pretty well stocked for most elements.

Table 5.36 Standing crop of nutrients in the litter layer (kg ha^{-1}; upper rows) and their approximate residence times (yr; italic) as calculated by equation 5.10

Location	Vegetation type and age (yr)	Nutrients stored in litter (kg ha^{-1}) and their approximate residence times (yr)									
		Ca	Mg	Na	K	P	SiO_2	Al	Fe	Mn	O.M.*
Plantations											
Indonesia	*Agathis* 35	73 *0.7*	12 *0.7*	1.2 *0.3*	11 *0.5*	2 *1.1*	127 *3.1*	12 *8*	5 *3*	2.3 *2.3*	4700 *0.8*
	Agathis 11	60 *0.4*	10.5 *0.7*	0.8 *0.4*	11 *0.8*	2.5 *1.6*	64.5 *4.1*	10 *8*	2.5 *2*	1.6 *1.6*	4000 *1.1*
	Tectona 25	106 *0.9*	14 *0.9*	1.2 *0.9*	12 *0.6*	2.5 *0.6*	227.5 *(0.8)*	15 *3.5*	6 *2.3*	0.6 *1.7*	4700 *0.8*
	P. merkusii 12	67 *2.3*	15 *1.2*	1.6 *0.5*	17 *0.6*	2.5 *0.7*	30.5 *0.4*	25 *20*	13 *4.4*	4 *2.0*	8200 *0.8*
	Eupatorium	87 *0.6*	20 *1.1*	1.8 *3.0*	17 *3.0*	4 *1.0*	103 *0.9*	52 *7.5*	30 *5*	2.4 *2.5*	5970 *1.5*
Nigeria[2]	*P. caribaea* 10	39 *1.1*	14 *1.2*	- -	47.5 *3.3*	2 *3.3*	- -	- -	- -	- -	19710 *3.2*
Tanzania[3]	*P. patula* 20	340 *7.4*	61 *4.6*	- -	17.5 *3.6*	24.5 *18.7*	- -	- -	- -	- -	31700 *5.0*
Natural forests											
Malaya[4]	LRF	20.0 *0.3*	4.0 *0.2*	0.5 -	7.3 *0.2*	1.35 *0.5*	- -	- -	- -	- -	4370 *0.4*
Puerto Rico[5]	LMRF	11 *0.2*	6 *0.5*	1 *0.2*	1 *0.5*	- -	- -	- -	23.6 *21.4*	0.6 *0.3*	5980 *0.6*
Panama[6]	LMRF	70:8 *0.7*	11.1 *0.5*	1.5 *0.1*	24.1 *1.3*	0.8 *0.05*	- -	9.6 -	5.2 *4.0*	1.8 *0.7*	4820 *0.5*
Papua[7]	LMRF	162	25	-	24	9	-	-	-	-	6460 *0.9*
Venezuela[8]	MRF	216 *5.0*	54.5 *3.9*	7.2 *26.7*	59.4 *1.8*	29.2 *7.3*	- -	245 *272*	192 *240*	14.8 *4.0*	38000 *5.4*

[1] present study
[2] Egunjobi & Bada (1979), Egunjobi & Onweluzo (1979);
[3] Lundgren (1978);
[4] Yoda (1978) & Lim (1978);
[5] Jordan *et al.* (1972);
[6] Golley *et al.* (1975);
[7] Edwards (1973), quoted by
[8] Steinhardt (1979);
*organic matter (1/k), see text for limitations
LRF Lowland Rain Forest;
(L)MRF (Lower) Montane Rain Forest

The approximate residence time of a nutrient in the litter layer (T_x) can be computed by comparing the amounts in store with those brought in annually. In formula :

$$T_x = \frac{L.a_x}{A_t.b_x} \tag{5.10}$$

where a_x and b_x are the concentrations of nutrient x in the litter layer (L) and the litterfall (A_t) respectively. This conventional estimate of T_x does not take into account the additional inputs by canopy wash (C), direct rainfall (P) and the like (Gosz *et al.*, 1976), *i.e.*

$$T_x = \frac{L.a_x}{(A_t.b_x) + (P.c_x) + (C.d_x) + \ldots} \tag{5.11}$$

Residence times have been calculated according to equation 5.10, as very few studies report throughfall chemistry *and* groundlitter chemical composition. Results are given in Table 5.36(italics). Reduction of the latter will occur to the extent that canopy drip contributes to the overall inputs. As related in section 5.4.2 (Table 5.23) this can be considerable in the case of Na and K, but occasionally for other elements too (*Eupatorium* !).

Conventionally computed residence times for micronutrients generally tend to be higher than for the other elements, of which Na often exhibits the shortest residence time. Such differences may partly be explained in terms of element mobility and perhaps contamination with mineral soil. Similarly K usually remains in the ground litter for a shorter period than Mg, Ca and P. In view of the limited amount of samples (both in space and in time) no definite comparisons can be made between species. Values for *Agathis* and *Eupatorium* should probably be raised somewhat whilst those for *Tectona* and *P. merkusii* will be on the high side.

The available nutrients in the humic layers of the forest floor derive mainly from mineralization of decomposing organic material, but some have been retained from passing rainwater (*cf.* HELVEY, 1964). Part of the available stock is taken up by the vegetation (which often has roots in the F- and H-layers (STARK & JORDAN, 1978) and part is transported into the soil profile by infiltrating precipitation.

In an attempt to estimate the quality of rainfall entering the mineral soil, water dripping from raised trays supporting proportional amounts of ground litter (KENWORTHY, 1971) was collected. Sampling dates coincided with those for throughfall, thus permitting estimates to be made of nutrient losses from the litter layer through leaching. Table 5.37 summarizes results along with data from a few other locations in the (sub)tropics.

Leachate from *Eupatorium* litter is notably high in Ca, Mg and dissolved Si and somewhat low in Na as compared to the coniferous species. The water percolating through the coniferous litter has a fairly uniform composition although there seems to be a slight tendency towards higher dissolved Si, Al and Fe concentrations in the case of *P. merkusii*.

> *Yet, litter from Agathis australis has been shown to have an acidifying and podzolating effect on soils in New Zealand (TAYLOR &*

Table 5.37a Weighted mean composition of litter leachate (mg l^{-1}) in selected natural and man-made forests in the (sub)tropics

Location	Vegetation and age (yr)	Nutrient concentration (mg l^{-1})								
		Ca	Mg	Na	K	"SiO_2"	Al	Fe^+	Mn^+	PO_4^{3-}
Indonesia[1]	*Agathis* 35	1.3	0.75	2.0	3.0	< 0.4	< 0.11	< 0.08	< 0.02	< 0.05
	Agathis 11	2.1	0.9	1.7	2.1	< 0.4	< 0.15	< 0.09	< 0.03	< 0.05
	P. merkusii 12	1.1	0.8	1.9	3.5	< 0.9	< 0.19	< 0.13	< 0.03	< 0.05
	Eupatorium	2.6	1.8	1.3	2.8	5.2	< 0.11	< 0.15	< 0.03	< 0.05
Costa Rica[2*°]	LRF	1.3	1.1	0.6	1.1	-	-	0.59	0.03	0.00
Malaysia[3**]	LMRF	1.0	0.4	-	4.0	-	-	-	-	-
Papua[4***]	LMRF	-	233	299	309	1335	-	-	-	-
Venezuela[5°]	MRF	5.1	2.1	0.4	38.4	-	1.1	0.55	0.10	0.29°°°
Australia[6°°]	*P. radiata* 33	1.9	0.7	2.4	3.3	-	-	-	-	-

[+] until 1 July, 1977; *2 weeks only; **6 months; raised litter trays; ***25 gr of litter for 48 hr in contact with 750 ml of distilled water in presence of air stream; °tension lysimeter; °°roving gauges level with forest litter; °°°total phosphorus

[1] present study; [2] McColl (1970); [3] Kenworthy (1971); [4] Turvey (1974); [5] Steinhardt (1979); [6] Feller (1978).

Table 5.37b Amounts of nutrients leached from the forest floor (kg ha^{-1} yr^{-1}) in natural and man-made forests in the tropics

Location	Vegetation and age (yr)	Amount leached (kg ha^{-1} yr^{-1})							
		Ca	Mg	Na	K	"SiO_2"	Al	Fe	Mn
Indonesia[1]	*Agathis* 1942	32.7	17.6	47.3	52.6	3.2	1.5	-	-
	Agathis 1966	50.7	21.0	30.5	39.7	*-4.1**	0.7	-	-
	Pinus 1965	16.0	12.5	25.3	38.6	8.3	2.9	-	-
	Eupatorium	-18.9*	20.0	25.1	-12.5*	96.2	1.4	-	-
Malaysia[3]	LMRF	-7.1	3.8	-	31.5	-	-	-	-
Venezuela[5]	MRF	57.1	23.0	0.8	411.9	-	11.0	6.4	12.4

[1-5] as Table 5.37a;

*minus sign not significant at $\alpha < 0.05$

DIXON, 1938; BLAKEMORE & MILLLER, 1968). Both leaves and bark of kauri contain water-soluble compounds which will dissolve ferric and aluminium oxides and are capable of reducing the former to the ferrous state under aerobic conditions (BLOOMFIELD, 1953). Agathis leaves appeared to be more active in this regard than needles from Scots pines, the complexing capacity of which was about equal to that of kauri bark. The few field observations available for Al and Fe concentrations in tropical forest litter leachate suggest higher values than observed in the present study (McCOLL, 1970; STEINHARDT, 1979 - Table 5.37a). Pine leachate composition from Java is quite similar to that observed in Victoria, Australia under P. radiata (FELLER, 1978).

Very little material is available on amounts of nutrients actually leached from the floors of tropical forests (Table 5.37b). Fairly low values have been reported for a Malayan Lower Montane Rain forest by KENWORTHY (1971). His measurements pertain to the drip from litter that accumulated in raised trays rather than original forest floor samples. Concentrations (and accordingly leached amounts) were much higher in the case of a Montane Rain forest in Venezuela as related by STEINHARDT (1979).

The combination of data on net leaching from the humic layer (Table 5.37b) and standing crop of nutrients (Table 5.36) permits the calculation of approximate nutrient residence times and as such provides an interesting check upon values obtained by applying equation 5.11 (total input). Table 5.38a shows both estimates to be quite close for K, Na and Mg (coniferous litter). The leaching approach gives higher values for Ca, (dissolved) Si and Al. The suggested "accumulation" of K and Ca in *Eupatorium* litter is not supported by the results obtained via the "input" approach. Also, average concentrations for both elements were essentially similar in both throughfall and leachate and it can be concluded that the "accumulation" is fortuitous.

Table 5.38a Approximate residence times of nutrients in the forest floor compartment as culated from net outflow rates (upper rows) and total input rates (italics) (1 February, 1977 - 1 February, 1978)

Location	Vegetation & age (yr)	Residence time (yr)						Organi matter
		Ca	Mg	Na	K	SiO_2	Al	
Indonesia[1]	*Agathis* 35	2.2 *0.7*	0.7 *0.5*	0.03 *0.05*	0.2 *0.2*	37 *2.4*	8 *3.3*	0.8
	Agathis 11	1.2 *0.4*	0.6 *0.5*	0.03 *0.04*	0.3 *0.3*	"acc." *2.1*	14.3 *2.0*	1.1
	Pinus 12	4.2 *1.6*	1.2 *1.0*	0.06 *0.07*	0.4 *0.4*	3.7 *0.3*	8.6 *1.7*	0.8
	Eupatorium	"acc." *0.3*	1.0 *0.3*	0.07 *0.1*	"acc." *0.15*	1.1 *0.5*	37 *5.6*	1.5
Venezuela[2]	MRF	3.8 *4.8*	2.4 *3.1*	9 *1.5*	0.14 *0.6*	-	22.3 *22*	5.4

[1] present study;

[2] Steinhardt (1979), acc = accumulating ?

*stock divided by annual litterfall (see Table 5.35)

Differences between the two methods will derive from the quality of the data (leachate composition had to be estimated occasionally - limited replication) and the artificial set-up (raised trays and thus no access for soil fauna and plant roots; drier conditions). Yet it remains peculiar, that good agreement is found for some elements, whereas differences are exceedingly large for others. However, the "fit" obtained by STEINHARDT (1979) in a well-replicated study is not much better reflecting the complexity and spatial variability of the processes involved.

It should be noted that the leached amounts presented in Table 5.37b pertain to the period 1 February, 1977 - 1 February, 1978. The total flux of water percolating through the litter layer was c. 20 % below average during this period and the quantities of nutrients removed are considerably underestimated. Although the input of nutrients deriving from canopy wash will also be greater during a wetter year this will not make up for the increased leaching loss due to differences in nutrient concentration (cf. Tables 5.37a and 5.20).

Trial calculations suggest the leached amounts to be underestimated by c. 25 % (Agathis : Ca, Mg, K, Al, also Si in all cases) to c. 33 % (Pinus, Eupatorium : Ca, Mg, K, Al). This again is reflected in slightly shorter residence times than calculated in Table 5.38a.

It is interesting to compare the residence times obtained for the non-living biomass (Table 5.38a) with those for the living biomass. Since the relative importance of twig, bark and seed litterfall is only poorly known, no attemps were made to carry out calculations other than for the foliar component. The inventory of nutrients in the foliage has already been presented in Table 5.28. The ratio of this inventory (kg ha^{-1}) to the total output of nutrients via litterfall and net canopy wash (Table 5.23; kg ha^{-1} yr)^{1} has the dimension of time (yr) and can be conceived of as the approximate residence time of nutrients in the foliage. As with the litter compartment the inclusion of canopy wash has the effect of greatly reducing the magnitude of the residence times for Na and K. Again these figures are slight over-estimates as the net-canopy wash is underestimated (section 5.4.2). Results are given in Table 5.38b.

Table 5.38b Approximate residence times of nutrients in the foliage (yr)

Species, Age (yr)	Ca	Mg	Na	K	SiO_2	Al°	Fe°	Mn°	P°	N°	O.M.°
Agathis 35	2.1	2.9	0.8	1.5	2.6	5.9	4.0	4.5	13	6	3.6
Agathis 11	1.0	1.3	0.2	1.6	5.6	3.4	1.0	2.1	6.6		2.0
Tectona 25	0.4	0.7	0.1	1.3	0.3	0.6	0.6	0.4	2.0		1*
P. merkusii 12	4.3	1.9	0.4	1.4	0.6	0.4	2.3	4.4	4.0		2.2
Eupatorium	0.5	0.7	1.1	0.5	0.4	4.0	1.6	1.7	1.6		2.7

°based on leaffall only;
*mass of foliage equated to annual leaffall

Ideally the computed residence times for the various elements should be similar except where leaching becomes dominant (Na, K) or where the trees are able to retranslocate certain elements before leaf shedding (P, N ?).

On average leaves remain longer on the trees than in the ground litter. The various elements and species exhibit quite different patterns, however (Table 5.38b). Residence times in the a-biotic compartment (soil) are expected to be much larger than the above estimates (*cf.* ODUM, 1971) and constitute one of the subjects of the next section.

5.7 Available nutrients in the soil compartment

The soils of the study plots were sampled up till a depth of 150 à 200 cm during the wet season (February, 1977). The top layers (A_1-horizon) were sampled again during the dry season (July, 1977). The present discussion of available nutrients in the soil compartment will be restricted to the upper 100 cm as roots have been observed in this zone mainly (*cf.* Table 2.2). Only a very limited number of replications could be made and the results represent an order of magnitude rather than a very precise estimate. Seasonal differences in top soil concentrations were quite small in most cases, however. Largest scatter was observed for exchangeable Ca (*Eupatorium, Pinus*) and (to a much lesser extent) Mg (*Tectona, Pinus*). At present it is sufficient to note that the A_1-horizon is the most fertile, but that nutrient concentrations between 25 and 100 cm depth vary little. The same phenomenon has been reported for volcanic ashes in Tanzania (LUNDGREN, 1978). Available nutrient concentrations in intensely leached "latosols" in the same region appeared to drop sharply with depth as the organic matter content decreased. Table 5.39 presents nutrient inventories for the uppermost 10, 50 and 100 cm of soil profile for the study sites and several other locations in the tropics. Both sets of data lead to the same conclusions :

- Although *Agathis* and *Eupatorium* are growing on similar substrates (young volcanic ashes), the soil beneath the 35-yr old *Agathis* contains much less exchangeable Ca, Mg and (in the top layer perhaps) K. The upper horizon in the young *Agathis* plot is also poor in bases as compared to the *Eupatorium* site, although not as much
- The older volcanic ashes (now planted with *Tectona* and *P. merkusii*) seem to have a better supply of exchangeable bases. Levels of available phosphorus (not total P !) are quite low under *Eupatorium, Agathis* and *Tectona*.
- Sodium levels are quite similar regardless of soil- or vegetation type.
- The (slightly eroded) soils under *Tectona* have become a little poor in organic matter and N.

The low P_a content of the younger ashes (Eupatorium & Agathis) can be attributed to fixation to amorphous constituents, as is often reported for young volcanic deposits (MOHR et al., 1972). The store of available P for the Tectona plot (old volcanic ashes with only 5 % amorphous material), however, is equally small. Considering the relatively high P concentration in Tectona trees (Table 5.26) this may reflect depletion of the soil rather than leaching (cf. the relatively high amounts of available P under P. merkusii growing on similar soils).

Amounts of available bases in top soil under Agathis are considerably lower than reported for Araucaria (a relative of Agathis) in Queensland (Table 5.39a; especially Brasell's site 1, which contains volcanic elements, is much more fertile). The apparently low quantities of total P, C and N under Agathis as compared to the Australian sites reflect the low bulk density

Table 5.39a Nutrient inventory of top soils (0-10 cm) under various natural and plantation forests in the tropics (kg ha^{-1})

Location	Vegetation & age (yrs)	exchangeable								
		Ca	Mg	Na	K	$P_{available}$	P_{total}	C	N	pH (H_2O)
Indonesia[1]	*Agathis* 35	100	40	27	85	11	720	30100	3100	5.2
	Agathis 11	160	75	26	120	10	–	30600	2630	5.2
	Tectona 25	900	230	36	280	18	560	25350	2300	5.5
	P. merkusii 12	1030	245	33	450	54	800	30550	3060	5.5
	Eupatorium	710	200	28	100	9	560	35600	3450	5.5
Trinidad[2]	LRF*°	156	75	–	29	6	–	–	1810	3.7
	P. caribaea° 6	267	52	–	17	4	–	–	1240	4.2
Malaya[3]	LRF*+	17	23.5	23	82	–	14	28500	1800	3-4
Queensland[4]	*Araucaria* 41	5030	500	15	400	–	2400	45600	4400	6.8
	42	2060	260	17	71	–	1825	41000	3500	5.9
Ivory Coast[5]	*Terminalia*°° 22	–	–	–	–	66	–	32560	2200	4.1-4.4
	38	–	–	–	–	5	–	35880	2600	4.3-4.7
Tanzania[6]	LMRF**++	4800	450	–	975	15	1850	69500	7200	6.7
	P. patula++	4100	280	–	1250	48	2350	56100	5400	6.4
Papua[7]	LMRF	1350	270	54	200	–	108	66000	6048	5.5
Venezuela[8]	MRF***	140	60	12	120	–	470	45500	3700	–

[1] present study;
[2] Cornforth (1970b);
[3] Yoda (1978);
[4] Brasell *et al.* (1980);
[5] Bernhard (1977); Bernhard & Huttel (1975);
[6] Lundgren (1978);
[7] Edwards (1973), quoted by :
[8] Steinhardt (1979);
*Lowland Rain forest;
**Lower Montane Rain forest;
***Montane Rain forest
° sites 1 & 2, upper 3 inches only;
\+ sites VII & RO
°° Banco & Yapo resp.
++ andosols at *c.* 2000 m a.s.l.

