Soils, water and nutrients in a forest ecosystem in Suriname

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R.L.H. Poels

SOILS, WATER AND NUTRIENTS IN A FOREST ECOSYSTEM IN SURINAME

Proefschrift

ter verkrijging van de graad van
doctor in de landbouwwetenschappen
op gezag van de rector magnificus,
dr. C.C. Oosterlee,
in het openbaar te verdedigen
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Abstract

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Water and nutrient flows were measured in catchments on strongly weathered loamy sediments of the Zanderij formation in Suriname under undisturbed forest and forest silviculturally treated whereby 40 % of the biomass was killed. The topography of the two catchment areas studied (each of about 150 ha) is gently undulating. The main soil is a well drained loamy Ultic Haplorthox which covers most of the plateaus and upper slopes while sandy soils occur on lower slopes and in valley bottoms.

Measured data on rainfall, discharge, evaporation, groundwater levels and hydraulic conductivity were used in computer simulation of water flows. It was found that large amounts of water were available to the forest and that transpiration reduction in the dry seasons was only small. The average effective rooting depth was calculated to be 450 cm. The contribution of transpiration, interception and soil evaporation to total water use (1640 mm/y) was calculated, annual rainfall being 2140 mm.

Nutrient amounts and flows were determined in both the organic matter cycle and the hydrological cycle for the treated and untreated catchments. A computer simulation of organic matter flows showed that large amounts of nutrients were liberated during the 3 years after treatment. Only a very small proportion of these nutrients left the catchment area with the discharge water. The higher nutrient influx in rainwater than nutrient losses in drainage water indicates that there was a small accumulation of nutrients in both the untreated and treated catchments. Thus it is concluded that the forest treatment did not result in unacceptable losses of nutrients from the ecosystem.

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ERRATA Thesis Poels

Curriculum vitae, line 14: replace "was door" by "was hij door"
line 16: replace "bosbouw" by "bosbouw-"
line 19: insert before "Sinds 1985": "De uitwerking van de in Suriname verzamelde gegevens vond in Wageningen plaats gedurende 1984 en 1985."
Preface, page 1, line 13: replace "outside" by "beyond"
page 2, line 9: replace "increases" by "increase"
page 2, line 14: replace "extend" by "extent"
page 24, Fig. 2.11, last line LEGEND: replace "slopes ≤=" by "slopes ≤ 2%"
map unit 8.5 cm from top of page and 3.0 cm from the left belongs to Footslopes
map unit 5.0 cm from top of page and 9.5 cm from the left should be blank
page 25, line 5: delete "(map unit P 1.2)"
page 34, LEGEND: replace "S/SL" by "S-SL"
page 51, Table 2.7, line 3: replace "Concentration" by "Concentration **"
page 61, Fig. 3.4, LEGEND: replace "Deepboring no. 3" by "Deepboring"
Lower right corner: line between central and eastern waterdivide should also be marked as water divide, as in Fig. 2.12, page 28
page 72, Fig. 3.11: replace "WOFOST4" by "WOFOST"
page 102, lower right corner: mark water divide as in Fig. 3.4, page 61
Indicate "Eastern Creek area" below plot 9 and "Western Creek area" below plot 8
page 106, 5th line from below: replace "increase in" by "increase"
page 108, Table 4.4, line 31, last column: replace "25.5" by "125.5"
page 116, title Fig. 4.4: replace "phytomass" by "phytomass,"
page 141, Table 4.21, line 2/3: replace "table 4.20)" by "(Table 4.20)"
page 166, remove line 22
page 185, line 23: replace "130/115" by "130/150"
page 192, line 1: remove "and clay"
page 197, above lower table insert: "(continued)"
page 222, line 19: replace "influences" by "influenced"
page 228, Table IV.4, line 9: replace "-oo" by "-∞"
page 252, line 1: replace "catchment" by "catchments".

Stellingen

1. In de natuurlijke bossen op lemige zanderijgrond te Kabo, Suriname treedt accumulatie van nutriënten (plantevoedende stoffen) in het ecosysteem op, door een grotere instroming van nutriënten met het regenwater dan afvoer met het rivierwater.

   Dit proefschrift.

2. De meest recente terugval in hoeveelheid nutriënten in het bos te Kabo is waarschijnlijk veroorzaakt door indiaanse zwerflandbouw.

3. De extreme verarming van de bodems in het Zanderij gebied is vooral tot stand gekomen gedurende perioden met savannevegetatie in het Plioceen en het Pleistoceen.

4. Alle vlak gelegen, onvoldoend gedraineerde Zanderij sedimenten zullen bij voortduren van het huidige klimaat door podzolisatie in witte kwartszanden overgaan.

   Lucas, Y., R. Boulet and A. Domeny, 1982. Acid soils of French Guiana. In: Wienk, J.F. and H.A. de Wit (eds): Workshop on the management of low fertility acid soils of the American humid tropics. IICA, San José, Costa Rica.

5. Het hoge waterverbruik van het tropisch regenbos tijdens de droge tijd is zijn belangrijkste wapen tegen uitspoeling van nutriënten.

6. Bosbehandeling volgens het “Celos Silvicultural System” leidt niet tot onaanvaardbare verliezen aan nutriënten uit het ecosysteem.

   Dit proefschrift.

7. In plaats van het geven van subsidies voor het kappen van tropisch bos zou de overheid de (kunstmest)waarde van de in de biomassa aanwezige nutriënten als belasting aan de ontginner moeten opleggen.

   N.R. de Graaf, 1982. Sustained timber production in the rainforest of Suriname. In: Wienk, J.F. and H.A. de Wit (eds): Workshop on the management of low fertility acid soils of the American humid tropics. IICA, San José, Costa Rica.

8. Communaal gebruik van grond bij een matige tot sterke bevolkingsdruk leidt vaak tot zeer sterke landdegradatie en moet daarom zoveel mogelijk tegengegaan worden.

9. Grondbelasting, gedifferentieerd naar opbrengstpotentieel en landgebruik, is een beter middel om het grootgrondbezit te verminderen dan onteigening.

10. De computer dreigt in de bodemkunde meer doel dan middel te worden.

11. Tijdens de onderhandelingen tussen Suriname en Nederland over de onafhankelijkheid in 1975, heeft de Surinaamse delegatie o.l.v. Henk Arron gretig en met veel succes gebruik gemaakt van het bij de Nederlandse onderhandelaars levende schuldgevoel over 300 jaar koloniaal bewind.

12. Het schrijven van een proefschrift houdt je jong, althans geestelijk.

Stellingen behorende bij het proefschrift van R.L.H. Poels: Soils, water and nutrients in a forest ecosystem in Suriname.

Wageningen, 23 september, 1987.

Aan mijn ouders
aan Ellen
aan Katheleen, Arjan en Elineke

Curriculum vitae

Renier Laurentius Hubertus Poels werd geboren in Meerlo (L) op 21 december 1941. Na de lagere school en een jaar lagere landbouwschool doorliep hij van 1955-1961 het Gymnasium-B te Venray. Na het vervullen van de militaire dienstplicht begon hij in 1963 zijn studie aan de Landbouwhogeschool te Wageningen, waar hij in 1971 het ingenieursdiploma behaalde in de studierichting Bodemkunde en Bemestingsleer.

Van 1971-1974 was hij werkzaam als assistent-deskundige voor de FAO in Thailand en Indonesië, in bodemkundig-cultuurtechnisch onderzoek voor ontginning van getijdemoerassen en herstel van gedegradeerde drooglandgebieden. Van 1974-1977 was hij in dienst van het Duitse ingenieursbureau Agrar- und Hydrotechnik. Voor dit bureau werkte hij in Zambia, Soedan, Tanzania en opnieuw in Soedan, waarbij hij voornamelijk bodemkarteringen uitvoerde voor ontwikkelingsprojecten. Van 1977-1983 was door de Landbouwhogeschool gedetacheerd bij het CELOS in Suriname en werkzaam als bodemkundige en agrohydroloog in een bosbouw en in een landbouwproject. In deze periode verrichtte hij ook de waarnemingen in een stroomgebied onder tropisch regenbos die de basis van dit proefschrift vormen.

Sinds 1985 is hij als medewerker verbonden aan de vakgroep Bodemkunde en Geologie van de Landbouwuniversiteit Wageningen.

Contents

Appendices

Preface

The tropical rain forest ecosystem is overwhelmingly complex. Users often understand little about its functioning and its potential beyond their immediate scope. The forest system has a wide variety of functions and products and different users can find what they need. However because of this variety, single products are often found only in small concentrations. A hunter finds only a few animals to hunt. A concessionaire usually takes only few trees, the rest being unsuited to his requirements or unknown to him. The subsistence farmer uses only the nutrients tied up in the forest biomass, liberating them by burning in order to grow crops for a few years. Others look for fruits, medicinal substances or plants to be used in breeding programmes. Many users wish to change the forest system in order to increase the concentration of products of interest to them. Because of lack of knowledge of the values of the forest outside the scope of the user and because of considerations of efficiency, there are strong tendencies to simplify the forest system to favour the users needs. Most foresters prefer monocultures of high quality timber trees and farmers favour clearing extensive areas for agriculture or cattle grazing.

These system simplifications to increase efficiency have disadvantages. Soils may be too poor to support monocultures and a monoculture may result in the loss of other forest functions and products, both known and as yet unknown. Better understanding of the different values of the rain forest and acknowledgement of the limitations of non-forest land uses are considered to be essential for sound land use planning.

Land use systems in between the natural forest and monocultures could possibly give higher yields than the natural forest and may not have the disadvantages of monocultures. On the extremely poor soils in Suriname and other parts of the tropics with limited potential for agriculture and plantation forestry, timber production in manipulated natural forests could be a viable land use.

In 1977, the Agricultural University Wageningen, the Netherlands and the University of Suriname began a co-operative study in the project entitled 'Human interference in the tropical rainforest ecosystem', at the Centre for Agricultural Research (CELOS) in Suriname. A team from both universities carried out a number of experiments in the forest areas of Suriname between 1977 and 1983. This research, which was a continuation of earlier research by CELOS and the

Suriname Forest Service (LBB) was focused on the consequences of interference on the potential productivity of the natural forest, its environment and its capacity for sustained timber production. A silvicultural system based on the natural forest was developed and tested. This system, the Celos Silvicultural System (CSS), aims at increasing sustainable production of tropical hardwoods in the natural forest. Competition of trees and lianas with commercial tree species is reduced in this system by poisoning a large part of the biomass.

Treatment according to the Celos Silvicultural System has been shown not only to increases the production of quality hardwood in the natural forest but also to leave most of the other functions of the natural forest intact. It may compare favourably with other possible land uses and so contribute to slowing down the alarming rate of forest destruction throughout the tropics. The purpose of this study is to investigate whether this type of treatment disrupts water and nutrient cycling to such an extend that the production capacity of the forest is affected in the long term.

The orginal idea for this study of water and nutrient flows in the tropical rain forest ecosystem came from the late Professor J. Bennema of the Department of Soil Science and Geology of the Wageningen Agricultural University. He proposed that I should write the work up as a doctoral thesis and that he together with Professor W.H. van der Molen, Department of Agrohydrology, be my promoters. Professor Bennema guided the study until his sudden death in January 1985. I am very grateful to him for his enthusiastic encouragement and guidance in setting up the study. Professor van der Molen visited the project area in 1980 and 1983. He gave much valuable advice which has greatly influenced the field-work and the reporting of the project. On the death of Professor Bennema, Professor L.J. Pons of the Department of Soil Science and Geology took over the task of guiding this study. I am indebted to him for his critical comments and time taken in discussions particularly of the soils and geology of the project area.

I very much appreciate the co-operation and continued support of the successive directors of CELOS, especially Drs. H.O. Prade, and their staff who made the field-work in Suriname possible and who provided administrative and laboratory services. I wish to thank Dr. G.A.M. van Marrewijk and the various members of the commissions for co-operation between both universities for making this project possible.

Throughout this study I have been helped and encouraged by many people. I value very much their support and in particular I would like to mention:

- my colleagues and fellow team members in Suriname for their support and comradeship, and especially Dr. N.R. de Graaf and Ir. W.B.J. Jonkers for the pleasant co-operation in the field
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1 Introduction

Suriname, situated on the north coast of South America, is 16 million ha in area and has a population of 350 000, with a population density of 2.2 per km^2. The land is predominantly low lying, the climate warm and humid, and the vegetation mainly forest.

The population is concentrated in the swampy northern part of the country, where fertile marine clay soils are cultivated. The dry, undulating to hilly hinterland has remained largely untouched because of poor accessibility and low soil fertility. However, since the 1960s, timber has been extracted by selective logging from the luxurious hinterland forests of northern Suriname. There is a modest domestic timber market, and also some export of wood and wood products. Agriculture on these well drained areas is mainly small-scale shifting cultivation. With few exceptions, efforts to establish permanent, larger-scale agriculture have been largely unsuccessful because of poor crop performance and high costs.

Low soil fertility is considered to be the main obstacle to agricultural crop production. Most inland soils are extremely poor in plant nutrients and have very low buffering capacities for plant nutrients (Boxman, in press). Nutrient surpluses in the soil, resulting from fertilizer application or the decomposition of organic matter, are readily lost and removed by drainage water.

Forestry appears to be the best type of land use for these areas. However the practice of selective logging of the best trees has done much damage to the remaining vegetation and regrowth has been too slow for further profitable exploitation of the natural forest (de Graaf, 1986).

In about 1960, experiments were started to increase forest production by planting monocultures of mostly exotic trees. Initially, promising results were obtained from these plantations, but later growth often slowed down. Weed growth was also a serious problem. Subsequently several silvicultural systems were investigated in the natural forest with the aim of stimulating the growth of promising trees of marketable species by eliminating competing trees and lianas (de Graaf, 1986).

The natural forest has adapted to the low nutrient level of the soil by maintaining an almost closed nutrient cycle. Most nutrients in the ecosystem are retained in the living biomass. Nutrients released by decomposing organic matter are quickly taken up by the perennial green vegetation thus preventing leaching. Forest has a more closed nutrient cycle than most agricultural systems, and nutrient losses are less. Natural forest is expected to have a more closed cycle with smaller losses than monocultures of even-aged trees, because of the diversity of species and sizes, and because of the small variation in biomass amounts.

The CELOS Silvicultural System, (CSS; de Graaf, 1986) was developed to increase the timber production in natural rain forest in Suriname. In this system, the biomass is reduced regularly by harvesting and refinement. Harvesting is selective logging and refinement is a treatment to reduce competition by poisoning non-commercial trees. This may kill up to half of the biomass. Reduction of the biomass during harvesting is relatively small but is accompanied by removal of nutrients with the stemwood. Refinement does not include removal of material but the increased supply of nutrients from decomposing organic matter is subject to leaching. The cycle in this system is 20 to 30 years and comprises two or three refinements and one harvest of only a few stems per ha of high quality wood.

This silvicultural system has been developed for natural rain forests on extremely poor soils of limited agricultural potential. A system such as this may be applicable to the vast expanses of tropical rain forests, especially in South America. These forests are being cleared at an alarming rate for the cultivation of agricultural crops. Because of the poverty of the soil cultivation can only be sustained for a period of a few years after which the land is left or used as low productivity grazing land. When timber production in these forests could be made profitable by a silvicultural system such as CSS, the rate of forest clearing could be slowed down without economic disadvantage.

Eliminating competing trees in a silvicultural system accelerates the turn-over of nutrients in the ecosystem. Tree fall followed by decomposition, release of nutrients and uptake of the nutrients by the remaining living vegetation is a natural process. However if many trees with a large biomass are killed at the same time, the release of nutrients by decomposition may surpass the uptake capacity of the remaining vegetation, and the surplus of nutrients could then leach from the system. It is important to know whether the CSS results in unacceptable losses of nutrients from the ecosystem which may endanger the long-term productivity of the forests.

This study was carried out of the soils, the water and nutrient flows in undisturbed forest and in forest treated under the CELOS Silvicultural System to gain a better understanding of the functioning of the forest ecosystem.

The study area is in the Zanderij belt which is a large, gently undulating area of sedimentary origin between the hilly hinterland and the low-lying coastal plain. Soils are heavily weathered and of very low nutrient content. They also have very low nutrient holding capacities. Large parts of the Zanderij area are covered with forests that maintain a high biomass in which large amounts of nutrients are stored.

For this study data were collected from a number of experiments (for location see Chapter 3) in the forest area near Kabo, approximately 100 km south-west of Paramaribo. The main study area is known as hydrological experiment 78/34. This is a catchment area of about 300 ha, subdivided into two catchments of similar area, one under undisturbed natural forest and the other is under the same natural forest, but here the CELOS silvicultural system is being implemented. CELOS is an abbrevation for "Centrum voor landbouwkundig onderzoek in Suriname", the agricultural research centre in Suriname.

The flows of water and nutrients were investigated by measuring rainfall and creek discharges and also the composition of rain-water and discharge water. Soil distribution and properties were studied in order to determine their effect on cycling of water and nutrients. The turn-over of organic matter and nutrients was studied in the representative soil profile under undisturbed and treated forest.

Adjacent to experiment 78/34 is a fertilizer experiment (82/2) in natural forest on a soil representative of the catchment area. Data on forest biomass and soil composition were collected from the plots before fertilizer application. Data were also collected on the effects of refinement from the forestry experiment (78/5) adjacent to and partly overlapping experiment 78/34, in which variations of the Celos Silvicultural System have been tried out (Jonkers, in press). Data on vegetation structure were collected from experiment 82/15 (van Leeuwen, 1985) on the relationship between soil and vegetation on a strip within the catchment area.

This study consists of three parts because of the close interrelationship of soil, water and nutrients:

- a study of the physical environment of the study area including the geology, climate, soils and vegetation, and consideration of the extend to which the study area is representative of the Zanderij area and Suriname as a whole
- a study of the hydrology of the study area on a catchment area scale
- a study of the nutrient cycling in the study area based on the hydrology

The study of the physical environment is presented in Chapter 2. These data provided basis for the study of the water and nutrient cycling, and also established the conditions in the study area for extrapolating results to other areas. Particular attention was given to the genesis of the Zanderij area and the strong weathering which has resulted in the extremely poor soils. A detailed soil survey of the study area was carried out and attempts were made to get more insight into the soil forming processes which were occurring. The collection of climatic data needed for the hydrological study is discussed and a description is given of vegetation types in the Zanderij area in relation to the soil. The structure, biomass and nutrient content of a representative forest in the study area is given.

The hydrology of the study area is discussed in chapter 3. Data collected on rainfall, discharge, leakage losses, evaporation, topography, geological substratum, groundwater levels, hydraulic conductivities and pF relationships are discussed. The computer model WOFOST4 for simulating water flows in the representative soil profile and forest growth is described. This model was used to predict evapotranspiration of the forest in wet and dry periods, water uptake, interception losses, and drought induced transpiration reduction.

In Chapter 4, the nutrient balance in undisturbed forest and treated forest is compared. Two nutrient cycles are distinguished: in the hydrological cycle and in the organic matter cycle. Exploitation and refinement in the treated forest and the effect on litter and soil are discussed. A model is presented to describe amounts and flows of organic matter and nutrients in the undisturbed forest and the changes resulting from treatment. The inflow of nutrients by rainfall and their outflow by creek water are given for the undisturbed and treated sub-catchments. These flows were calculated by combining measured rainfall and discharge amounts with concentrations of nutrients in these waters. Finally changes in water composition during flow through the ecosystem are discussed.

2 Physical environment

The location of the study area is indicated in Fig. 2.1 as Kabo/Tonka, in the Zanderij belt. Kabo is an agricultural experimental area of 30 ha surrounded by undisturbed natural forest, with field offices, living quarters and a meteorological station serving both the agricultural and forestry experiments. Tonka is a small forest camp, 4 km west of Kabo, near hydrological experiment 78/34, forest fertilizer experiment 82/2, forestry experiment 78/5 (Jonkers, in press) and soil-vegetation study 82/15 (van Leeuwen, 1985 and Jonkers, in press). For location of these experiments, see Chapter 3 (Fig. 3.4).

This chapter gives some general information on the geology of Suriname with emphasis on the Zanderij area and the study area, and this is followed by climatic data of the study area and a nearby larger meteorological station. A literature review of soils in the Zanderij and soil research which has been carried out in the study area are presented in Section 2.4. The chapter ends with a short description of the vegetation, emphasing particularly the biomass and nutrient content.

This chapter is a study in its own right, and describes the physical environment of a part of the Zanderij area. It also supports the subsequent chapters on Hydrology (Chapter 3) and Nutrients (Chapter 4), giving data on geology, climate, soils and vegetation.

2.1 Main landscapes of Suriname

Suriname is situated on the north coast of South America between latitude 2° and 6° N and longitude 54° and 58° W. More than 80 % of the country is on the Precambrian Guiana Shield, a deeply weathered, rain forest hill and mountain area, stretching from the Amazon river in Brazil to the Orinoco in Venezuela (Bosma et al., 1984). The remaining 20 % consists of low-lying sediments mostly flat and close to sea level and a smaller part which is slightly higher with a flat to undulating relief.

On the basis of geology and landform, three major areas were distinguished by van der Eyk (1957): residual, old sedimentary and young sedimentary areas. The old sedimentary area is subdivided into the Old Coastal Plain and the "Dek" landscape, later known as the Zanderij landscape.

Krook (1984) distinguished two major areas: Crystalline Shield and Coastal Area

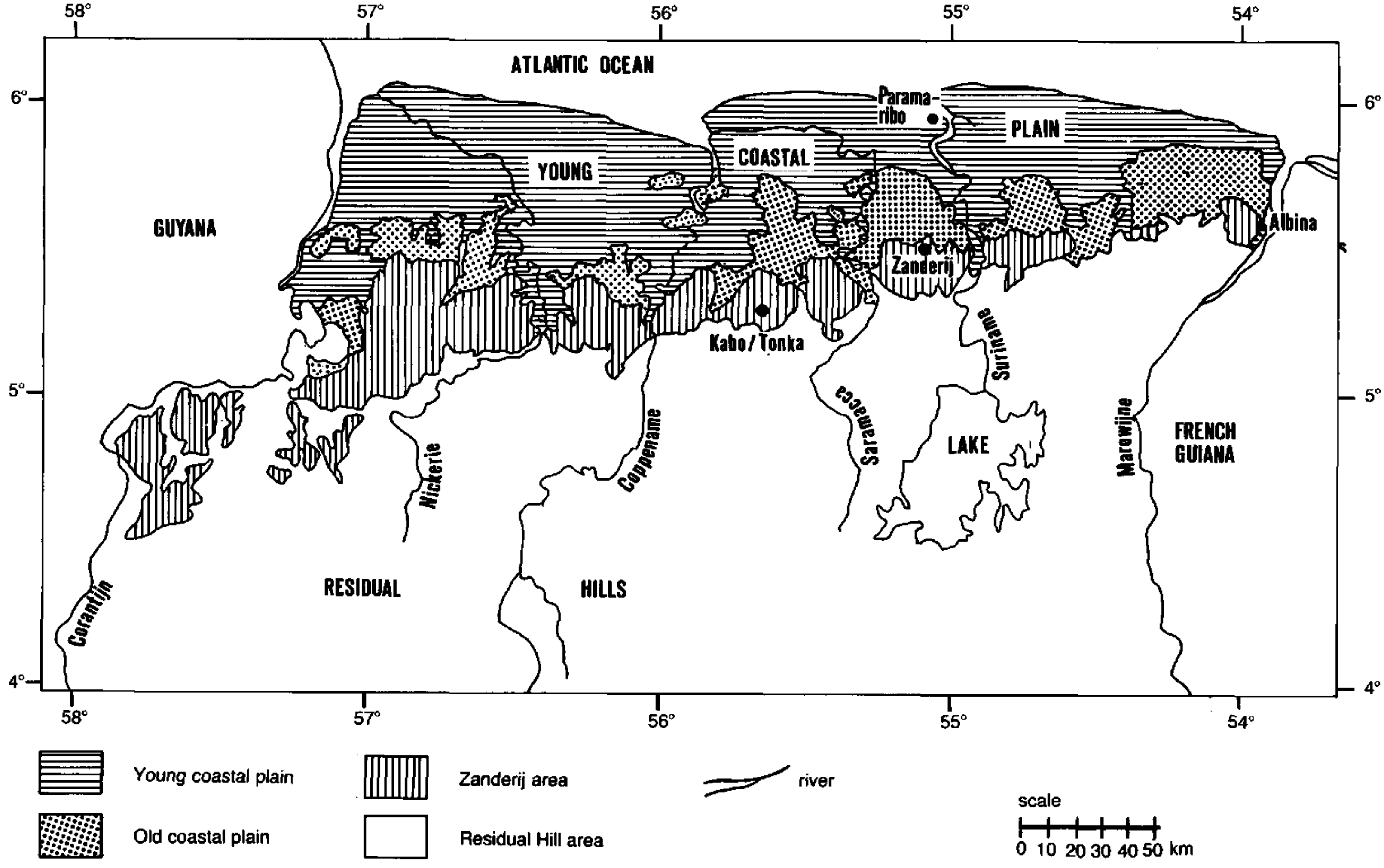


Fig. 2.1 Simplified geological map of northern Suriname based on Geological Map of Suriname, 1:500 000. (GMD, 1977)

the latter being subdivided into Pliocene, Pleistocene and Holocene sediments. While giving a more detailed subdivision especially of the Shield, the Geological Map of Suriname (Bosma et al., 1984) uses roughly the same classification. On the basis of this, four main landscapes have been distinguished; residual hills, Zanderij, Old Coastal Plain and Young Coastal Plain (see Table 2.1).

The Residual Hills, which cover 80 % of the country, consist of rolling to hilly and locally mountainous areas of mainly residual soils. The rocks are mainly of Precambrian origin but dolerite dikes of Permo-Triassic age, bauxite/laterite caps of Oligocene age and recent valley sediments also occur (Bosma et al., 1984). Main rock types are granites, schists and gneisses, which are mostly deeply weathered.

The Zanderij area is level to undulating, with sandy and loamy deposits of coarse brown and white sands, subordinate gravels and kaolinitic clays (Bosma et al., 1984), which rest on weathered basement. The deposits are up to 25 m thick in the north, although Wong (1986) has suggested 20 m, and become shallower towards the south. The project area, Kabo is located in this landscape (Fig. 2.1). IJzerman (1931, in van der Eyk, 1957) considered these sediments to be "continental alluvia". Van der Eyk (1957) concluded from granular compositions, analysed according to the method of Doeglas (1950), that the origin is fluviatile.