Table 5.39b Nutrient inventory of the soil compartment (0-50 cm; 0-100 cm) of selected
and plantation forests in the tropics (kg ha^{-1})

Location	Vegetation & age (yrs)		Ca	Mg	Na	K	P_{av}	P_{total}	C	N
0-50 cm										
Indonesia[1]	*Agathis*	35	460	190	200	540	40	3270	108000	12000
	Tectona	25	3770	1050	200	1410	60	2680	97500	9850
	P. merkusii	12	4210	1140	180	2500	225	3520	118000	12800
	Eupatorium		2550	700	160	340	50	2550	114000	13000
Ivory Coast[2]	*Terminalia*	22	20	80	-	120	330	-	-	-
		39	190	150	-	90	25	-	-	-
Tanzania[3]	*P. patula*		21800	1350	-	6100	75	13100	224400	23400
	LMRF*		18100	1380	-	4420	29	11400	250000	28300
0-100 cm										
Indonesia[1]	*Agathis*	35	750	340	400	1340	110	5650	156000	20200
	Tectona	25	6370	1830	620	3380	105	5000	141500	14900
	P. merkusii	12	7650	2210	525	5580	345	5960	171250	17900
	Eupatorium		4130	1220	330	540	90	4960	145000	20100
Malaya[4]	LRF**		47 ± 27	43 ± 1	225 ± 35	283 ± 34	-	56 ± 24	76800 ± 5500	7120 ± 3365
Venezuela[5]	MRF***		1610	390	170	840	-	5240	268000	24130

[1] present study;
[2] Bernhard (1977);
[3] Lundgren (1978);
[4] Yoda (1978);
[5] Steinhardt (1979);
*Lower Montane Rain forest on volcanic ashes at *c.* 2000 m a.s.l.;
**Lowland Rain forest; mean of plots VII & RO;
***Montane Rain forest

of the young volcanic soil rather than differences in concentrations. The soils of the Lowland Rain forests (Trinidad, Malaya) and lowland plantation forests (Trinidad, Ivory Coast) are thoroughly leached and therefore quite poor. In fact they resemble the soils under Agathis in many respects. The soil profile under the Lower Montane Rain forest of Tanzania (LUNDGREN, 1978) and to a lesser extent in Papua New Guinea (EDWARDS, 1973) is much more fertile. The Papuan top soil is very similar to that of the P. merkusii and Tectona grandis plots of the present study. It is richer, however, in C and N - as most high-altitude forest soils are -, although poor in total P.

It is of interest to compare the stock of nutrients in the soil compartment with those of the other stores, viz. the living vegetation and the forest floor (Fig. 5.1). Such a comparison has been made for the *Agathis* 1942, *Tectona, Pinus* and *Eupatorium* sites. Results are given in Figure 5.11.

The upper 100 cm of the soil profile was chosen to represent the soil compartment. Naturally the result is a much larger store of nutrients than when the upper 25 or 50 cm had been taken. The present choice is considered to be more realistic, however, in view of the constant fertility of the soil up to this depth and the concentration of plant roots in this zone (cf. Table 2.2). Even so these figures must be underestimates as water (and nutrients) will also be extracted from greater depths, considering the prolonged rate of potential evapotranspiration exhibited by the catchment vegetation during the dry season (cf. section 3.3).

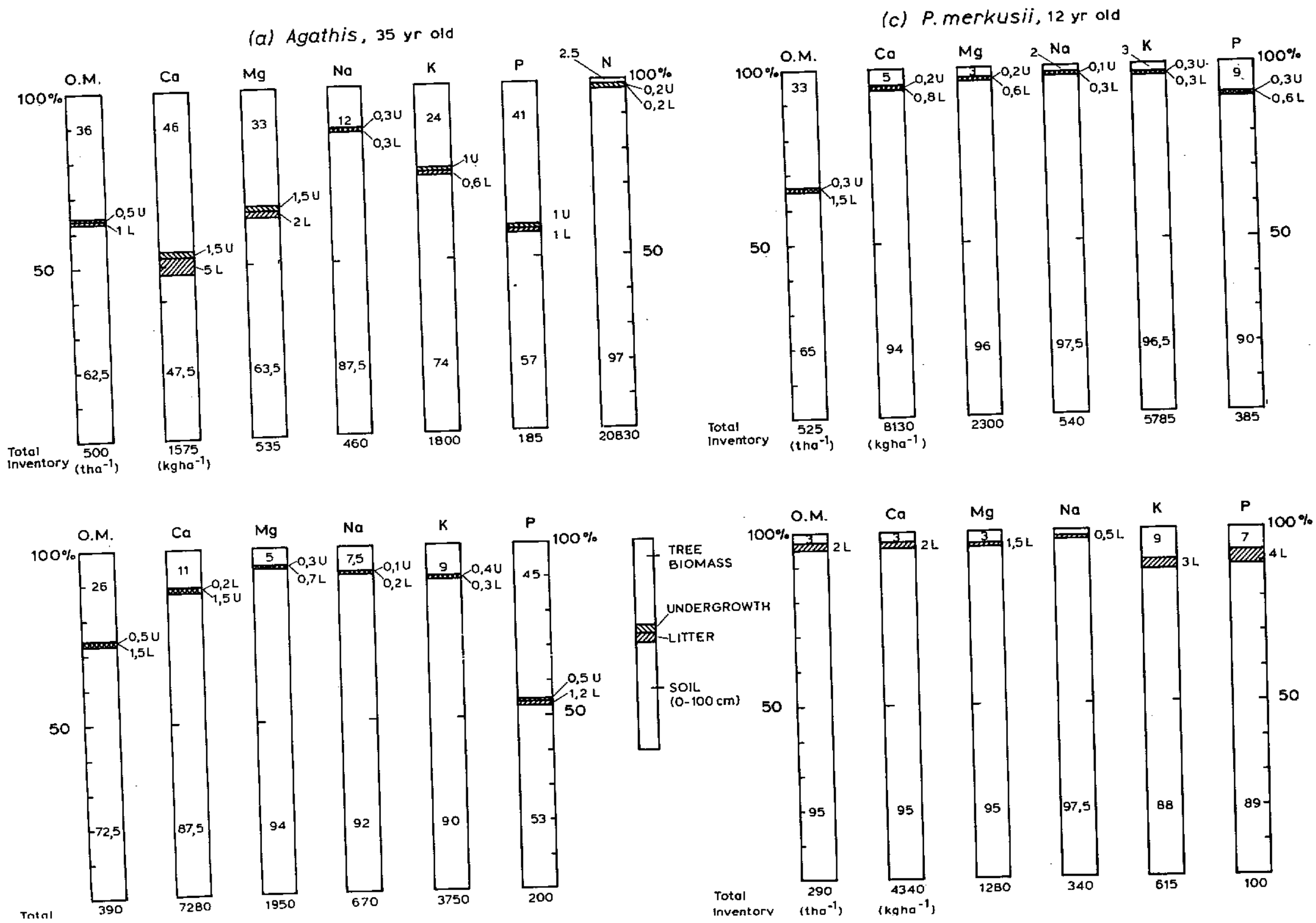
It appears from Fig. 5.11 that the nutrient stores of the soil are generally much larger than the amounts immobilized in the organic compartment. Some exceptions are noteworthy, however. For instance, the balances for Ca and P are quite unfavourable in the case of 35-yr old *Agathis*, whereas considerable amounts of Mg and K have been taken up by this stand as well. Similarly the P-economy of the tuffs of the *Tectona* site may become marginal in time (which depends on the intra-system cycle efficiency as well). *Eupatorium* finally seems to place heavier demands on K reserves than on any other element store.

Results for the two coniferous plantations are contrasting, although perhaps not strictly comparable (Fig. 5.11 a & c). Distribution of organic matter is quite similar for both stands, but that of the individual nutrients much less.

The *above-ground* inventory of the pine plantation has been expressed as a percentage of the (lower) *below-ground* store of the *Agathis* site in order to obtain a rough assessment of any"*Agathis* effect". This yielded much lower (relative) values for the amounts of nutrients held in the vegetation compartment than originally given in Figure 5.11a for the same mass of organic matter. It is (tentatively) suggested that soil reserves may last somewhat longer under *P. merkusii* given similar wood production. Clearly here is a case for further investigations.

Nutrient distribution in the Agathis plot is quite similar to that reported for a Montane forest in Venezuela (STEINHARDT, 1979). Differencess lie mainly in the Ca economy (more favourably in the latter case where limestones are the parent rock) and the distribution of K (taken up in much larger quantities by the

Fig. 5.11 Distribution of organic matter and nutrients between tree biomass, undergrowth, litter and soil



(a) *Agathis*, 35 yr old

(c) *P. merkusii*, 12 yr old

cloud forest). The distribution of organic matter in the Indonesian plantations can be compared to the situation in the Lowland Rain forest of Malaya (KIRA, 1977) and the Lower Montane Rain forest of Papua New Guinea (EDWARDS & GRUBB, 1977), where values have been determined up till 1 m depth. (Other studies have limited themselves to much shallower or unspecified depths.) The leached soil in Malaya provides only 21 % of the total organic matter, in contrast to the 79 % found in New Guinea. The trends observed in the present study therefore are very similar to the latter result, which also pertains to a forest growing on a possibly volcanic soil (EDWARDS & GRUBB, 1977).

Before the overall nutrient situation of the plantation forest ecosystem can be evaluated knowledge is needed of the rate of supply from atmospheric sources and - more important - chemical weathering. The latter aspect will be dealt with in the next section.

5.8 Implications for the calculated weathering rate

As related in chapter 4 the chemical mass balance for the catchment represents an apparent rate of chemical denudation only. We are now in the position to indicate to what extent the elemental budget should be modified by accounting for the annual immobilization of nutrients in the vegetation. Combining the data on annual net uptake by the vegetation of the various study plots (Table 5.32) with information on areal distribution patterns (Fig. 2.6) the immobilization rate for the entire catchment could be estimated. The contribution of the "homegarden" (Ind. pekarangan) component was estimated by applying chemical compositions intermediate between those of *Agathis* (1956) and *Tectona* (1952), with a tree density of 500 trees ha^{-1} and a growth rate similar to 21-yr old *Agathis*. Results are presented in Table 5.40 in conjunction with the old and the modified elemental budgets.

The purely geomorphological approach of the study of chemical denudation leads to serious underestimates for most elements, ranging between 12 and 17 % for non-essential nutrients (Si, Na) to 70 % or more in the case of essential nutrients (K, Ca).

Reference material in this respect is restricted to temperate-zone catchments bearing natural forests such as regenerating northern hardwoods in the U.S.A. (Likens et al., 1977) and mature coniferous forests in Oregon (SOLLINS et al. 1980). The latter forest did not acquire biomass anymore, but for the still rapidly aggrading hardwood forest described by LIKENS et al. (1977) the budget approach resulted in denudation underestimates that are similar to those obtained in the present study (except for Ca, which is apparently taken up less vigorously by the American forest). Virtually all P was immobilized in the vegetation, less than 1 % leaving the catchment (LIKENS et al., 1977). Although no detailed figures are available for the Mondo basin with respect to losses of P the degree of uptake (5.2 kg $ha^{-1}yr^{-1}$) suggests an equally small loss in the present case.

Now the overall speed of chemical weathering is known and the chemical dynamics of the biotic compartment of the ecosystem have been discussed, it has become possible to evaluate the present findings in terms of their consequences for forest management. This constitutes the subject of the following section.

Table 5.40 Annual uptake of nutrients by the vegetation of the K. Mondo catchment in relation to chemical denudation. Unrounded values in kg ha^{-1} yr^{-1}

	Ca	Mg	Na	K	P	SiO_2	Al	Fe	Mn	Sum
SHRUBS	10.4 (18)°	3.5 (28)°	0.5 (19)°	7.0 (26)°	0.7 (13)°	6.5 (9)°	2.3 (64)°	0.9 (39)°	0.2 (18)°	
TREES	46.9	9.1	2.1	19.9	4.5	65.4	1.4	1.4	0.9	
TOTAL UPTAKE	57.3	12.6	2.6	27.0	5.2	71.9	3.6	2.3	1.1	
Apparent rate of chemical denudation (1)*	18.1 (19.1)**	25.4 (26.5)**	13.1	11.6 (12.4)**	-	508.5 (527)**	-	-	-	577 (598)**
Actual rate of chemical denudation (2)	75.4 (76.4)	38 (39)	15.7	38.6 (39.4)	-	580.4 (599)	-	-	-	748 (769)
(1) as % of (2)	24	67	83	30	-	88	-	-	-	77

*Table 4.7; 1 December, 1976 - 1 February, 1978

**Table 4.8; "average" year

°Relative importance of the shrub layer (%)

5.9 Management implications

The uptake of nutrients by vigorously growing plantation forests in the tropics has only recently become an object of study (LUNDGREN, 1978; CHIJIOKE, 1980). In order to more fully assess the impact of intensive forestry practices on the nutrient reserves of the (often poor) tropical soils, knowledge is needed of *both uptake by the vegetation over a given rotation period and the nutrient inputs into the plantation forest ecosystem*. Information on accession rates of nutrients in bulk precipitation in the tropics is slowly becoming available (*cf.* section 4.2), but good estimates of the supply of nutrients by chemical weathering is virtually lacking.

Using the data on nutrient concentration of the vegetation, on tree biomass and the overall flux of nutrients, as obtained in the present study, it has become possible to evaluate the general nutrient balance for an ideally-stocked (*i.e.* stand densities according to standards given by SUHARLAN *et al.*, 1975) plantation of *Agathis loranthifolia* (siteclass III) over a rotation period of 40 years.

Combination of the growth figures predicted by equations 5.2-5.7 (section 5.5.2) for individual trees, after conversion to an areal basis (Appendix 2) with the corresponding concentrations of Ca, Mg, K and P (Table 5.26) yielded estimates of total uptake by the above-ground tree component over the rotation period (Appendix 2). To this should be added an undergrowth component (Table 5.31) to arrive at the total (above-ground) net nutrient requirements of the plantation. Adopting the rate of nutrient immobilization exhibited by the undergrowth of the well-stocked *Agathis*-1956 plantation (viz. Ca 6, Mg 2, K 6 and P 0.5 kg ha^{-1} yr^{-1}) extra amounts of *c.* 240, 80, 240 and 20 kg ha^{-1} for these constituents were obtained.

Table 5.41 compares these (total) nutrient requirements of the vegetation over a 40-yr period with inputs via bulk precipitation and chemical weathering, along with the range in nutrient reserves of the upper metre of soil observed at the study sites.

Total input of Ca and K matches total uptake, whereas inputs of Mg exceed requirements. The pattern is reversed for P, where total uptake is considerably higher than supplies. Taking into account the low (available) reserves of the latter element in the soil compartment it will be clear that here lies a case for careful management.

Total-tree harvesting removes unnecessarily large amounts of nutrients from the plantation ecosystem (JORGENSEN *et al.*, 1975; STONE, 1979). Indeed if only the scaled boles would be harvested (*i.e.* leaves, twigs, bark and branches remain on site for decomposition) *c.* 80 % of Ca and Mg and over 70 % of P and K would be saved for the ecosystem (*cf.* Table 5.41, 7th column).

The question arises to what extent it will be feasible to leave branches, twigs, etc. behind when the local population is in desperate need for fuelwood (*cf.* ECKHOLM, 1976). A good compromise might be to have the larger branches taken away, but have the more nutrient-rich leaves, bark and twigs left on the forest floor. This option would still prevent 70 % of the possible Ca- and Mg losses. Corresponding figures for K and P amount to 60 and 55 % respectively. The P-balance would become unfavourable if more material would be allowed to be taken away. The findings of the present study therefore indicate that long-term growing of *Agathis* is well possible on the volcanic soils of Central Java as long as total-harvesting tech-

Table 5.41 Nutrient balance* for an ideally-stocked plantation of *Agathis loranthifolia* over a rotation period of 40 yr (kg ha^{-1}; site class III)

Nutrient	Atmospheric inputs+	Chemical weathering++	Total input	Uptake**		Soil nutrient reserves of study plots***
				Total	Stemwood	
Ca	396	3056	3452	3556	659 (19)°	750 - 7650
Mg	88	1564	1652	786	153 (19)°	340 - 2210
K	384	1576	1960	1894	437 (23)°	540 - 5580
P	36	200	236	368	107 (29)°	90 - 345

*unrounded values
**Appendix 2
***Table 539b (section 5.7)
+Table 4.8 (section 4.2)
++Table 5.40 (section 5.8)
°percentage of total uptake

niques are not applied.

Another aspect of management on which some comments are possible (again based on the present investigation's results) is the necessity of control of *Eupatorium* in young tree plantations. Control is often considered necessary (personal communications to the author). However, , if the annual returns of nutrients via litterfall and net canopy wash are compared to the annual gross uptake of nutrients, then the balance appears to be much more favourable in the case of 5-yr old *Eupatorium* thicket than for 5- or 10-yr old and ideally stocked plantations of *Agathis*. Full-growing *Eupatorium* for example returns about 90 % of the total amounts of Ca, Mg or K and at least 80 % of the total P it takes up annually. A fully-stocked 10-yr old stand of *Agathis* (site class III) on the other hand will return (on an annual basis) *c*. 70 % of the total Ca, less than 60 % of the total Mg, less than 40 % of the total K and *c*. 20 % of the total P it has taken up*. It should be noted, however, that growth rates of undergrowth in a well-stocked *Agathis*plantation are *c*. 2.5 times smaller than for the studied *Eupatorium* thicket (section 5.5.2). Although the dynamics of a less well-developed shrub layer (still dominated by *Eupatorium*) are not fully investigated, it is clear that a considerable portion of the nutrient returns to the forest floor happens via the liquid phase (section 5.4.2). This rapid return of nutrients by *Eupatorium* theoretically involves a danger of nutrient losses via leaching from the forest floor. Erosion by surface wash under *Eupatorium* is minimal, however, because of the excellent infiltration rates of the top soils rich in organic material (COSTER, 1938). Similarly these upper horizons are quite capable of retaining nutrients long enough to be taken up again by the shrubs (*cf*. mean chemical composition of litter leachates and soil moisture in the top layers of the soil profile under *Eupatorium*; Table 6.13). It is tentatively concluded that *Eupatorium* has a beneficial rather than a deteriorating influence on soil conditions and plantation development.

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*This is a consequence of the evergreen habitat of the *Agathis* leaves through which the trees are able to conserve nutrients in their biomass for a longer time (thus lessening the possibilities for losses of nutrients to occur).

The data collected so far on P. merkusii do not permit the calculation of a balance sheet as presented above for Agathis. *It is intended, however, to continue work on this aspect in 1983 in plantations of P. merkusii.*

5.10 Final remarks

The various pools and transfers of nutrients in the forest biogeochemical cycle have been discussed rather individually in the foregoing sections. Here an attempt will be made to characterize the overall nutrient dynamics of the investigated sites.

The concept of "nutrient turnover" is frequently used in this respect. In general the term denotes the ratio of inventory (of a certain nutrient in a particular compartment) to total output or throughput (of that nutrient from that compartment), which has the dimension of time (ODUM, 1971; see also section 5.6 on forest floor dynamics).

The "total eco-system turnover rate" then is the ratio of the total amount of a bio-element stored in soil and biomass to the annual net loss from the eco-system. The former quantity depends strongly on the depth selected to represent the soil compartment, and is therefore somewhat ill-defined. Even the 100 cm adopted in the present study (Fig. 5.11) is not wholely representative (the ash cover being 6-12 m thick) and computed ratios will be underestimated. The annual net loss of nutrients is known for the study catchment (Table 5.40), where the *Agathis* and *Eupatorium* plots are located. Nutrient losses for the other (*Tectona, Pinus*) sites are unknown but must be very similar.

Table 5.42 presents the approximate overall turnover times for the investigated stands as well as for a few locations elsewhere in the world.

The various turnover times in Table 5.42 cannot be compared directly as they are based on different soil depths. Also the Indonesian forests have not yet reached steady-state conditions (as the South American examples have done). This resulted in a smaller nutrient loss from the catchment which again leads to higher turnover times. The impression therefore that the Javan sites exhibit a relatively tight cycling pattern is somewhat biased.

Phosphorus is often accumulated in the forest biomass, except for the 450-yr old Douglas fir forest reported upon by SOLLINS *et al.* (1980). The present index is therefore unable to express overall differences in P-dynamics. Various other indices exist, most of them involving the soil compartment as the central store, *e.g.* the ratio of soil reserves to annual uptake or to net drainage losses, or to the sum of these. However, since the values given in Table 5.42 largely depend on soil reserves too, they do not give much extra insight in the present case except for P. The low Ca- and Mg contents of the soil under old *Agathis* and the equally low K levels of the *Eupatorium* site (followed by the *Agathis* plot) are reflected again in relatively short turnover times. Similarly the P situation is least favourable under *Agathis* and *Tectona* and about twice as good for the *P. merkusii* stand which was afterall observed to exhibit "excellent growth" (section 5.5.2).

Table 5.42 Total eco-system turnover rates (yr) for the investigated plots and various other eco-systems

	Ca	Mg	Na	K	P	P•
tropical regions						
Agathis 1942[1]	83	20	35	143	acc.	6.5
Agathis 1966[1]**	154	29	13	(44)	acc.	5
Eupatorium[1]	228	48	98	49	acc.	7.5
Tectona 1952[1]***	383	74	51	298	acc.	6
P. merkusii 1965[1]***	428	87	41	449	acc.	15
LMRF, Puerto Rico[2]°	29	28	54	76	-	-
MSDF, Panama[3]°°	194	68	19	acc.?	acc.	2
temperate latitudes						
Douglas fir, U.S.A.[4]+	32	37	2.0	81	768	acc.
Northern hardwoods, U.S.A.[5]++	108	> 35	> 2	> 284	acc.	-

[1] present study
[2] Jordan *et al.* (1972)
[3] Golley *et al.* (1975)
[4] Sollins *et al.* (1980)
[5] Likens *et al.* (1977)

*(soil + *above ground* biomass) ÷ net loss
**soil reserves as for *Eupatorium* site (0-100 cm)
***net losses as for study catchment (Table 4.8)
°25 cm soil depth
°°30 cm soil depth
+100 cm soil depth
++estimates for Mg, Na and K do not include available nutrients in the soil and are serious (*c.* 30 %?) underestimates
• (soil reserves) ÷ (uptake + net loss)

The soil of this plantation and that of the *Eupatorium* study plot has been sampled and analyzed in great deal to investigate the nature of the mineral transformations involved in the process of chemical weathering. This constitutes the next chapter, called "water-rock interactions".

6 WATER-"ROCK" INTERACTIONS

6.1 Introduction

The black box approach to the chemical weathering of the volcanic deposits underlying the study basin (described in chapter 4) has been made a little greyer by the evaluation of the quantities of chemical elements taken up annually by the catchment vegetation (sections 5.5.4 and 5.8). Since the *rate* of weathering is now known with fair precision it is of interest to investigate the *mode* of weathering as well. This will constitute the subject of the present chapter.

The weathering sequence of volcanic ashes under humid (warm-) temperate conditions is well-established, mainly through work conducted in Japan (*e.g.* AOMINE & WADA, 1962; WADA & AOMINE, 1973; MIZOTA & AOMINE, 1975) and New Zealand (*e.g.* FIELDES, 1955; NEALL, 1977).

A good deal of information on the weathering mineralogy of volcanic ash soils in certain parts of the tropics has been collected over the past twenty years as well. Examples are the dacitic and andesitic ashes of Papua New Guinea (RUTHERFORD & WATANABE, 1966; RUXTON, 1968; BLEEKER & PARFITT, 1974), the andesitic tuffs of Java (VAN SCHUYLENBORGH, 1958; TAN & VAN SCHUYLENBORGH, 1959; TAN, 1969; KITAGAWA *et al.*, 1973; TAN *et al.*, 1975), Ecuador (COLMET-DAAGE *et al.*, 1967), Colombia (CALHOUN *et al.*, 1972), Costa Rica (MARTINI, 1976) and Hawaii (SHERMAN, 1957; LAI & SWINDALE, 1969 ; WADA & WADA, 1976) and the basaltic deposits of Cameroon (SIEFERMANN & MILLOT, 1969).

Virtually all these studies dealt with the inventarization of physico-chemical properties and the (clay)-mineralogy of soil profiles under contrasting climatic conditions or of varying age. Differences in soil properties were then related to pedogenesis. This approach has resulted in a fair knowledge of the weathering sequence of tropical volcanic ash soils in relation to the main soil forming factors (parent material, climate, biotic influences and time). It has perhaps produced less insight, however, into the "why" of specific mineral occurrences under certain conditions.

The present study deviates from the above-mentioned approach in that it pays attention to both the solid phase (*i.e.* the material subjected to weathering as well as secondary products) and the liquid phase (the weathering agent). As will be appreciated from the foregoing such a combined approach to pedogenesis/rock weathering is still comparatively rare. Detailed work of this nature has been carried out by VERSTRATEN (1977; 1980) and WAYLEN (1979) in the humid temperate zone. For the (sub)tropics the studies of DREVER (1971) (Mexico; various efflata including rhyolitic tuffs and andesite), NORTON (1974) (Puerto Rico; andesite), TRESCASES (1976) (New Caledonia; ultramafic rocks), DIRVEN *et al.* (1976) (Cuba; serpentinite) and WEAVER & BLOOM (1977) (Amazonia; sands) should be mentioned. In the first three of these (tropical) investigations the liquid phase was represented by stream- and spring water samples. WEAVER & BLOOM (1977) simulated it by shaking their soil samples in a dilute acid solution for 4 months, whilst DIRVEN *et al.* (1976) compared theoretically derived (*i.e.* derived from the weathering model) with published values. None of the quoted tropical studies gave actual chemical compositions of *in situ* soil water.

In the following the chemical weathering of basalto-andesitic volcanic ashes in and around the study catchment will be described. After a brief discussion of field and laboratory procedures (section 6.2) the chemical and mineralogical composition of progressively older ash layers is given culminating in a tentative weathering history of these deposits (section 6.3.1). This is followed by a description of the chemistry of the liquid phase (springs emerging from the ashes and soil moisture extracted from the various horizons; *cf.* section 6.2) in section 6.3.2. The information on the solid and liquid phases is then combined in a mineral-stability diagram (section 6.3.3). Finally the present results are put into perspective in section 6.4.

6.2 Field and laboratory procedures

6.2.1 *Field procedures*

The soil profile selected to illustrate chemical weathering sequence and process was described from a freshly dug profile pit (up to a depth of 200 cm) in February, 1977 (second half of rainy season) according to the FAO guidelines for soil profile descriptions (FAO, 1968) and Japanese color scales (published by M. OYAMA & H. TAKEHAN in 1967). Additional sampling and describing was done to a depth of 425 cm by augering in May, 1978 (end of wet season). Samples were taken from each distinguishable soil horizon *c.q.* ash layer and flown to the Netherlands for analysis at the Laboratory for Physical Geography and Soil Science, University of Amsterdam.

Soil water samples were obtained with porous cup soil water samplers installed to a depth of 200 cm. Soil water held under a tension of less than 80 cbar (pF < 2.9) could be extracted this way (WOOD, 1973) and was treated as specified for other water samples (section 4.2.1).

6.2.2 *Laboratory procedures*

Laboratory procedures are summarized in the following. Details can be found in "Methods of soil, rock and water analyses" of the Laboratory of Physical Geography and Soil Science of the University of Amsterdam.

- *Granulometric analysis of the samples was performed in the field-wet state as their clay fraction shrinks irreversibly upon air-drying (VAN SCHUYLENBORGH, 1954). Maximum peptization of the suspended fine material (< 50 μm) occurred at different pH-levels, which had to be determined by trial and error. The silt (2-50 μm) and clay (< 2 μm) fractions were obtained by the pipetting method of Robinson using Stokes' law. The sand fractions (50-2000 μm) were determined by dry sieving.*
- *Organic carbon : organic matter was oxidized in the air-dry state by $K_2Cr_2O_7$ in concentrated H_2SO_4 while heating up to 175° C for 90 seconds. The colour intensity of the formed green chromo-ions was measured colorimetrically.*
- *pH : pH was determined potentiometrically by means of a combined glass-calomel electrode in a soil suspension (10 g fine earth plus 25 ml distilled water c.q. 0.01 M $CaCl_2$) obtained after shaking for two days.*

- *H_2O^+ : loss on ignition by heating to 950° C corrected for oxidation of organic matter and Fe (II).*
- *Separation of the clay fraction for elemental analysis : dispersion with 4N NaOH (pH = 9). The clay separate was saturated with Li by equilibration with 2M LiCl (pH = 7) and dialyzed against distilled water until free of Cl. The clay was recovered by freeze drying.*

  Elemental analysis of the fine earth fraction (< 2 mm) consisted of destruction in HF/H_2SO_4 and HCl, followed by the determination of total Al, total Fe, Mn, Ca, Mg and Ti by an argon plasma emission spectrometer (with $LiNO_3$ as a buffering agent); sodium and K were estimated by flame photometry, P and Fe (II) - Fe(III) by means of colorimetry (as the blue phosphorus-molybdate complex and according to the method of BEGHEYN (1979) respectively). Silicon was estimated after soda fusion by means of atomic absorption spectrometry.
- *The clay fraction was decomposed in a mixture of HF/H_2SO_4 and resolved in HCl. Potassium and Na (using CsCl as a buffering agent); Ca and Mg (with $LaCl_3$ as a releasing agent), total Al (using KCl as a buffering agent), total Fe and Mn were determined by emission- and atomic absorption spectrometry. Lithium was estimated by means of flame photometry and Si, Ti, P and Fe (II)-Fe(III) as specified for the fine earth fraction.*
- *Oxalate-extractable matter : 250 mg of clay was shaken in 25 ml of 0.15 M NH_4-oxalate/oxalic acid in the dark for 4 hours (TAMM, 1934); iron, Al and Si concentrations in the extract were determined with an argon-plasma emission spectrometer (cf.SEARLE & DALY, 1977); weight loss after extraction was taken as the amount of amorphous material (FEY & LE ROUX, 1977).*
- *X-ray diffraction analysis : X-ray diffraction analyses on disoriented fine-earth and clay samples were carried out with a quadruple Guinier-de Wolff camera using Co Kα radiation.*
- *Differential thermal analysis : Mg-saturated clay samples were subjected to gradual heating at a rate of 10° C/minute up till 1000° C using a Linseis L-62 apparatus.*
- *Mineralogy of the sand fraction was studied microscopically at the Institute of Soil Research, Bogor, Indonesia (upper 200 cm only) and at the Institute of Earth Sciences, Free University, Amsterdam (lower part of profile).*
- *Thin sections of undisturbed soil horizons were prepared according to specifications similar to those given by JONGERIUS & HEINTZBERGER (1975), the size of the present sections being smaller, however.*

6.3 Chemical weathering of basalto-andesitic volcanic ashes under humid monsoonal conditions

6.3.1 *Solid phase*

6.3.1.1 *General characteristics of soil profile 2* (Humic Andosol)

A soil profile was selected to illustrate the nature of weathering of basalto-andesitic volcanic ash deposits in the area, a description of which is given below :

Profile 2 : Humic Andosol (FAO/UNESCO, 1974)

Located on a near-level part of the northern water divide of the investigated catchment (Fig. 3.1). Altitude 600 m a.s.l. Mean annual rainfall 4760 mm with a dry season of 2-3 months; mean annual temperature 22° C (*cf.* section 2.2 for further climatological details). Vegetation : *Eupatorium* thicket.

A_1	0- 25 cm	7.5 YR 3/3 (dark brown) fine sandy loam; crumbly; friable to slightly firm; many pores; many fine to medium roots; common biological activity; clear and wavy change to
AB	25- 70 cm	7.5 YR 4/4 (brown) silty loam, crumbly to moderate fine to medium angular blocky; friable to slightly firm; many pores; many fine roots; high biological activity (krotovina's, and holes, pedotubules); few matrans, gradual and smooth change to
IIB_{21}	70-107 cm	7.5 YR 4/4 (brown) silty loam with many gravel-sized 5 YR (5/8) (light reddish brown) litho-relicts**; moderate medium angular blocky; firm; many pores; few roots; few matrans; gradual change to
$IIIB_{22}$	107-200 cm	7.5 YR 4/4 (brown) silty clay loam with few 7.5 YR 2/3 (very dark brown) litho-relicts; moderate to strong medium angular blocky; firm to very firm; common pores; few roots; few biological activity; common matrans; gradual change to
$IVB^*_{1(b)}$	200-228 cm	7.5 YR 5/4 (brown) silty (clay) loam with very few 2.5 YR litho-relicts; medium angular blocky; slightly firm to firm; common pores; very few fine roots; common matrans; gradual change to
$IVB^*_{21(b)}$	228-260 cm	7.5 YR 4/4 (brown) silty clay loam with few weathered mineral grains; medium (?) angular blocky; slightly firm; no roots; common matrans; gradual change to
$IVB^*_{22(b)}$	260-290 cm	7.5 YR 4/4 (brown) silty clay loam with common weathered mineral grains and 2.5 YR litho-relicts; medium to coarse (?) angular blocky; slightly firm; few matrans; gradual change to
VB^*_{21b}	290-320 cm	7.5 YR 4/3-4/4 (brown) clay with few 7.5 YR litho-relicts and common weathered mineral grains; coarse angular blocky; firm; matrans?; gradual change to
VB^*_{22b}	320-350 cm	7.5 YR 4/3-4/4 (brown) silty clay with common 7.5 YR litho-relicts and common weathered mineral grains; coarse angular blocky (to massive ?); slightly firm to firm; matrans ?; gradual change to
VB^*_{23b}	350-425$^+$cm	7.5 YR 4/3-4/4 (brown) clay with few 7.5 YR litho-relicts and common weathered mineral grains; massive; firm; few to common matrans; moister, stickier and more massive with depth.

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*described from aggregates obtained by augering

**having illuviation ferri-argillans without birefringence.

It seems that profile 2 can be divided roughly into four characteristic parts, viz. ^{1}) 0-70 cm, ^{2}) 70-200 cm, ^{3}) 200-290 cm and ^{4}) 290-425 cm. This subdivision is reflected in the choice of horizon notations. For example, the subscript "(b)" ("buried") has been assigned to the IV-B horizons in which the beginnings of a pedogenetical cycle were detected that differed from the one that is presently active. Similarly the notation VB_{2b} for the deepest layers has been used to indicate yet another and quite advanced cycle of soil formation.

The data on organic matter, mechanical analysis and amounts of non-crystalline ("amorphous") material, given in Figure 6.1, are in accordance with the subdivision mentioned above.

The description of a soil profile considered representative for the steep hillsides in the catchment, given by BRUYNZEEL (1976), is very similar to the one presented here. The slightly less clayey horizon found at 200-228 cm in profile 2 is developed more clearly in the sloping profile, however, and it is possible that some lateral movement of soil water occurs along it (*cf.* section 3.4.1).

Finally a word about the mass illuviation occurring in the investigated soil. Matrans were observed from a depth of 25 cm onwards. Microscopical examination revealed that these matrans did not show birefringence, *i.e.* they are of a non-crystalline nature. The mobilization of "amorphous" matter under the prevailing conditions ($pH < 5$) is in accordance with the values for the iso-electric points for 'allophane' reported to range from pH 6-8 for 'allophanes' with a low SiO_2/Al_2O_3 ratio to pH 4 for 'allophanes' with a ratio of 2 (WADA, 1977). It is in contrast, however, to the findings of VAN SCHUYLENBORGH (1958), who observed clay migration in various soil types derived from andesitic ash in West Java, except for the so-called "acid brown earths" to which the present soil shows strong resemblance. He assumed an iso-electric point at pH 5 to explain the phenomenon.

6.3.1.2 *Chemical composition*

The elemental analyses of the fine earth- (< 2 mm) and clay (< 2 µm) fractions of the humic andosol are given in Tables 6.1 and 6.2 respectively. The above-mentioned subdivision into four distinct groups of horizons is again borne out from these data.

Taking - as a start - the TiO_2 concentrations of the clay fraction as an index of the degree of weathering (assuming one sample source area for the various eruptive phases) it appears that the deepest (and therefore oldest) layers (VB_{2b}) exhibit the most advanced stage of weathering, in accordance with a high clay content and a low amount of oxalate-extractable matter (see Fig. 6.1). Top layers have relatively low TiO_2 concentrations (representing a less advanced stage of weathering), whereas groups 2 and 3 show intermediate values.

Considering the distribution of concentrations of bases (MgO, K_2O) in the clay fraction the upper part of the profile is slightly less-weathered than the IVB group. Yet there is hardly any difference in clay content and/or amounts of "amorphous" matter extracted from the latter horizons and the $IIB_2/IIIB_2$-layers (Fig. 6.1). Similarly the concentrations of SiO_2 and Al_2O_3 in the corresponding "amorphous" clays resemble each other very much (Table 6.3), although "amorphous"

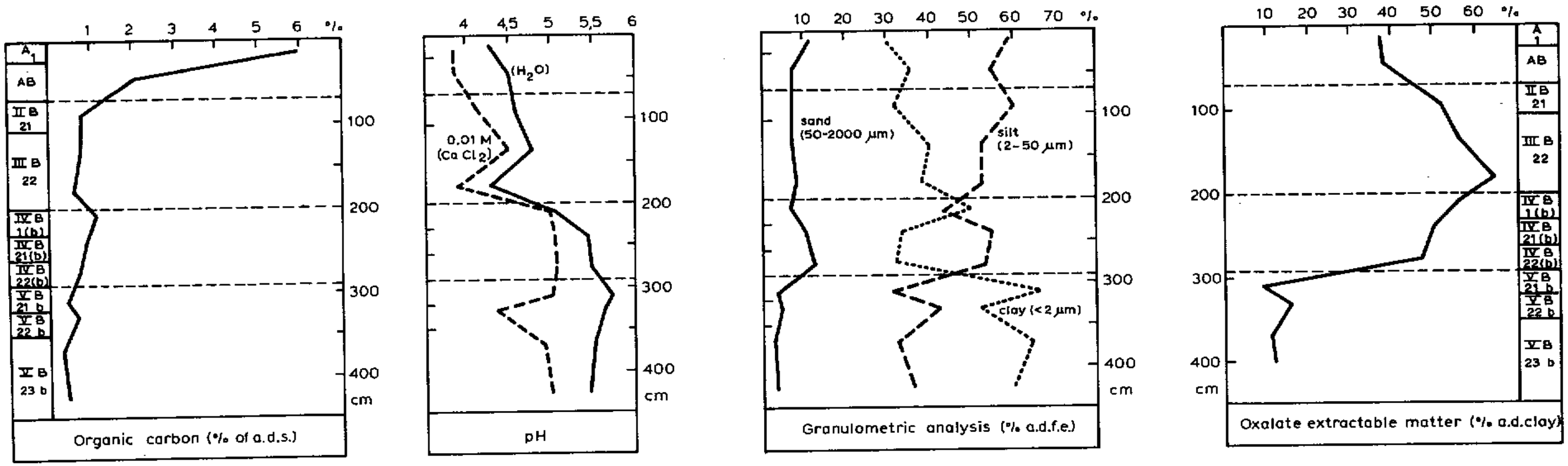


Fig. 6.1 Physical and chemical characteristics of profile 2 (humic andosol)

clay in the older layers has increasingly lower molar SiO_2/Al_2O_3 ratio's (Fig. 6.2a). However, 'amorphous' constituents of the IVB-horizons have much larger Al_2O_3/Fe_2O_3 ratio's than either younger (which exhibit intermediate values) or older layers (Fig. 6.2b) due to the quite low Fe_2O_3(t) concentrations found for the IVB-group (Table 6.3).