Some of these deposits, especially the white sands after which the Zanderij area is named, are covered with savannah vegetation. This forms the most conspicuous feature of the Zanderij area, even though it covers only a small proportion of it. About 40 % of the area has bleached soils (white sands) but only about 7 % is covered with savannah vegetation of grasses and low shrubs (van der Eyk, 1957). The remainder of the white sands are covered with high savannah shrubs or savannah forest. The brown sands and loams in this landscape are covered with high forest.

The Old Coastal Plain, which was formed in the Pleistocene, is a marine terrace, formed in two stages, each stage consisting of a geogenetic phase during a high sea level in an interglacial period and a pedogenetic phase during a low sea level in a glacial period (Veen, 1970). Bosma et al. (1984, pp. 43-44) summarize what is known about the Old Coastal Plain as follows: "It can be subdivided into a northern part with predominantly sand ridges and a southern part consisting of clay flats. The ridges form broad bundles of predominantly E-W orientation with

TABLE 2.1 Main landscapes in Suriname

	Area (km^2)	Elevation (m above or below sea level)	Geological period	Relief
Residual Hills	135 000	50 - 1280	Precambrian	rolling to hilly
Zanderij	8 750	6 - 70	Pliocene	level to undulating
Old Coastal Plain	4 300	2 - 12	Pleistocene	flat to slightly undulating
Young Coastal Plain	16 200	-1 - 4	Holocene	flat

an elevation varying from 4 – 12 m above mean sea level. The dissected clay flats are found at 2-7 m above sea level. They consist mainly of firm grey silty loams and silty clays with commonly red and purple mottles at some depth. They have a kaolinite-illite clay mineral association and evidence of strong weathering. They probably have been deposited during the Riss-Würm interglacial transgression (Eemian) in a marine environment similar to that of the Young Coastal Plain and have subsequently been dissected by numerous gullies in the last (Würm) glacial".

The Young Coastal Plain along the Atlantic Ocean consists mainly of clayey brackish and fresh-water swamps, beside sandy beach ridges, silty clay natural levees and peat swamps (Brinkman and Pons, 1968). During a period of rising sea level (up until 6000 years ago) vertical sedimentation took place under actively growing vegetation and much pyrite and organic matter accumulated in the clays. About 6000 years ago, lateral sedimentation began to occur under a stable sea level and clays with low contents of pyrite and organic matter were deposited. Bosma et al. (1984, pp. 41-42) state: "Deposition of the clays took place – and is taking place – by longshore currents transporting the bulk of the clay supplied by the Amazon river, to the west. Sedimentation is not continuous but takes place in separated mud banks moving along the coast with an average speed of 1.5 km per year. The mud banks are separated by shallow throughs along which coastal erosion and sand ridge formation takes place. This type of sedimentation, causing a rapid lateral accretion of the coast with wide intertidal mudflats, started about 6000 years ago when the sea reached its present level. The surface of the clays is situated from 1 m below to about 2.5 m above, present sea level and the clay deposits are up to 25 m thick near the coast. These sediments are very heavy textured, non-calcareous clays with over 60 % clay sized particles which are characterized by a kaolinite-illite-vermiculite-montmorillonite clay mineral association and by low contents of pyrite and organic matter".

The marine clays are interrupted by sand and shell ridges (individual or in groups) running parallel to the coastline, mainly in the area west of major river deltas. These ridges range from 3 to 7 m in height. Many of the younger ridges are 2.0 to 2.5 m above mean sea level (MSL), the older ridges are slightly higher. Sand and shells were deposited in beach ridges and offshore bars, coarser sand coming mainly from the coast of French Guiana and finer sand from the Pleistocene shelf and from the Amazon (Krook, 1984).

The Holocene and Pleistocene sediments are deposited on top of the Pliocene sediments, which remain exposed in the Zanderij area.

2.2 The Zanderij area

2.2.1 *Literature review*

The Zanderij area is a transitional zone between the well drained inland hills and the poorly drained coastal plain (Fig. 2.1). With some interruptions, mainly along rivers, the Zanderij extends in an east-west direction across Suriname and into the neighbouring countries. In the west it is about 50 km wide, narrowing towards the east to 5 to 10 km. To the south of the main Zanderij landscape there are several small outliers amidst the Residual Hill landscape of the interior (van der Eyk, 1957).

The Zanderij landscape comprises level to undulating plains, extending to vast areas especially in the west. On the whole, the land is well drained with some marshy regions varying in altitude from 6 to 10 m above MSL in the north to about 70 m above MSL in the most southerly part where isolated outliers are found. The plains are dissected by many creek valleys which are shallow in some places and 10 to 15 m deep in others. The flat bottom of such a valley consists of a narrow strip of swamp or marshland on either side of the creek (van der Eyk, 1957).

In white sand areas the sediment consists almost entirely of quartz. At the base of the sediment there is often a gravel bed (van der Eyk, 1957; Wong and van Lissa, 1978). In French Guiana Lucas et al. (1982) found that "The base of the Zanderij sediment on the crystalline basement rock is consistently marked by a thin bed (5 cm) of smooth quartz pebbles. Thicker beds mark the position of larger water courses" (p. 39). Krook and Mulders (1971) found sedimentary structures below 5 m depth, in a white sand pit near Albina. Here the alternating layers of sand and gravel indicated deposition in a braided river. Upper layers do not show sedimentary structures.

The brown coloured sediments also consist of quartz sand but with varying amounts of kaolinitic clay. According to van der Eyk (1957), the grain size distribution indicates fluviatile origin. Generally, thick homogeneous layers are found with textures varying from sand to sandy clay. Alternate layers of sand and clay were probably mixed by biological homogenization to deep profiles with a sandy loam or sandy clay loam texture.

Krook and Mulders (1971) found all the sediments to be of continental origin, except for the deeper layers in the north where some marine influence was found. The heavy mineral content of the sand is very low (generally less than 0.1 %) and only non-weatherable components occur, such as zircon and rutile. Krook and Mulders presumed that the sands were deposited in a less weathered state and that the weathering was post-depositional. The composition of the heavy minerals in the sand varies from east to west with the varying influences of granite and schist. They conclude that the sediments were derived from the hinterland. In the area between Zanderij and Kabo for example, sediment profiles show both granite and schist/arenite influence. Deeper in the profiles more zircon was found and in the upper layers more rutile.

Thus Krook and Mulders (1971) conclude that initially the source area was larger because further south large granitic areas occur supplying zircon. Later the small area directly south of the Zanderij Formation with meta-arenites (Rosebel Formation) became the most important source. This resulted in a supply of more rutile. They think that the uppermost layer is of very local origin and was deposited by short braided rivers flowing northward in a relatively dry period. Further this succession of different kinds of sedimentation may be an indication of a change from subhumid to semi-arid conditions.

Gravel beds at the base of the Zanderij sediment are more pronounced near large rivers. According to Krook and Mulders (1971), this may indicate that these rivers (Marowijne, Suriname and Saramacca) were already present when the Zanderij sediment was deposited. Wong and van Lissa (1978) found gravel beds of 1 m thickness near the Marowijne and between 10 cm and 2 m near the Saramacca. Rounded quartz pebbles of 30 cm and more were found in these beds. Rounded granitic stones have also been found that fell apart upon disturbance. These are deposited as hard rock and weathered afterwards (Dost, 1986). Angular quartz pieces were also found particularly in the lowest parts of these beds.

The occurrence of gravel is restricted to narrow, elongated zones. The coarse gravels along the southern margin of the Zanderij area become finer and thinner and wedge out in a northern and north-western direction. The overlying medium coarse to very coarse sands have angular to subrounded grains (Wong and van Lissa, 1978). The large rounded pebbles indicate a long transport distance in the river bed, while the angular sand on top of the gravel and elsewhere in the Zanderij sediment indicates a short transport distance.

2.2.2 Formation of the Zanderij area

It is possible to conclude from the above information that the genesis of the Zanderij area is as follows. During the early Pliocene, sea level rose to Zanderij (Fig. 2.1). Clays were deposited in a near-shore environment in the northern part of the Zanderij area. The climate was warm and humid and the vegetation of the hinterland, tropical forest. As a result of the regression of the sea together with the change to a semi-arid climate, deposition of the sandy facies of the Zanderij formation began. Braided rivers were formed. These carried vast amounts of coarse and fine material from the Precambrian Shield, which at that time was less protected due to the presence of a savannah vegetation.

Gravel and boulders were deposited in the river beds at the southern edge of the plain in what is now the Zanderij area and finer material was moved further to the north. The gravel and boulders are well rounded and consist predominantly of quartz. As the climate became drier alluvial fan formation started at the boundary of highland and plain producing a landscape of coalescing alluvial fans, gently sloping to the north. More coarse sand and less gravel was transported in the large braided rivers as the discharge diminished. Material was deposited in the alluvial fans, which had been pre-weathered in the foregoing humid period. Much of the finer particles was transported outside the Zanderij area leaving the sediment considerably coarser than the weathered mantle from which they were formed.

In later periods much of the sediment has been eroded and the surface has become undulating in many places because of creek incisions. As a result of erosion and the deposition of the Old and Young Coastal Plain the area with Zanderij deposits at the surface has been reduced to less than 9000 km^2.

2.2.3 Pre- and post-depositional weathering

The most conspicuous feature in the Zanderij area are the white sands covered with savannah vegetation. According to Krook and Mulders (1971), the sands became white and bleached after their deposition. The formation had a regular distribution pattern of sands, loams and clays. During the last glacial period the climate in the Guianas was much drier than it is now, and a vegetation of open grass savannah was widespread (van der Hammen, 1963). Large parts of tropical and sub-tropical South America had a humid climate during the interglacial periods and a more arid climate during the glacial periods. Krook and Mulders (1971) suggest that during these relatively dry periods, clay illuviation occurred resulting in a low clay content in the topsoil in which podzolization started. The forest recolonized the savannah areas after the dry ("glacial") period. On the white podzolized sands the forest could not reach the luxuriant state that occurs on the other soils and lower and poorer vegetations developed.

How far were the Zanderij sediments weathered before being deposited by a braided river system? If conditions had been semi-arid for a long period before deposition, then the eroded material from the hinterland may have been mineralogically immature and therefore little affected by chemical weathering. The sediment was, however, not rich. In post-depositional weathering of a rich sediment a large variation in the content of unstable minerals might be expected between the samples. This is because the intensity of weathering may be assumed to vary greatly from place to place and at different depths (places with more or less vertical water movement; topsoil versus deep subsoil). Yet as all samples are practically devoid of unstable minerals, pre-depositional weathering must have already been strong.

Krook and Mulders (1971) postulate that the Zanderij sands were deposited in a less weathered state and that weathering was post-depositional. Krook (1984) however, thinks that the eroded material deposited as the Zanderij sediment was already rather mature and weathered. He assumes that a humid phase of weathering in which unstable minerals disappeared, preceded the erosion in the hinterland which started as a result of the climate becoming drier and the vegetation becoming sparser. This also explains the difference in fluviatile transport. In the earlier, moister period transport was done by large rivers draining an extensive area of mixed mineralogy. Later it was done by short braided rivers or

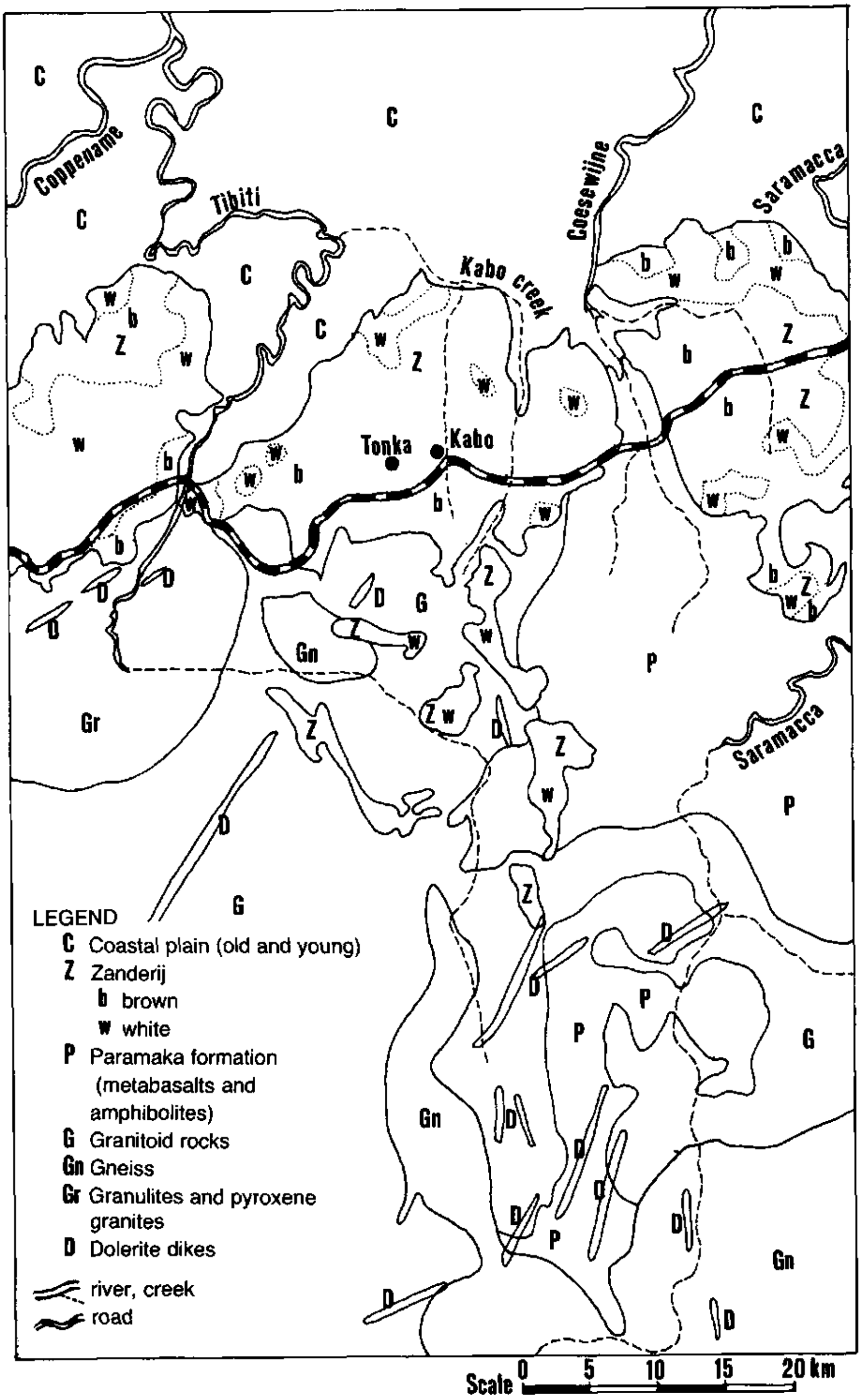


Fig. 2.2 Geology of the area around Kabo, adapted from the Geological Map of Suriname (GMD, 1977)

by ephemeral streams which formed alluvial fan-like deposits of very local origin.

Strongly weathered as the sediment may have been, the formation of the white bleached sands must have taken place after deposition. This can be deduced from the fact that the transition between bleached and brown sands is often sharp (Cohen and van der Eijk, 1953) and also from the occurrence of humic hardpans at depths of 1-5 m in the white sands (Bosma et al., 1984).

2.2.4 Area around Kabo

The geology of the area around Kabo is given in Fig. 2.2. Near Kabo and Tonka the Zanderij belt is 10 to 20 km wide and the layer of Zanderij sediment on Precambrian material is rather thin, about 3 m on average. There are several small outcrops of Precambrian material which are not shown in Fig. 2.2. In larger creek valleys no Zanderij sediment occurs. There is no data on the mineralogical composition of the Precambrian substratum in the study area. In the field it was observed that the substratum generally consists of kaolinitic clay, sometimes sandy clay, reddish in colour or mottled red and white. The substratum is often gravelly with lateritic and quartzitic gravel and there are also scattered occurrences of cemented laterite sheets.

Mainly granitoid rocks and gneisses occur to the south of the study area, while slightly to the east there are vast occurrences of metamorphic rocks, such as metabasalts and amphibolites (see Fig. 2.2). To the south-west an area of granulites of the Bakhuis structural zone occurs which could affect the substratum in the study area. It is expected, however, that the geological substratum in the study area consists mainly of granitic material. More information about the substratum is given in Sections 2.4.3, 2.4.5 and 3.2.5.

2.3 Climate

The climate of the project area and of the northern part of Suriname in general is wet tropical, Af following the classification of Köppen (1936). The average annual rainfall is approximately 2200 mm and the average annual temperature is 27° C with average maximum and minimum temperature of 32.5 and 22.5° C respectively. The relative humidity is very high, 70 to 90 %.

Four seasons can be distinguished: a long rainy season from April to mid-August; a long dry season from mid-August to the end of November; a short rainy season in December and January and a short dry season in February and March. The long rainy and dry seasons are generally pronounced and predictable, while the short rainy and dry seasons are unreliable both in time and amount of rainfall. Extremely dry seasons do not occur. The average rainfall in the driest month, generally September, October or November, is often about 60 mm.

From analysis of climatic data for the period 1908 and 1958, Schulz (1960) found a large range in annual rainfall from 880 to 2765 mm. For the entire period of 50 years only 3 months had no rain at all.

2.3.1 Data collection at Kabo and Tonka

Climatic data were collected in the study area at Kabo and Tonka and additional data from Zanderij airport (see Fig. 2.1). At Kabo a simple meterological station was constructed in a cleared area, about 50 m from the forest boundary. In the period February 1980 to April 1984 data were collected on rainfall, temperature, air humidity, evaporation of a Class A Pan, cloudiness and duration of sunshine. Wind speed was measured for only a very limited period.

At Tonka rainfall was measured in the period November 1980 to July 1984. Rain meters were placed in a clearing (80 x 100 m) on the water divide of the catchment area under study. Two rain-gauges were placed in the centre of this clearing. One gauge, with an opening of 200 cm^2, was placed 1.5 m above the soil surface and read once a day for the daily total. The other was a self-recording rain meter with a large opening of 2472 cm^2 situated just above ground level, in which the water level was read automatically every 30 minutes. This large instrument is known as the RECOVER gauge (for details see Chapter 3).

The climatic data from Kabo and Tonka are not complete with respect to sunshine hours, humidity and wind speed. The Zanderij station has a complete set of data for the period November 1979 to December 1982. Only rainfall and pan evaporation data from Kabo and Tonka have been used to calculate the water balance after the relationship between pan evaporation and potential evapotranspiration (PET, according to Penman) was established.

2.3.2 Data from Zanderij meteorological station

The meteorological station at Zanderij airport (Fig. 2.1), 60 km east north-east of Kabo, is the largest in the area and data from this station are the most reliable. As this station is in the Zanderij area, environmental conditions (physiography, elevation and distance to the sea) are similar to those of the stations at Kabo and Tonka. However the vegetation cover near Zanderij is lighter than that near Kabo because of the presence of some large areas of savannah.

In Fig. 2.3, daily amounts of extra-terrestrial radiation are given. Average monthly meteorologic data for the Zanderij station for the period November 1979 – December 1982 are given in Figs. 2.4-2.9 and monthly data for Zanderij and Kabo-Tonka stations in Appendix I. The monthly values for Zanderij were calculated from data received from Goense (1985). These data are required for the calculation of the potential evapotranspiration and the growth of the forest (Chapter 3). There is some variation between the years with temperature but more

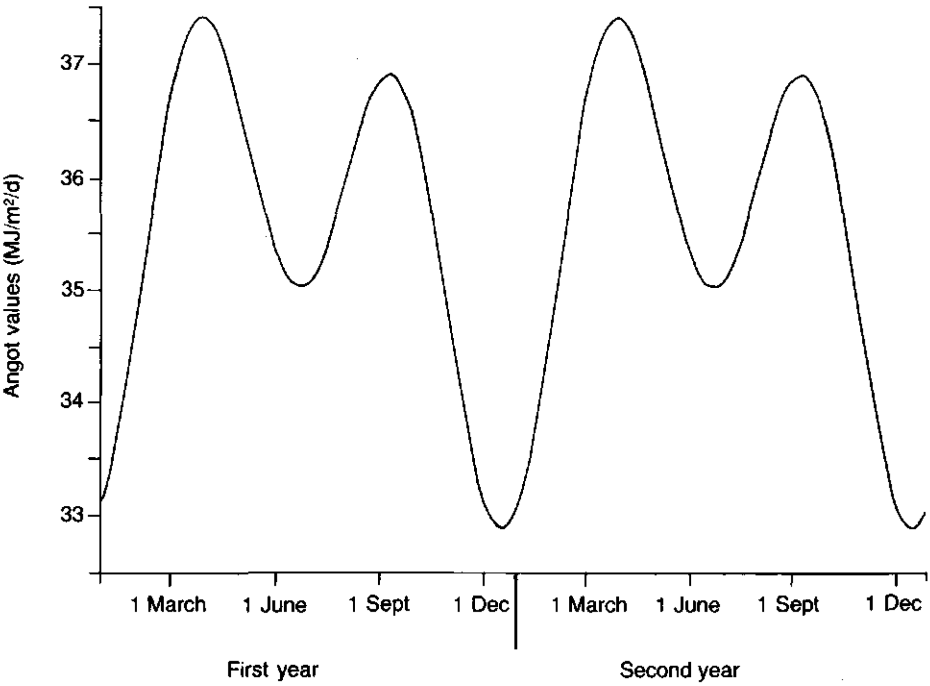


Fig. 2.3 Angot values for extra-terrestrial radiation for a location 5°22′ N, near Kabo, Suriname

particularly with relative humidity, rainfall, wind speed, sunshine and evapotranspiration.

Extra terrestrial radiation

Goense (1987) determined solar radiation values for a location 5°22′ N, just north of the experimental area Kabo (5°15′ N). These Angot values are important for the calculation of the potential evapotranspiration (for values during two successive years, see Fig. 2.3). Goense used a solar constant of 1353 J/m^2/s and a varying distance between earth and sun for the calculation of the Angot values.

The effects of the location between the tropics (two maxima per year, on 30 March and 10 September), the location north of the equator (in June higher than in December) and the varying distance to the sun (in March higher than in September) are all visible in Fig. 2.3. The maximum variation within the year is only 12 %, from 32.9×10^6 on 18 December to 37.4×10^6 Joules per m^2 per day on 30 March.

Temperature

Highest maximum temperatures (Fig. 2.4) are measured in September and lowest in or around February. Minimum temperatures vary only slightly throughout the year. The lowest minimum temperatures occur in January-February. They increase during the main rainy season to above 23° C, and oscillate at a slightly

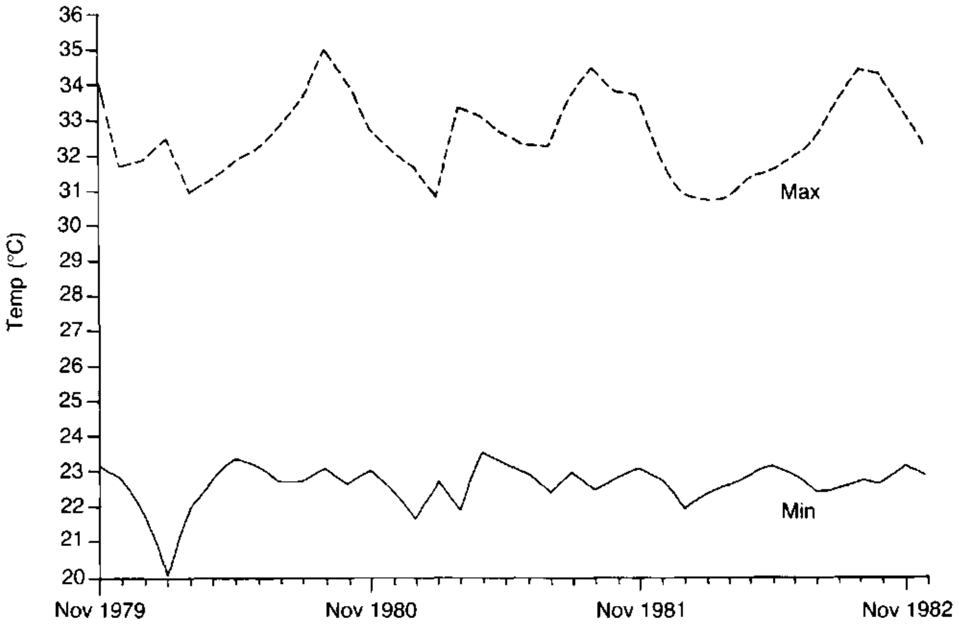


Fig. 2.4 Mean monthly maximum (Max) and minimum temperatures (Min) at Zanderij

lower level throughout the remainder of the year. Minimum temperatures are important for plant respiration, high minimum temperatures resulting in lower net assimilation. With respect to radiation and temperature, the growing season lasts all year.

Humidity

Average relative air humidities for Zanderij at 8.00 and 14.00 hours are given in Fig. 2.5. Humidities were measured at 08.00, 14.00 and 18.00 hours (Appendix I). Maximum humidities occur generally late at night and early in the morning. Humidity at 08.00 hours is an approximation of this humidity but slightly below the maximum occurring at about 06.00 hours. Minimum humidities occur generally in the early afternoon, the humidity of 14.00 hours is an approximation of this minimum. As the times of maximum and minimum vary each day, the average humidity at 08.00 hours and at 14.00 hours are under and over estimations respectively of the maximum and minimum relative air humidity.

Daily minima of relative air humidity were extracted from continuous records for the Kabo station. As expected, the Kabo values are about 10 % less than those of Zanderij for 14.00 hours. Average minimum daily relative air humidities vary from about 60 % in the main rainy season to near 40 % in very dry months. Lowest humidities are measured in September or October and highest in April or May. In the minor dry (February-March) and minor wet (December-January) seasons, humidities are unpredictable.

In extremely dry periods (October-November 1983), average monthly minima

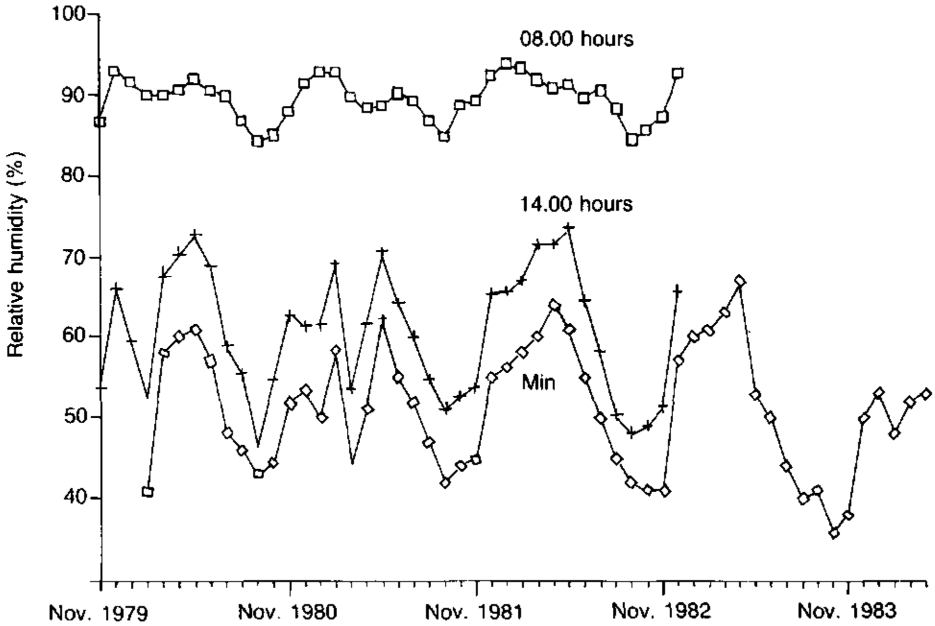


Fig. 2.5 Average monthly relative air humidity at 08.00 and 14.00 hours at Zanderij compared with average monthly minimum relative humidity at Kabo (Min)

fall below 40 % and extreme daily minima between 25 and 30 % have been measured. At average relative humidities of 70 – 90 %, periods of such dryness were not expected. However, the forest vegetation is adapted to these temporary droughts, having small, thick, sclerophytic leaves in the canopy and larger thin leaves in the undergrowth.

Rain

Monthly rainfall for Zanderij and Kabo is given in Fig. 2.6. Both stations have comparable rainfall regimes and amounts, although there was a slight variation in the timing of the rainy season in 1981. As rain falls mostly in convective showers daily amounts of both stations vary much more than suggested by the monthly total. There is considerable variation between years, 1983 and 1984 being much drier than preceding years.

Wind

Wind speeds (Fig. 2.7) increase during the day and decrease at night, and day winds have a different pattern from night winds. In the dry seasons, night winds (08.00 hours) are stronger than throughout the remainder of the year. Day winds (14.00 hours) generally peak at the beginning of the main rainy season in March, decrease during the rainy season and are irregular between August and November. With speeds at night of about 1 m/s and in daytime of 2-3 m/s, the wind regime is relatively calm. However strong winds of short duration, together with

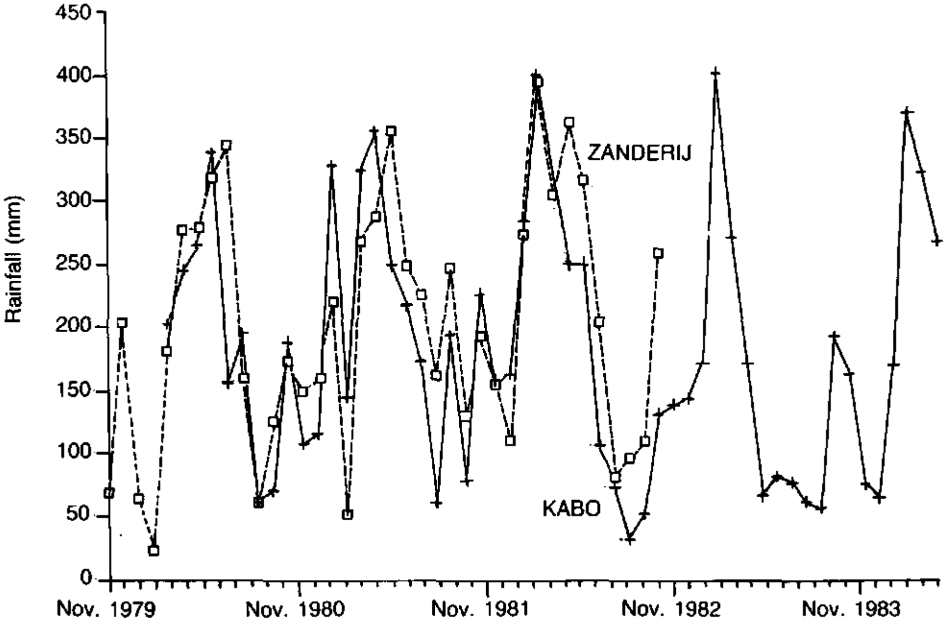


Fig. 2.6 Monthly rainfall for Zanderij and Kabo

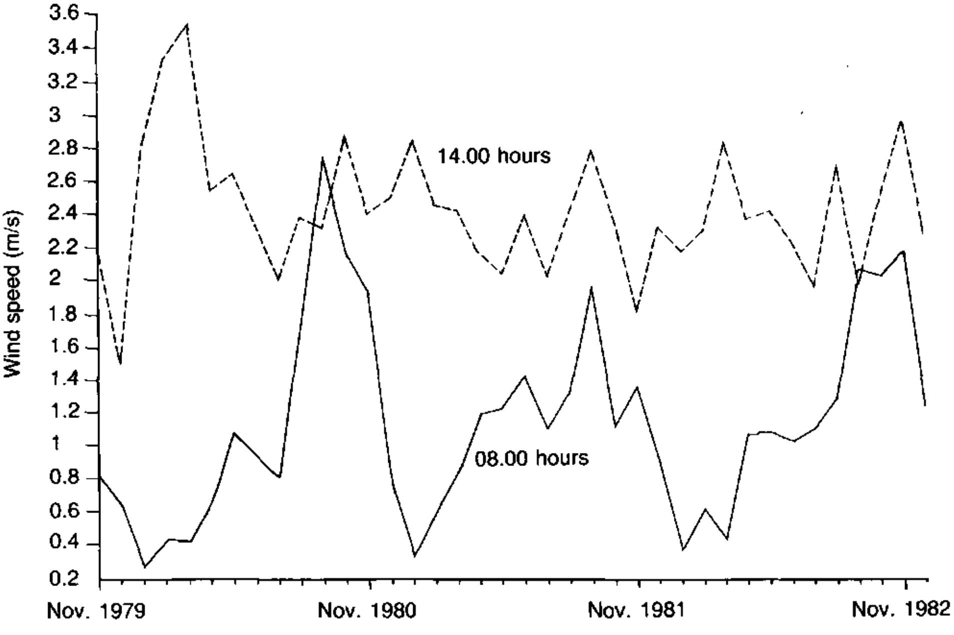


Fig. 2.7 Average monthly wind speed at Zanderij at 08.00 hours and at 14.00 hours

rain storms, occur from time to time overthrowing large trees in the forest.

Sunshine

The average monthly fractions of sunshine for Zanderij and Kabo are given in Fig. 2.8. These fractions are expressed as the ratio of actual and maximum number of sunshine hours. The actual number of sunshine hours was read from Campbell strokes, in which the sun burns a mark when it shines. As the sun is too weak to mark the stroke directly after sunrise and directly before sunset, the maximum number of measured sunshine hours is approximately 10 instead of 12. Therefore the Suriname practice of giving the ratio marked period:10 has been followed. This is justifiable as there is no reason to assume that the average cloudiness of the first and the last hour of the day differs from the remainder of the day.

No data are available for Kabo for the period January 1981 to February 1982, and data for Zanderij do not extend beyond December 1982. As there is close agreement between the two sets, Zanderij data have been used for the Kabo station for the missing period. Daily hours of sunshine vary greatly with the season, the lowest (30-40%) being measured at the beginning of the main rainy season which is mostly in April, and the highest (80-90%) at the peak of the main dry season which is mostly in September.

Evapotranspiration

The potential evapotranspiration (PET), calculated by Goense (1987) using the corrected Penman method (Doorenbos and Pruitt, 1977) follows the sunshine

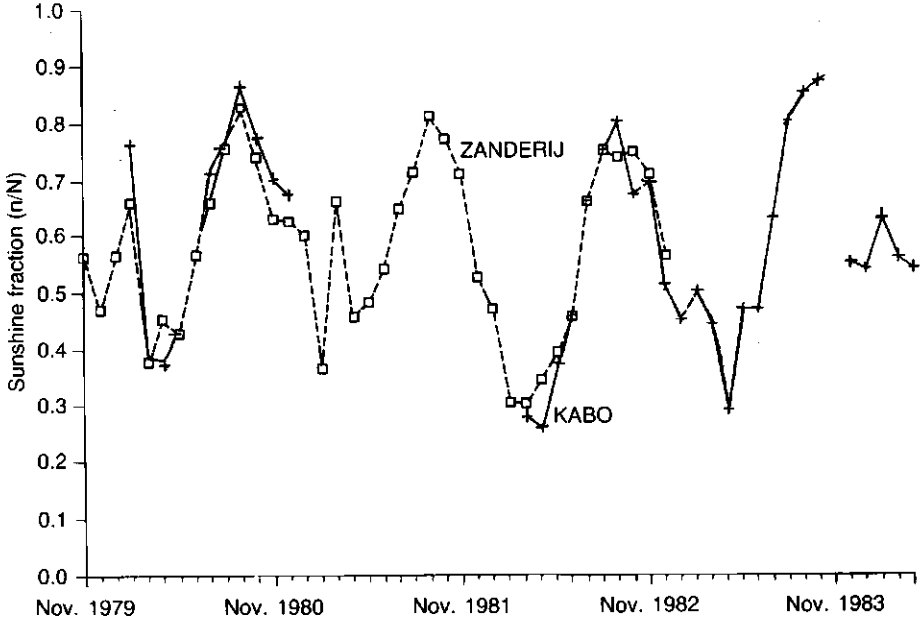


Fig. 2.8 Sunshine fraction at Zanderij and Kabo (ratio of measured (n) to maximum (N) sunshine hours)

duration closely (Fig. 2.9). Temperature, air humidity, sunshine and wind speed data for Zanderij were used in the calculation and because of the close agreement between the meteorological data for Zanderij and Kabo and the small distance between both stations, these evapotranspiration values are considered to be applicable also for Kabo/Tonka.

The Class A Pan evaporation at Kabo is also given in Fig. 2.9. Pan evaporation data for the Zanderij station are given in Appendix I, (EPan Zand). Because of the large number of missing values, values for Zanderij are not considered to be reliable, and there is little agreement between the Kabo and Zanderij data.

PET is supposed to be lower than E0, the open water evaporation (Penman frequently used the relationship: PET = 0.8 E0). Class A Pan evaporation is supposed to be higher than E0. Because of extra insolation at the pan, being placed above the soil surface, a higher evaporation of the pan would be expected compared with a large body of open water. Doorenbos and Pruitt (1977) calculate PET (of short grass) and they give as ratio between open water evaporation E0 and PET:

$$E0 = 1.1\ PET \qquad (2.1)$$

The relationship between PET and Epan is expressed as:

$$PET = kp * Epan \qquad (2.2)$$

Values for kp (Pan Coefficient) vary greatly, but according to Doorenbos and Pruitt (1977), for green areas in not too windy, moist climates, these values are about 0.8. Combining both equations gives E0 = 0.9 Epan, hence the order Epan > E0 > PET is to be expected. In our situation however (Fig. 2.9) Epan is smaller than PET. In periods of high evaporation, the difference is small but in the wet months the difference may increase to more than 0.5 mm/d.

These low Class A Pan evaporation data are difficult to explain. Already Kamerling (1974) found that on the Suriname coastal plain, EPan for all seasons was lower than E0 when calculated according to Penman. Possibly, evaporation is lowered by the rim of the pan, which is about 7.5 cm above the water level. This effect could be greater in a moist climate with low wind speeds than in the dry climates, which provide a large part of the data in Doorenbos and Pruitt (1977). As they use PET instead of calculating E0, comparisons with other studies are difficult to make.

The relationship between the monthly values of EPan and PET (from Fig. 2.9) is given in Fig. 2.10. This relationship, which is only valid for the range given, is approximately:

$$PET = 0.816\ EPan + 1.28 \qquad (mm/d) \qquad (R^2 = 0.91) \qquad (2.3)$$

The equation shows that the difference between Epan and PET diminishes for

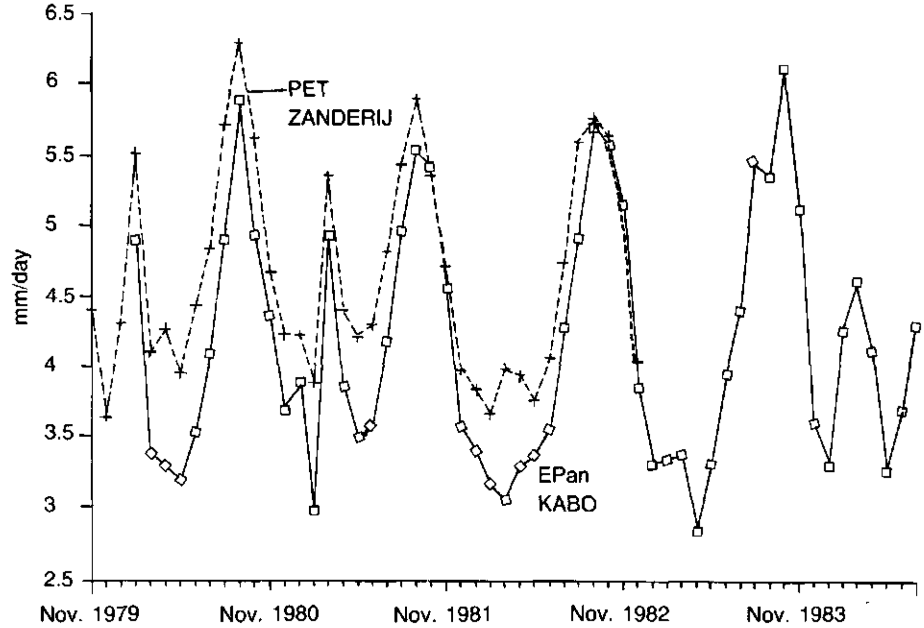


Fig. 2.9 Potential evapotranspiration (PET) for Zanderij, calculated according to Penman by Goense (1987), and evaporation of a Class A Pan, measured at Kabo

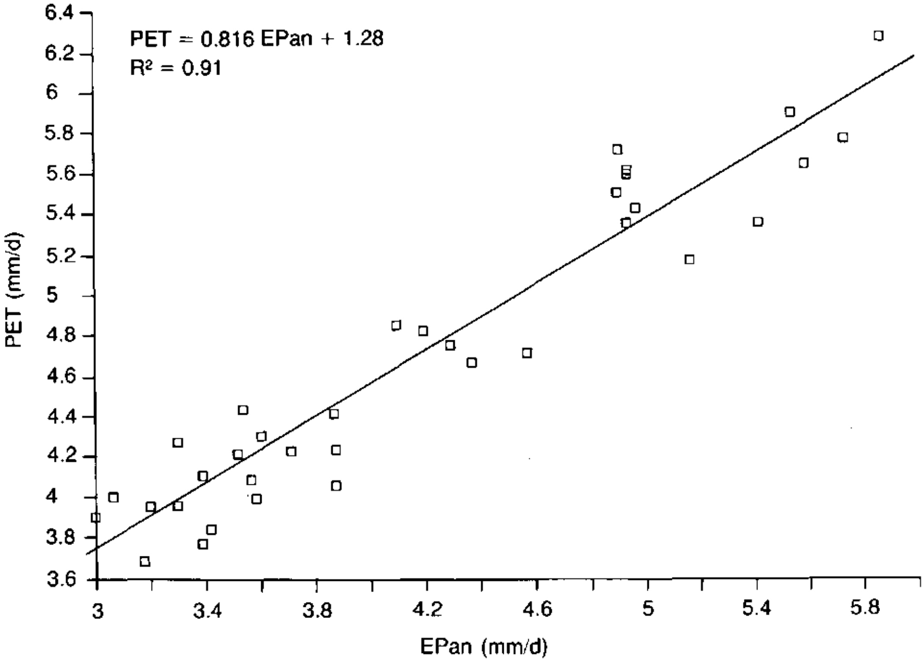


Fig. 2.10 Relationship between calculated evapotranspiration (PET) at Zanderij and measured pan evaporation (EPan) at Kabo

higher values, as is also demonstrated by Fig. 2.9. In Chapter 3, the evapotranspiration of the forest is related to the PET, calculated with this equation from measured Epan values.

2.4 Soils

2.4.1 Parent material and soil distribution

Parent material

As stated in Section 2.2, the Zanderij sediment is of Pliocene age. Deposited at the start of a rather dry period by short braided rivers, the sediment forms a thick layer downstream to the north, thinning out upstream to the south. The sediments were strongly weathered before deposition, and therefore contained few weatherable minerals. The white sand areas were formed after deposition, as a result of extreme leaching and podzolization. The Zanderij sediment consists mainly of quartz sand and kaolinitic clay of low iron content, and covers weathered basement rock mainly of kaolinitic clay and laterite, but generally of a higher clay content than the sediment itself. As the project area is located in the southern part of the Zanderij landscape (Figs. 2.1 and 2.2), the sediment is relatively thin on Precambrian material of the Guiana Shield.

According to van der Eyk (1957), the granular composition of the original sediment was changed drastically by eluviation and illuviation of clay and by homogenization by living organisms. Silt contents are always below 5 % indicating pre-depositional weathering. Clay contents in the sediment vary from less than 1 to 50 % and the bulk of the sand fraction is between 300 and 500 µm. In the project area, the texture of the subsoil is generally sandy clay loam. Locally more sandy material occurs, possibly deposited near apexes of alluvial fans.

The origin of the low iron content and the corresponding yellow colour of the Zanderij sediment is unknown. The hinterland of residual hills has generally reddish soils of higher iron contents. Possibly reducing conditions existed during and after sedimentation, before erosion carved drainage patterns in the alluvial fan-like sediment.

Soils in the Zanderij area

The soils in the Zanderij area may be grouped as follows (Krook and Mulders, 1971)

- brown loams, approximately 30 %
- brown sands, approximately 30 %
- white sands, approximately 40 %.

The brown soils are generally well or moderately well drained. Establishment of the drainage class of the white sands is complicated by their very low moisture holding capacity. This often results in extremes of dryness or wetness in the same profile during dry or wet seasons. There are many theories about the formation of these sands. Van der Eyk (1957) has postulated that the white sands (bleached soils) were formed by very strong podzolization from brown soils. These white sands have thick bleached E horizons, often deeper than 2 m and with a clay content below 2 %. He sometimes found the underlying B-horizon at between 2 and 3 m as a dark brown to black hardpan, 15-30 cm thick, where organic matter had cemented the sand. In some places he found two or even three such ortstein pans on top of each other, separated by layers of white sand. In all profiles studied the lowest pan was directly overlying the weathered crystalline rock of the basal complex, sometimes separated from it by a layer of rounded gravel. Krook and Mulders (1971) give the composition of the hardpan as: 1 to 2 % carbon, about 0.7 % alumina, and in places, a small proportion of iron.

In the well drained bleached soils the litter decomposes slowly. Van der Eyk (1957) refers to thick organic layers under savannah wood vegetation; a 5 to 10 cm thick layer of dark red matted or fibrous "mor" under mixed savannah forest and a 40 to 60 cm thick layer of loose litter, merging downwards into a more or less greasy "mor" under pure dakama (*Dimorphandra conjugata*) forest. These thick litter layers do not occur in the poorly drained bleached soils probably because of restricted plant growth.

The non-bleached soils are predominantly brown to yellow or reddish yellow in colour, the A-horizons containing 3 to 25 % of clay.

2.4.2 *Geomorphology and soils in the area around Kabo*

Melitz (1976) prepared a land suitability map (scale 1:100 000) of a large area which included the study area. This map is based on reports of the Soil Survey Department (Legger et al., 1968; Melitz, 1970; and Mulders and Melitz, 1971). Melitz (1976) shows that most of the study area consists of level to slightly undulating plateaus of well drained loamy soils, which he considers to be the best soils of the Zanderij area. Under forest these soils are permeable and provide a good supply of water and air to plant roots. After clearing, surface sealing and compaction is a problem, and fertility is extremely low (Boxman, in press).

Taus (1979) made a semi-detailed soil survey of an area of 3000 ha (scale 1:40 000), including the study area. He presented a geomorphological map from which Fig. 2.11 has been derived, and also a soil map. Fig. 2.11 shows that the area consists of level plateaus of Zanderij sediment sloping to alluvial plains with Holocene sediments. The map shows several small areas of weathered Precambrian material at the surface indicating the thinness of Zanderij material in the southern part of the area. The small outcrops of residual material occur generally parallel to creeks, on slopes where the Zanderij sediment has been eroded. The agricultural experiment area Kabo, the forest camp Tonka and the dam over the Ingipipa creek where the discharge for the hydrological experiment

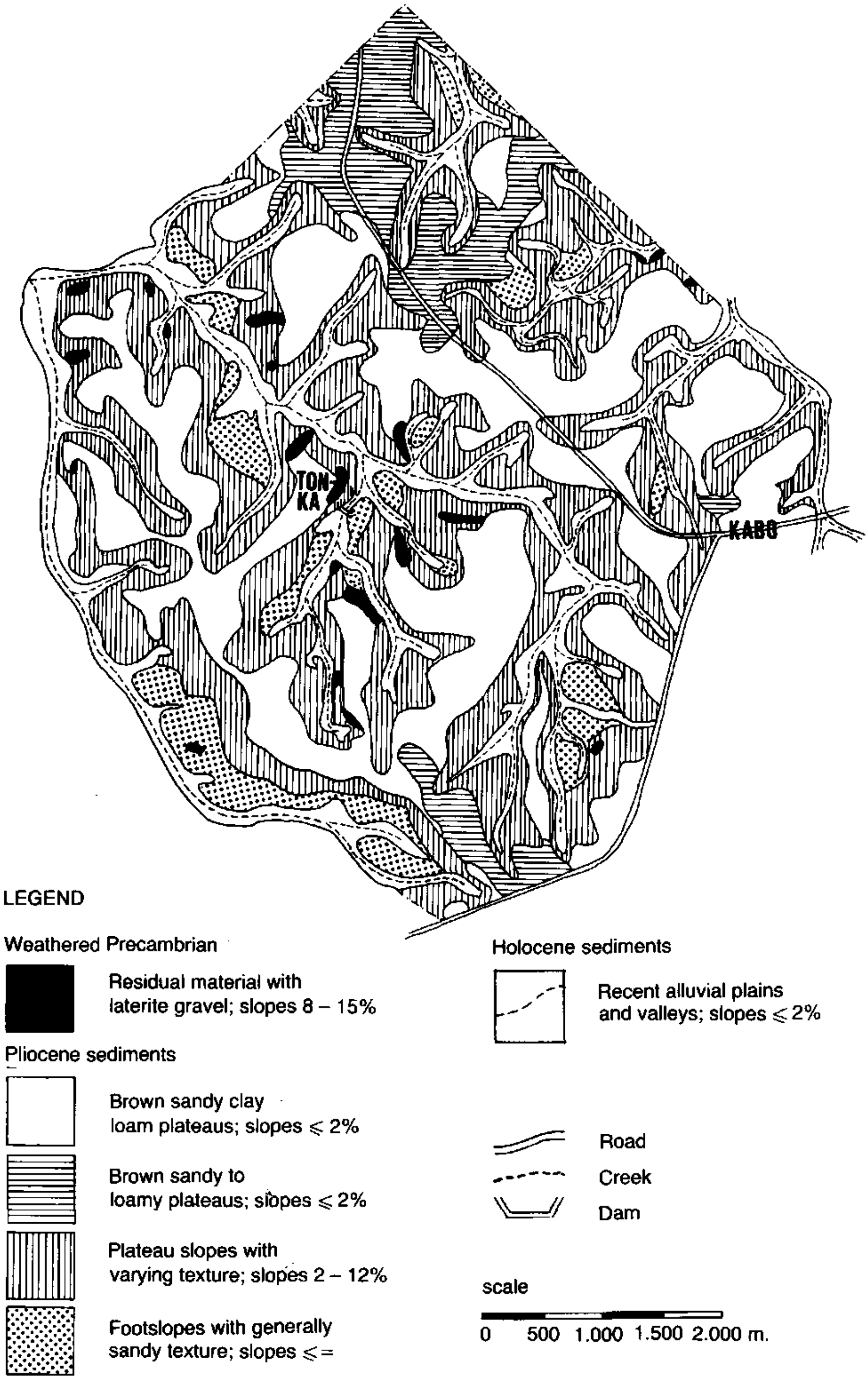


Fig. 2.11 Geomorphological map of the Kabo-Tonka area (adapted from Taus, 1979)

was measured are also indicated on the map. Plateaus generally have a sandy clay loam texture in the subsoil, while footslopes are mostly sandy. Plateaus occur which have been built up of a more sandy textured sediment. These can be found in the northern part of the map and also in the south, where such a sandy plateau just reaches the catchment area of the hydrological experiment (map unit P 1.2). This area may have been near an apex of an alluvial fan during the deposition of the Zanderij area.

The soil map made by Taus (1979) does not show units with bleached soils. The occurrence of the grey horizon (chroma ≤ 3, value > 3, moist colours) is the most important criterion for drainage classification. The map gives too favourable an impression of the area because the estimates of clay contents are high and podzolization in the topsoil with corresponding sandy textures was not considered.

A detailed soil survey (scale 1:5000) was carried out of a small area of 100 ha of brown loamy Zanderij soils at Kabo (Fig. 2.11) 3 km east of the study area (Bruin and Tjoe Awie, 1980). This had been partly cleared for agricultural experiments. White sands do not occur within the area and the soils are not bleached and generally loamy but there are some transitions to bleached soils. A grey horizon in the topsoil is described having a colour value of 4 or more and a colour chroma of 3 or less. This grey horizon, which is generally thin on the plateau, becomes thicker on the slope and is well expressed and thick on footslopes. Although not giving an explanation of the genesis of this grey layer, Bruin and Tjoe Awie (1980) consider that water plays an important role in its formation. Samples of this grey material show a high percentage of natural clay (soil particles smaller than 2 μm after shaking with water, in contrast with total clay, being the soil particles smaller than 2 μm after treatment with peptizing agents which break the micro-aggregates open). Such an occurrence of natural clay indicates a low structural stability which may be attributed to the low content of iron oxides. They conclude that "these phenomena do not deny the presumption that water plays an important role in the genesis of these soils" (p. 13). De Boer (1980) suggested that the grey soils may be related to periodic reduction in the presence of organic matter associated with a lateral flow of water.