Despite this overall similarity in the chemical compositions of the clay fractions of the $IIIB_2$ and IVB groups, there is an interesting and sudden increase in the CaO and MgO concentrations in the fine earth fractions of the latter. This is undoubtedly a reflection of differences in the mineralogy of the sand fractions as we will see later (section 6.3.1.2).

Trends in molar ratio's in the *total* clay fraction (*i.e.* including crystalline and non-crystalline material) differ per group of horizons (*cf.* Table 6.2) : the uppermost layers (A_1-, AB- and IIB_{21} horizons) show with depth decreasing SiO_2/Al_2O_3 and Al_2O_3/Fe_2O_3 (t) ratio's. This indicates relative enrichment of the top horizon with silica and a probably greater mobility for Fe than for Al. Trends for the IIIB & IVB groups are such that Al is more mobile than Fe, whereas in the VB layers a strong enrichment with Fe_2O_3 is observed (with SiO_2 and Al_2O_3 being virtually constant) reflecting the strongly weathered nature of these old horizons.

These trends can be explained as follows :

1) The high silica content of the topsoil clay may well be the result of prolonged exposure to the organogenous silicic acid released by the litter of the Rain forest prior to the establishment of the present plantation forest. Rain forest litter is well-known for its high silica concentrations (VAN SCHUYLENBORGH & VAN RUMMELEN, 1955; see also Table 5.14) and a distinctly higher SiO_2/Al_2O_3 ratio in the topsoil clay has been reported for most upland soils under natural forest in West Java (VAN SCHUYLENBORGH, 1958).

   This hypothesis is consistent with the fact that plant opal has been found in the sand fraction of the A_1-horizon.

2) The present andosol strongly resembles the so-called "acid brown earths" described by VAN SCHUYLENBORGH (1958) very much. These soils develop from andesitic ashes under wet monsoonal condition at elevations between 600 and 1000 m a.s.l. in Java. VAN SCHUYLENBORGH (1958) also found Al to be more mobile than Fe in these soils. He attributed this feature to the absence of the Fe-complexing compounds that are so important in temperate climates. This absence would be due to a fast and complete mineratlization of organic matter on the forest floor. The difference in solubilities of $Al(OH)_3$ and $Fe(OH)_3$ would then be reflected in the greater mobility of Al. Reality is probably more complex. A large portion (over 60 %) of the organic matter in the "acid brown earths" consists of fulvic acids (TAN & VAN SCHUYLENBORGH, 1959), that are known to form complexes with both Al and Fe (SCHNITZER & KODAMA, 1977). It has been shown that in a very acid medium (pH 3) fulvic acids extracted more Al from gibbsite than Fe from goethite, although at pH > 5 this would be the reverse (SCHNITZER & SKINNER, 1963). Indeed topsoil pH is lower than subsoil pH in the present profile also (Fig. 6.1) with a major increase occurring in both pH and Al_2O_3/Fe_2O_3 ratio at about 200 cm depth (see also the next section on the mineralogical composition of the sand fraction).

Table 6.1 Chemical composition of the fine earth fraction of soil profile 2 (humic andosol) (% of absolute dry soil free from organic matter)

	SiO_2	Al_2O_3	Fe_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	TiO_2	P_2O_5	H_2O^{+*}	"free Fe_2O_3"	Humus**
A_1	38.1	31.0	11.6	2.08	0.37	1.42	1.51	0.73	0.37	1.33	0.27	11.23	7.82	11.90
AB	37.7	29.2	13.7	1.64	0.38	0.97	0.31	0.14	0.10	1.43	0.20	13.82	9.80	4.22
IIB_{21}	29.5	34.9	13.75	1.81	0.35	1.08	0.16	0.07	0.07	1.47	0.24	16.61	10.55	1.58
	35.3	29.2	12.7	1.78	0.41	0.98	0.15	0.06	0.07	1.34	0.17	18.72	9.33	1.56
IIB_{22}	33.6	33.1	11.9	1.98	0.42	1.25	0.23	0.07	0.07	1.30	0.22	15.41	9.32	1.36
$IVB_{1(b)}$	33.3	33.5	12.5	1.43	0.37	0.97	0.19	0.07	0.06	1.67	0.28	15.43	8.28	2.08
$IVB_{21(b)}$	33.4	32.75	12.0	2.47	0.28	2.41	0.50	0.04	0.02	1.70	0.24	15.85	7.88	1.74
$IVB_{22(b)}$	36.2	31.1	10.2	2.67	0.26	2.66	1.23	0.10	0.10	1.49	0.22	15.12	6.66	1.50
VB_{21b}	38.0	32.5	11.7	1.23	0.27	0.45	0.10	0.03	0.02	1.57	0.07	16.04	8.21	0.84
VB_{22b}	37.5	32.5	12.3	1.42	0.32	0.67	0.15	0.02	0.02	1.70	0.11	14.56	7.81	1.34
	37.1	33.9	12.4	1.00	0.29	0.45	0.07	0.03	0.02	1.60	0.09	13.77	8.16	0.74
VB_{23b}	37.9	32.8	12.6	0.96	0.26	0.52	0.16	0.03	0.02	1.64	0.13	13.71	8.15	0.96

*computed as : (% Loss on Ignition) - (2 % organic carbon) + (8/71.85 % FeO)

**computed as two times % organic carbon

Table 6.2 Chemical composition of the Li-saturated clay fraction of profile 2 (humic andosol) (% of absolute dry clay)

Sample	SiO_2	Al_2O_3	Fe_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	TiO_2	P_2O5	H_2O^+	Li_2O	"free Fe_2O_3"	Clay content
A_1	31.5*	36.1	11.8	0.20	0.14	0.30	0.06	0.09	0.11	0.89	0.52	18.0	0.26	8.80	30.2
AB	30.3*	36.1	12.4	0.10	0.27	0.31	0.03	0.04	0.07	1.00	0.30	18.8	0.27	9.58	36.9
IIB_{21}	29.4*	36.5	13.0	0.07	0.29	0.34	0.03	0.05	0.09	1.17	0.32	18.6	0.14	11.35	32.1
	33.2*	34.4	12.0	0.03	0.31	0.33	0.03	0.05	0.09	0.81	0.30	18.3	0.10	9.97	40.1
$IIIB_{22}$	31.9*	35.8	11.8	0.04	0.31	0.37	0.04	0.06	0.12	1.07	0.34	18.0	0.15	9.62	38.7
IVB_1(b)	30.8	36.8	10.5	0.09	0.18	0.17	0.04	0.03	0.03	1.16	0.41	20.8	0.03	9.08	50.0
IVB_{21}(b)	31.5	37.6	9.6	0.09	0.31	0.16	0.04	0.03	0.03	1.09	0.42	20.2	0.04	8.20	33.5
IVB_{22}(b)	33.5	35.8	8.8	0.10	0.23	0.19	0.24	0.03	0.03	0.95	0.48	20.3	0.06	8.07	32.1
VB_{21b}	37.8	35.8	9.75	0.04	0.22	0.12	0.04	0.03	0.03	1.00	0.13	15.7	0.15	8.10	65.0
VB_{22b}	37.5	35.4	10.2	0.04	0.20	0.11	0.04	0.02	0.03	1.12	0.20	15.5	0.13	8.50	52.5
	36.3	35.0	11.0	0.05	0.21	0.05	0.04	0.02	0.02	1.20	0.16	15.3	0.12	9.31	64.9
VB_{23b}	37.2	34.1	11.75	0.03	0.17	0.05	0.04	0.02	0.02	1.31	0.18	15.5	0.10	9.76	60.1

*100-(sum of other constituents)

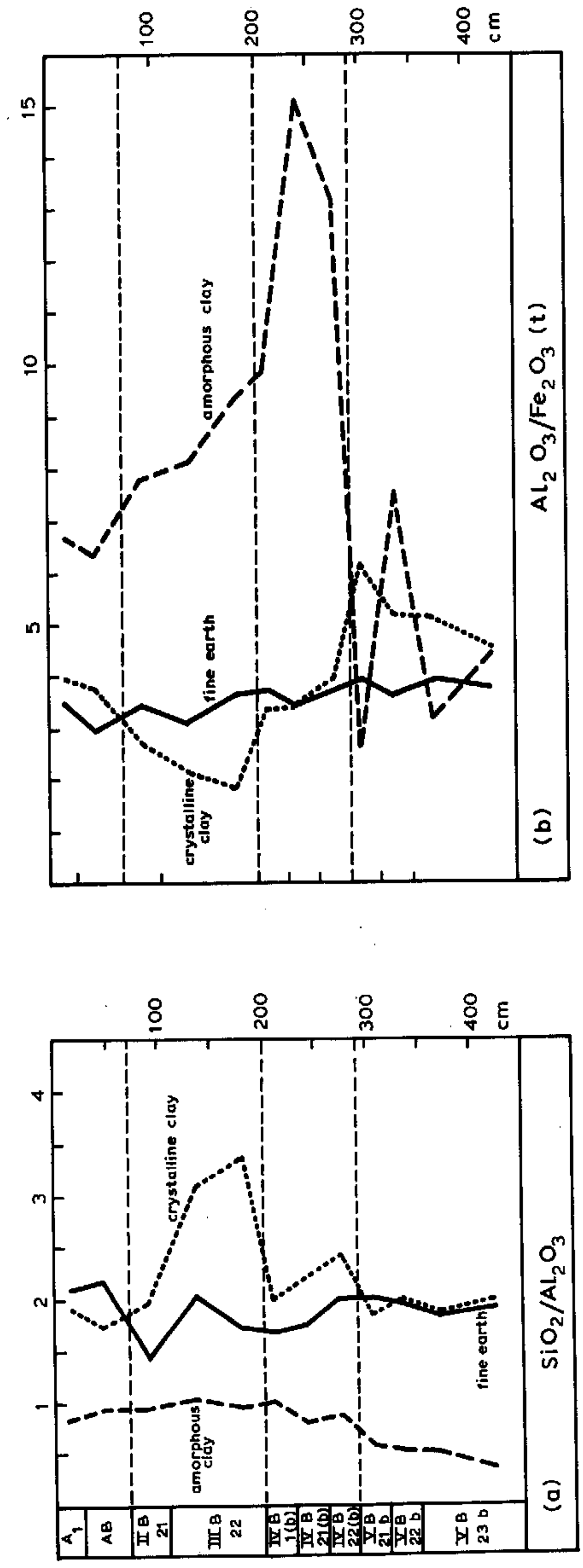


Fig. 6.2 Molar ratios for fine-earth- and clay fractions of profile 2 (humic andosol)

Table 6.3 Chemical composition of oxalate-extractable matter in the clay fraction of profile 2 (humic andosol).

a) expressed as % of total absolute dry clay
b) expressed as % of amorphous absolute dry clay

	(a)					(b)			
	weight loss after extraction	SiO_2	Al_2O_3	Fe_2O_3	H_2O*	SiO_2	Al_2O_3	Fe_2O_3	H_2O^+
A_1	37.4	7.0	14.3	3.3	12.8	18.7	38.2	8.8	34.3
AB	38.4	8.0	14.3	3.5	12.6	20.8	37.2	9.1	32.9
IIB_{21}	51.7	12.0	21.5	4.3	13.9	23.2	41.6	8.3	26.9
	56.5	15.1	24.5	4.7	12.2	26.7	43.4	8.3	21.6
$IIIB_{22}$	64.5	15.4	27.5	4.6	17.0	23.9	42.6	7.1	26.4
$IVB_{1(b)}$	55.3	12.3	21.0	3.3	18.7	22.2	38.0	6.0	33.8
$IVB_{21(b)}$	50.0	10.3	21.3	2.2	16.2	20.6	42.6	4.4	32.4
$IVB_{22(b)}$	47.6	9.8	19.2	2.3	16.3	20.6	40.3	4.8	34.2
VB_{21b}	8.8	0.6	1.7	1.0	5.5	6.8	19.3	11.4	62.5
VB_{22b}	15.8	1.5	4.8	1.0	8.5	9.5	30.4	6.3	53.8
	11.3	0.65	2.1	1.05	7.5	5.7	18.6	9.3	66.4
VB_{23b}	12.6	0.6	2.8	1.0	8.2	4.8	22.2	7.9	65.1

*computed as (% weight loss) - (Σ % SiO_2, Al_2O_3, Fe_2O_3(t))

3) The (seemingly ?) greater mobility of Fe (over Al) in the uppermost layers might reflect the present vegetation cover (*Agathis* forest surrounding the clearing in which the profile pit was dug). Both leaves and bark litter of *Agathis* are known to have a strong tendency of forming complexes with Fe rather than Al (BLOOMFIELD, 1953b). The relatively short time over which the soil has been exposed to these leachates might be an answer to the question as to why the phenomenon is observed in the topsoil only. Interestingly enough has the same trend been observed in the upper layers of a soil profile under Merkusii pine nearby. Leachates of pine litter are also reported to have a preference for complexing Fe rather than Al (BLOOMFIELD, 1953a). The matter requires further investigation.

6.3.1.3 *Mineralogical composition*

Four different approaches have been followed to gain an idea of the mineralogical composition of the ash layers, viz.

1) optical (microscopic) examination of the sand fraction
2) x-ray diffractometry for both fine earth and clay fractions
3) differential thermal analysis (DTA) of the clay fraction, and
4) transformation of the chemical data into a normative mineralogical composition according to methods outlined by VAN DER PLAS & VAN SCHUYLENBORGH (1970) (crystalline clays only)to further elucidate weathering trends.

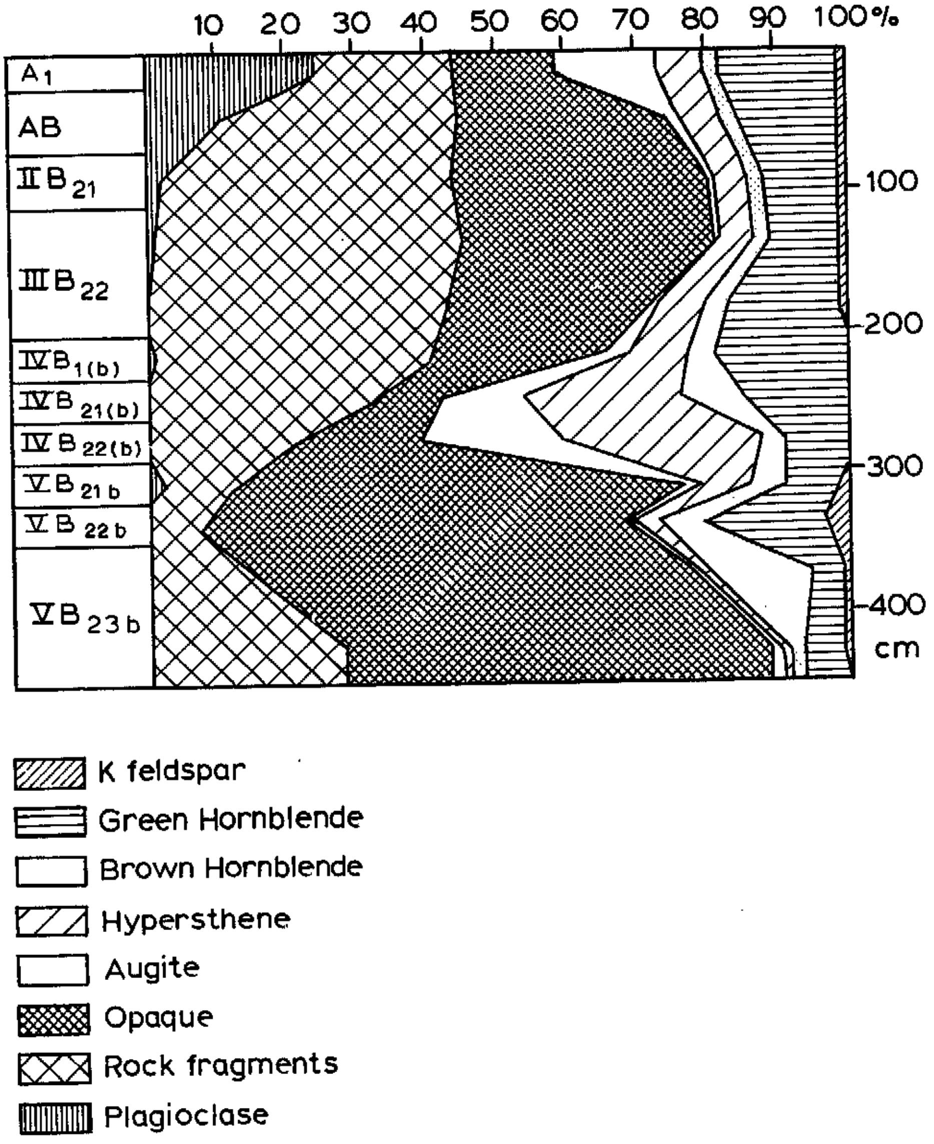
Results will now be discussed in the same order.

- The *mineralogical composition of the sand fraction* (50-420 µm) of the various ash layers is illustrated in Figure 6.3.

  Observed minerals are typical for (basalto) andesitic ashes in Central Java, but there are notable differences in relative amounts between the four groups of horizons distinguished so far.

  - Top layers (A_1, AB) are less weathered considering the relatively high amounts of plagioclase and augite and rather low concentrations of opaque minerals. Amounts of hypersthene do not vary much, whereas concentrations of both plagioclase and augite decrease rapidly with depth over the upper 150 cm. Yet hypersthene usually weathers more easily than augite and its relative abundance in the top horizons may suggest rejuvenation by later eruptions (*cf.* BAAK, 1949). However, some of the observed trends could be the result of a change in chemical composition for later stages of the eruptive phase (*cf.* MOHR *et al.*, 1972).
  - The deepest horizons (VB) are entirely dominated by opaque minerals (mainly magnetite and ilmenite) with only minor amounts of primary minerals left. This again reflects the deeply weathered nature of these layers (*cf.* section 6.3.1.2).
  - The mineralogical composition of the sand fractions of groups III and IV differs again in that there is a rapid increase with depth of concentrations of hypersthene and augite in contrast to the number of opaque minerals which decreased rapidly with depth (Fig. 6.3). This is in accordance with the sudden changes in elemental composition of the fine-earth fraction reported in the foregoing section (Table 6.1). The IV-B horizons therefore seem to be somewhat less weathered in their sand fraction (not so in their clay fraction, see Table 6.2). The absence of the usually stable K-feldspar (still present in the

Fig. 6.3 Mineralogical composition of the sand fraction of profile 2 (humic andosol)



oldest horizons) in these layers suggests, however, that not only lack of weathering but possibly also a different type of parent material is reponsible for the observed mineralogical composition. The relatively low degree of weathering might be associated with a fairly rapid burial of group IV by the $IIIB_2$ deposits, although other explanations are possible also (see section 6.3.2.2).

- *X-ray diffraction analysis* of the clay fraction (Table 6.4) revealed definite trends with depth for halloysite and gibbsite. Hydrated halloysite (Hal 10 Å) is found in the deeper layers only where seasonal desiccation is less severe (IVB) or absent (VB). Gibbsite is absent in the more weathered layers, where both types of halloysite become more abundant. Significant amounts of both halloysite (7 Å) and gibbsite occur together in the uppermost layers only.