Considering the drainage pattern on the geomorphological map (Fig. 2.11), it seems that structural control occurs, influencing the direction of the creeks. This influence is probably exerted by the Precambrian substratum, as it is not to be expected of the unconsolidated Zanderij sediment (see also Section 2.4.5).

2.4.3 Preparation of the soil map

Soil data from various sources were collected and analysed to produce a soil map of the study area. From a detailed soil survey of the catchment and surrounding area Catalan Febrero (1984) prepared a soil map (scale 1:5000). Other data collected during the study included 23 profile descriptions with physical and chemical data of the study area and immediate surroundings, descriptions of 18 borings to a depth of 750 cm, chemical properties of soils in treated and untreated parts of the catchment area and in fertilizer experiment 82/2, and studies by Taus (1979), Carilho (1983), Vierhout (1983), de Fretes (1984) and van Leeuwen (1985).

The soil map (Fig. 2.12) is based on field-work carried out by Catalan Febrero (1984). This included 522 profile descriptions of augerings 120 cm deep and seven descriptions of profile pits. The sites and profiles were classified according to geology, physiography, drainage, texture and soil colour respectively.

Three geological groups are distinguished: Pliocene sediments; Precambrian material; and Holocene sediments. The poorly and very poorly drained valley bottoms containing flowing creeks have been classified as Holocene sediments, according to the practice of the Suriname Soil Survey Department. Profiles were grouped into this category on the basis of drainage class only. The other profiles were grouped into soils of Pliocene and of Precambrian material according to parent material.

In the study area the Pliocene sediments have a medium coarse sand fraction and a low to medium clay content which does not exceed 30 %. The soil colour is also typical. The subsoil of the well drained soils on Pliocene sediments (Zanderij soils) is yellowish brown (10-7.5 YR 6/6-7/8); paler and darker colours also occur, particularly under restricted drainage. The Precambrian substratum consists generally of clayey material often of reddish or red and white mottled colours. Gravels and stones occur in this substratum, sometimes quartzitic but mostly lateritic, occurring as either gravel layers or as as cemented sheets. Therefore Precambrian was easily distinguished from Pliocene material. Clayey textures (finer than sandy clay loam), reddish coloured soil material (redder than 7.5 YR) and gravel/stones were classified as being derived from Precambrian. The remainder were considered to have been derived from Pliocene parent material.

If the Precambrian material starts within a depth of 60 cm, the soil is considered to belong to the Precambrian group. If the Pliocene material is thicker and Precambrian material is not reached within 60 cm, the soil is considered to belong to the Pliocene group. For profiles with the Precambrian starting between 60 and 120 cm, shallow phases of the Pliocene map units are distinguished on the basis of parent material. The Precambrian group is subdivided by stoniness. Ironstone outcrops and very shallow massive laterite are grouped into one map unit. The less stony soils are grouped according to drainage class. No subdivision on physiography, texture and colour was made because of limited extent of the soils in Precambrian parent material.

The soils on Pliocene parent material are classified according to physiography, drainage class, soil texture, and where possible and necessary, according to soil colour. Two physiographic units are distinguished, one comprising the plateaus and upper slopes and the other the footslopes. Physiography and drainage classes are closely related, plateaus and upper slopes having generally well and moderately well drained soils, and footslopes imperfectly drained soils. The typical well drained Zanderij soil has a sandy loam topsoil and a sandy clay loam subsoil of a yellowish brown colour. Since the iron contents in Zanderij soils are low, the drainage class is sometimes difficult to determine.

In this study the following drainage class criteria have been used. The well drained class has subsoil chromas of more than 4, hues of 7.5 or 10 YR and no or few faint mottles within 100 cm depth. Moderately well drained soils have a subsoil with chroma 4, or with hue 2.5 Y, or clear mottles between 50 and 100 cm, or a grey (chroma < 4) topsoil of at least 60 cm thickness. Imperfectly drained soils have chromas that do not reach 4 within 120 cm depth. They are grey, black or white. The water table in poorly and very poorly drained soils reaches the surface in wet periods. These soils have also low chromas throughout, and additional wetness characteristics, such as a thin peaty surface layer, and a vegetation of swamp species, including Pina palm (*Euterpe oleracea*), Watra Bebe (*Pterocarpus officinalis*) or Laagland Matakki (*Symphonia globulifera*).

Grey soils have chromas below 4 throughout, a criterion common to all imperfectly drained footslope soils. The soils with a thick dark grey to black layer have a dark horizon, at least 30 cm thick below 20 cm depth, which has some characteristics of a podzol B horizon. The colour criteria adopted for this dark layer are: value and chroma of 4/1 or 3/2 or darker.

Light grey soil material occurs almost exclusively in sands, and is considered to be the result of extreme leaching. The colour criteria are: values 7 or 8 and chromas 1 or 2. Soils with light grey horizons have been subdivided into those consisting purely of this bleached, light grey material below a shallow A1 horizon and those with only bleached material in the deeper subsoil.

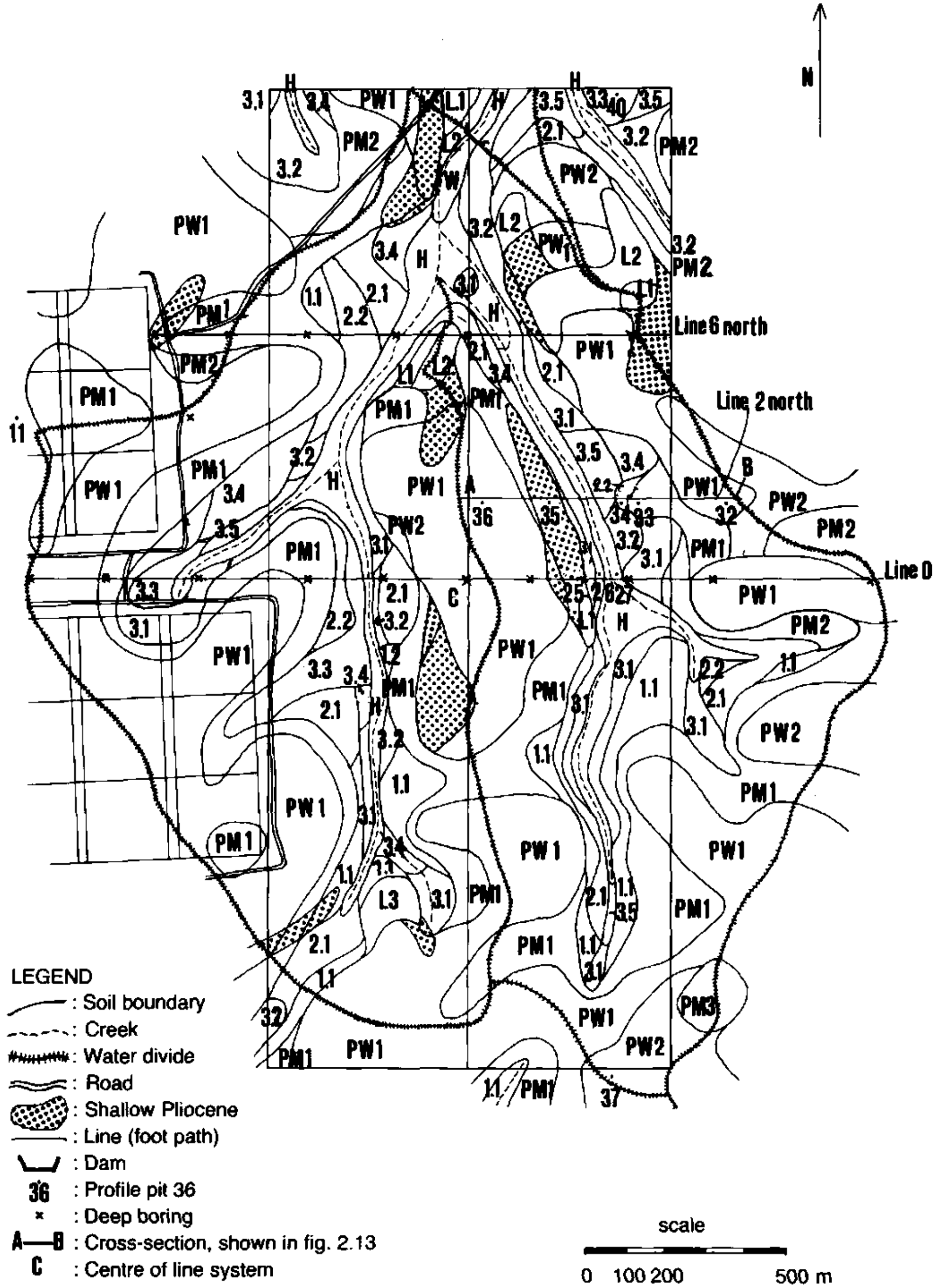
2.4.4 The soil map

The soil map showing 19 map units (scale 1:12 500) presented in Fig. 2.12 is based on the map (scale 1:5 000) of 66 map units which was prepared by Catalan Febrero (1984). There is a close relationship between soils and topography (see topographic map Fig. 3.4).

In the study area, most soils have developed in Zanderij sediments of Pliocene age. The Precambrian material below these sediments consists of kaolinitic clays and laterite layers (massive and gravels), with sandy clays and quartzitic stones in some places. In the small areas where Precambrian material is at or near the surface, soils have developed which are different from those on Pliocene sediments. The valley bottoms consist mainly of reworked Zanderij material with hydromorphic soils.

In the Pliocene (Zanderij) sediments chemically very poor soils have developed. The yellowish brown Oxisols cover the largest area. The remnants of the Guyana Shield, with residual material of Precambrian age, carry Oxisols and Ultisols which are generally more clayey, redder in colour, and slightly richer. Soils in the swampy valley bottoms, which may be of Holocene age, are generally sandy and grey and often covered with a thin peaty top layer.

The most common soil in the study area occurs on plateaus and upper slopes



For legend of map units, see below

Fig. 2.12 Soil map of the project area

LEGEND OF THE SOIL MAP OF THE EXPERIMENT AREA

SOILS DEVELOPED ON PLIOCENE SEDIMENTS		CLASSIFICATION (Soil Taxonomy)
Soils of the plateaus and upper slopes (generally convex slopes)		
Well drained brown or yellow[1] loamy soils		
PW 1	: sandy loam to sandy clay loam topsoil and sandy clay loam subsoil	Ultic Haplorthox
PW 2	: sand to loamy sand topsoil and sandy loam subsoil	Quartzipsammentic Ultic Haplorthox
Moderately well drained brown or yellow loamy soils		
PM 1	: loamy sand to sandy loam topsoil and sandy clay loam subsoil	Ultic Haplorthox
PM 2	: sand to loamy sand topsoil and sandy loam subsoil	Quartzipsammentic Ultic Haplorthox
Moderately well to imperfectly drained grey[2] loamy soils		
PM3	: sand to loamy sand topsoil and sandy loam to sandy clay loam subsoil	Quartzipsammentic Ultic Haplorthox
Soils of lower slopes (generally concave slopes)		
Imperfectly drained soils		
sand to sandy loam topsoil and sandy clay loam subsoil		
PI 1.1*	: grey soils	Ultic Haplorthox
PI 1.2	: grey soils with a thick dark grey to black[3] layer	Tropohumod
sand to loamy sand topsoil and sandy loam subsoil		
PI 2.1	: grey soils	Quartzipsammentic Ultic Haplorthox
PI 2.2	: grey soils with a thick dark grey to black layer	Tropohumod
sand to loamy sand topsoil and subsoil		
PI 3.1	: grey soils	Aquic Quartzipsamment

* PI has been omitted from the map, short notation 1.1 etc has been used

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1) brown or yellow: hues are 7.5 YR to 2.5 Y and chromas are 4 or more in the subsoil
2) grey: chromas do not reach 4 within 120 cm from the surface
3) thick dark grey to black layer: values and chromas are 4/1 or 3/2 or darker over at least 30 cm below 20 cm depth

TABLE 2.2 Area of each soil mapping unit (ha) and proportion of total catchment area (%)

Map	Unit	Area (ha)	Proportion of total catchment (%)
PW	1	118	40
	2	6	2
	total	124	42
PM	1	66	22
	2	3	1
	3	1	0.4
	total	70	24
PI	1.1	14	5
	1.2	0.3	0.1
	2.1	17	6
	2.2	6	2
	3.1	15	5
	3.2	9	3
	3.3	1	0.3
	3.4	8	3
	3.5	3	1
	total	73	25
L	1	1	0.4
	2	4	1
	3	2	0.6
	total	7	2
Shallow phase of Pliocene on Precambrian *		15	5
Total L + shallow phase of Pliocene on Precambrian		23	8
Valley bottom	H	20	7
	W	1	0.4
	total	21	7
Total catchment area		295	100
Total clayey (+ laterite)		7	3
Total loamy (SCL subsoil)		198	67
Total sandy loam (SL subsoil)		33	11
Total sandy (S subsoil)		57	19
Total well drained		127	43
Total moderately well drained		72	25
Total imperfectly drained		75	25
Total poorly/very poorly drained		21	7

* These soils belong to Pliocene map units and should be omitted in totalling of area; shown on the soil map (Fig. 2.12) as ░

process may also cause clay decomposition because of dissolution of clay minerals at very low Al and Fe hydroxide activity products (Brinkman, 1979).

A dark layer, sometimes found in the lower footslopes, has been defined as having values and chromas of 4/1 or 3/2 or darker, over at least 30 cm below 20 cm depth. The layer may extend from the surface to about 1 m depth. Bruin and Tjoe-Awie (1980) think that this layer is formed by lateral supply of organic matter. On the soil map soils having this dark layer (units PI 1.2, 2.2, 3.2 and 3.5) are all situated on the lower edge of rather level footslopes where lateral flow could bring appreciable amounts of water containing organic components. However lateral flow may be too erratic to cause such a layer. The groundwater level on 3 July 1984 (shown in Fig. 2.13) in the eastern catena comes quite close to the dark layer. Thus the brown coloured groundwater found in deep borings in the sandy footslopes could also supply the material for the dark layer in the wet season. The light grey subsoil, having colour values of more than 6 and chromas of less than 3, occurs deeper in the profile.

A description of the soils in each map unit is given in Appendix II and nine descriptions of representative soil profiles together with analytical data are listed in Appendix III. The area of each map unit and the proportion of the catchment area are given in Table 2.2. Two-thirds of the area comprises loamy soils, that is the soils developed in Zanderij sediment with a sandy clay loam subsoil. Most of the experiments, for example 78/5 (Jonkers, in press) and 82/2, were carried out on these soils, on well and moderately well drained positions on the plateaus and upper slopes. A representative profile of these loamy soils is used in the simulation of water flows and growth of the forest in Chapter 3.

2.4.5 Relationships between the soil units

The soil map indicates that physiographic position is closely related to soil properties, such as texture and colour. Furthermore the soil catena on the convex ridges differs from those on concave slopes.

The two soil catenas to be discussed are on opposite sides of the Eastern creek (Figs. 2.12 and 2.13). Each catena runs from the water divide to the creek. The western catena is shorter and steeper, and on the steepest part of the slope, the Precambrian substratum is within 120 cm of the surface. The profile sequence is PW 1, PM 1 shallow on Precambrian material, PM 1, PI 3.1, PI 3.4 and H (for map unit code see Legend of the Soil Map, Fig. 2.12). Of these the well and moderately well drained loamy soils (PW 1 and PM 1) cover the largest area. Towards the creek the sandy clay loam subsoil stops abruptly and the soil becomes grey and sandy (PI 3.1). Very close to the swampy valley bottom a light grey sandy subsoil appears under the grey sandy upper layers within 120 cm (map unit PI 3.4).

The eastern catena has the soil profile sequence; PW 1, PM 1, PI 1.1 (too narrow to be shown on the soil map), PI 2.2, PI 3.5 and H. Compared with the western catena, a smaller proportion of the area has well and moderately well drained

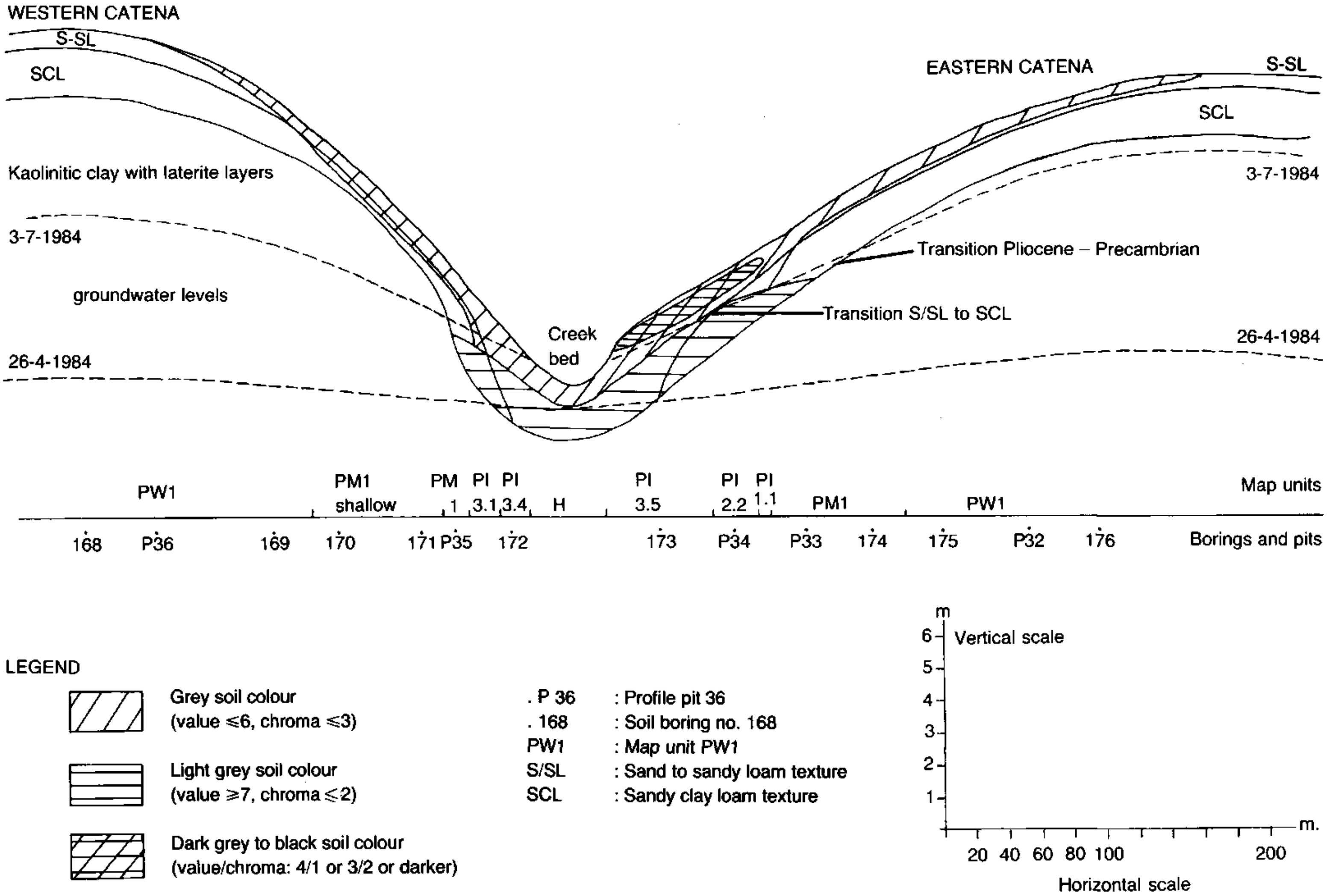


Fig. 2.13 Cross section of the Eastern Creek showing two soil catenas (see Fig. 2.12 for location of

loamy soils. A dark grey to black horizon occurs immediately below the topsoil of the footslope (PI 2.2 and PI 3.5). Descending the plateau, the grey topsoil increases in depth giving the loamy grey soil PI 1.1. The topsoil becomes more sandy and deeper and the dark coloured layer appears but sandy clay loam texture is still encountered within 120 cm (PI 2.2). Near the valley bottom the sandy topsoil becomes thicker, the dark layer becomes more pronounced and light grey colours appear in the deep subsoil (map unit PI 3.5). The valley bottom (H) is sandy throughout with a thin peaty top layer in some places. The light grey subsoil is sometimes encountered within 120 cm depth.

Groundwater levels were not measured on these catenas but were measured instead on the central east-west line, 200 m to the south, where the western catena is similar. The eastern catena on the central line is somewhat longer but still comparable (Fig. 2.12). The groundwater levels in Fig. 2.13 have been taken from this central line. The lowest and highest groundwater levels are given for 1984 and were measured on 26 April and 3 July respectively. Because the eastern catena is part of a larger physiographic unit than the western catena, the amount of water to be discharged is greater. This results in higher groundwater levels in the wet season, when other factors, such as hydraulic conductivity, are equal. Groundwater may be very important in soil-forming processes down slope.

The surface of the Precambrian substratum follows the soil surface closely (Fig. 2.13) indicating that the present landform is derived from the Pliocene era before the deposition of the Zanderij sediment. The undulating surface was covered with a thick layer of sediment, which has mostly been removed by erosion and the creek beds have reverted to their original location. The structural control in the drainage pattern (Fig. 2.11) is further support for this. However it is likely that after the creeks reverted to their former location, the valleys were deepened by erosion during periods of low sea levels in the Pleistocene and partly filled with erosion material of Zanderij origin afterwards. It is possible that on plateaus and upper slopes the Zanderij sediment is still in situ, while in valley bottoms and lower footslopes it is displaced material. This may also explain the sandy textures in the lower profiles.

As stated in Section 2.4.3., the Precambrian substratum is close to the surface at several places, especially at the shoulders of the plateaus (Fig. 2.11 and 2.12). This substratum which consists mainly of kaolinitic clay and laterite gravel will surely influence forest growth, groundwater flows and the composition of groundwater and creek water.

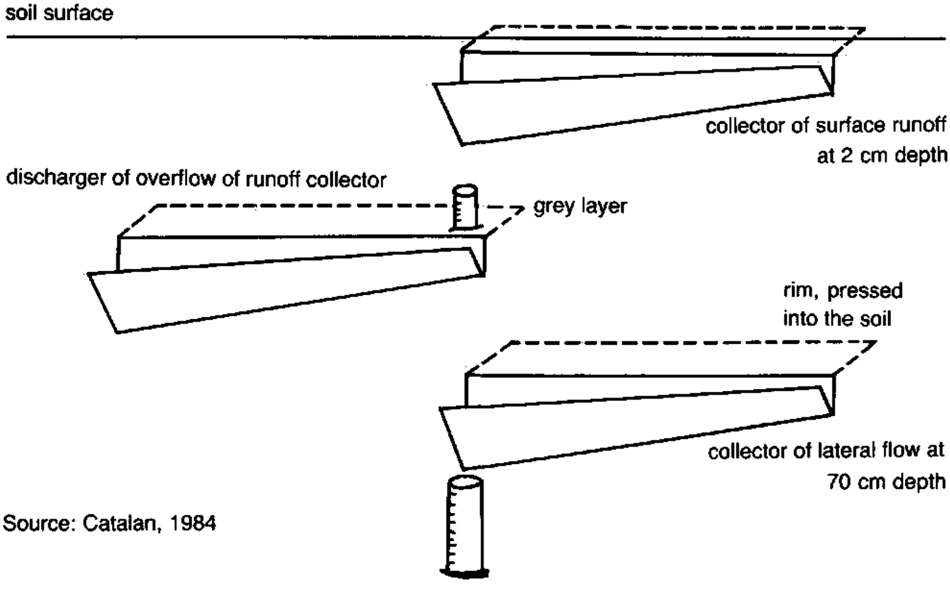
2.4.6 Surface runoff and lateral flow

Most of the rainfall on the water divide enters the soil profile because the topography restricts surface runoff and also because infiltration capacity and permeability are quite high. However permeability of the sandier topsoil is somewhat greater than that of the more clayey subsoil. At Profile 35 (Appendix III), on a lower slope where the subsoil still has a sandy clay loam texture and where lateral flow may be considerable, a permeability has been measured of 250 mm/h in the layer 10-20 cm; 35 mm/h in the layer 30-40 cm; and 12 mm/h in the layer 70-80 cm depth (Catalan Febrero, 1984).

Because of the higher permeability water may be expected to stagnate in the topsoil for short periods during and after heavy rainfall. During these periods reduction may occur as a result of lack of oxygen in the presence of easily oxidizable organic matter.

Under wet conditions water may flow laterally through the permeable topsoil over the less permeable subsoil. On an undisturbed slope surface runoff was rarely observed, all rainwater infiltrating the soil during heavy rains. These amounts of water, augmented by lateral supply, saturate the upper sandy horizons, while percolation into deeper layers continues. Down-slope the continually increasing stream of water saturates the topsoil. This temporary saturation may explain the increasing thickness of the grey sandy upper layers by soil forming processes, such as ferrolysis (Brinkman, 1979) which can cause removal of iron (pale colours) and decomposition of clay (sandier texture).

To test whether lateral flow is responsible for the increasing thickness and intensity of the grey layer in a down-slope direction, water collectors were installed in profile 35 (see Catalan Febrero, 1984). In the large pit of profile 35, located down-slope in map unit PM 1 near the transition to PI 3.1 (Figs. 2.12 and 2.13), two sheet iron collectors (each 1 m wide) were placed in the wall of the pit to direct all water from the wall into a measuring cylinder (Fig. 2.14). One collector was placed



Source: Catalan, 1984

Fig. 2.14 Experimental set-up to measure lateral flow in profile pit 35

TABLE 2.3 Surface runoff and lateral flow measured at the wall of profile 35

Date of observation (1983)	Date of rainfall (1983)	Rainfall (mm)	Surface runoff (ml)	Lateral flow (ml)
15- 7	11- 7	20	95	0
10- 8	9- 8	8	10	0
31- 8	27- 8	31	110 *	250
5-10	30- 9	9	80	0
4-11	26-10	50	110 *	600 *

* Minimum values because of overflow.

at a depth of 2 cm to collect surface runoff. The second, which was placed below the first at a depth of 70 cm just below the grey layer, collected all water from the profile wall between depths of 2 and 70 cm. The amounts collected in a five-month period (June-November 1983) are given in Table 2.3.

Rain showers of about 10 mm produced some surface runoff but larger amounts of rainfall were required for lateral subsurface flow. Rainfall of at least 30 mm appears to be necessary to generate some lateral flow. These flows are assumed to occur for short periods during and after heavy rain and may well contribute to the formation of the grey sandy topsoil.

2.4.7 Soil forming processes

Hydrolysis and leaching of silica and basic cations

Most soils on the plateaus and upper slopes have subsurface horizons that meet the requirements of an oxic-B horizon. Large map units occur on the soil map in these places, as compared with the low-lying areas along the creeks where narrow, strip-like map units are common. The standard profile of the area is an Ultic Haplorthox, as represented by profiles 36 and 11 (see Appendix III). This soil is found on well drained sites on plateaus and upper slopes. The texture of the topsoil is loamy sand to sandy loam and in the subsurface horizons sandy clay loam to a considerable depth. The soil is not a Typic Haplorthox because the topsoil is too sandy. Hydrolysis of weatherable minerals including clay minerals and leaching of the released silica and basic cations with consequent residual accumulation of quartz, kaolinitic clay and sesquioxides, is the main soil forming process in the area. This process formerly called laterization, in combination with biological homogenization has produced the oxic horizon.

Clay eluviation and other possible causes for the sandy topsoil

The lighter textured topsoil could have resulted from clay eluviation during the formation of an argillic horizon. This theory was not seriously considered initially, because clay skins were not observed in the B horizons. However micromorphological analysis of profile 11 by de Fretes (1984) has shown that the B22 horizon (108-180 cm) contains oriented clay, mostly as papules, which are considered to be remnants of an old argillic horizon, now being destroyed by bioturbation. Horizon B22 still qualifies as an argillic horizon. Clay eluviation-illuviation could have been an important soil forming process during some periods in the Pleistocene when the climate was drier and the vegetation sparser.

Bennema (1982) suggests that the dry period during the last interpluvial (Würm glacial period), when most of the area was covered with savannah, greatly affected the soil. This vegetation provided less protection against loss of clay from the topsoil (by either erosion and/or clay eluviation). This loss has not yet been counterbalanced by biological activity.

Krook and Mulders (1971) assume that the white sands were formed by podzolization during the glacial period with savannah vegetation, but podzolization is not very probable under a rather dry climate. Lucas et al. (1982) consider the podzolization to be a presently ongoing process. The distinct black colour of the water draining the white sand areas and the somewhat brown colour of the water draining the areas of unbleached sandy and loamy Zanderij soils support this proposition.

Therefore clay eluviation in former periods has probably resulted in the lower clay content in the topsoils of the oxisols and for this reason these oxisols are classified as Ultic Haplorthox. Clay eluviation stopped when the climate became wetter. Clay skins have disappeared as a result of biological homogenization and argillic-B horizons have acquired oxic characteristics. The process of clay eluviation cannot explain the increasing sandiness of the topsoil down-slope. One or more of the processes clay wash, ferrolysis, or podzolization, must also have occurred.

The formation of bleached soils

Van der Eyk (1957) states that strong bleaching only occurs when the A horizon contains less than 2 to 3 % of clay and that the difference between bleached and non-bleached soils is the result of a difference in the clay content of the parent material. Bleached soils developed where the initial clay content was relatively low and where it subsequently dropped below the critical value of 2 to 3 % because of the eluviation of clay. Van der Eyk (1957), observing narrow strips of poorly drained bleached soils bordering on large areas of well drained non-bleached soils which were relatively poor in clay, concluded that drainage condition could also be a decisive factor in this soil formation.

In studies on the genesis of the white sands in French Guiana (Lucas et al., 1982) imperfect or poor drainage is considered to be the crucial factor in the formation of bleached soils. The transformation of a strong brown (7.5 YR 5/6-5/8) sandy clay mantle of Zanderij sediment to a deep profile of white sand is described. Leaching, leading to disappearance of clay, starts in areas of periodic water stagnation, for example, at the centre of level plateaus and on footslopes. The process of clay disappearance is referred to as silting by Lucas et al. (1982). It may be related to ferrolysis (Brinkman, 1979), which is a process whereby clay is destroyed in an alternating wet and dry environment. According to Lucas et al. (1982) white colours appear when clay contents fall below 3 %. The process from silting to white sand is called podzolization. Because of the removal of material (destruction of clay and removal of its components) during this process, the surface is lowered and the drainage condition worsened, intensifying water stagnation and therefore the podzolization process.

Elsewhere in the Zanderij area white sands occur on well drained sites. They could have been formed under both well and poorly drained conditions. Ferrolysis is not possible under well drained conditions and podzolization is a slow process. In this climate extremely sandy and nutrient poor conditions would have been necessary to form these white sand areas under well drained conditions. This combination is possible in very sandy sediments deposited near the apexes of alluvial fans. It is more probable, however, that these white sand areas have been formed under poorly drained conditions but that drainage has improved afterwards, for instance by incision of nearby creeks.

2.4.8 Organic matter profiles and ECEC of clay and organic matter

Bennema (1982) refers to the brown loamy Zanderij soils as Yellow Kaolinitic Oxisols graduating to Ultisols. Important characteristics of the Yellow Kaolinitic Oxisols are kaolinitic clay mineralogy, low iron content and therefore low structural stability, increase of clay content with depth, and very low fertility. The increase of clay content with depth is explained by a gradual loss of clay, by erosion from the topsoil and/or by slow destruction of the clay minerals under influence of organic matter combined with biological homogenization. Some clay eluviation may also be present in the brown Zanderij soils. Bennema (1982) shows that the organic carbon content (% C) of typical oxisols decreases as a power function with depth (cm):

$$C = a_0 \times \text{depth}^b \text{ or}$$
$$\log C = a + b \log \text{depth} \qquad (2.4)$$

a_0 is the theoretical organic carbon content at 1 cm depth and b is a constant for a profile. It is often about -0.5, in which case the organic carbon content can be expressed as a_0 divided by the square root of the depth. Ultisols, intergrades to Ultisols, and soils that have been disturbed by human occupation do not follow this function, because the organic carbon content in the topsoil is mostly too low.

The carbon profiles of three soils in a double-log plot are shown in Fig. 2.15. Profile 11 is a well drained, deep loamy plateau soil; profile 37 is a well drained, deep sandy plateau soil; and profile 34 is a footslope soil with a thick dark brown to black layer down to 60 cm (see Fig. 2.12 and Appendix III). The straight course for

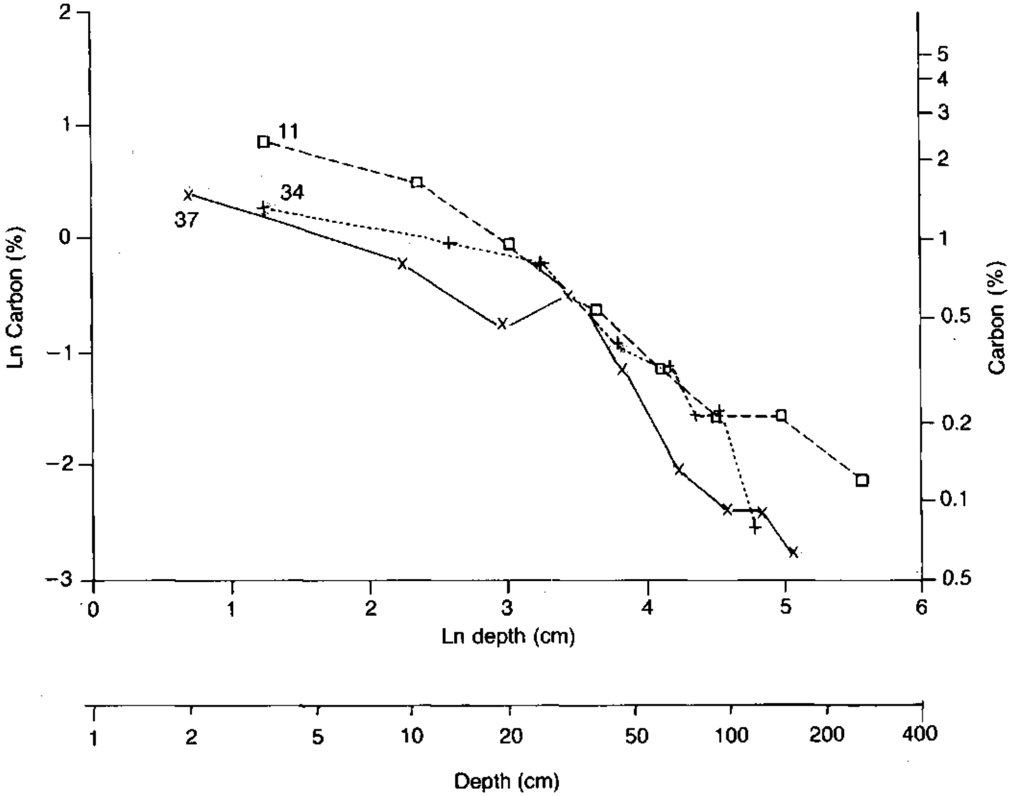


Fig. 2.15 *Logarithm of carbon content against logarithm of depth in the soil for profiles 11, 34 and 37* (see Appendix III for descriptions of soil profiles)

profile 11 corresponds with the oxisol concept of Bennema (1982). There is a small shortage of carbon in the topsoil, corresponding with the sandiness of the topsoil (Ultic Haplorthox). In profile 37 the extreme sandiness of the topsoil (Appendix III) corresponds with lower carbon contents. The Bhs horizon (24-41 cm) has some podzol B characteristics, a clear increase in carbon content and a slight brittleness that suggests cementation by illuvial material. Profile 34 shows a curved line with relatively high values for the horizons between 20 and 100 cm, of which 20-60 cm is the dark layer.

In Figs. 2.16 and 2.17, the ECEC of three profiles is given as a function of the organic carbon content. The same profiles were used as in Fig. 2.15 except that Profile 11 was replaced by Profile 36, which is also a loamy plateau soil. Profiles 11 is a representative soil of the larger loamy plateaus and Profile 36, with more clay in the topsoil, of the smaller ones. Both ECEC and C are given per 100 g clay, thus making it possible to distinguish between the contributions of clay and organic matter to the ECEC. Fig. 2.17 is an enlargement of the lower left corner of Fig. 2.16, and shows more clearly the ECEC relationships in the subsoil horizons. The ECEC of the clay fraction can be read from the graph by extrapolating the line

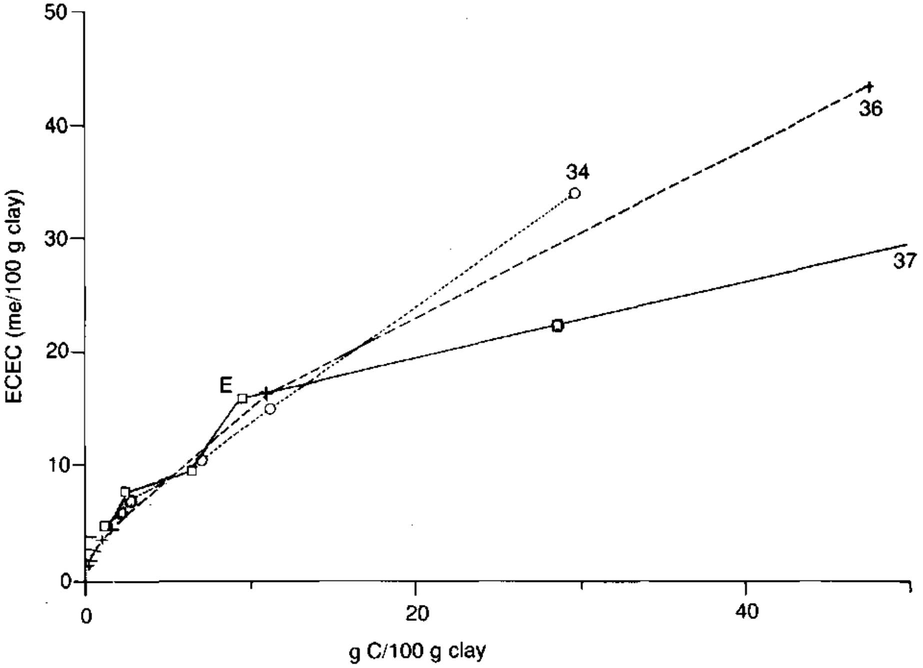


Fig. 2.16 ECEC of carbon and clay in profiles 34, 36 and 37 (see Appendix III for description of soil profiles)

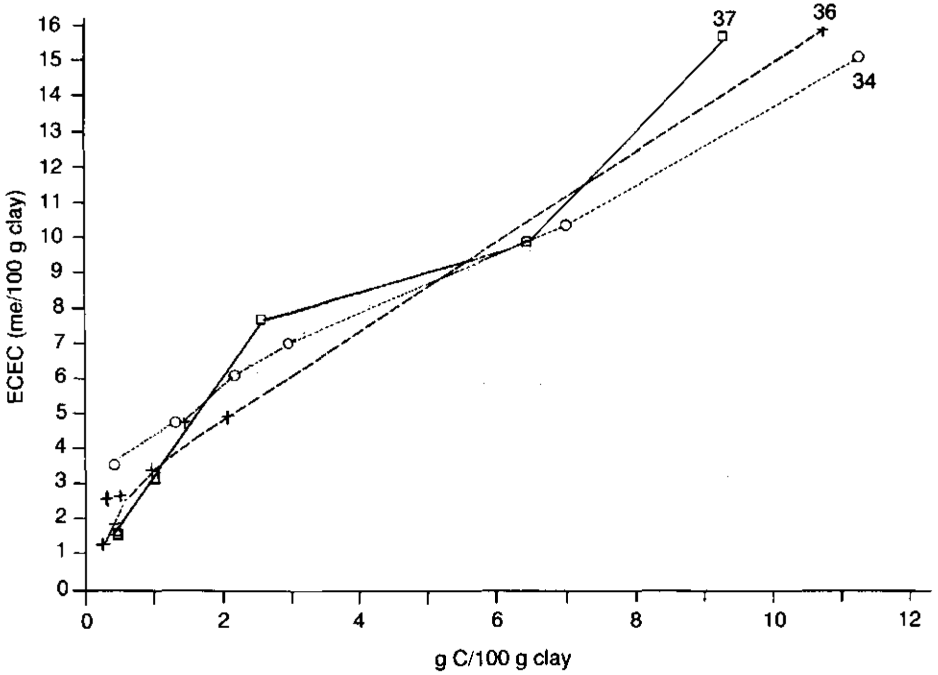


Fig. 2.17 ECEC of carbon and clay in the subsoil of profiles 34, 36 and 37

through two or more points to the vertical axis (C=0). The ECEC of the organic matter, expressed in ECEC per g carbon, is given by the slope of the lines. The lines through the points per profile are not straight. The ECEC per 100 g clay, calculated from the graphs, appear to be extremely low (see Table 2.4).

Brinkman (1979) sets out characteristics to distinguish between ferrolysis and cheluviation (podzolization) in clay fractions of eluvial horizons. Ferrolysis reduces the CEC of the clay fraction in the eluvial horizons by the formation of aluminium interlayers in 2:1 clay minerals. Podzolization gives a higher CEC of the clay fraction in the eluvial horizons by preferential dissolution of low activity clay (clay minerals with high aluminium and iron contents, Al-interlayers and free oxides). As there is no sharp increase in the ECEC of the clay fraction below the eluvial horizon, the acting soil forming process is not ferrolysis.

Ferrolysis and podzolization are mutually exclusive (Brinkman, 1979). Ferrolysis, which requires periodic saturation, is inhibited when sufficient fulvic acids are available for the chelation of produced Fe^{2+}-ions. A high production of fulvic acids seems possible in the acid, nutrient-poor environment of the forest floor, where a constant supply of organic matter is available. The podzolization process, which is intensified in situations of periodic water saturation, must be active here.

The slightly curved line for ECEC for Profile 36 (Fig. 2.16 and 2.17), indicates a decreasing clay activity with depth. Profile 37 has a relatively high clay ECEC in the topsoil (Ah and E horizons), a lower ECEC in the Bhs, increasing again in the subsoil, which suggests podzolization. In contrast, the line through the points in profile 34 is almost straight, rising slightly for the subsoil layers.

The ECEC per g organic carbon is also given in Table 2.4. The ECEC of the organic matter in the topsoil is lower than deeper in the profile, probably because of the better decomposition status of the organic matter in the subsoil. The organic matter in the topsoil of profile 37 has an extremely low ECEC, corresponding with the podzolic character of profile 37. It has a mor type of humus, a very high proportion of bleached sand and a well developed root mat, all indicating slow decomposition and humification. In Profile 34, the ECEC of both clay and organic matter do not vary greatly with depth. It is probable that much of the organic matter in this profile comes from below with seepage water which could be partly derived from lateral flow, but probably comes mainly from the shallow groundwater during the wet season (Fig. 2.13).

2.4.9 *Explanation of the observed features*

The following explanation is put forward for the observed features. A podzolization process is active in the topsoil of all soils, both on plateaus and slopes. This podzolization is possible because of the sandy texture of the topsoils and also their extremely poor nutrient status and their acidity. The occurrence of pockets of bleached sand in the upper few centimetres of most profiles supports

TABLE 2.4 Values of ECEC per 100 g clay and per g organic carbon

Profile no.	Horizon	Depth (cm)	ECEC (me/100 g clay)	ECEC (me/g C)
36	Ah1,Ah2	0-10	8.	0.76
	E-Bhs	10-63	2.4	1.2
	Bws1-Bws4	63-130	1.0	2.4
37	Ah1-E	0-24	12.5	0.35
	Bws1-Bws3	41-112	0.45	2.9
34	Ah1-E	0-30	3.5	1.0
	Bhs2-Bhs3	30-70	3.6	1.2
	2Bwsg1-2Bwsg2	88-136	3.0	1.3

Data derived from Figs. 2.16 and 2.17.

this hypothesis. The process forms amorphous complexes of organic matter and aluminium, with or without iron. These are transported by lateral flow or by groundwater.

An intensive flow of groundwater or laterally moving water during wet seasons may carry sufficient oxidizable organic matter to bleach the permeated soil layers light grey by reduction and removal of iron. This is the case in the subsoil of lower footslopes and concave areas, such as the heads of creeks where much lateral water concentrates.

A dark accumulation layer is only formed in the profiles of the lowest footslopes, directly bordering the valley bottoms. The more or less permanent groundwater flow brings dissolved complexes of (aluminium and) organic matter. Capillary rise and evapotranspiration of this water concentrate these complexes, leading to precipitation higher in the profile. This results in the dark colour of certain horizons in the profiles of the lower slopes. A shallow groundwater table (less than about 1 m deep) appears to be necessary for the formation of this dark horizon.

Profile 34, the footslope soil with the dark top layer, shows a slight increase in organic matter in the dark horizon (Appendix III and Fig. 2.15). The free iron and amorphous iron contents show practically no increase and are very low throughout. There seems to be only an accumulation of organic matter because total amounts of iron and aluminium in soil and clay do not show clear accumulations. It is therefore questionable whether the dark layer qualifies as a spodic horizon. Slight as the accumulations may be, the process is still considered to be podzolization. Organic matter is transported with little or no iron or aluminium.

In the loam subsoil, enough aluminium is present for the chelates to precipitate. Therefore, the groundwater in loamy soils is colourless and has a lower carbon content than creek water (Appendix VII). Shallow groundwater, moving laterally through sandy top layers containing much organic matter and small amounts of sesquioxides, is dark in colour because of large amounts of mobile organic matter. This can be observed in some deep borings in sandy footslopes. Some of this water is discharged to creeks and some is removed by evapotranspiration. The sandier the catchment area is, the darker the drainage water. Water from white sand savannahs is black; water from loamy Zanderij areas such as the study area is slightly brown; and water from catchment areas of residual soils is colourless. The slightly brownish drainage water from Eastern and Western creeks contains about 800 mmol carbon but only 1 mmol aluminium and about 1-10 mmol iron per m^3 (Appendix VII).

Microscopic observations of the black layer (30-60 cm) and the topsoil (0-7 cm) of profile 34 and of topsoil (0-10 cm) and subsoil (102-130 cm) of profile 36 support this theory. Topsoils have bleached sand grains, the topsoil of profile 34 having more than that of profile 36. The black layer shows dark plasmatic material, partly covering the sand grains. The plasmatic material in the subsoil of profile 36 is lighter in colour, indicating a lower organic matter content. Heating of the soil in a furnace gave pale colours for the samples of profile 34, indicating de-ironing, and light red colours for the samples of profile 36.

Loamy soils, even those with sandy clay loam subsoils, in well drained positions are subject to slight podzolization in the topsoil. Down-slope, where there are increasing amounts of stagnating water in the topsoil, the process intensifies and extends to a greater depth, resulting in a grey topsoil of increasing thickness. Moderately well drained plateau soils (PM1, PM2 and PM3) have more podzolic features than well drained plateau soils, and sandy soils are more subject to podzolization than loamy soils of the same drainage class. For instance, podzolization is active in the topsoil of the well drained profile 37 in unit PW 2 in the south-east of the area (Fig. 2.12) as indicated by the many bleached sand pockets in the topsoil and the brittleness and slightly higher organic matter content of the Bhs horizon. The relatively small biomass, the thick root mat and the rather thick litter layer, all suggest an extremely low buffering capacity and fertility, conditions which are favourable to podzolization.

Landform also plays a very important part in the soil forming processes. The soil map shows that the soil is less bleached on the smaller interfluves and on areas of better drainage because of steeper slopes, higher elevation, or convex slopes. Comparison of the soil map with the topographic map (Fig. 3.4) shows that concave areas which collect lateral drainage water from surrounding slopes are grey for considerable distances from the creek. At the same elevation soils on a convex slope for instance, belong to soil unit PW 1, while soils on a nearby concave slope may belong to soil unit PI 3.2.

The area between the two creek valleys consists mainly of soils of the units PW 1 and PM 1, well and moderately well drained sandy clay loams. Because of the normal slopes and a moderate distance between creeks (600 m), this physiographic unit as a whole is well drained. In the southern part, the strip of soil unit PM 1 connecting both valleys is a saddle, far above the groundwater level but receiving lateral drainage water. The interfluve areas to the east of the Eastern creek and to the west of the Western creek are larger, their width being roughly twice the distance from the creek to the water divide. Consequently larger amounts of drainage water have to be discharged in wet periods, resulting in higher groundwater levels. This is also clear from Fig. 2.13 where the groundwater level in the wet season is higher in the eastern than in the western catena. Therefore as a whole they are more poorly drained than smaller units, especially in the footslopes, where drainage water concentrates.

Not only the footslopes but also the centres of the large interfluves can have impeded drainage. Areas of restricted drainage occur (map units PM 1 and PM 2) in the central part of rather flat plateaus. Profile 11 (Fig. 2.12), which is on a large level plateau in map unit PW 1 close to the boundary with unit PM 1, is well drained but the sandy layers on top are quite thick (Appendix III). As lateral drainage is almost impossible here large amounts of rainwater are transported in the profile. It is likely that profile 11 graduates into the moderately well drained drainage class.

Hydromorphic white sands occur in the north-eastern corner of the soil map (Fig. 2.12) where podzolization has resulted in deep white sandy profiles. Map unit PI 3.3 consists of deep white sands with a thin layer of raw humus on top, covered with a sparse savannah forest vegetation. As stated in Appendix II, the land is almost flat, only slightly above creek level, and the groundwater table fluctuates greatly from near the surface to a depth of about 2 m. These soils, which are also called giant hydromorphic podzols, are in the final stage of soil formation (Lucas et al., 1982). All deep Zanderij soils situated slightly above drainage level will eventually become white sands.

2.5 Vegetation

2.5.1 Composition and structure

The vegetation of the Zanderij area is closely related to the soil. Most of the area is covered with high forest but there are also low forests with thin stems, savannah forests, and open savannah vegetations. On the bleached soils, several vegetation types have been distinguished (Table 2.5).

During the last glacial period, most of the area was covered with savannah vegetation (van der Hammen, 1963). According to Bennema (1982) the transition from savannah to forest after the dry period on these extremely poor soils must have been slow because the soil was not able to supply the much larger amount of nutrients present in a forest as compared with a savannah vegetation. The nutrients necessary to form a forest again were probably brought by rain and dust.

Bennema therefore considers the forested Amazon area including Suriname to be a sink of nutrients, while the savannahs of Central Brazil, for instance, are a source of nutrients because of the six-month dry season and the frequent fires. This

TABLE 2.5 Vegetation types in the Zanderij area

Soil	Hydrology	Vegetation	Comment
Brown loamy soils	well drained	High dry land forest	
Brown loamy/ sandy soils	well drained	Grass and shrub savannah (Coesewijne type)	compaction and burning
Brown sandy soils	well to excessively drained	High dry land forest	
Valley bottom soils	poorly drained	Swamp or marsh forest	
Bleached sandy soils	well drained	High dry land forest	favourable location
Bleached sandy soils	well drained	High savannah forest	dry land
Bleached sandy soils	well to excessively drained	Low savannah forest	dry land
Bleached sandy soils	well to excessively drained	Dakama forest	dry land
Bleached sandy soils	excessively drained	Shrub and open savannah (Cassipora type)	dry land
Bleached sandy soils	imperfectly drained (flowing groundwater)	Walaba forest	footslopes
Bleached sandy soils	imperfectly drained (stagnating groundwater)	Open grass and shrub savannah (Zanderij type)	level plains
Bleached sandy soils	imperfectly to poorly drained	Wet savannah forest	water courses

Adapted from Cohen and van der Eijk (1953); van der Eijk (1957); and Lindeman and Molenaar (1955)

savannah, the Cerrado of Central Brazil, is considered to be edaphic, because insufficient nutrients seem to be available for forest growth in the savannah ecosystem, although a deciduous forest would be climatically possible.

Krook and Mulders (1971) propose that everywhere in the Zanderij area forest is replacing the savannahs and this process is only retarded by burning carried out by man. Bennema (1982) however, thinks that the savannah remnants in the Zanderij area will not become forest again, not only because of the lack of nutrients but mainly because of unfavourable physical conditions. They are too wet in the rainy season because of impermeable soil layers and too dry in the dry season. Therefore these savannahs should also be called edaphic.