Table 6.4 Mineralogical composition of the clay fraction of profile 2 (humic andosol) according to X-ray diffraction analysis

	10 Å Hydrated-Halloysite	7 Å Meta-Halloysite	Quartz (%)	Cristo-balite	Gibbsite
A_1		+	?	(x)	x
AB		+(+)	?	(x)	x(x)
IIB_{21}		+	?	(x)	x
$IIIB_{22}$		(+)	?	(x)	(x)
		(+)	?	x	tr
IVB_1(b)	tr	(+)	<< 1	(x)	tr
IVB_{21}(b)	tr	(+)	<< 1	(x)	tr
IVB_{22}(b)	+	+	<< 1	(x)	tr
VB_{21b}	++	+	<< 1	(x)	
VB_{22b}	+(+)	++	<< 1	(x)	
	++(+)	+(+)	< 1	(x)	
VB_{23b}	tr	++(+)	< 1	(x)	

Symbols indicate intensity of X-ray reflection and range from trace (tr) to abundant (++++) for clay minerals or (tr) to (xxxx) for non-clay minerals.

X-ray diffraction analysis of the fine-earth fraction (not depicted) gave traces of amphiboles and haematite and considerable amounts of magnetite. Some plagioclase was detected in the upper layers.

- *Differential thermal analysis* curves for the clay fraction are presented in Figure 6.4. Results confirm the findings obtained from X-raying. The low-temperature endotherm represents water bound in 'amorphous' matter and halloysite. As such it is interesting to note the deepening of this endotherm as well as a slight temperature shift (108° C -118° C) when progressing from the A_1 to the IVB_2 horizons. This is thought to represent water derived from the "allophane" rather than the halloysites as both the magnitude and the center of the water endotherms for the lowermost layers (poor in non-crystalline matter, but high in halloysites) are significantly different.

  The presence of gibbsite is revealed by an endotherm occurring between 280° C and 290° C and the pattern follows the X-ray ratings closely (although now traces of gibbsite are detected in the VB_{21b} horizon also).

  The exotherm corresponding to halloysite is found between 494° C and 518° C. Halloysites of the second and third sets of horizons exhibit shallow peaks located at 494° C whereas the deepest

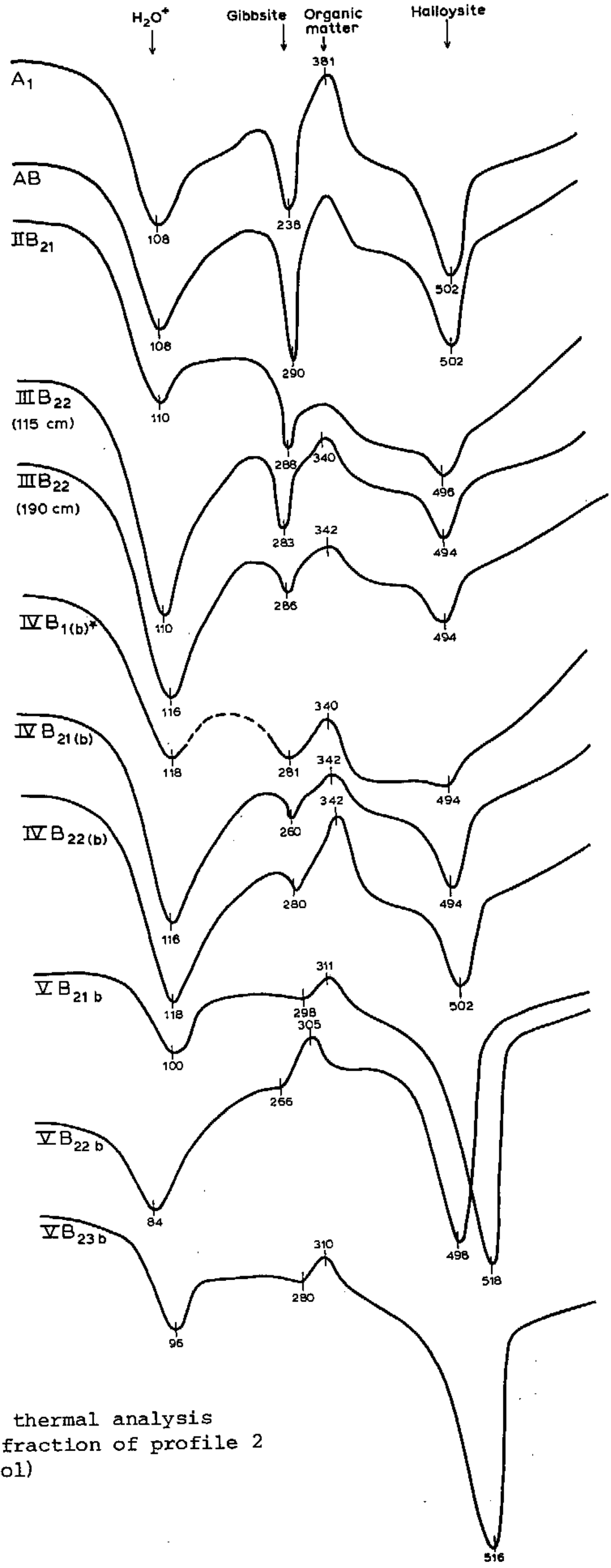


Fig. 6.4 Differential thermal analysis of the clay fraction of profile 2 (humic andosol)

layers show increasing peak intensities along with higher peak temperatures, reflecting greater crystallinity and/or abundance.

The slight exotherm between 305° C and 380° C is interpreted as the oxidation of organic matter (LAI & SWINDALE, 1969).

An endothermic peak at 410-430°C, typical for imogolite (YOSHINAGA & AOMINE, 1962) is absent from all samples. It has been concluded that imogolite is not present in any significant quantities (although molar ratios of the "amorphous" clay are similar to those reported for imogolite : see Fig. 6.2).

- A *normative mineralogical composition* of the clay fraction of profile 2 was calculated by transforming the chemical concentrations of the clay into normative minerals as outlined by VAN DER PLAS & VAN SCHUYLENBORGH (1970). Chemical-element concentrations for the crystalline fraction of the clay were computed by subtracting the amounts incorporated in "allophane" and 'amorphous' iron compounds (as determined by oxalate extraction) from those present in the total clay (Tables 6.3 and 6.2 respectively).

  Results are presented in Table 6.5. The general trends observed so far come out well : primary minerals decrease in importance with depth (notice the paroxysmal nature of this decrease), while halloysite and gibbsite generally follow the results of the semi-quantitative estimates obtained from X-ray diffraction- and DTA-techniques. Occasional deviations are probably the result of analytical errors in the determination of amount and chemical composition of "allophane". Despite these minor irregularities it can be concluded that the normative mineralogical calculations support the initial subdivision of the soil profile into four distinct categories.

Table 6.5 Goethite-normative composition of the *clay fraction* of profile 2 (humic andosol) (equivalent %; unrounded values)

	Hal	Allo	Gibb	Go	Q	Misc.
A_1	48.2	37.5	2.5	6.4	0.2	5.3
AB	45.6	38.5	4.6	7.0	0.2	4.2
IIB_{21}	35.2	51.5	1.3	6.9	0.2	4.7
	31.0	56.5	1.5*	6.2	0.2	4.5
$IIIB_{22}$	24.3	64.5	0.7*	5.3	0.3	4.9
IVB_1(b)	35.7	55.5	0.7	5.1	0.1	3.1
IVB_{22}(b)	39.4	50.0	0.1	5.5	1.8°	3.2
IVB_{22}(b)	44.0	47.5	0.1	4.8	0.1	3.4
VB_{21b}	(81.8)°	8.8	-	6.9	0.1	2.4
VB_{22b}	74.6	15.8	-	7.1	0.1	2.5
	78.3	11.5	-	7.9	0.05	2.2
VB_{23b}	76.8	12.5	-	8.3	tr	2.1

Hal = halloysite; Allo = non-crystalline material; Gibb = gibbsite; Go = goethite; Q = quartz/cristobalite; Misc. = miscellaneous : feldspars, biotite, ferro-magnesian minerals, apatite, Ti-minerals, MnO_2
*relative amounts estimated from DTA endotherms; °overestimate

Application of the Rittmann subvolcanic facies normative computation (RITTMANN, 1973) resulted in minor improvements such as the inclusion of magnetite instead of goethite, etc., but also posed serious problems with respect to the clay mineralogy. For instance, metamorphic minerals, such as sillimannite and cordierite appeared in the calculations due to the weathered nature of the soil. Since the present discussion will focus on the triad "allophane", halloysite and gibbsite mainly (all well-covered by the present scheme) the data in Table 6.5 have been retained as such.

6.3.1.4 *Weathering history of profile 2 (humic andosol)*

The data on the physical, chemical and mineralogical characteristics of the humic andosol under consideration have been combined to reconstruct a (tentative) weathering history. Results are given in schematic form in Figure 6.5, which speaks mostly for itself.

Phase 3 of pedogenesis is still active presently, although there are indications of a new superimposed stage (4) with the arrival of the tree genus *Agathis* whose litter shows different complexation trends than does the Rainforest litter (*cf.* section 6.3.1.2).

Amounts of gibbsite in the clay fraction decrease with depth and are absent from the VB_{21b}-layer onwards (Table 6.4). To explain this phenomenon we will now take a closer look at the variations in chemical composition of the soil water in the next sections.

6.3.2 *Liquid phase*

6.3.2.1 *Introduction*

Since the process of chemical weathering involves the interaction of the water percolating through the soil with the solid phase, it seems natural to pay attention to the former as well. Due to the very large ratio of solid over liquid phase this approach has the additional advantage of magnifying small, undetectable changes in the chemical composition of the solid phase to such an extent that these show up as detectable changes in the percolating liquid.

Rainwater enters the soil profile after hitting the canopy of the standing vegetation and the litter layer on the forest floor, whereby it undergoes considerable changes in chemical composition as shown in sections 5.4.2 and 5.6.2 of the present work. Especially the litter leachates under young secondary vegetation, such as *Eupatorium* in the present case, exhibited high concentrations (although the amounts of chemical elements leached from this compartment are comparable to those leached from *Agathis* and pine litter, (see Table 5.38ab). After infiltration into the mineral soil the leachates acquire a different chemical composition again.

In the following the extremes in chemical concentrations of litter leachates (the "inputs") and soil waters extracted from the various horizons (up to a depth of 2 m) will be given for the profile under consideration as well as for the *Pinus merkusii* study site (profile 4; a humic cambisol).

The chemical composition of water in contact with the material present in the IV-B layers (rather than that of the underlying VB-horizon which are more clayey) has been approximated by that of various springs emerging from the bottoms of the slopes in the study catchment (section 6.3.2.2).

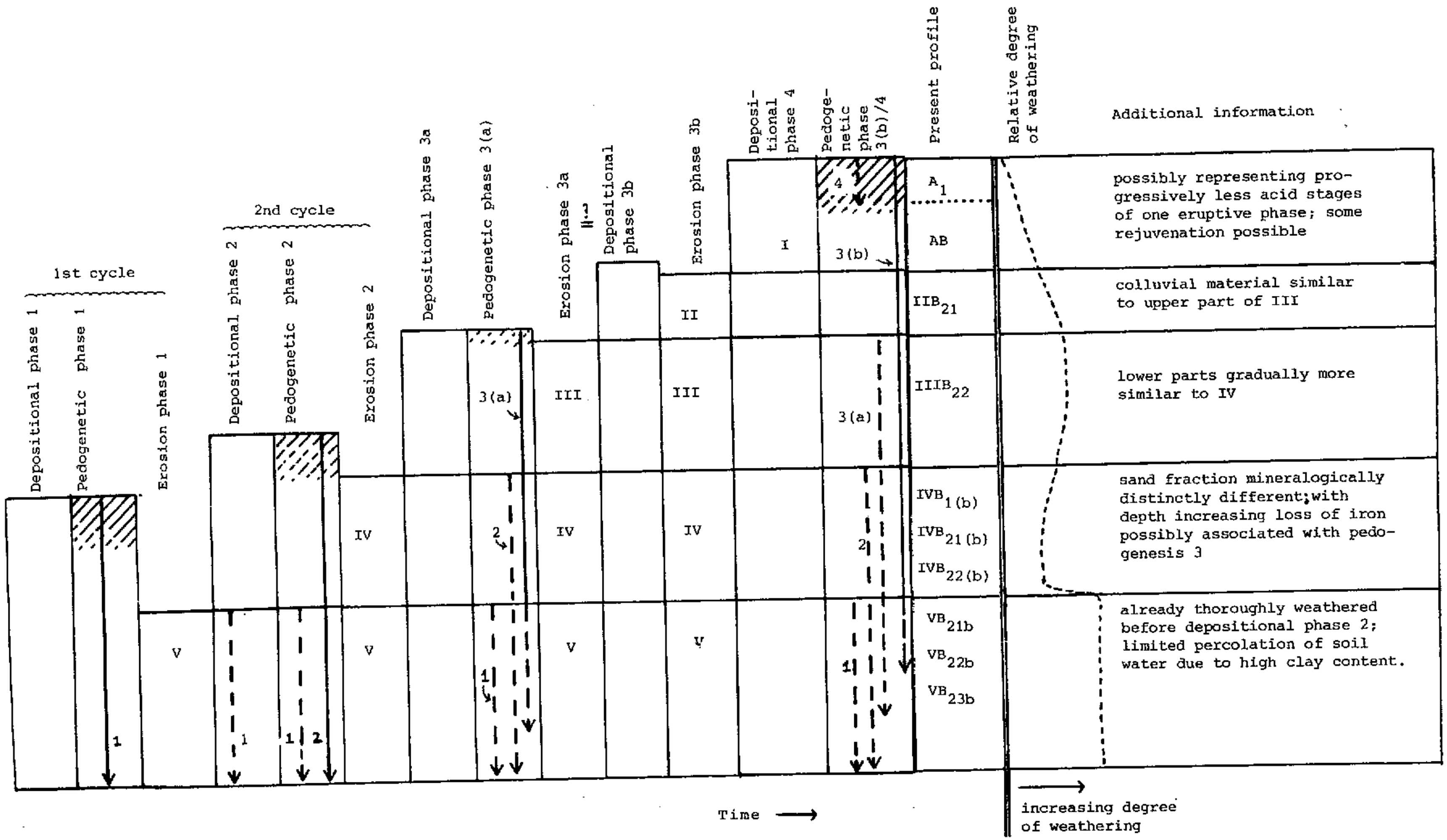


Fig. 6.5 Reconstructed weathering history of profile 2 (humic andosol)

6.3.2.2 *Soil water quality*

The mineralogical composition of the clay fraction (considered to be the most reactive fraction) in the studied soil is wholely dominated by halloysites and'amorphous'matter ("allophane") with lesser amounts of gibbsite, cristobalite and quartz (Table 6.4).

None of these minerals contains any elements other than Si, Al and (O)H. It is therefore permitted to assume that any other elements - like Ca, Mg, Na, K, etc. - released from primary minerals are not incorporated in secondary minerals but rather disappear out of the profile (as is excess silica) via the process of leaching ("desilication"; MOHR *et al.*, 1972). The discussion of (soil) water quality will therefore be concentrated on these three elements : Si (present as $H_4SiO_4^\circ$), Al and H.

Table 6.6 summarizes the range in elemental concentrations found in water that has percolated through the litter and the various soil horizons. A distinction is made between profile 2 (Table 6.6a) and profile 4 (Table 6.6b) because of differences in altitude (600 vs. 450 m a.s.l. resp.) and vegetation cover (viz. *Eupatorium/Agathis* vs. *Pinus merkusii*).

Maximum concentrations in the leachates were observed at the end of the dry season (November, 1977), and in the soil water during the first flush after the return of the rains (samples extracted around 1 December, 1977). The minimum values typically occur during the rainy season and show little internal variation indicating a considerable and fast buffering mechanism in the soil (*cf.* SMITH & DUNNE, 1977). However, the minima in concentrations of dissolved Si and Al in the soilwater held in the A_1-horizon of profile 2 underestimate normal wet season values somewhat. More representative figures for this layer would be 1.10^{-4} and $3.0 \cdot 10^{-6}$ moles 1^{-1} respectively. Concentrations of chemical elements in soil water under *P. merkusii* (profile 4) are distinctly higher (*e.g.* dissolved Si) than in the humic andosol/profile 2 (although there are not enough samples available for the former profile to test this hypothesis statistically). It would be in accordance, however, with the higher concentrations of SiO_2, lower soil pH as well as the generally drier nature of the soil at site 4. No distinct differences in pH between profiles were found except for a topsoil under pine that is slightly more acid.

The maximum elemental concentrations in the *leachates* may exceed those found in the top layer *soil water* occasionally according to Table 6.6. This is a result of sampling procedures rather than a real phenomenon. Concentrations in litter leachates rose to unprecedented levels due to prolonged exposure to (dry) deposition during the dry season, whilst no synchronous observations on soil water quality could be made due to desiccation of the soil profile. Higher than normal concentrations were found in soil water extracted soon after the return of the northwest monsoon, but are diluted by the fresh wave of precipitation. Only one sample could be extracted from profile 2 during the dry season. It showed a notably high concentration of Al ($43.5 \cdot 10^{-6}$ mol 1^{-1}), while other constituents were within the range given in Table 6.6a.

Highest concentrations of dissolved silica in the soil water of both profiles are observed in the deeper layers. There is a regular increase in concentration with depth in profile 4, whereas this is somewhat less obvious in the other profile. There levels of dissolved Si in the AB-horizon exceed those of the $IIIB_2$ horizon. The higher concentrations found in the spring water ("IVB_2") reflect a

Table 6.6 Range in concentrations of chemical elements in litter leachates, soil water and (profile 2 only) spring water (moles l^{-1})

(a) *Profile 2* (humic andosol)

			Ca	Mg	Na	K	SiO_2	Al	Fe(t)	Mn	H^+
litter leachate	*Eupatorium*	max					$4.20\cdot10^{-4}$	$1.70\cdot10^{-4}$			$\sim10^{-4}$
		min					$3.10\cdot10^{-5}$	$<1.36\cdot10^{-6}$			$10^{-6.2}$
	Agathis	max					$4.41\cdot10^{-5}$	$5.75\cdot10^{-5}$			$10^{-5.85}$
		min					$<3.7\cdot10^{-6}$	$<1.30-10^{-6}$			$10^{-6.5}$*
soil moisture	A_1	max	$7.0\cdot10^{-5}$	$16.1\cdot10^{-5}$	$14.0\cdot10^{-5}$	$25.8\cdot10^{-6}$	$1.64\cdot10^{-4}$	$13.8\cdot10^{-6}$	$(2.2\cdot10^{-6})$	$1.4\cdot10^{-6}$	$10^{-5.85}$
		min	$7.6\cdot10^{-6}$	$1.5\cdot10^{-5}$	$1.5\cdot10^{-6}$	$5.9\cdot10^{-6}$	$0.80\cdot10^{-4}$	$1.0\cdot10^{-6}$	$<1.1\cdot10^{-8}$	$<4.3\cdot10^{-6}$	$10^{-6.9}$
	AB	max	$3.3\cdot10^{-5}$	$10.8\cdot10^{-5}$	$8.3\cdot10^{-5}$	$15.8\cdot10^{-6}$	$1.92\cdot10^{-4}$	$12.9\cdot10^{-6}$	$(<15.2\cdot10^{-6})$	$1.0\cdot10^{-6}$	$10^{-5.6}$
		min	$7.7\cdot10^{-6}$	$1.0\cdot10^{-5}$	$1.9\cdot10^{-5}$	$4.6\cdot10^{-6}$	$1.13\cdot10^{-4}$	$1.1\cdot10^{-6}$	$<6.1\cdot10^{-7}$	$<2.7\cdot10^{-7}$	$10^{-6.5}$
	$IIIB_{22}$	max	$4.1\cdot10^{-5}$	$17.6\cdot10^{-5}$	$11.4\cdot10^{-5}$	$14.8\cdot10^{-6}$	$1.50\cdot10^{-4}$	$17.2\cdot10^{-6}$	$5.0\cdot10^{-6})$	$1.5\cdot10^{-6}$	$10^{-5.3}$
		min	$5.9\cdot10^{-6}$	$1.6\cdot10^{-5}$	$1.1\cdot10^{-5}$	$4.3\cdot10^{-6}$	$1.03\cdot10^{-4}$	$2.4\cdot10^{-6}$	$<3.6\cdot10^{-7}$	$<3.7\cdot10^{-7}$	$10^{-6.5}$
spring water**	IVB_2	max	$6.3\cdot10^{-5}$	$4.1\cdot10^{-5}$	$9.0\cdot10^{-5}$	$14.3\cdot10^{-6}$	$2.59\cdot10^{-4}$	$6.5\cdot10^{-6}$	$0.8\cdot10^{-6}$	$3.1\cdot10^{-6}$	$10^{-5.65}$
		min	$3.0\cdot10^{-5}$	$2.0\cdot10^{-5}$	$5.9\cdot10^{-5}$	$6.0\cdot10^{-6}$	$1.60\cdot10^{-4}$	$<0.5\cdot10^{-6}$	$4.9\cdot10^{-6}$	$4.6\cdot10^{-7}$	$10^{-6.9}$

(b) *Profile 4* (humic cambisol)

			Ca	Mg	Na	K	SiO_2	Al	Fe(t)	Mn	H^+
litter leachate	*P.merkusii*	max					$2.74\cdot10^{-4}$	$4.04\cdot10^{-5}$			$10^{-5.8}$
		min					$3.0\cdot10^{-6}$	$2.72\cdot10^{-6}$			$10^{-6.55}$*
soil moisture	A_1/B_2	max	$19.1\cdot10^{-5}$	$28.0\cdot10^{-5}$	$19.8\cdot10^{-5}$	$7.7\cdot10^{-5}$	$2.82\cdot10^{-4}$	$15.0\cdot10^{-6}$	$(6.5\cdot10^{-6})$	$(1.9\cdot10^{-6})$	$10^{-\;.1}$
		min	$1.6\cdot10^{-5}$	$2.3\cdot10^{-5}$	$2.8\cdot10^{-5}$	$2.7\cdot10^{-5}$	$1.87\cdot10^{-4}$	$1.7\cdot10^{-6}$	$3.8\cdot10^{-6}$	$6.5\cdot10^{-7}$	$10^{-6.9}$
	$IIIB_1$(b)	max	$5.3\cdot10^{-5}$	$15.3\cdot10^{-5}$	$11.0\cdot10^{-5}$	$6.1\cdot10^{-5}$	$3.04\cdot10^{-4}$	$35.8\cdot10^{-6}$	$(2.0\cdot10^{-6})$	$(5.3\cdot10^{-6})$	$10^{-5.7}$
		min	$1.5\cdot10^{-5}$	$1.9\cdot10^{-5}$	$2.6\cdot10^{-5}$	$4.6\cdot10^{-5}$	$2.39\cdot10^{-4}$	$3.6\cdot10^{-6}$	$(<1.2\cdot10^{-6})$	$<9.2\cdot10^{-7}$	$10^{-6.7}$
	$IIIB_2$	max	$8.2\cdot10^{-5}$	$20.0\cdot10^{-5}$	$22.3\cdot10^{-5}$	$3.8\cdot10^{-5}$	$3.15\cdot10^{-4}$	$4.6\cdot10^{-5}$	$(8.0\cdot10^{-6})$	$(1.8\cdot10^{-6})$	$10^{-5.4}$
		min	$1.4\cdot10^{-5}$	$2.4\cdot10^{-5}$	$4.0\cdot10^{-5}$	$1.9\cdot10^{-5}$	$2.17\cdot10^{-4}$	$1.6\cdot10^{-6}$	$2.0\cdot10^{-6}$	$<3.6\cdot10^{-7}$	$10^{-6.5}$

*no information on pH available for actual minimum; values estimated from similar samples

**springs found at contact of volcanic ash and volcanic breccia (section 3.2); springs associated with faults have a smaller variation in chemical composition and a slightly higher pH longer residence time possibly linked with the higher clay content of the deeper layers (Fig. 6.1). These relatively high silica levels might (at least partly) be a possible explanation for the relatively unweathered nature of the sand fraction of group IV (section 6.3.1.3).

The data on soilwater composition will now be inserted into a mineral stability diagram which illustrates the (meta-)stability of certain minerals in relation with the chemical composition of solutions in contact with these minerals (GARRELS & CHRIST, 1965; HELGESON, 1968).

6.3.2.3 *Mineral stability considerations*

As related before, the relatively simple Al_2O_3-SiO_2-H_2O system (at 25° C and 1 atmosphere) will cover the description of the major chemical transformations occurring in the investigated clays. Therefore, a diagram has been constructed showing the stabilities of the relevant minerals (viz. halloysite (7 Å & 10 Å), kaolinite, amorphous silica, cristobalite and gibbsite) with respect to the soil solution (Fig. 6.6).

A clear account of the procedures involved in such a construction is given by KITTRICK (1969). It basically involves the computation of the solubility lines of the individual minerals via the standard free energy of each reaction (ΔG_r°). The next step is then to compare these stabilities in a single diagram. KITTRICK (1969) has shown that the parameters $pH_4SiO_4^\circ$ and $pH -1/3\ pAl^{3+}$ were quite convenient in describing the nature of the solution. The former is placed on the abscis, the latter on the ordinate (Fig. 6.6).

Standard free energies of the reactions involved were calculated from the internally consistent set of standard free energies of formation (ΔG_f°) for the various minerals based on the ΔG_f° of Al^{3+} adopted by SADIQ & LINDSAY (1979) in their review. Reactions and values of ΔG_f° and ΔG_r° are given in Appendix 3. The data of Table 6.6 have been converted into activities ("effective concentrations") and from these values for ($pH -1/3\ p\ Al^{3+}$) and $pH_4SiO_4^\circ$ were determined via standard procedures (LINDSAY, 1979) for insertion in Figure 6.6.

It appears from Figure 6.6 that the chemical composition of the percolating solution is governed by halloysite ·7Å mainly.

In an attempt to estimate the ΔG_f° of the "amorphous" fraction of the clay BRUYNZEEL (1976) equilibrated the clay fraction < 1 µm of the IIB_{21}, $IIIB_{22}$ and IVB_{21} horizons of the humic andosol with distilled water for three months. Chemical concentrations of the liquids were then determined after centrifuging and an apparent value for the ΔG_f° of "allophane" was computed for the dissolution reaction

$$SiO_2 \cdot Al_2O_3 \cdot 4H_2O(s) + 6H^+ \rightleftarrows 2Al^{3+} + H_4SiO^\circ{}_4 + 5H_2O \qquad (6.1)$$

("allophane")

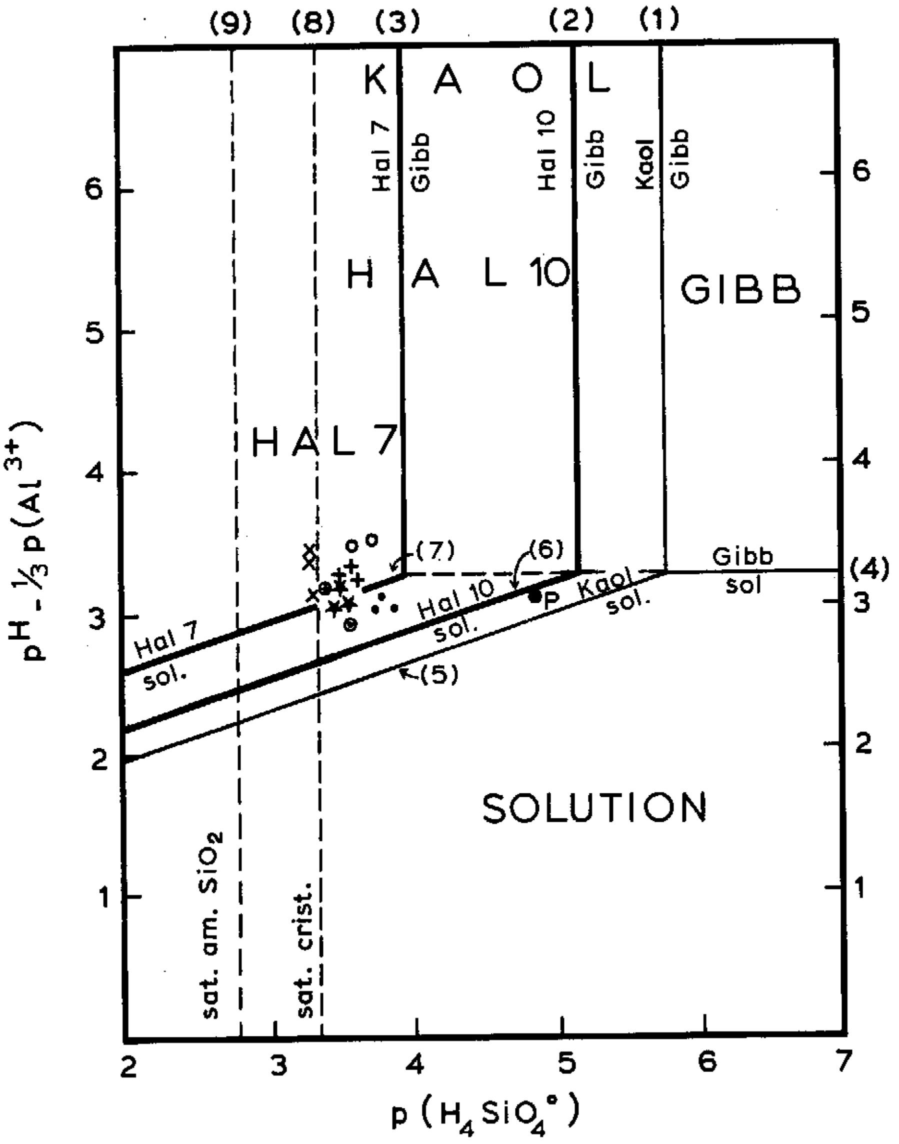
When, however, the ΔG_f° for halloysite·7Å was computed from the same dissolution data using the reaction

$$AlSi_2O_5(OH)_4\ (s) + 6H^+ \rightleftarrows 2Al^{3+} + 2H_4SiO_4^\circ + H_2O \qquad (6.2)$$

(halloysite·7Å)

a value of -900.6 ± 0.15 k cal mol^{-1} was obtained, *i.e.* not significantly different from that published by REESMAN & KELLER (1968) for poorly crystalline halloysite (-901.0 ± 1.0 k cal mol^{-1}). It had to be concluded that halloysite governed the dissolution characteristics of the fine clay fraction (< 1 µm) as well. Moreover, as no ΔG_f° for

Fig. 6.6 Mineral stabilities in the Al_2O_3-SiO_2-H_2O system (298,15° K; 1 bar) - see Appendix 3 for construction details



Kaol = kaolinite; Hal 10 = hydrated halloysite; Hal 7 = meta-halloysite; gibb = gibbsite; crist = cristobalite

•chemical composition soil water during wet season (profile 2)
*_ibidem_ profile 4
⊛ibidem spring water
+_ibidem_ during the first flush of rain after dry season (profile 2)
×_ibidem_ profile 4
⊕ibidem spring water
P●soil water extracted from red paleosoil
°distilled water after three months of equilibration with clay fraction < 1 μm (profile 2)

"allophane" is available (rejecting the one given by KELLER *et al.*, 1967 as it was more negative than ΔG_f° halloysite) "allophane" could not be included in the stability diagram.

Although halloysite·7 Å seems to govern the composition of the soil water solution, both hydrated- and meta-halloysite are metastable phases with respect to kaolinite (Fig. 6.6). There is a trend towards formation of hydrated halloysite (hal·10 Å) during most of the year, except for the dry season when concentrations of the dissolved silica in the soil water rise and meta-halloysite formation is "preferred". The latter trend is stronger for the *Pinus merkusii* site (cambisol) in accordance with the slightly drier climate prevailing there (*cf.* SAIGUSA *et al.*, 1978). Eventually both types of halloysite will be transformed into kaolinite. This is illustrated by point P in Figure 6.6 which represents the chemical composition of water extracted from a nearby red paleosol derived from Tertiary (?) basalto-andesitic breccia deposits (*cf.* chapter 2). Halloysites have become unstable with respect to this paleosoil water, whereas kaolinite is still stable. This is concordant with the observation that the paleosoil contains a fair amount of poorly-crystalline kaolinite but no halloysite or gibbsite (BRUYNZEEL, 1976). Therefore, although weathering has proceeded quite far in the paleosoil (late Tertiary or early Pleistocene age), it has not yet reached the final stage of weathering where gibbsite has become a stable mineral.

Both gibbsite, (most probably) "allophane" and cristobalite are unstable with respect to the solutions *presently* percolating through the humic andosol (profile 2) : see Figure 6.6. Since gibbsite is present in significant quantities in the (younger) part of the profile it follows that it must have been present in the older layers as well and has disappeared during later times.

Gibbsite has been observed in the weathering rims of feldspars without any halloysitic intermediate under conditions of extreme leaching (YOUNG & STEPHEN, 1965; SHERMAN *et al.*, 1967). As such the presently observed gibbsite may have originated in a time when leaching was more intense and soil water concentrations were lower than presently observed (*i.e.* they would fall in the stability field of gibbsite of Fig. 6.6). This is not wholely impossible as Java has experienced considerable climatic variation during the Pleistocene (VERSTAPPEN, 1974; see also Fig. 6.5 for an alternation of depositional and erosive phases). Resilication will therefore have occurred when the climate became more seasonal and favourable for the formation of halloysite rather than gibbsite (SIEFFERMANN & MILLOT, 1969). This is in accordance with the data on soil water composition presented in Figure 6.6 for both profile 2 (humic andosol) and profile 4 (humic cambisol). As noted before, concentrations of aqueous silicic acid in the soil water of the latter site are higher than those in profiles throughout the year. It will be no surprise therefore, that gibbsite is completely absent in the soil of the pine plantation.

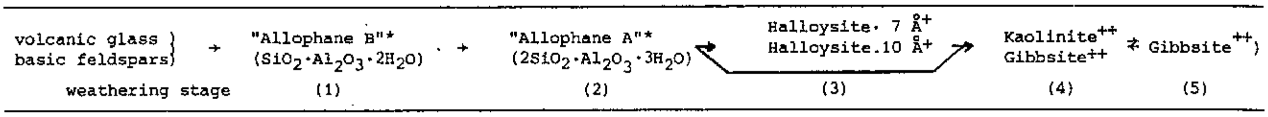
It is of interest to investigate how the present results relate to the findings of other studies dealing with the weathering of volcanic ashes in the tropics (section 6.4).

6.4 *Discussion*

In their review of Andosols MOHR *et al.* (1972) describe the process of chemical weathering of volcanic ash as the leaching of soluble components (accelerated by carbonic acid released from the litter layer) followed by residual enrichment of sesqui-oxides and the formation of secondary minerals. Both chemical composition of parent material and leaching conditions are important in determining the type of secondary minerals.

In intermediate and basic ashes and under conditions of excessive drainage the molar ratio of SiO_2/Al_2O_3 in the clay fraction may become smaller than 1, whereas it may exceed 3 when drainage is impeded and enough Mg and Fe are available for the formation of 2:1 lattice clay minerals. Usually those molar ratios vary between 1 and 2 in young volcanic soils with a tendency to increase to 2 in older deposits.

The following scheme (compiled from FIELDES (1955), SIEFFERMANN & MILLOT (1969) and MOHR *et al.* (1972) summarizes the various transformations under *well-drained* conditions.



*terminology of FIELDES (1955); chemical compositions according to WADA (1977)
+moderately intense leaching
++(very) intense leaching

Although speculations on the time-scale involved have been published (BESOAIN, 1969; WADA & HARWARD, 1974) it is felt that time as such has little meaning since environmental conditions (rainfall; temperature, etc.) have an overriding effect on leaching rates.

RUXTON (1968) for example published values for the half-life of volcanic glass from dacitic ash in New Guinea that ranged from 1650 to 5600 years depending on effective rainfall.

The statement of BESOAIN (1969) that the addition of kaolinite to the weathering sequence of FIELDES (1955) was a logical but hypothetical possibility (since even the oldest soils developed from ash had not yet passed the stage of halloysite) is no longer valid, since several *old* volcanic soils in the tropics have now been found to contain (poorly crystalline) kaolinite (BLEEKER & PARFITT, 1974; TAN *et al.*, 1975; WADA & WADA, 1976). On the other hand, SIEFFERMANN & MILLOT (1969) reported the *synchronous* occurrence of "allophane", well-crystallized kaolinite and gibbsite in *young* basaltic deposits in the superwet zone of Cameroon (annual precipitation 10,000 mm, no dry season).

Likewise, in Japan, halloysite is not found in ash layers less than *c.* 8600 years old (AOMINE & MIYAUCHI, 1963), whereas on St. Vincent, B.W.I. (HAY, 1960) and New Britain (BLEEKER & PARFITT, 1974) appreciable amounts of halloysite (and "allophane") were observed in ash falls dated 4000 and less than 1000 (320 and 830) years old respectively.

All this suggests environmental conditions (reflected in the chemical composition of the percolating water) rather than time in the absolute sense to determine the weathering sequence *c.q.* the clay-mineralogical composition of these soils.

As for the *deposits dealt with in the present study* there is only the general information (VAN BEMMELEN, 1949) about time spans that most ashes are of Pleistocene age, although some rejuvenation may have occurred during recent times (BAAK, 1949).

As related before, halloysite and "allophane dominate the clay fraction of layers I till IV with minor amounts of gibbsite being present as well. The older horizons contain little allophane" and no gibbsite, but consist of halloysite mainly (Table 6.5). Molar SiO_2/Al_2O_3 ratio's found for "amorphous" matter in the clay fraction (layers I-IV) are close to 1, suggesting the presence of "Allophane-B". Since the latter is found in very young soils without halloysite (FIELDES, 1955; BLEEKER & PARFITT, 1974) it is suspected that the oxalate extraction has included another form of amorphous (organically bound ?) Al-compounds as well.

In conclusion, all horizons in the investigated profile exhibit a stage intermediate between 2 and 3 (see scheme given above) with the younger layers (I-IV) being closer to the allophane-dominated phase (2) and the older ones (V) closer to the halloysitic phase (3). The paleosols exposed at some sites in the study catchment (chapter 2) represent stage (4).

7. SUMMARY

The investigations reported upon in the present thesis were carried out between 1 December, 1976 and 1 February, 1978 with financial support from the Netherlands Foundation for the Advancement of Tropical Research (WOTRO). Part of the work was done in association with the "NUFFIC Serayu Valley Project" (ITC/GUA/VU1&2).

A small forested catchment, whose characteristics are described in chapter 2, has been selected in the hilly headwater area of the Mondo river near the village of Watubelah, some 5 km south of Banjarnegara. The area is part of the wet-monsoonal northern rim of the South Serayu range (South Central Java).

The following items were studied :

- the water and chemical mass balances on a catchment scale to estimate the rate of on-going chemical weathering in the andesitic tuffs underlying the area;
- the hydrological behaviour of the catchment during rainstorms and in periods of drought;
- the cycling of nutrients through the catchment vegetation (viz. 11-, 21- and 42-yr old plantation forest of *Agathis loranthifolia* and *Eupatorium* shrubs) and nearby plantations of *Pinus merkusii* (12-yr old) and *Tectona grandis* (25-yr old);
- the mode of the chemical weathering of the andesitic volcanic ash.

This resulted in the integrated description of the hydrological and biogeochemical features of the basin.

The drainage basin received some 4670 mm of rain during the study period, of which 3460 mm (74 %) ran off as streamflow. During the exceptionally severe dry season of 1977 actual evapotranspiration did not deviate from the potential rate over a period of 3.5 months, but then decreased considerably (section 3.3).