At present the normal vegetation in the Zanderij area is high forest. Other vegetations occur where physical and chemical soil conditions are poor or as a result of human disturbance. Van der Eyk (1957) considers the "Coesewijne savannah type" on non-bleached soils to be man-made, a result of repeated burning. The other deviating vegetations occur on bleached soils, which are extremely poor chemically but which vary greatly physically, depending on their position.

On favourable sites the forest contains many species. Lindeman and Moolenaar (1955) found, in high dry land forest, 50 tree species per ha with minimum diametres of 25 cm, increasing to 90 species for an area of 4 ha. Poorer conditions not only give a lower vegetation type, but mostly fewer species too. High dry land forest occurs on almost all brown soils and on favourable locations on a small area of the bleached sands (Table 2.5). The remainder of the bleached sands is covered with forests dominated by one or a few species or by a savannah type of vegetation.

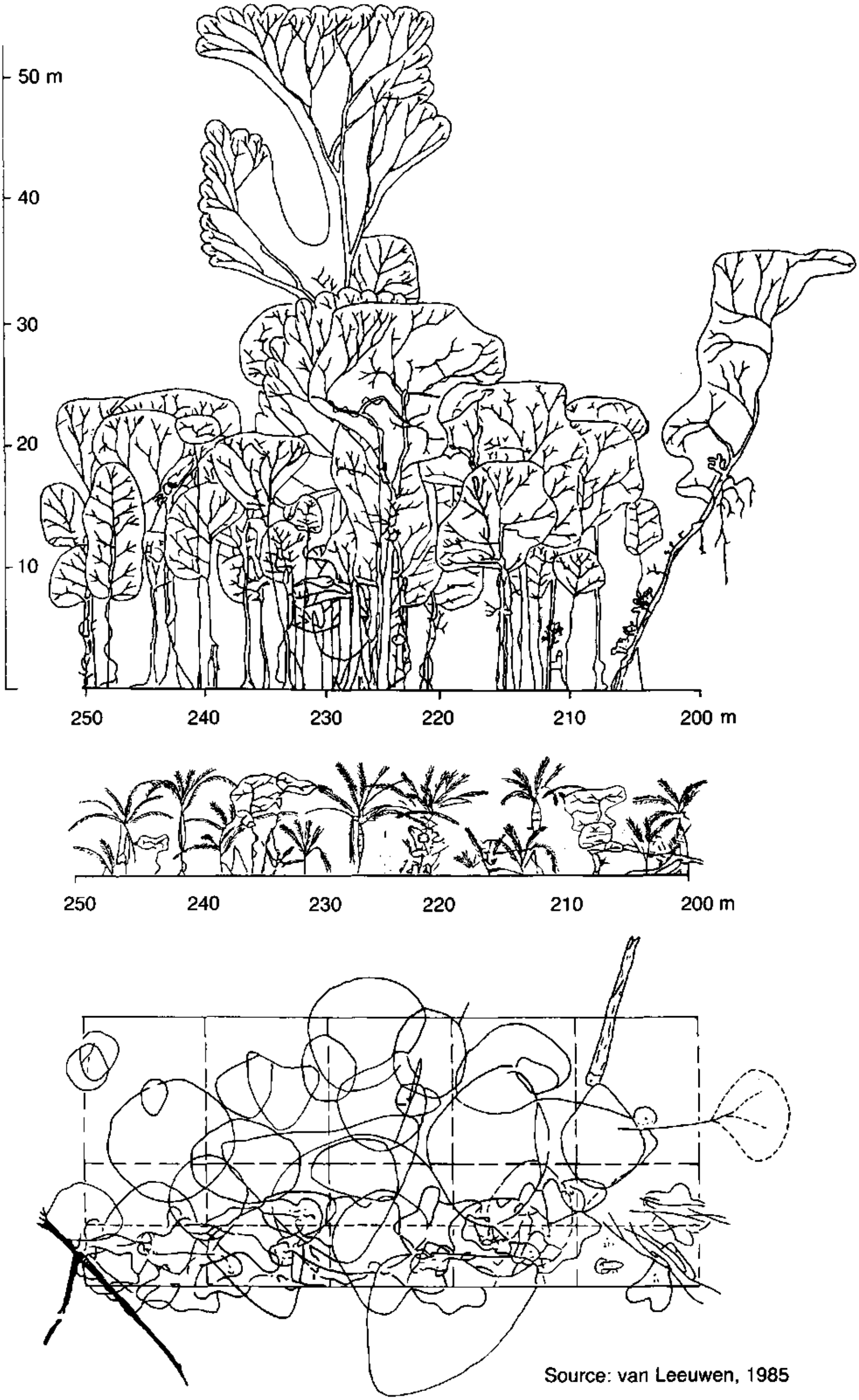
There are two types of forest dominated by one species, Walaba and Dakama, both belonging to the botanical family Leguminosae. Forests in which the Walaba tree (*Eperua falcata*) dominates occur on sites of good physical conditions for tree growth and they often attain great height and biomass. The Dakama tree (*Dimorphandra conjugata*) forms almost pure stands in better drained bleached sand areas. Because of the slow rate of decomposition, these stands often have a very thick litter layer and are therefore prone to fire. On dry land the Cassipora type of savannah occurs, consisting mainly of high shrubs. On periodically wet, level plains, the Zanderij type of savannah occurs being the poorest in biomass and growth potential.

Is it possible that forest will replace all savannahs, as proposed by Krook and Mulders (1971)? In areas of bleached soil, where soil physical conditions are somewhat better, such as edges of plateaus or footslopes along creeks, the open savannah vegetation may gradate into savannah forest, provided left undisturbed. Where conditions are poorer, such as the centres of large low-lying, white sand plateaus, saturated with stagnant water in the wet season and extremely dry in the dry season, the vegetation is unlikely to improve very much. These areas might perhaps improve slightly if left undisturbed, the open grass savannah becoming savannah with somewhat more shrubs, and shrub savannah gradating to low open savannah forest.

In the catchment area under study, 93% is covered with high dry land forest and the remainder with swamp forest (map unit H, Fig. 2.12). The savannah forest of map unit 3.3 in the north-eastern part of the soil map occurs just beyond the catchment area.

An example of the structure of the high forest on loamy Zanderij soil, which is the main soil in the study area, is given in Fig. 2.18. This is a cross-section of forest profile (50 x 20 m) of a transect of 600 x 20 m (van Leeuwen, 1985). This segment is located in map unit PW1, 100-150 m east of point C (Fig. 2.12). Because of the large number of small trees, higher and lower trees have been separated to eliminate crowding in the lower part of the drawings.

Because of the many chablis, that is natural gaps in the canopy because of fallen trees, and the emergent trees, the upper canopy is not closed. Van Leeuwen counted up to 5 chablis per hectare. Canopy height is about 30 m but varies considerably and the maximum height of emergents is between 50 and 60 m. A detailed description of this forest profile, including botanical names, is also given by Jonkers (in press). Lianas and epiphytes are visible in some trees. The understore vegetation in the centre of Fig. 2.18 consists mainly of palms, of which



Source: van Leeuwen, 1985

Fig. 2.18 Profile drawing of plateau forest area (50 x 20 m) on soil map unit PW1.
Upper: all trees higher than 10 m over a width of 20 m.
Centre: all vegetation between 2 and 10 m high over a width of 5 m.
Lower: location of trees (including fallen trees) with crown projections

the Bugrumakka (*Astrocaryum sciofillum*) with stem and the Paramaka palm (*Astrocaryum paramaca*) without stem are the most important. Vegetation lower than 2 m consists mainly of seedlings of trees, lianas and palms. Grasses and herbs are rare. The vegetation shown in Fig. 2.18 is representative of the plateaus and upper slopes. Emergents taller than 50 m are rare. The vegetation on footslopes generally has less biomass and is somewhat more homogeneous with respect to tree size. Canopy height varies less on footslopes, where there are many thin-stemmed trees and emergents are fewer and smaller.

2.5.2 *Biomass and nutrient content*

The forest at Kabo is on heavily weathered soil, poor in plant nutrients. Nutrients available to plant roots are derived largely from decomposing organic matter. In the study of nutrient amounts and nutrient flows, the nutrients in the biomass, both living and dead, have to be taken into account. Biomass includes plants and animals. Animal weights and nutrient concentrations in animal biomass were not determined, but compared with phytomass, the animal biomass in these forests is very small. In a dry land forest in Central Amazonia, which is considered to be more or less comparable with the forest at Kabo, Klinge (1973) reported only 200 kg fresh animal weight, compared with a living plant biomass of 1000 t/ha fresh weight.

At Kabo the phytomass and the nutrient content of the phytomass have been determined by destructive sampling (Ohler, 1980; Schmidt, in press). Twelve plots (10 x 10 m) selected at random were harvested and all the trees measured, height, diameter at breast height (dbh), stem length, dry weight of leaves, branches and stem. The relationship between diameter (mm dbh) and dry weight of leaves, branches and stems was then determined (Schmidt, in press). With these relationships it is possible to determine phytomass in similar forests from measurements of diameters at breast height. After logarithmic transformation, the following relationship was found between the weight of various components of the forest phytomass and dbh:

$$W = \{10^{(a+b \log d^2)}\} \times \{e^{0.5\, S^2 \ln^2 10}\} \qquad (2.5)$$

This equation can be simplified:

$$W = k \times d^{2b} \qquad (2.6)$$

in which $k = 10^a \times \mathrm{EXP}(0.5 \times S^2 \ln^2 10)$,

a, b, S and k are constants,

d is diameter at breast height (mm) and

W is dry weight of phytomass (kg).

For the Kabo forest, the constants are:

	a	b	S^2	k
leaves	– 3.76	1.00	0.087	2.168×10^{-4}
branches	– 4.85	1.42	0.138	0.203×10^{-4}
stems	– 3.49	1.26	0.042	3.659×10^{-4}

The forest on the plateaus and upper slopes of the catchment is represented by the forest of the fertilizer experiment 82/2, just outside the catchment area. This experiment comprises 9 plots of 35 x 35 m measurement area in 50 x 50 m treatment area. All trees above 50 mm dbh were measured at the beginning of the experiment. The weights of leaves, branches and stems of the measured trees were estimated with the above equation from dbh and totalled to dry weights per ha (Table 2.6).

In a similar forest at Kabo the average phytomass from destructive sampling of twelve 10 x 10 m plots was found to be higher (Ohler, 1980). Because of the considerable variation in the occurrence of large trees, this area (0.12 ha) was too small to be representative of the surrounding forest. Measurements of single trees, however, were used in developing the equations given above. This 0.12 ha of forest had an average basal area of 42.8 m^2/ha, yet measurements over larger areas gave an average basal area of between 25 and 30 m^2/ha. By omitting some of the large trees harvested, Ohler (1980) gave corrected phytomass data for a forest with 25.6 m^2 basal area per ha.

Measured and corrected phytomass data by Ohler (1980) are given in Table 2.7, together with the calculated tree biomass in experiment 82/2, completed with the data from Ohler for small trees, palms, lianas and epiphytes. The weight of roots has been estimated. Ohler arrived at only 65 t/ha compared with an above-ground living biomass of 597 t/ha, merely 11 % of the total. This is certainly an underestimate. The roots came from soil pits 50 cm deep and many roots occur below this depth. These soil pits did not include the place of a large tree where the large roots are concentrated. These two factors would more than double the root weight. An above ground biomass of 434 t/ha as found in experiment 82/2 should therefore have at least 96 t/ha of roots.

Root weights of up to about 30 % of above-ground living phytomass are reported in literature. Root weight depends on edaphic factors, being relatively

TABLE 2.6 Tree biomass above ground in experiment 82/2, calculated from dbh of single trees (average of 9 plots of 35 x 35 m)

	Leaves	Branches	Stems	Total
Mean (t/ha)	7.6	117.6	283.5	408.7
SD (t/ha)	1.3	46.6	85.0	132.6
SD (%)	17	40	30	32

TABLE 2.7 Phytomass of undisturbed forests and nutrient concentrations

		Phytomass (dry weight, t/ha)			Concentration (%)				
		Ohler *	Ohler (corr)*	82/2	N	P	K	Ca	Mg
Leaves	trees (dbh >5cm)	(8.4)	(6.5)	7.6	1.68	0.085	0.80	0.76	0.219
	trees (dbh<5cm), forbs, epiphytes	(1.5)	(1.5)	1.5	1.52	0.078	1.35	0.83	0.239
	palm	8.0	8.0	8.0	0.94	0.068	1.07	0.25	0.102
	liana	0.5	0.5	0.5	1.73	0.093	1.59	0.98	0.299
	total	18.4	16.5	17.6	1.34	0.068	0.99	0.54	0.170
Branches	large (trees dbh >5 cm)	142.7	84.9	94.0	0.27	0.017	0.23	0.57	0.043
	small and twigs (trees dbh>5cm)	36.5	29.8	23.5	0.76	0.071	0.64	0.82	0.128
	small (trees dbh <5 cm)			0.1					
	liana	3.2	3.2	3.2	0.64	0.046	0.33	0.48	0.058
	total	182.4	117.9	120.8	0.38	0.028	0.31	0.62	0.060
Stems	trees (dbh>5cm)	(383.7)	(268.3)	283.5	0.27	0.016	0.23	0.54	0.044
	trees (dbh<5cm)	(1.0)	(1.0)	1.0	0.58	0.042	0.44	0.66	0.092
	palm	4.5	4.5	4.5	0.40	0.029	0.58	0.16	0.068
	liana	6.6	6.6	6.6	0.55	0.031	0.47	1.34	0.083
	total	395.8	280.4	295.6	0.28	0.016	0.24	0.55	0.045
Total above ground phytomass		596.6	414.8	434.0	0.35	0.022	0.29	0.57	0.054
Total roots		65.3	65.3	108.5	0.79	0.053	0.35	0.41	0.073
Total living phytomass		661.9	480.1	542.5	0.44	0.028	0.30	0.54	0.058
Litter	coarse, (branches and stems)	22.6	22.6	21.5	0.49	0.020	0.10	0.64	0.066
	decomposed wood	–	–	3.3	2.82	0.030	0.10	0.13	0.021
	fine, on soil	9.3	9.3	10.4	1.52	0.054	0.15	0.32	0.151
	fine, above soil	2.9	2.9	2.9	1.22	0.049	0.41	0.87	0.147
	total	34.8	34.8	38.1	1.03	0.031	0.14	0.52	0.092
Total phytomass without soil		696.7	514.9	580.6	0.48	0.028	0.29	0.54	0.060
Soil	0 -120 cm depth	129.2	129.2	172.7	4.34	0.087	0.30	0.43	0.130
organic	120-170 cm depth			16.4	9.24	0.183	0.65	0.93	0.274
matter	170-300 cm depth	27.0	27.0	27.0	11.39	0.230	0.80	1.14	0.341
	total	156.2	156.2	216.1	5.60	0.112	0.39	0.56	0.168
Total phytomass		852.9	671.1	796.7	1.86	0.051	0.32	0.54	0.089

* Source: Ohler, 1980

** Sources:
- Ohler (1980) for concentrations in living phytomass and coarse litter
- from experiments 78/34 and 82/2 for decomposed wood and fine litter
- concentrations in soil organic matter have been calculated, using the method described in Section 4.1.2

higher in nutrient deficient locations. For Central Amazonia, on a soil which seems to be comparable to the soil in the study area with respect to edaphic factors, Klinge (1973) gives 778 t/ha above ground and 225 t/ha below ground fresh living phytomass, the weight of roots being 29 % of the above-ground biomass. However, for a similar forest he gives 473 t/ha total dry phytomass of which 14.2 %

TABLE 2.8 Nutrients in vegetation, litter and soil organic matter in undisturbed forest of experiment 82/2

		Nutrient (kg/ha)				
		N	P	K	Ca	Mg
Leaves	trees (dbh >5cm)	128	6	61	58	17
	trees (dbh<5cm), forbs, epiphytes	23	1	20	12	4
	palm	75	5	86	20	8
	liana	9	0	8	5	1
	total	235	12	175	95	30
Branches	large (trees dbh >5 cm)	254	16	216	536	40
	small and twigs (trees dbh>5cm)	179	17	150	193	30
	small (trees dbh <5 cm)	1	0	1	1	0
	liana	20	1	11	15	2
	total	454	34	378	745	72
Stems	trees (dbh>5cm)	765	45	652	1531	125
	trees (dbh<5cm)	6	0	4	7	1
	palm	18	1	26	7	3
	liana	36	2	31	88	5
	total	825	48	713	1633	134
Total	above ground phytomass	1514	94	1266	2473	236
Total	roots	857	58	380	445	79
Total	living phytomass	2371	152	1646	2918	315
Litter	coarse (branches and stems)	105	4	22	138	14
	decomposed wood	93	1	3	4	1
	fine, on soil	158	6	16	33	16
	fine, above soil	35	1	12	25	4
	total	391	12	53	200	35
Total	phytomass without soil	2762	164	1699	3118	350
Soil organic matter	0 -120 cm	7487	150	524	749	225
	120-170 cm	1515	30	106	152	45
	170-300 cm	3075	62	215	308	92
	total	12077	242	845	1209	362
Total	phytomass	14839	406	2544	4327	712

was roots or 17% of the above-ground mass (Klinge, 1976). In eastern Amazonia on a sandy Ultisol, Russell (1983) found a root-to-shoot ratio of 0.255 on 15 exhumed native forest trees. He also found a marked discrepancy between amounts of roots found in soil pits (44 t/ha) and calculated with the root-to-shoot ratio (104 t/ha). For an estimated living root mass of 25 % of the above-ground living phytomass or 20 % of total living phytomass, the average weight of roots at Kabo was calculated to be 109 t/ha (Table 2.7).

The concentrations of nutrients in the phytomass are also given in Table 2.7. The amounts and concentrations of phytomass have been combined to give amounts of nutrients in the phytomass for undisturbed forest (see Table 2.8). These amounts are large, especially compared with the amounts of available nutrients in the soil (Chapter 4).

3 Hydrology

3.1 Introduction

The study of the hydrology of the forest on a catchment area scale was considered necessary in order to understand the way in which the ecosystem functioned. A small catchment area of 295 ha, representative of the area of the forestry experiments, was selected. Two small creeks of approximately equal size, Eastern Creek and Western Creek, rise in the catchment area and flow into the the Ingipipa Creek. Here a dam with a measuring weir was built a short distance from the confluence of both tributaries. In this chapter the hydrology of the whole catchment area draining through the dam in the Ingipipa Creek is discussed.

Data were collected on rainfall, evaporation, discharge, topography, soil, substratum and groundwater for the hydrological study. A computer model, WOFOST4, was used to combine measured data and to estimate those features for which observations were not available.

3.2 Collection of hydrological data

3.2.1 Rainfall and evaporation measurements

Rainfall measurement

Rainfall was measured daily using hand operated, 1.5 m high, rain-gauges with a surface area of 200 cm^2. Rainfall was also measured automatically every 30 minutes from a rainfall recorder just above ground level whose surface area was 2472 cm^2. Both rain-gauges were located in a clearing of 80 x 90 m, near the western side of the watershed (R on Fig. 3.4). These rain-gauges are called Hand Tonka and RECOVER respectively. Most of the RECOVER is situated below ground level, the part above ground is shown in Fig. 3.1. The RECOVER operated from 1 November 1980 and the Hand Tonka from 6 March 1981. Rainfall data from Kabo meteorological station, 4 km north-east of the Tonka site, were used for the earlier period. These were determined with a hand operated, 1.5 m high rain-gauge, referred to as Hand Kabo. Details of the rainfall measurement are given in Appendix IV.

Fig. 3.1 Hand-operated rain gauge at a height of 1.5 m in the background and "Recover" automatic rainfall recorder in the foreground. To the left the large funnel 10 cm above the soil surface and to the right the uncovered water level recorder

Monthly data of rainfall, evaporation (Class A Pan), and creek discharge, including leakage losses, are given in Table 3.1, together with totals per hydrological year (1 November to 31 October) for the period 1979/80 to 1983/84. During this period, rainfall varied from 1794 to 2466 mm and discharge from 295 to 862 mm.

Evaporation measurement

Evaporation was measured with a Class A Evaporation Pan at Kabo meteorological station. Each day the water-level in the 1.21 m^2 pan was restored to 7.5 cm under the rim, measuring the amount of water needed, and correcting for rainfall. Meteorological components related to evaporation, such as sunshine, cloudiness, temperature and air humidity were also measured, and for a very limited period wind speed was recorded. Potential evapotranspiration (PET) was calculated by Goense (1987) for Zanderij meteorological station, where sufficient data were available. PET and Class A Pan values were not in close agreement. At higher evaporation, Class A Pan values were similar to PET but at lower evaporation they were lower (Fig. 2.9). Monthly values for Class A Pan evaporation are given in Table 3.1.

TABLE 3.1 Rainfall, evaporation of Class A Pan (EPan) at Kabo and discharges from the catchment per month and per hydrological year

Month and Year	Rainfall (mm)	EPan (mm)	Discharge* (mm)	Month and Year	Rainfall (mm)	EPan (mm)	Discharge* (mm)
1179	(95)	(144)	0	1182	54	155	0
1279	(165)	(115)	0	1282	132	120	1
0180	(144)	(108)	0	0183	140	103	6
0280	(27)	(98)	0	0283	144	94	2
0380	(203)	(105)	0	0383	173	105	7
0480	(244)	99	0	0483	413	86	63
0580	(266)	99	19	0583	273	103	97
0680	(339)	106	106	0683	173	119	68
0780	(156)	127	84	0783	67	137	34
0880	(195)	152	61	0883	83	169	13
0980	(64)	176	20	0983	79	161	4
1080	(71)	153	5	1083	63	189	0
79/80	(1976)	(1482)	(295)	82/83	1794	1541	295
1180	189	131	6	1183	58	154	0
1280	108	115	6	1283	194	112	0
0181	116	120	6	0184	164	103	0
0281	328	84	27	0284	77	124	0
0381	145	153	49	0384	65	143	0
0481	324	116	57	0484	171	124	0
0581	356	109	97	0584	372	102	18
0681	249	108	124	0684	325	111	62
0781	218	130	92	0784	269	133	95
0881	174	154	63				
0981	63	166	37				
1081	196	168	37				
80/81	2466	1554	601	83/84	(1695)	(1106)	(175)
1181	80	137	12				
1281	227	111	24				
0182	158	106	24				
0282	164	89	27				
0382	285	95	46				
0482	402	99	165				
0582	319	105	194				
0682	252	107	147				
0782	252	133	117				
0882	108	153	67				
0982	75	172	29				
1082	32	173	10				
81/82	2354	1480	862				

( ) Estimated values.
* Including leakage losses.

3.2.2 Discharge measurements

Dam and measuring weir

Discharge was measured with a sharp-crested triangular weir, commonly known as V-notch or Thomson weir. In the 1979 dry season an earthen dam was built across the creek and the adjoining swampy lands to the north of the catchment area (Figs. 2.11 and 2.12). In an opening 2.85 m wide in the dam, a weir was constructed of wooded planks, driven vertically into the soil to a depth of 1 m below the creek bottom. The construction was facilitated by little rain and negligible discharge during the short rainy season, December 1979 to January 1980. A V-shaped triangle with a notch angle of 90° was sawn out of these planks. Thin aluminium strips were nailed to the wood on the upstream side of the V-shape notch to give the necessary sharpness (< 2 mm) to the crest (see Figs. 3.2 and 3.3).

The opening of the weir was lowered in November 1980 resulting in a decrease in the distance between vertex and creek bottom from 0.6 to 0.5 m. For details of the construction and the measuring of the water head, see Appendix IV.

Measurement of leakage losses

Leakage losses, defined as discharges that do not pass the weir, could only be measured when the weir had no discharge. In a dry period when the water level

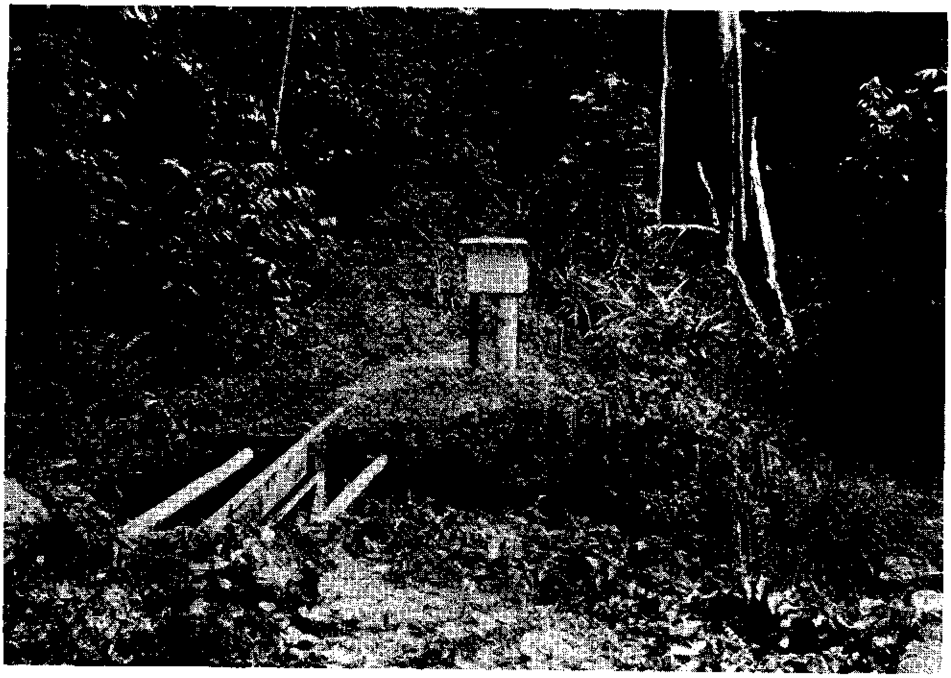


Fig. 3.2 Earthen dam across the swampy valley bottom with measuring weir in the foreground and water level recorder in the background; dry season, no water before dam

Fig. 3.3 Sharp-crested triangular weir for measurement of discharge; wet season

dropped below the vertex ($h < 0$), a small discharge continued in the creek bed behind the weir. If the water level dropped sufficiently this flow stopped or went underground. The flow resulted from leaks in the dam, along or through pores in the weir or through the sand under the dam. These leakage losses had to be taken into account in calculating water and nutrient balances. Weir discharges and leakage losses have been combined to obtain the total discharge.