Stormflows made up a very small portion (< 10 %) of the total runoff and consisted of a mixture of channel precipitation, Horton overland flow from compacted surfaces and various sorts of subsurface stormflow, notably localized pipeflow and throughflow. Occurrence and importance of the various flow types could be evaluated on a lumped basis by combining the "minimum contributing area" concept with field observations. Detailed water quality sampling of individual runoff waves revealed that subsurface stormflow contributed throughout the storms via the mechanism of "displacement flow" (section 3.4).

The flux of nutrients (*i.e.* total load of chemicals carried out of the basin by the stream minus input of chemicals into the catchment from atmospheric sources) was calculated for the period of investigations as well as for an "average" year (section 4.2).

Net losses of elements amounted to 527 (SiO_2), 26.5 (Mg), 19.1 (Ca), 14.1 (Na), 13.5 (Al), 12.4 (K), 12 (Fe) and 1 (Mn) kg ha^{-1} yr^{-1}. Ortho-P accumulated at a rate of 0.2 kg ha^{-1} yr^{-1}.

Converting the gross solute output data to oxides one obtains a total solute load of 80.7 t km^{-2} over the period of study. To this have to be added the amounts of material transported in suspension (306 t km^{-2}) - of which 15 t km^{-2} is carried by basal flow- and along the streambed (44.5 t km^{-2}), giving a grand total output of material of 431 t km^{-2} or 442 t km^{-2} for the "average" year (section 4.3).

The vigorously growing vegetation of the catchment acts as a long-term sink of nutrients realeased by weathering, rendering the catchment chemical flux an underestimate of the true chemical denudation rate. Actual immobilization of nutrients by the catchment vegetation during the study year has been evaluated by an extensive programme of biomass and chemical content determinations in plantations of varying age (section 5.5). Results indicated the traditional budget approach to underestimate the rate at which the various elements are released by chemical weathering by 11 % (SiO_2) to 75 % (Ca).

Part of the nutrients taken up by the vegetation returns again to the forest floor via the processes of litterfall and tree crown leaching. After decomposition of the litter and/or transportation of the nutrients into the soil these can be taken up again. These internal cycles constitute the so-called biogeochemical cycling of chemical elements elaborated upon in chapter 5.

Most of the Ca, Mg and Si returning to the forest floor did so via litterfall in contrast to Na and K which "preferred" the pathway of crown leaching. Relative proportions differed between species (sections 5.3 & 5.4).

Amounts of rainfall intercepted by the various plantations generally did not differ much, statistically speaking. Extremes are represented by *Eupatorium* (9 % intercepted) and the dense *P. merkusii* plantation (30 % intercepted) - see section 5.4.1. The throughfall component showed a definite enrichment with nutrients as compared to rainfall in the open in all cases. Amounts of nutrients in rain under *Eupatorium* shrubs, however, were distinctly higher, possibly due to the influence of nocturnal guttation (section 5.4.2).

The soils of the investigated plantations were of intermediate fertility regardless their age. Expressed on an areal basis the amounts of available nutrients stored in the younger ash deposits were smaller than those of the older ashes due to their lower bulk density. Phosphorus stores were notably low for all sites except for the pine plantation, whereas the soil under the oldest *Agathis* forest contained relatively small amounts of Ca and Mg as well (section 5.7).

Using the data on nutrient concentrations in the vegetation, in combination with information on tree biomass increase with age it became possible to compute the total net requirement of nutrients for an ideally stocked plantation of *Agathis* of average site class over a rotation period of 40 years. Comparison of these requirements with mean annual input of chemicals into the plantation eco-system from atmospheric sources and released by chemical weathering revealed possible shortages of P in the (near) future (section 5.9). It is thus advisable to refrain from total-tree harvesting and leave as much organic residue on site as possible. If only stems (scaled) and heavier branches would be taken away some 55 % of the maximum possible loss of P would be prevented. Corresponding figures for K, Ca and Mg amount to 60 and 70 % respectively.

Percentual returns of nutrients by *Eupatorium* shrubs are very high, *i.e.* over 90 % of the bases and *c.* 80 % of the total P taken up is returned to the forest floor, in contrast to the patterns exhibited by young *Agathis* forest. It has been concluded tentatively that it is not necessary to remove *Eupatorium* from young forest plantations in Central Java.

The chemical weathering of the Quaternary andesitic volcanic ash in and around the catchment has been studied by chemical and mineralogical analysis of progressively older ash layers (section 6.3). Four sets of horizons could be distinguished, each with characteristic quantities of the major clay minerals prevailing in the area.

Non-crystalline material ("allophane") was most abundant in the second and third groups of layers (immediately followed by halloysites). It was present in minor quantities only in the oldest ash layers which were dominated by halloysites. The youngest horizons contained intermediate amounts of allophane, fair quantities of halloysites and a significant percentage of gibbsite. Amounts of the latter mineral decreased quickly with depth.

Analysis of the chemical composition of the percolating solution (soil water) confirmed the observed mineralogical trends in terms of mineral stabilities. Allophane and gibbsite are both unstable with respect to the solution, whilst hydrated halloysite is converted to metahalloysite during the dry season when concentrations of dissolved silica in the soil moisture rise. Weathering of the ashes has not yet proceeded far enough for the formation of kaolinite.

8. SAMENVATTING

Het onderzoek waarover verslag wordt uitgebracht in deze dissertatie is uitgevoerd tussen 1 december 1976 en 1 februari 1978 op Midden Java met geldelijke steun van de Stichting voor Wetenschappelijk Onderzoek van de Tropen (WOTRO). Een deel van het werk vond plaats in samenwerking met het NUFFIC "Serayu Valley Project" (ITC/GUA/VU/1 & 2).

Een bebost stroomgebiedje (waarvan de kenmerken in hoofdstuk 2 beschreven zijn) werd uitgekozen in het heuvelachtige brongebied van de Mondo rivier, nabij het gehucht Watubelah, ± 5 km ten zuiden van Banjarnegara. Dit zeer regenachtige gebied behoort tot de meest noordelijke rand van het zgn. Zuid Serayu heuvelland. In dit stroomgebied zijn de volgende onderwerpen bestudeerd :

- de waterbalans en de netto uitvoer van opgeloste scheikundige elementen teneinde de snelheid van de chemische verwering van de andesitische vulkanische assen in het gebied te schatten;
- het gedrag van het stroomgebied tijdens regenbuien en perioden van droogte;
- het circuleren van voedingsstoffen in de vegetatie, zowel in het stroomgebied zelf (11-, 21- en 42 jaar oude aanplant van *Agathis loranthifolia* en *Eupatorium* struikgewas) als in nabijgelegen aanplant van *Pinus merkusii* (12 jaar oud) en teak (*Tectona grandis*; 25 jaar oud);
- de wijze waarop genoemde vulkanische assen chemisch verweren.

Zo werden op elkaar afgestemde beschrijvingen verkregen van de water- en voedingsstofhuishoudingen in het gebied.

Er viel in totaal ± 4670 mm regen tijdens het veldonderzoek, waarvan ongeveer 3460 mm (74 %) door de beek werd afgevoerd. Gedurende de eerste 3½ maand van het ongewoon lange droge seizoen van 1977 week de verdamping door de vegetatie niet af van het maximaal mogelijke bedrag. Daarna liep zij echter vrij snel terug (zie paragraaf 3.3).

De hoeveelheden water die afgevoerd werden tijdens regenbuien (engels : "stormflows") droegen voor minder dan 10 % bij aan de totale afvoer. Zij bestonden uit een mengsel van op de beek en zijn naaste omgeving vallende neerslag ("channel precipitation" en "precipitation onto saturated areas"), afstroming langs het oppervlak van verdichte delen in het terrein ("Horton overland flow") en verschillende soorten ondergrondse afstroming ("subsurface stormflow"). Voor wat betreft de herkomst van het laatstgenoemde type dienen genoemd te worden de pijpsystemen in het bovenstroomse deel van het stroomgebied, de vochtige lagere stukken van de hellingen en de delen met een ondoorlatende laag op geringe diepte. Voorkomen en belang van de verschillende typen konden samengevat worden door combinatie van het begrip "kleinste gebied dat direct bijdraagt aan de snelle afvoer" ("minimum contributing area") en veldwaarnemingen (zie paragraaf 3.4.2). Door verschillende afvoergolven in detail te bemonsteren en deze monsters vervolgens scheikundig te ontleden, bleek dat de ondergrondse afvoer (die water levert met betrekkelijk hoge concentraties) gedurende vrijwel de gehele regenbui bijdraagt aan de piekafvoeren.

De netto-uitvoer van opgeloste scheikundige elementen uit het stroomgebied is berekend voor de onderzoeksperiode (14 maanden) en voor een "gemiddeld" jaar (paragraaf 4.2). Netto verliezen aan de verschillende elementen bedroegen 527 (opgelost silica), 26.5

(Magnesium), 19.1 (Calcium), 14.1 (Natrium), 13.5 (Aluminium), 12.4 (Kalium), 12 (IJzer) en 1 (Mangaan) kg ha^{-1} yr^{-1}. Fosfor daarentegen hoopt zich (schijnbaar, zie de volgende alinea's) op in het gebied in een tempo van 0.2 kg ha^{-1} jr^{-1}.

Wanneer men de bruto hoeveelheden afgevoerde voedingsstoffen uitdrukt in oxydevorm en bij elkaar optelt verkrijgt men een totaal van 80.7 t km^{-2} over de onderzoeksperiode. Hierbij dienen de hoeveelheden sediment toegevoegd te worden, die door de beek weggevoerd worden in de vorm van zwevende deeltjes (306 t km^{-2}) en rollend over de bedding (44.5 t km^{-2}). Daarmee komt men op een totale materiële uitvoer van 431 t km^{-2}, overeenkomend met 442 t km^{-2} voor een jaar van gemiddelde regenval (zie paragraaf 4.3).

De snelgroeiende vegetatie van het stroomgebied slaat jaarlijks een deel van de bij chemische verwering vrijkomende voedingsstoffen op in haar weefsel. Dit gedeelte wordt daardoor gevrijwaard voor uitspoeling. Dat betekent dat de berekende netto uitvoer van voedingsstoffen uit het onderzochte gebied (de "nutriëntenflux") geen directe afspiegeling meer is van de snelheid van chemische verwering, maar deze onderschat. De mate waarin voedingsstoffen blijvend opgeslagen worden in de begroeiing is geschat aan de hand van een uitgebreid programma van bepalingen aan zowel de biomassa als de scheikundige samenstelling van de vegetatie (zie paragraaf 5.5). Op deze wijze bleek de traditionele schatting van de verweringssnelheid met 11 % (opgelost silica) tot 75 % (calcium) te laag uit te vallen (zie paragraaf 5.8). Fosfor komt wel vrij bij verwering, maar wordt zo sterk opgenomen door de vegetatie dat het verschil tussen in- en uitvoer op stroomgebiedsbasis positief wordt.

Een deel van de opgenomen voedingsstoffen keert terug naar de bosbodem als strooiselval en kroondrup. Na vertering van het strooisel en inspoeling van de nutriënten in de bovenste lagen van de bodem kunnen deze opnieuw worden opgenomen door de begroeiing. Dit soort van kringlopen wordt wel biogeochemisch genoemd om aan te duiden dat de voedingsstoffen doorlopend circuleren tussen levende (vegetatie) en dode (bodem)materie (zie paragraaf 5.1).

De elementen calcium, magnesium en silicium worden voornamelijk via strooiselval teruggevoerd, terwijl de chemisch meer beweeglijke elementen natrium en kalium vooral via kroondrup terugkeren naar de bosvloer. De onderlinge verhoudingen verschillen per soort (zie paragrafen 5.3 & 4).

De hoeveelheden regenval die onderschept worden door het kronendak van de verschillende opstanden verschilden statistisch gesproken niet veel. Uitersten werden gevonden bij *Eupatorium* (slechts 9 % onderschepping) en het dennenbos (30 % onderschept), zie paragraaf 5.4.1.

De neerslag onder bos was gewoonlijk sterk aangerijkt met voedingsstoffen in vergelijking met de neerslag in het open veld. Concentraties waren met name hoog in het geval van *Eupatorium* struikgewas, mogelijk als gevolg van het gedurende de nacht uitzweten van geconcentreerd vocht (guttatie) (zie paragraaf 5.4.2).

De bodems in de bestudeerde bossen waren van een voor Midden Java gemiddelde vruchtbaarheid. De hoeveelheden voor vegetatie beschikbare voedingsstoffen in de jongere vulkanische assen waren geringer dan die in de oudere afzettingen als gevolg van het hogere soortelijk gewicht van de laatstgenoemden. Met name de voorraden aan beschikbaar fosfor in de bodem waren laag (met uitzondering van het dennenbos). De bodem onder de oudste *Agathis*-aanplant bevatte bovendien betrekkelijk weinig calcium en magnesium (zie paragraaf 5.7).

De totale netto behoefte aan voedingsstoffen (d.w.z. benodigd voor de vorming van biomassa) van een "gemiddelde" en op ideale wijze beheerde *Agathis* aanplant over een periode van 40 jaar zijn vergeleken met de toelevering van voedingsstoffen uit de atmosfeer en chemische verwering. Een tekort aan fosfor werd waarschijnlijk geacht (zie paragraaf 5.9). Het is daarom geboden om bij kappen van het bos zoveel mogelijk organisch materiaal achter te laten voor latere vertering. Dit zou ook de hergroei van de struiklaag bevorderen en daarmee eventueel bodemverlies tegengaan. Wanneer alleen de geschilde stammen en de zware takken geoogst zouden worden, in plaats van de bomen in hun geheel, dan zou dat een besparing opleveren van 55 % (P) tot 60 % (K) à 70 % (Ca, Mg).

De hoeveelheden voedingsstoffen die terugkeren naar de bosbodem zijn in het geval van *Eupatorium* struikgewas dermate gunstig (in vergelijking tot de opname *uit* de bodem) dat het niet nodig is deze soort te verwijderen uit jonge bosaanplant.

De chemische verwering van de Kwartaire andesitische vulkanische assen in en rond het stroomgebied is bestudeerd door middel van scheikundige en mineralogische ontleding van een reeks aslagen van verschillende ouderdom (zie paragraaf 6.3). Vier afzonderlijke groepen van bodemhorizonten konden worden onderscheiden, elk met kenmerkende onderlinge verhoudingen in de hoeveelheden kleimineralen.

Niet-kristallijn materiaal ("allofaan") kwam in de grootste hoeveelheden voor in de 2e en 3e groep, onmiddellijk gevolgd door halloysieten. Allofaan was echter in veel mindere mate aanwezig in de oudste lagen, die gedomineerd werden door halloysieten. De jongste horizonten bevatten middelgrote hoeveelheden niet-kristallijn materiaal, iets meer halloysiet en een niet te verwaarlozen percentage gibbsiet. De hoeveelheden van laatstgenoemd mineraal namen sterk af met de diepte.

Bestudering van de scheikundige samenstelling van het door de bodem sijpelende water bevestigde de waargenomen tendensen. Allofaan en gibbsiet zijn beide onstabiel met betrekking tot de bodemvochtsamenstelling. De halloysieten zijn meta-stabiel en zullen uiteindelijk worden omgezet in kaoliniet. De verwering van de assen is echter nog niet zover gevorderd dat er al kaoliniet gevormd is. Wel wordt gehydrateerde halloysiet in het droge seizoen omgezet tot meta-halloysiet, als gevolg van de dan optredende hoge concentraties aan opgelost kiezelzuur in het bodemvocht.

9. RINGKASAN

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Penelitian dalam rangka penyagian tesis ini, dilaksanakan mulai 1 December 1976 hingga 1 Februari 1978, dengan bantuan pembiayaan dari The Netherlands Foundation for the Advancement of Tropical Research (WOTRO). Sebagian pekerjaan, dilaksanakan dalam rangka kerjasama dengan NUFFIC "Serayu Valley Project" (ITC/GUA/VU 1 & 2).

Suatu daerah aliran sungai kecil yang tertutup hutan dan dengan karakteristik seperti di uraikan pada bab 2 telah dipilih sebagai daerah penelitian. Daerah ini terletak di bagian hulu sungai Mondo yang berbukit bukit, dekat kampung Watubelah, lebih kurang 5 km sebelah selatan Banjarnegara. Daerah tersebut merupakan bagian tepi utara dari deretan Pegunungan Serayu Selatan yang bermusim basah (Jawa Tengah bagian selatan).

Hal-hal yang ditelitikan adalah sebagai berikut:

- kesetimbangan air dan fluks hara mineral pada dasar daerah aliran sungai (d.a.s.), untuk memperkirakan ringkat berlangsungnya pelapukan kimia pada lapisan-lapisan tanah abu andesitis ("andesitic tuffs") yang mendasari daerah tersebut;
- tingkah laku hidrologikal dari d.a.s. selama hujan lebat dan selama musim kemarau;
- peredaran hara mineral dalam vegetasi di d.a.s. (yaitu hutan tanaman *Agathis loranthifolia* (berumur 11, 21 dan 42 tahun), semak-semak *Eupatorium*, hutan tanaman dekat dengan *Pinus merkusii* (umur 12 tahun) dan *Tectona grandis* (umur 25 tahun);
- bentuk pelapukan kimia dari lapisan-lapisan tanah abu andesitis.

Hasil ini berupa suatu sifat kenampakan hidrologikal dan biogeokhemikal dari d.a.s. tersebut.

Daerah penadah ini, mendapatkan curah hujan sejumlah 467C mm selama berlangsungnya penelitian, dimana 3460 mm (74%) mengalir melalui aliran sungai ("stream flow"). Selama lebih dari 3,5 bulan pada musim kemarau 1977, evapotranspirasi aktuil tidak menyimpang dari angka potensiil, tetapi kemudian sangat menurun.

'Stormflow' yang terjadi sangat kecil (< 10%) dari "run off" total dan terdiri dari campuran antara "channel precipitation", "Horton overland flow" dari permukaan yang padat dan berbagai macam "subsurface stormflow" serta "pipeflow" dan "throughflow" lokal.

Adanya dan pentingnya berbagai jenis aliran dapat dievaluasi berdasarkan kombinasi antara konsepsi "minimum contributing area" dengan pengamatan medan. Hasil analisa kwalitas air secara detil dari sampel limpasan tunggal menunjukkan bahwa "subsurface stormflow" menyumbang badai aliran ("stormflow") dengan cara "displacement flow" (bagian 3.4.2).

Fluks hara mineral (yaitu total muakan kimia yang terbawa keluar d.a.s. oleh sungai dikurangi dengan input muakan kimia kedalam daerah tersebut penadah dari udara) dihitung selama berlangsungnya penelitian dan selama tahunan rata-rata (bagian 4.2).

Angka-angka bersih hilangnya unsur-unsur utama mencapai 19,1 (Ca); 26,5 (Mg); 14,1 (Na); 12,4 (K) dan 527 (SiO_2) kilogram per hektar per tahun. Ortho-P terkumpul pada nilai 0,2 kg/ha/th, sedangkan Al, Fe dan Mn yang hilang, masing-masing 13,5; 12 dan 1 kg/ha/th.

Jika data solusi keluar ini dikonversikan terhadap oksida, diperoleh angka muatan solusi 80,7 ton per kilometer persegi selama penelitian berlangsung. Bersama-sama dengan muatan solusi ini terangkut pula muatan dalam bentuk suspensi (306 ton/km^2), dimana 15 ton/km^2 diangkut oleh aliran dasar, dan lewat dasar sungai (44,5 ton/km^2) sehingga total muatan keluar adalah 431 ton/km^2 atau rata-rata tahunan 442 ton/km^2 (bagian 4.3).