Measurement of the leakage losses are described in Appendix IV. The following relationship between discharge Q (l/s) and overflow level h (m) was found

Before 12 November 1980: $Q = 0.98\,h + 0.326$ (3.1)
After 12 November 1980: $Q = 0.98\,h + 0.245$ (3.2)

Leakage losses were relatively low. The mean annual discharge was 586 mm (Table 3.1), corresponding to a mean discharge of 55 l/s. At an overflow level of 27.5 cm, which produced a discharge of 55 l/s, leakage was 0.51 l/s. Thus leakage is estimated to be about 1 % of the total discharge.

3.2.3 Calculation of the discharge

To calculate the discharge at 15-minute intervals, Discharge Measurement Structures (Bos 1976) was used:

$$Q = Ce \times 8/15 \times 2g^{0.5} \times \tan 0.5a \times h_e^{2.5} \tag{3.3}$$

where

Q : discharge (m^3s^{-1})
Ce : coefficient of discharge
g : gravitational acceleration (ms^{-2})
a : weir notch angle –
h : water head (m)
h_e : effective upstream head over crest ($h+Kh$) (m)
Kh : head coefficient (m)
p : water depth in front of the weir if $h=0$ or distance between vertex and creek bottom (m)

The coefficient of discharge Ce and the value of the gravity g have been examined in detail (Appendix V). Gravity at the dam site was calculated to be 9.78 m/s^2. Ce appeared to be dependent on the overflow level h, the distance between vertex and creek bottom p, and on the adopted value of the head coefficient Kh. For Kh of 0.0008 m, the following relationships for Ce were found:

$$Ce=0.57835 + 0.2226\times|h-0.15|^{1.56} \quad \text{for } h \leqslant 0.08\text{m} \tag{3.4}$$
$$Ce=0.57835 + 8.423\times10^{-5}\times e^{57.14\times|h-0.15|} \quad \text{for } 0.08<h<0.15\text{m} \tag{3.5}$$
$$Ce=0.57835 + 4.034\times10^{-5}\times e^{63.61\times|h-0.15|} \quad \text{for } 0.15\leqslant h<0.19\text{m} \tag{3.6}$$
$$Ce=0.57835 + 0.02178\times|h-0.15|^{1.134} \quad \text{for } h\geqslant 0.19\text{m},\ p=0.6\text{m} \tag{3.7}$$
$$Ce=0.57835 + 0.02402\times|h-0.15|^{1.176} \quad \text{for } h\geqslant 0.19\text{m},\ p=0.5\text{m} \tag{3.8}$$

where $|\ \ |$ denotes absolute value.

Introducing the values for g, a and Kh in (3.3) gives

$$Q = Ce \times 2.35877\ (h+0.0008)^{2.5} \qquad m^3s^{-1}\ (h>0) \tag{3.9}$$

3.2.4 Determination of the size of the catchment area by topographical survey

An essential factor in water balance studies is the size of the catchment. Discharge is measured for the whole catchment whereas rainfall is measured over a very small area, the surface area of the rain-meter opening. The amount measured must be extrapolated to find the amount of rain-water over the whole catchment.

A topographical survey was made of the catchment area and surroundings and from the resulting contour map, the boundaries of the catchment were constructed (Fig. 3.4). For details, see Appendix IV. The total catchment area, that is the total area draining through the dam, was calculated to be 295 ha; 140 ha in the Eastern creek area and the area east of the main creek beyond the confluence of both

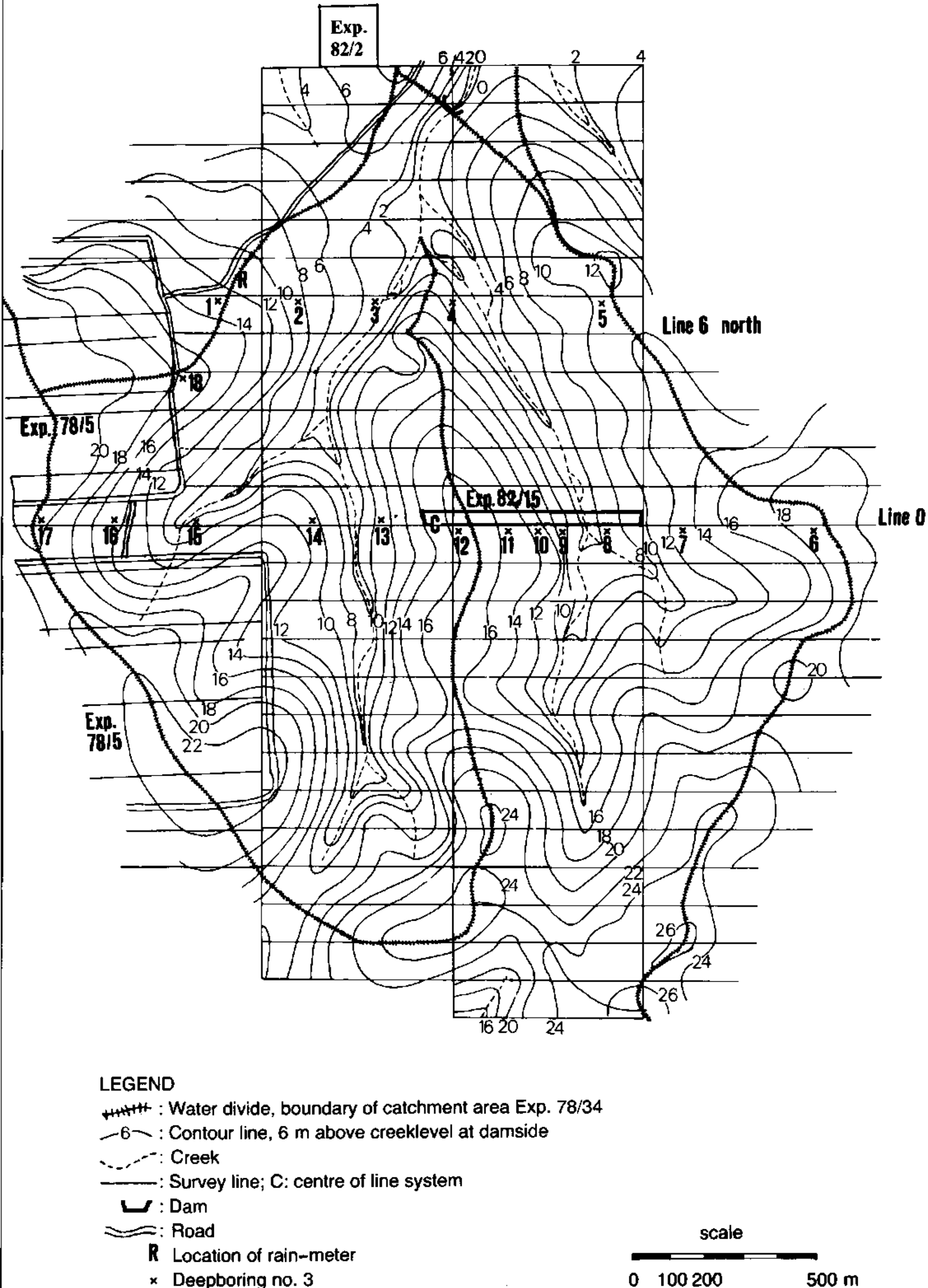


Fig. 3.4 Topographical map showing contour lines, location of experimental areas and deep borings

tributaries, and 155 ha in the Western creek area and the area west of the main creek beyond the same confluence.

The catchment area was slightly undulating with rather level plateaus and with convex slopes to the creek valleys. The creek valleys are concave, narrow upstream and become wider near the dam. During the soil survey and the preparation of the soil map, much use was made of the topographical map, because topography and soil appeared to be strongly related.

3.2.5 Measurement of groundwater levels in deep borings

In the project area 18 deep borings were made to a depth of 7.5 m (Appendix IV). All borings except one, no. 18, are on two lines, Line 6 north and Line 0 (Figs. 2.12 and 3.4). Cross-sections through these lines showing the location of the deep borings and the composition of the soil and substratum, are given in Fig. 3.5. This composition was recorded as the deep borings were being augered. The Zanderij sediment, which is up to 4 m thick in these cross-sections, overlies residual material which generally consists of kaolinitic clay with varying amounts of laterite gravel. Textures in other locations are more sandy, either sandy clay or sandy clay loam. In some places there are cemented sheets of laterite, with or without quartz gravel. The deeper part of the borings generally had a clay texture. Near the creeks the Zanderij material does not consist of sandy clay loam but of sand to loamy sand.

The measured groundwater levels (see Appendix VI) fluctuated considerably throughout the year. At the peak of the rainy season (May 1983, July 1984) levels in some holes were more than 4 m above those recorded at the end of very dry periods (December 1982 and 1983, April 1984).

The lowest amplitudes, that is the differences between highest and lowest levels, were observed close to creeks, deep borings nos. 8, 13 and 15. The highest amplitudes were found in the centre of large interfluves, for example in Line 6 western part, borings 1 and 2; and Line 0 eastern part, borings 6 and 7. The amplitude of the water-levels in boreholes nos. 1 and 6 on the plateaus of these interfluves could not be established because these holes were dry for long periods each year. The other boreholes on the plateaus (nos. 5, 11, 12 and 17) were often dry, too. Maximum amplitude in borehole no. 1 was estimated to be 7.5 m and in borehole no. 6 it was 6.5 m.

The time at which seasonal highest or lowest levels occurred differed from borehole to borehole. For example, in the 1983 rainy season boreholes nos. 4, 7, 9, 11, 13 and 14 reached their highest levels on 4 May, while the other boreholes reached their maxima later. It appears that small interfluves reacted quickly while large interfluves took longer to respond.

Groundwater samples from the deep borings were taken on 1 June and on 17 August 1983 and analysed for chemical composition. This is discussed in Chapter 4.

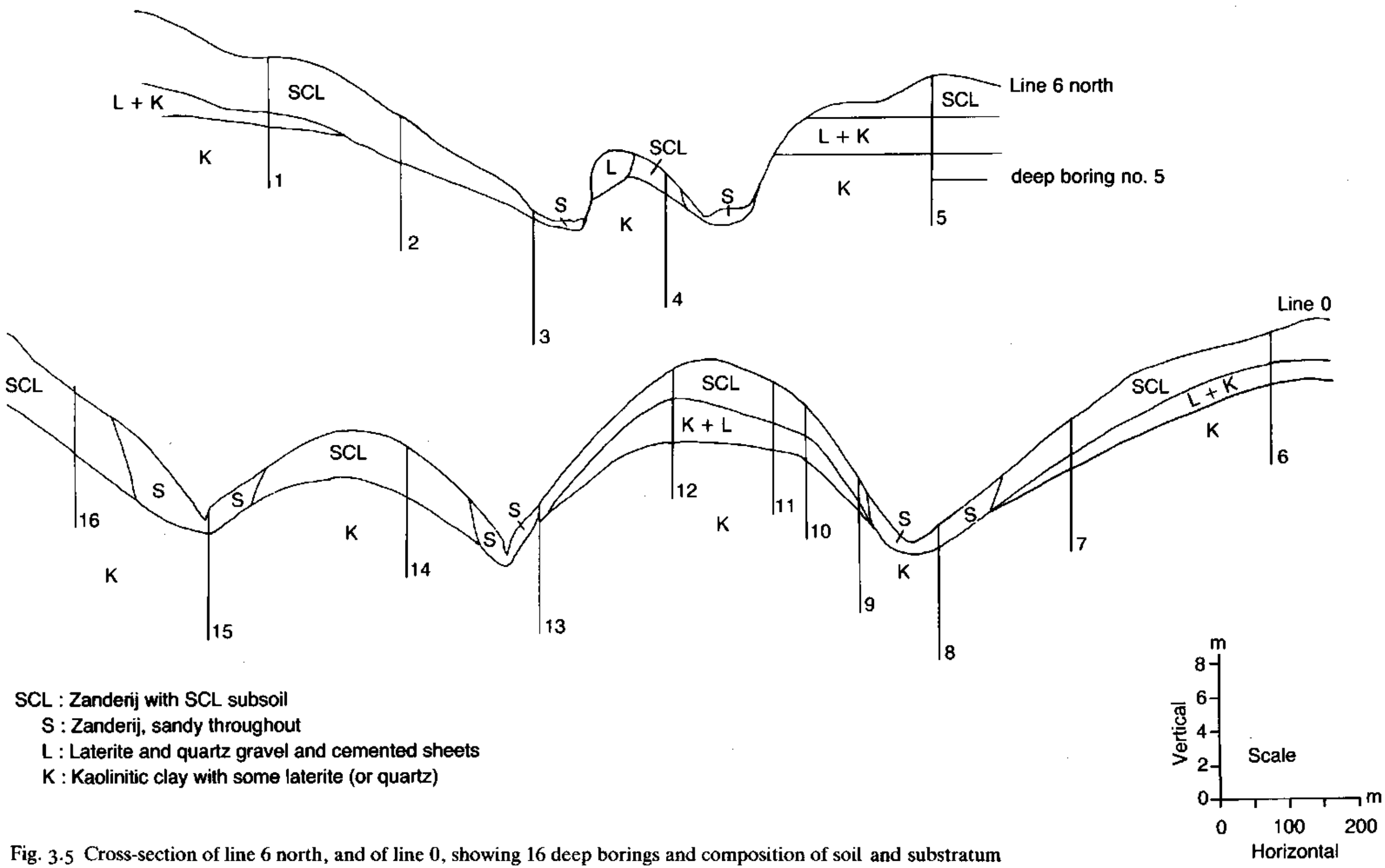


Fig. 3.5 Cross-section of line 6 north, and of line 0, showing 16 deep borings and composition of soil and substratum

The hydraulic conductivities of the soil layers below the groundwater table to the bottom of the boreholes were measured on 16 and 17 August 1983 using the Hooghoudt method (van Beers, 1958). The rise of the groundwater table was measured with the same chain and sounder used to measure weekly groundwater levels. Details of measurement and calculation are given in Appendix IV.

To calculate the hydraulic conductivity, the logarithm of the drawdown of the groundwater table was plotted against time. In most cases a linear relationship was found and a straight line could be drawn through the points until t=0, the moment of bailing. At the intersection y_0, the maximum drawdown just after bailing can be read. The graph for deep boring no 3 is given in Fig. 3.6 .

The hydraulic conductivities varied from 0.16 to 10 m/d (see Table 3.2). Depth had a slight influence. Conductivities were higher near the surface, reflecting the effects of the more permeable Zanderij sediment and greater biological activity in the upper layers. Conductivities varied considerably in the borings near the creeks, where very permeable sandy layers, and in some places impermeable clay layers occurred. Being high above the groundwater table at the time of measurement, conductivities in the top layers of the plateaus and slopes could not be measured. The porous granular structure, the absence of signs of waterlogging, and rapid infiltration of rain-water indicated that these layers conduct water rapidly. During

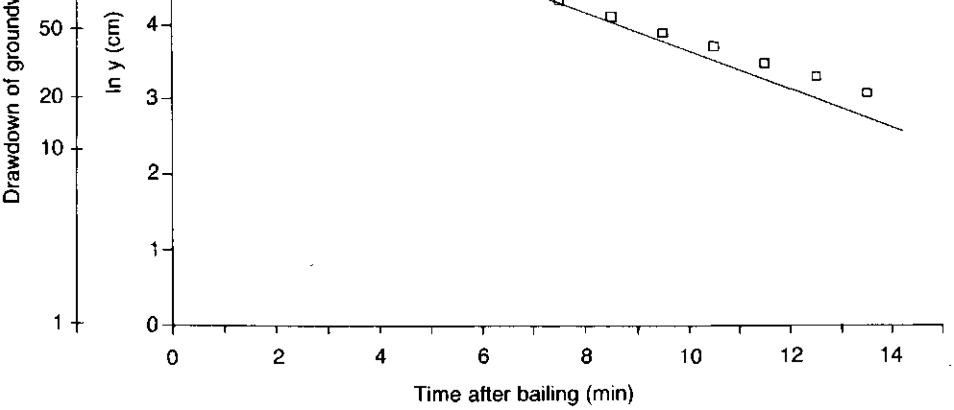


Fig. 3.6 Logarithm of drawdown of the groundwater (Y) in relation to time after bailing used in calculation of saturated hydraulic conductivity

TABLE 3.2 Measured hydraulic conductivities (K in m/d) in deep borings and the composition of the corresponding soil layers

Bore hole no.*	Measured layer (cm)		Hydraulic conductivity (m/d)	Drain depth** (cm)	Distance between average measured layer and drain depth (cm)	Soil composition of measured layer***
	range	mean				
1	667-783	725	0.16	1020	295	hard laterite
2	442-739	591	1.0	640	49	KC
3	20-386	203	0.54	60	-143	KC and SC
4	273-642	458	3.0	300	-158	KSC on KC
5	661-779	720	0.4	880	160	KC
6				970		
7	515-756	636	3.0	740	104	KSC
8	62-332	197	2.0	110	- 87	sand and KC
9	337-697	517	1.9	400	-117	KC on SC
10	705-800	753	1.5	840	87	KC
11				1010		
12				1120		
13	282-696	489	6.0	340	-149	KSCL on KSC
14	548-770	659	1.0	610	- 49	KSC
15	113-202	158	10.0	80	- 78	sand on coarse SC
16	496-773	635	4.0	770	135	coarse KSC
17				1320		
18	756-792	774	3.5	1320	546	KSC

* No measurement made for boreholes nos. 6, 11, 12 and 17.

** The distance from the soil surface near the borehole to a horizontal line through the creek level.

*** K is kaolinitic; C is clay; S is sandy; L is loam.

very wet periods the groundwater rose high into these layers (Appendix VI). Their conductivity is therefore important in the drainage of rainfall peaks.

No clear relationship was found between the location of the measured layer with respect to drain depth and conductivity (Table 3.2). Hydraulic conductivity seemed only to be affected by the distance to the surface. Measured layers, to 5 m depth, had an average conductivity of 4.3 m/d and measured layers, deeper than 5 m, had an average conductivity of 1.8 m/d.

3.2.7 Diurnal variations of water-levels in creeks and deep borings

Variations were observed in creek discharge throughout the day during dry periods. The most extreme observation was at the Western creek at line 6 north, during a dry sunny period in October 1982. A very low discharge had stopped completely, and had resumed half a day later. Yet no rain had fallen. Discharge at the dam site showed similar diurnal variation.

Discharges, including leakage losses for the period 14 – 22 October 1982, are

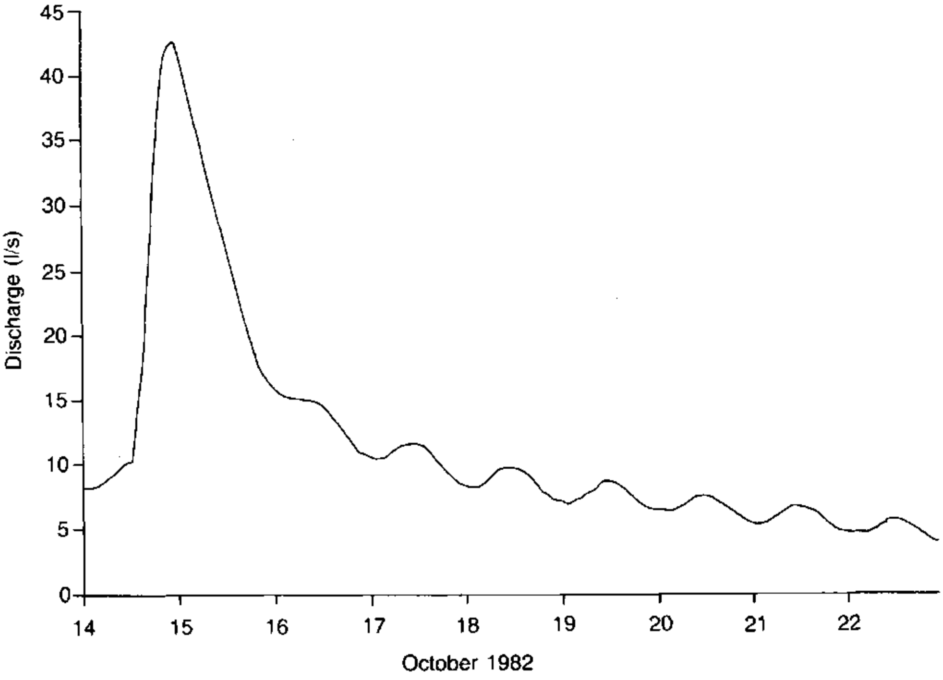


Fig. 3.7 Peak and diurnal variations in creek discharges, including leakage losses for the period 14 – 22 October 1982

given in Fig. 3.7. Discharges were low and decreasing and they stopped completely at the beginning of November 1982. On 14 October, 15.6 mm of rain was recorded and on 15 October 0.1 mm. In the period 16 – 22 October there was no rain at all. The discharge peak on 14 and 15 October shown in Fig. 3.7, consisted mainly of direct flow. A transitional period was noted on 16 and 17 October and a period with only base flow occurred from 18 to 22 October. In this latter period clear diurnal variations are visible, discharges being lowest from 23.00 to 02.00 hours and highest from 11.00 to 14.00 hours.

The withdrawal of water by trees in the swampy valley bottom is probably the main cause of these variations. Transpiration is highest about midday and maximum withdrawal of water by the roots occurs slightly later. The resulting water-levels are therefore expected to be lowest in the late afternoon. At the dam site, however, the lowest levels came about 8 hours later. This probably corresponds with the average travel time of discharge waves in the creek.

To investigate whether the forest outside the valley bottom also extracted phreatic water, water-levels in three deep borings were measured at two-hourly intervals from 08.00 hours on 24 October 1983 to 08.00 hours on 25 October 1983. Measurements were made with chain and sounder and are therefore not very accurate. They are given in Fig. 3.8. Boring 3, line 6 200 m west, situated in the swampy valley bottom with a water-level approximately 90 cm below surface,

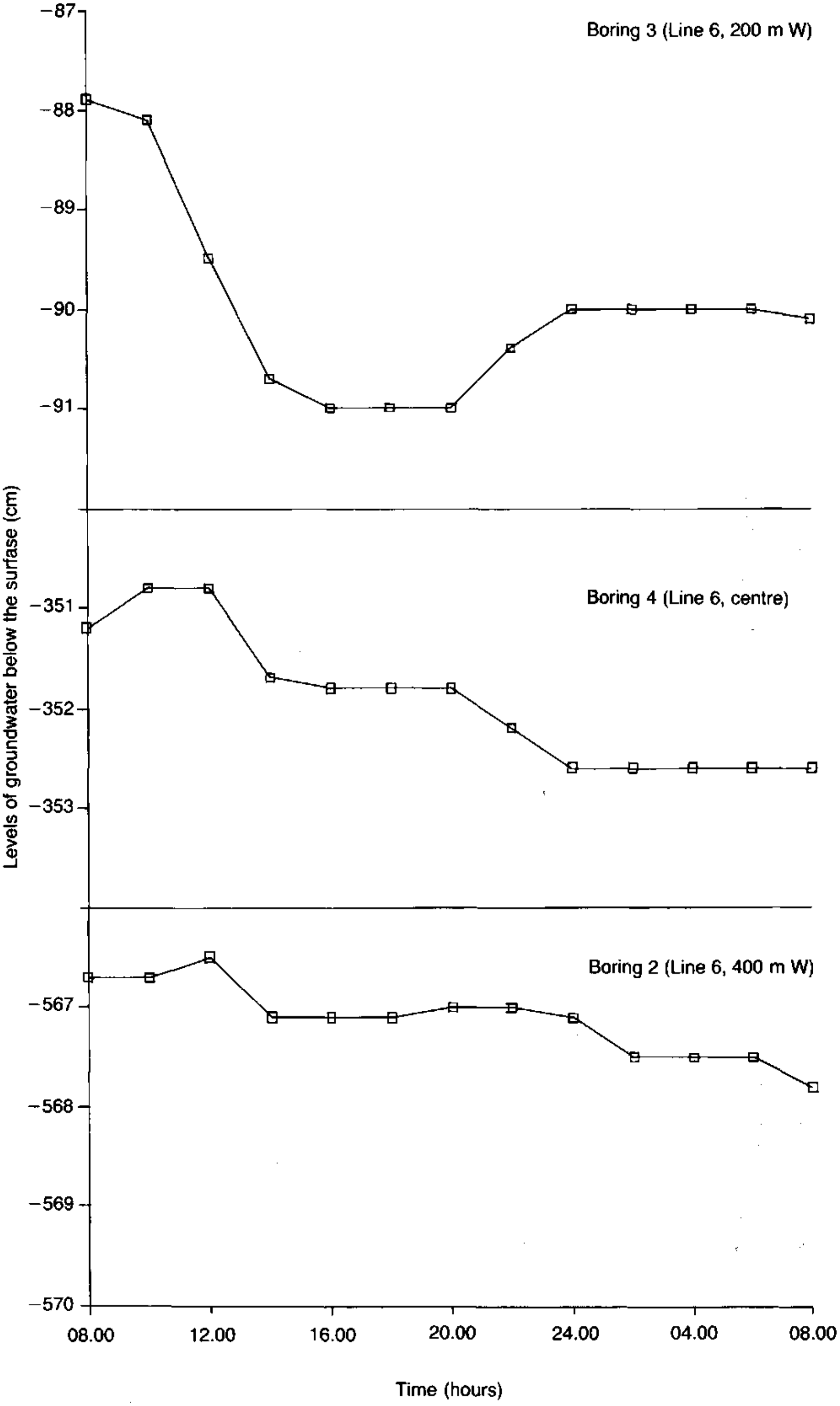


Fig. 3.8 Diurnal variations in groundwater levels in a valley bottom (boring 3), on a footslope (boring 4), and on an upper slope (boring 2)

Fig. 3.9 Stereo photograph of swamp forest in the valley bottom, in the foreground plastic pipe of deepboring no 3. Note abundance of swamp palm species *Euterpe oleracea* and open canopy (courtesy: K.E. Neering)

showed the largest variation of about 2.5 cm. Levels in boring 4, line 6 centre, on a lower slope (Fig. 3.4) with the water-level at 350 cm depth, varied by 0.7 cm. In boring 2, line 6, 400 m west, halfway along a very long slope with groundwater at about 570 cm depth, the level varied by 0.4 cm. Apart from these fluctuations, water-levels declined because of the withdrawal of water by trees and the absence of recharge by rain. Creek discharge stopped on 21 September.