Biasanya kecepatan kelepasan hara mineral karena pelapukan dihitung dari fluks hara mineral untuk daerah aliran sungai. Pertumbuhan vegetasi di d.a.s. tersebut adalah cepat dan bagian unsur hara dilepasan karena pelapukan dimengikat dalam vegetasi. Karena itu angka erosi kimia yang berdasarkan fluks hara mineral adalah terlalu rendah dalam hal ini.

Pengikatan unsur hara oleh vegetasi d.a.s. telah dievaluasikan dengan pengukuran muatan hara mineral dari vegetasi tersebut (bagian 5.5). Hasilnya menunukkan bahwa pendekatan anggaran tradisionil bernilai lebih rendah dimana berbagai unsur diurai oleh pelapukan kimia dengan 75% (Ca); 32% (Mg); 15% (Na); 69% (K) dan 11% (SiO_2).

Sebagian dari unsur hara yang diserap oleh vegetasi kembali lagi ke dasar hutan melalu proses jatuhnya seresah dan pencucian mahkota tumbuhan. Sesudah terjadi dekomposisi dari seresah dan/atau pengangkutan unsur hara kedalam tanah, unsur hara ini dapat diserap kembali. Hal ini merupakan peredaran hara mineral yang diuraikan secara terperinci pada bab 5.

Sebagian besar Ca, Mg dan Si kembali ke dasar hutan melalui jatuhnya seresah dan berbeda dengan Na dan K yang lebih banyak melalui pencucian mahkota tumbuhan. Proporsi relatif berbeda antara jenis tumbuhan yang satu dengan yang lain (bagian 5.3 dan bagian 5.4).

Jumlah curah hujan yang terserap oleh berbagai tanaman, secara statistik dapat dikatakan pada umumnya tidak banyak perbedaan. Penyimpangan yang terjauh ditunjukkan oleh *Eupatorium* (9% terserap) dan tanaman *Pinus merkusii* yang rapat (30% terserap) - bagian 5.4.1. Hujan yang jatuh melalui tumbuhan ('throughfall') menunjukkan pertambahan unsur hara yang jelas jika dibandingkan dengah hujan ditempat terbuka. Jumlah unsur hara dari air hujan dibawah semak-semak *Eupatorium* ternyata lebih tinggi, mungkin karena pengaruh proses "guttation" (bagian 5.4.2).

Tanah yang berada dibawah hutan tanaman yang diteliti, dengan tanpa memandang umurnya dapat dikatakan berkesuburan sedang. Berdasarkan kenampakan wilayahnya, jumlah unsur hara yang tersedia pada endapan abu yang lebih muda adalah lebih rendah dari pada abu yang lebih tua, sesuai dengan kepadatannya yang lebih kecil. Timbunan phospor rendah pada semua bagian kecuali pada tanaman *Pinus*, sementara tanah yang berada dibawah hutan *Agathis* yang tertua mengandung Ca dan Mg dalam jumlah yang relatif sedikit (bagian 5.7).

Bendasarkan data kadar unsur hara didalam tumbuhan dan teori bahwa biomassa pepohonan meningkat sesuai dengan umur, dimungkinkan untuk menghitung kebutukan unsur hara bersih total secara ideal yang diperlukan untuk tanaman *Agathis* rata-rata pada suatu daur selama 40 tahun. Perbandingan antara kebutuhan ini dengan rata-rata input bahan kimia tahunan kedalam ekosistem hutan tanaman (yang berasal dari udara dan diuraikan oleh pelapukan kimia) menunjukkan kemungkinan kekurangan phosphor pada massa mendatang (bagian 5.9).

Disarankan supaya jangan mengambil semua bagian pohon dan mensisakan sebanyak mungkin sisa-sisa bahan organik. Jika hanya batang dan cabang-cabang besar saja yang diambil, lebih kurang sampai 55% dari kemungkinan kehilangan phosphor dapat dicegah. Demikian pula gambaran untuk K, Ca dan Mg masing-masing sejumlah 60 dan 70%.

Pemulangan hara mineral oleh semak-semak *Eupatorium* ternyata sangat tinggi, yaitu lebih dari 90% dari Ca, Mg dan K dan, lebih kurang 80% dari total phosphor yang diserap dikembalikan ke dasar hutan. Hal ini sangat berbeda dengan pola yang ditunjukkan oleh hutan *Agathis* muda. Kesimpulan sementara adalah bahwa *Eupatorium* tidak perlu dihilangkan dari tanaman hutan muda di Jawa Tengah.

Pelapukan kimia dari lapisan-lapisan abu vulkanis andesitis kwarter didalam dan disekitar d.a.s. diteliti dengan analisa kimia dan mineralogi (bagian 6.3). Empat kelompok lapisan dapat dibedakan, masing-masing dengan suatu susuhan mineral lempung yang tertentu.

Bahan yang tidak kristalin ("allophane") adalah yang paling banyak terdapat kelompok lapisan yang kedua dan ketiga (kemudian disusul oleh halloysit). Pada lapisan abu tertua, "allophane" ini hanya dalam jumlah yang kecil dan halloysit lebih menjajah.

Lapisan termuda, mengandung "allophane" dalam jumlah sedang, halloysit dalam jumlah yang cukup dan prosentasi gibbsit yang menyolok. Jumlah mineral yang disebut terakhir ini semakin dedalam semakin sedikit. Analisa susunan kimia dari lengas tanah ("soil water") memperkuat hasil pengamatan mineralogikal dalam arti kemantapan mineral. "Allophane" dan gibbsit keduanya mudah larut; selama musim kemarau dimana kadar larutan silika dalam lengas tanah naik, hydro-halloysit berubah menjadi meta-halloysit. Pelapukan dari abu belum berlangsung lanjut pada formasi kaolinit.

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11. LIST OF FIGURES

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Appendix 1 Mean amounts of canopy drip and standard errors of the mean per sampling occasion (mm)

Date	*Agathis* 1942		*Agathis* 1966		*Eupatorium*		*Tectona grandis*		*Pinus merkusii*	
	Mean	S.E.(%)	Mean	S.E.(%)	Mean	S.E.(%)	Mean	S.E.(%)	Mean	S.E.(%)
10/2/77	313.0	7.7	271.4	2.2	318.9	5.6	256.9	11.5	217.0^{+}	6.4
1/3	181.2	8.6	130.4	12.6	210.5	5.5	259.0	4.8	174.8	5.0
16/3	140.6	11.2	114.2	20.3	201.2	0.9	192.5	12.2	176.4	11.3
31/3	254.2	14.6	228.4	8.3	193.5	15.0	194.7	18.5	181.8	3.9
9/4	294.6	14.5	290.2	13.6	375.3	0.5	362***	-	197.9	21.4
30/4	331.0	6.6	250.4	9.4	279.8	3.3	313.9	6.6	192.1	5.4
31/5	79.1	7.2	84.5	12.5	94.4	3.7	92.4	6.8	116.7	6.2
20/6	337.4	7.2	342.5	4.4	351.4	6.6	381.0	2.9	272.5	2.6
1/7	60.2	10.1	72.3	11.3	66.0	7.8	76.9	8.1	52.6	7.4
1/11*	46	12.3	43	24.3	47	9.3	49	6.1	25.5	6.7
1/12	277.1	4.7	264.0	6.4	347.8	6.4	260.8	6.4	237.2	8.1
31/12	472**	-	433**	-	477**	-	399**	-	312.4	5.2
17/1/78	349.0	3.8	283.8	12.8	290.9	8.6	260.5	9.0	268.3	2.9
1/2	163.5	12.1	126.1	26.6	159.8	20.6	112.7	9.4	122.4	8.2
Total	3299	4.5^{++}	2935	2.6^{++}	3414	2.5^{++}	3212	2.3^{++}	2547	3.3^{++}

* corrected for evaporation from collector

** collectors overflowed; estimated value

*** one sample only

\+ from 2 February onwards

++ standard error of mean annual total per site

Appendix 2 Production of biomass and nutrient uptake in an ideally stocked+ plantation of *Agathis loranthifolia* (average site class)

2.1′ Accumulated tree biomass (kg $tree^{-1}$ o.d. wt)*

Age (yr)	Tree biomass (kg o.d. wt) Leaves	Branches	Twigs	Stemwood	Bark	Number of trees $(ha^{-1})^{+}$	thinnings $(ha^{-1})^{++}$
5	2.1**	1.8**	1.7**	9.5**	0.5**	2580	1440
10	8.4	8.9	7.6	44.0	2.6	1140	485
15	15.4	22.3	10.9	168.1	9.7	655	205
20	24.1	38.1	16.2	312.9	18.0	450	90
25	34.4	56.4	23.7	478.5	27.5	360	40
30	46.4	77.2	33.3	664.8	38.2	320	28
35	60.0	100.3	45.1	871.9	50.2	292	22
40	75.2	126.0	59.0	1099.8	63.4	270	

**cf.* Fig. 5.10 (section 5.5.2)
**estimated via 7-yr old trees (see section 5.5.2)
+according to Suharlan *et al.* (1975); siteclass III
++number of trees felled per 5 yr.

2.2 Biomass produced by standing crop (kg ha^{-1}.5 yr^{-1})

Age class	Leaves	Branches	Twigs	Stemwood	Bark	Number of trees (ha^{-1})
0-5	5420	4644	4386	24510	1290	2580
5-10	7182	8094	6726	40470	2394	1140
10-15	4585	8777	2161	81220	4650	655
15-20	3915	7110	2385	65160	3735	450
20-25	3708	6588	2700	59616	3420	360
25-30	3840	6656	3072	59616	3424	320
30-35	3971	6745	3446	60473	3504	292
35-40	4104	6939	3753	61533	3564	270
0-40	36725	55553	28629	452598	25981	

2.3 Biomass produced by (and removed as) thinnings (kg ha^{-1}.5 yr^{-1})

Age class	Leaves	Branches	Twigs	Stemwood	Bark	Number of thinnings (ha^{-1})
5-10	7560	7704	6696	38520	2232	1440
10-15	5771	7566	4486	51410	2983	485
15-20	4049	6191	2778	49302	2839	205
20-25	2632	4252	1795	35613	2048	90
25-30	1616	2672	1140	22866	1314	40
30-35	1490	2485	1098	21514	1235	28
35-40	1487	2489	1145	21689	1250	22
0-40	24605	33359	19138	240914	13901	

2.4 Cumulative uptake of nutrients* (kg ha^{-1})

2.4.1 *Calcium*

Time (yrs)	Leaves	Branches	Twigs	Bark	Wood	Total
5	105	20	35	21	23	204
10	389	88	142	95	98	812
15	589	158	201	217	224	1390
20	743	215	243	322	333	1856
25	865	262	294	409	423	2253
30	970	302	342	485	502	2601
35	1076	342	395	561	580	2954
40	1184	382	453	638	659	*3316 (+ 340)***

*tree component only
**cumulative uptake by undergrowth over 40 yr

2.4.2 *Magnesium*

Time (yrs)	Leaves	Branches	Twigs	Bark	Wood	Total
5	22	4	12	3	5	46
10	78	18	47	14	23	180
15	116	33	65	32	52	298
20	142	45	78	48	77	390
25	165	55	91	61	98	470
30	187	63	104	73	116	543
35	213	72	119	84	134	622
40	242	80	136	96	153	*706 (+ 80)***

2.4.3 *Potassium*

Time (yrs)	Leaves	Branches	Twigs	Bark	Wood	Total
5	41	30	31	4	15	120
10	153	121	125	18	65	482
15	232	190	171	39	149	781
20	292	227	207	54	221	1001
25	341	248	239	67	281	1176
30	382	264	268	80	333	1327
35	424	280	300	99	385	1488
40	466	295	334	122	437	*1654 (+ 240)***

2.4.4 *Phosphorus*

Time (yrs)	Leaves	Branches	Twigs	Bark	Wood	Total
5	6	4	6	1	4	21
10	22	18	25	4	18	87
15	34	30	34	8	40	146
20	42	38	41	12	60	193
25	49	43	48	17	75	232
30	55	48	56	22	87	268
35	61	53	66	31	97	308
40	68	57	76	40	107	*348 (120)***

*tree component only
**cumulative uptake by undergrowth over 40 yr

Appendix 3 Energies of formation and chemical reactions used for constructing Figure 6.6 (mineral stabilities in the Al_2O_3-SiO_2-H_2O system at 298.15° K and 1 bar)

3.1 Applied values for the energies of formation (ΔG_f°; kcal mol^{-1})

H_2O	- 56.69	- ROSSINI *et al.*, 1952
$H_4SiO_4{}^\circ$	-312.66	- REESMAN & KELLER, 1968
Al^{3+}	-117.33	- SINGH, 1976
$Al(OH)_4^-$*	-312.25	- KITTRICK, 1966
$Al(OH)_3^+$	-274.21	- *ibidem*
$Al_2Si_2O_5(OH)_4^*$ (Kaolinite)	-906.0	- REESMAN & KELLER, 1968
$Al_2Si_2O_5(OH)_4^*$ (Halloysite·10 Å)	-904.3	- *ibidem*
$Al_2Si_2O_5(OH)_4^*$ (Halloysite·7 Å)	-901.0	- *ibidem*

---

*recalculated with ΔG_f° Al^{3+} = -117.33 to obtain an internally consistent set of data.

+poorly crystalline

3.2 Reactions (numbers between parentheses correspond with numbered lines in the diagram)

(1) $Al_2Si_2O_5(OH)_4$ (s) + $5H_2O \rightleftharpoons 2Al(OH)_3$(s) + $2H_4SiO_4{}^\circ$

Kaolinite Gibbsite

ΔG_R° = 2(-117.33) + 2(-312.66) - (-906.0) - 5(-56.69) = 15.71 k cal mol^{-1}

$$\left.\begin{array}{l}\Delta G_R^\circ = 1.364\ p\ K_{(1)} \rightarrow p\ K_{(1)} = 11.52 \\ pK_{(1)} = 2p(H_4SiO_4{}^\circ)\end{array}\right\} \rightarrow p(H_4SiO_4{}^\circ) = 5.76$$

(2) $Al_2Si_2O_5(OH)_4$(s) + $5H_2O \rightleftharpoons 2Al(OH)_3$ (s) + $2H_4SiO_4{}^\circ$

Halloysite·10 Å Gibbsite

ΔG_R° = 14.01 kcal $mol^{-1} \rightarrow pK_{(2)} = 10.27 \rightarrow p(H_4SiO_4{}^\circ) = 5.14$

(3) $Al_2Si_2O_5(OH)_4$ (s) + $5H_2O \rightleftharpoons 2Al(OH)_3$ (s) + $2H_4SiO_4{}^\circ$

ΔG_R° = 10.71 kcal $mol^{-1} \rightarrow pK_{(3)} = 7.85 \rightarrow p(H_4SiO_4)^\circ = 3.93$

(4) $Al(OH)_3$ (s) + $3H^+ \rightleftharpoons Al^{3+} + 3H_2O$

Gibbsite

$\Delta G_R^\circ = -13.19 \rightarrow pK_{(4)} = -9.67 \rightarrow pH - 1/3\ p\ (Al^{3+}) = 3.22$

(5) $Al_2Si_2O_5(OH)_4$ (s) + $6H^+ \rightleftarrows 2Al^{3+} + 2H_4SiO_4^\circ + H_2O$
Kaolinite
ΔG_R° = -10.67 kcal mol^{-1} → $pK_{(5)}$ = -7.82 → pH - 1/3 $p(Al^{3+})$ =
1/3 $p(H_4SiO_4^\circ)$ + 1.30

(6) $Al_2Si_2O_5(OH)_4$ (s) + $6H^+ \rightleftarrows 2Al^{3+} + 2H_4SiO_4^\circ + H_2O$
Halloysite·10 Å
ΔG_R° = -12.37 → $pK_{(6)}$ = -9.07 → pH-1/3 $p(Al^{3+})$ = 1/3 $p(H_4SiO_4^\circ)$ + 1.51

(7) $Al_2Si_2O_5(OH)_4$ (s) + $6H^+ \rightleftarrows 2Al^{3+} + 2H_4SiO_4^\circ + H_2O$
Halloysite·7 Å
ΔG_R° = -15.67 → $pK_{(7)}$ = -11.49 → pH -1/3 $p(Al^{3+})$ = 1/3 $p(H_4SiO_4^\circ)$ + 1.91

(8) α-SiO_2 (s) + $2H_2O \rightleftarrows H_4SiO_4^\circ$
Cristobalite
$pK_{(8)}$ = $p(H_4SiO_4^\circ)$ = 3.35 (ELGAWHARY & LINDSAY, 1972)

(9) SiO_2(a) + $2H_2O \rightleftarrows H_4SiO_4^\circ$
Amorphous silica
$pK_{(9)}$ = $p(H_4SiO_4^\circ)$ = 2.74 (ELGAWHARY & LINDSAY, 1972)

Appendix 4 Summary of data on nitrogen in biomass and litterfall

Data on N-concentrations of *Tectona-*, *Pinus-* & *Eupatorium* biomass and litterfall came available after completion of the manuscript. Results of elementary processing of these data are presented below together with the corresponding figures for the 35-yr old stand of *Agathis*.

*Nitrogen concentrations of biomass** (mg g^{-1})

	Agathis '42	*Tectona* '52	*Pinus* '65	*Eupatorium*
leaves	12.7 ± 0.1	15.9 ± 2.8	14.0 ± 0.1	-
branches	2.4**	2.0 ± 0.0	0.9 ± 0.2	-
twigs	5.2 ± 0.8	3.3 ± 0.4	2.3 ± 0.5	-
stemwood	1.7 ± 1.1	2.0 ± 0.3	1.1 ± 0.2	-
bark	3.1 ± 0.3			-
undergrowth	6.6 ± 0.1	5.6 ± 0.6	-	9.9 ± 1.8
litter layer	7.5 ± 0.6	10.0 ± 0.4	6.4 ± 0.6	*c.* 20

**cf* Table 5.26
**one sample

Nitrogen inventories os standing crop (kg ha^{-1})*

	Agathis '42	*Tectona* '52	*Pinus* '65	*Eupatorium*
leaves	122	82	167	-
branches	39	29	25	-
twigs	37		12	-
stems	354	165	140	-
undergrowth	21	11	(10)	104
litter	35	47	52	69
Total	*608*	*334*	*406*	*173*
Soil (0-100 cm)	20.200	14.900	17.900	20.100

**cf* Table 5.28

Actual uptake of nitrogen during the study year (kg ha^{-1} yr^{-1})

	Agathis '42	*Tectona* '52	*Pinus* '65	*Eupatorium*
trees	23.5	13	106	-
shrubs	6.5	5.5	1.5	21
Total	*30*	*18.5*	*107*	*21*

**cf*. Table 5.32

*Total net uptake of nitrogen by Agathis over 40 years (ideal management)** (kg ha^{-1})

	thinnings	standing crop	total
leaves	312	466	778
branches	80	133	213
twigs	100	149	249
wood	410	769	1179
bark	43	80	123
total	*945*	*1597*	*2542 + 213** = 2756*

*applying nitrogen concentrations of *Agathis* 1942; *cf.* Appendix 2
**undergrowth

*Average concentration of nitrogen in litter fall** (mg g^{-1})

Eupatorium	leaves	21.4 ± 1.3	(March, July, October & January)
Agathis '42	leaves	7.4 ± 0.7	(January - August)
	twigs	4.8 ± 1.1	
	seeds	6.5 ± 0.9	
	bark	4.1 ± 0.9	
Tectona '52	leaves	9.6 ± 1.6	(as *Eupatorium)*
Pinus '65	needles	6.0 ± 0.6	(*ibidem*)
	cones	5.0 ± 0.6	(March & October)
Montane Rain forest	leaves	11.2 ± 2.6	(June, July, October & January)

**cf.* Tables 5.4 (*Agathis; Eupatorium*), 5.11(*Tectona, Pinus*) and 5.14(Rain forest).