Boring 3 had one oscillation per day, similar to the creek discharge (Fig. 3.8). This was in phase with water withdrawal by trees, but 5 to 8 hours earlier than in the creek at the dam. The more complex pattern in borings 2 and 4 of 2 or 3 oscillations per day may be explained as the delayed effect of groundwater withdrawal by tree roots in the upstream area between the boring and the water divide. A stereo-photograph of the swamp forest in the valley bottom near boring no. 3 is given in Fig. 3.9.

3.2.8 Air and water in a representative soil profile

Average pF profiles for different soil layers were made for the most common soil unit, the well to moderately well drained sandy clay loam soil of the plateaus and the upper slopes. Of the 28 profiles described and sampled, 13 belong to this category. Average pF values are given in Table 3.3. They have been calculated from Table IV.4 in Appendix IV.

Average pF relationships for the layers 0-300 cm and 0-1200 cm are also given in Table 3.3. The pF values for the layer 0-300 cm have been arrived at by averaging the sub-layers. In the values for the layer 0-1200 cm, average soil moisture contents for the root zone and measured values for the storage coefficient μ (Section 3.4.3), have been combined for use in hydrological models.

TABLE 3.3 Mean porosity and moisture content at different pF values for loamy plateau soils under forest at Kabo

Layer (cm)	Porosity (vol %)	Moisture content (vol %) at pF					
		1	1.5	2	2.7	3.5	4.2
0- 10	52.9	38.7	29.0	21.0	14.3	10.0	7.6
10- 20	48.2	36.5	29.5	22.6	15.6	12.5	9.9
20- 40	45.3	35.1	29.9	23.6	16.6	14.4	11.8
40- 60	45.0	34.7	30.1	24.2	17.3	15.5	13.1
60- 80	45.3	34.3	30.0	24.3	17.5	15.9	13.6
80-100	45.4	33.9	29.9	24.3	17.7	16.2	13.9
100-120	45.6	33.7	29.8	24.3	17.8	16.4	14.2
120-150	45.7	33.4	29.7	24.3	17.9	16.6	14.5
150-200	45.9	33.1	29.6	24.3	18.1	17.0	14.8
200-300	46.2	32.6	29.5	24.3	18.3	17.5	15.4
Mean 0- 300	46.0	34.2	29.8	24.0	17.4	15.7	13.5
Mean 0-1200	28.0	27.1	26.0	24.5	21.9	18.6	15.5

3.3 Computer models WOFOST and WOFOST4

An adapted version of computer model WOFOST (van Keulen and Wolf, 1986) called WOFOST4 was used to predict water movements in the soil. It was also used to estimate evapotranspiration of the forest during wet and dry periods and to gain insight into other aspects of the water balance, such as rooting depth and available soil moisture. Knowledge of these processes is needed in order to understand the nutrient cycling.

3.3.1 The original model WOFOST

WOFOST is a one dimensional model to simulate the water balance and growth of a particular vegetation (van Keulen and Wolf, 1986). It was thought that such a model may also simulate the water flows in the catchment. The water balance in the original WOFOST model, described by Driessen (1986), is composed of measured daily totals of rainfall, calculated daily discharge, evapotranspiration, the amounts of water in the root zone, the amounts of groundwater and the variations in these amounts.

WOFOST, written in FORTRAN, calculates potential crop production under given climatic and soils conditions. In this model, water flow is simplified to include only flow through the soil surface, the lower level of the root zone, the groundwater level, and the drainage base-level (Driessen, 1986). The root zone is not subdivided into compartments. The advantage of this simplification is that a micro-computer is sufficient to carry out the simulation.

The WOFOST model has been adapted to simulate growth and water balance in a tropical rain forest under prevailing weather conditions and assuming that nutrients are in optimal supply.

3.3.2 WOFOST4

In the catchment most of the net rainfall enters the soil and surface runoff is only important in the saturated valley bottoms which occupy 7 % of the area. The topographic map (Fig. 3.4) suggests that the average distance between creeks is about 600 m. The central part of the catchment area, where the Eastern and Western creek run parallel and 600 m apart was considered representative. Here the creek level, which acts as the drainage base, is about 10 m below the level of the plateau.

Plateaus and upper slopes which make up the major part of the catchment area are quite uniform in topography, soils and vegetation. Slopes are generally less than 4 % and the vegetation is high dryland forest. The soils are mostly sandy loam over sandy clay loam of Zanderij origin with groundwater tables at 4 to 7 m depth or even lower. WOFOST was applied to the conditions of the plateaus and upper slopes that were considered to be representative of the catchment area.

The following assumptions were made in the model: the land is level; all rainfall reaching the soil surface infiltrates and there is no surface runoff; drains are 600 m apart; all discharge occurs as groundwater flow, and rainfall, discharge and all other hydrological data are expressed in cm/d. A simplified relational diagram of the model is given in Fig. 3.10. The hydrological part of the model is given in Fig. 3.11. This shows how the water supply in the soil is generated by the water balance. The water supply is characterized by the soil suction which influences both transpiration and assimilation.

WOFOST4 is an adaptation of WOFOST and simulates water balance and forest growth in tropical rain forest. It describes only those functions of the rain forest related to water use, assimilation and biomass. Based on data from Van Keulen and Wolf (1986) the main characteristics of the rain forest are defined as follows:

Crop type C3; light extinction coefficient of the leaves 0.6; efficiency of conversion of assimilates to plant material ca 0.7; life span of leaves 365 days; the daily maintenance respiration fractions of leaves, roots and stems are 0.065, 0.015 and 0.0004 kg/kg respectively; the maximum death rate of leaves due to water stress was set at 0.025 kg/kg; the relative death rate of roots and stems is 0.00003 kg/kg initially and 0.01 kg/kg when roots and stems have reached maximum weights. The rooting depth was varied in different simulations between 1 and 8 m and the initial life weight excluding heartwood was taken as 99 t/ha. The development rate was 0.0014 and the fractions of the total net assimilate production partioned to

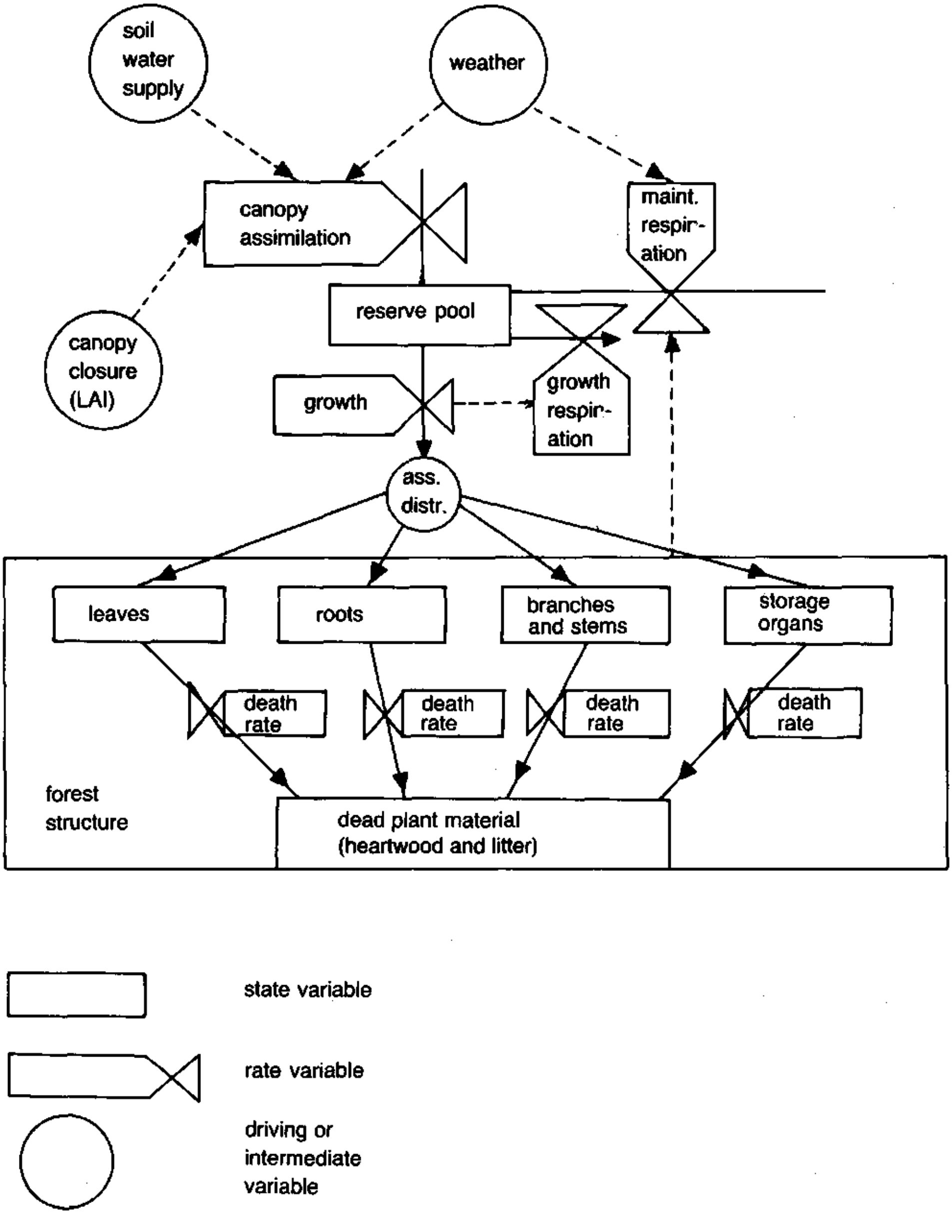


Fig. 3.10 Simplified relational diagram of the crop growth model in WOFOST. Solid lines: material flows; dotted lines: relationships between variables (adapted from Mohren, 1987)

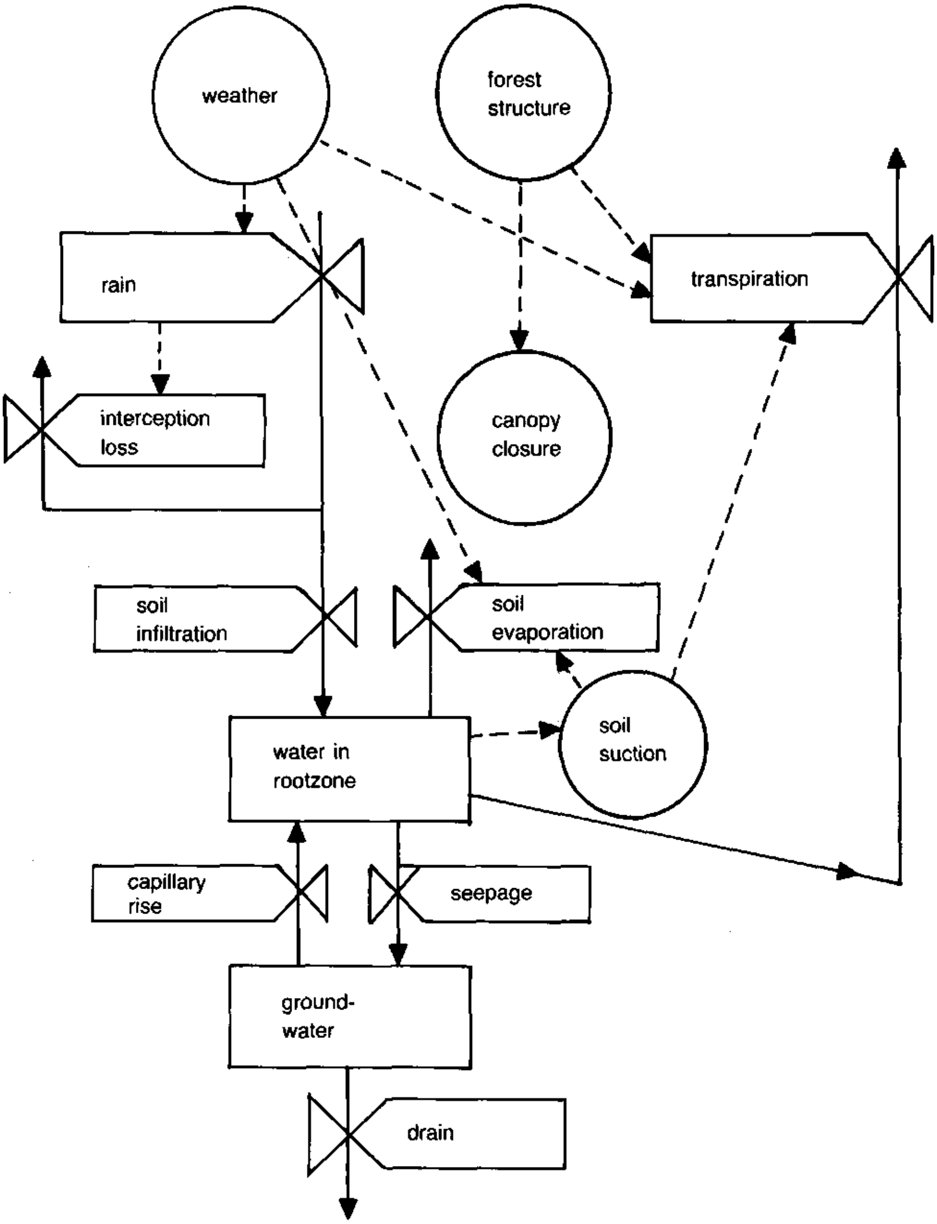


Fig. 3.11 Simplified relational diagram of the hydrological part of WOFOST4. Soil suction is a driving variable for transpiration and for crop growth (Fig. 3.10) (adapted from Mohren, 1987)

different organs were: roots 0.15, leaves between 0.13 and 0.34, stems between 0.72 and 0.48, and storage organs between 0 and 0.03. The specific leaf area was set at a steady 0.0007 ha/kg. The fraction of available soil water that can be withdrawn by roots at maximum transpiration rate (Tm) is lower at high Tm and higher at low Tm. At a Tm of 4 mm/d the fraction is 0.7 and when this fraction has been used, transpration reduction caused by water stress starts.

Detailed information about the meaning of these characteristics is given by Van Keulen and Wolf (1986). The principal changes involved in using this program for tropical rain forest instead of agricultural crops included the lenthening of the life span of leaves, a severe reduction of maintenance and development rates, the introduction of a maximum forest biomass by manipulating the death rate, and shifting the partitioning of assimilates from storage organs to stems and branches with the aim of bringing the phytomass amounts of the simulated forest closer to those of the real forest.

3.4 Main adaptations of WOFOST to WOFOST4

In this section the most important aspects of WOFOST4, especially the adaptations of WOFOST to WOFOST4 are described. Measured daily values of rainfall and pan evaporation provided the data for WOFOST4, instead of the monthly data used in WOFOST. WOFOST4 calculated the discharge from the water balance which was then compared with the measured discharge.

3.4.1 Potential Gross Assimilation Rate (PGASS)

In the simulation, more attention was given to the the water balance than to forest growth. The objective was to develop a forest model which had an effect on the water balance like the real forest and which showed realistic patterns of growth and biomass production. The potential gross assimilation rate (PGASS) depends on solar radiation. For Kabo, situated at 5° N, maximum PGASS was set at 525 kg dry matter per ha per day for a cloudless day, and a minimum PGASS of 190 kg of dry matter for a completely overcast day. This was based on data given by van Keulen and Wolf (1986). As daily sunshine hours or cloud covers were not available for the whole period, Class A pan evaporation was used to calculate PGASS. For a day with a Epan $\geqslant$ 6mm, a PGASS of 525 kg/ha has been assumed; for a day with a Epan $\leqslant$ 1 mm a PGASS of 190 kg/ha has been assumed and for a day with an Epan between 1 and 6 mm, PGASS was found by liniar interpolation.

3.4.2 Forest growth

It was assumed that the vegetation received an optimal nutrient supply. Simulation for a nutrient limited situation was not done. Actual dry matter increases might therefore be somewhat lower than the calculated increases. The water balance is not expected to be influenced very much by a limited nutrient supply. Because of the large biomass, maintenance respiration (MRES) consumes a large part of gross assimilation (GASS). It was postulated in the original model that MRES is never larger than GASS, so the vegetation is not self-consuming. This is important in dry periods when GASS falls below 200 kg/ha, while calculated MRES values are around 200 kg/ha. It is probably an oversimplification to suggest that MRES is always smaller than GASS, but the model was used unchanged. To bring MRES to a realistic level, maintenance respiration rates were drastically reduced in comparison with the values assumed for agricultural crops. The maintenance respiration rates which were finally adopted are hypothetical. They are not based on measurements or data from the literature but they do give a realistic forest growth.

Branches were treated as stems because both consist of wood and bark, 40 % of which is alive (sapwood). MRES is calculated only for the sapwood. Bark is treated as wood. The same applies to the roots, 40 % being alive and requiring maintainance respiration. A maximum live root weight of 40 t/ha and a maximum live branche+stem weight of 150 t/ha were introduced in order to reach a steady state in forest growth. This corresponded to a total dry weight of 100 and 375 t/ha respectively. When the living tissue reaches these weights, mortality increases so that life weights can be maintained at these levels. Mortality adds biomass to the DEAD compartment which includes heartwood and litter.

Leaves die as a result of water stress, when actual transpiration remains behind maximum transpiration ($T/Tm < 1$). They also die when the surface area of the leaves reaches the maximum leaf area index, LAI (set at 9) and because of senescence which occurs when leaves reach their maximum age (set at 365 days). In the model the maximum leaf age of 365 days was not reached because the oldest leaves were supposed to die first in cases of water stress and too high LAI and, because due to these losses, much leaf weight was removed. Dying leaves become litter, dying stems go partly to litter and partly to heartwood, dying roots become either heartwood or decompose in the soil. In the model, all dying plant material goes to the DEAD compartment.

3.4.3 Drainage

In the WOFOST model the drainage of groundwater to drains was calculated using the equation (Kirkham 1958; 1961):

$$D = \frac{K \times M0}{M0 + L/3.14 \times \ln(L/(3.14r))} \qquad (3.10)$$

where

D	is drainage rate (cm/d)
M0	gravity head (height of water-level above drain depth halfway drains) (cm)
K	saturated hydraulic conductivity (cm/d)
L	drain spacing (cm)
r	drain radius (cm).

Equation 3.10 is intended for deep homogeneous soils in which most flow occurs below drain depth. The relationship between drainage and gravity head is given as a steady state situation. This equation was not used in WOFOST4 because of the poor agreement between measured and calculated discharges, and between measured and calculated groundwater depths. Measured hydraulic conductivities in the auger holes varied considerably but were approximately 1 m per day. Conductivities of the upper layers are probably much higher because of the occurrence of strongly weathered, sandy clay loam textured, oxisol profiles. Most flow to the creeks is to be expected above drainage level, that is 10 m below surface level, and only a little below 10 m depth where rather dense kaolinitic clay occurs.

The Kirkham equation (3.10) only considers the flow below drain level, in this case the depth of creeks below the level of the plateaus. It is therefore unsuitable for describing the groundwater flow. Thus it was considered preferable to use a different drainage equation. Kirkham's equation was replaced by the equation of Hooghoudt (Van Beers, 1958) which deals with a two-layer profile with different hydraulic conductivities in each layer.

$$s = \frac{8 \times K(l) \times d \times M0 + 4 \times K(u) \times M0^2}{L^2} \qquad (3.11)$$

where

s	is rainfall (m/d)
K(u)	conductivity above drain level, set at 2 m/d
K(l)	conductivity below drain level, set at 1 m/d
d	equivalent depth of flow below drainage level, set at 25 m (later 10 m)
M0	gravity head halfway between drains (m)
L	distance between drains, set at 600 m

Equation 3.11 considers flow both below and above drain level. The flow below drain depth is still more important than the flow above drain depth, for the conductivities given above, even at a d-value of 10 m. Moreover, like equation

3.10, equation 3.11 describes a steady state situation. In reality flow is far from steady, particularly as most of the flow occurs above drain level. Large variations in discharge are measured from day to day.

Equation 3.11 performed slightly better in the simulations than Equation 3.10, but was still not good enough. It was obvious that an equation describing non-steady flow was needed. A suitable method had been developed by Ven (1979) for newly reclaimed polder land, which is highly permeable in the upper layers due to shrinkage cracks and impermeable in the subsoil below drain depth. In Ven's equation, the groundwater storage is equal to the drainable groundwater above drain level and the discharge rate is related to the size of this store. Ven concluded that a non-linear relationship is applicable because the permeability of the soil is not constant above the drain. The relationship between storage (S), discharge (Q), storage coefficient (μ) and gravity head (M0) given by Ven (1979) is

$$S = M0 \times \mu \qquad \text{and} \qquad Q_t = (S_{t-1}/K)^N \tag{3.12}$$

in which K and N are constants for a given drainage situation. The time step t is one day. Discharge depends on the amount of water in storage on the previous day. Ven assumes a rectangular shape of the groundwater level (M is taken as constant between drains = M0). Ven found K values of about 30 and N values of about 3.25. In the present study the shape of the groundwater level is more or less triangular (Fig. 3.12) making storage only half of Ven's by the same M0.

$$M = M0/2 \qquad \text{and} \qquad S = M \times \mu \tag{3.13}$$

The storage coefficient had to be established before Ven's equation could be applied. It was calculated from the fall in water-level as a result of discharge, after analysing several periods with known groundwater levels and discharges. Measured groundwater levels (ZT) and discharges (Q) are given in Table 3.4. Direct flow, that is flow that does not pass the groundwater reservoir, and transpiration losses from the groundwater reservoir, are disturbing factors in this calculation.

Storage coefficients calculated from the fall in groundwater level and the discharge varied between 0.263 and 0.013. Weeks with undisturbed base flow, that is flow from the groundwater reservoir, were rare. Both direct flow and transpiration loss affect the calculation of the storage coefficient. Direct flow is generated mainly by rainfall on saturated valley bottoms, and results in overestimation of the storage coefficient. Transpiration loss applies to the water consumed by trees in as far as it affects the rate of outflow. It includes the direct withdrawal of water by deep roots from the groundwater and water consumed by the vegetation along the water courses. It leads to an underestimation of the storage coefficient. Transpiration loss may be expected in periods of rain deficit, indicated by low rainfall and high pF figures (Table 3.4).

Only a few weeks remained where the discharge was expected to consist of

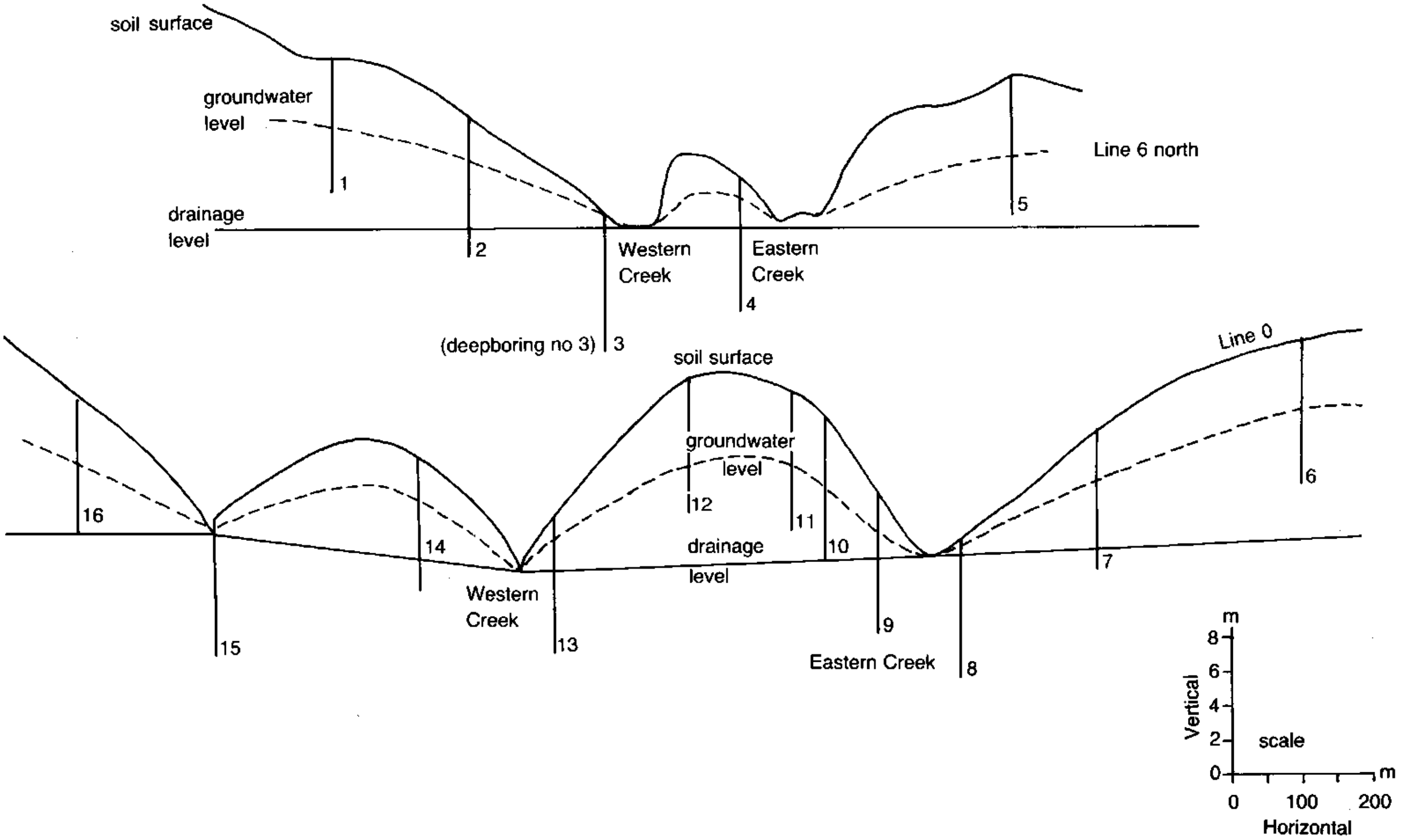


Fig. 3.12 Groundwater levels on 27 July 1984, showing the triangular shape of the phreatic surface and the location of 16 deepborings

TABLE 3.4 Estimated storage coefficient from measured groundwater level changes and discharges per week

Week ending	Rainfall (cm)	Discharge (cm)	Ground water level at end of week (cm)	Drop in ground water level (cm)	pF*	Storage coefficient **	Influences on storage coefficient
010982	3.95	1.42	818	18	2.7	0.079	direct flow
080982	0.45	0.83	834	16	2.9	0.052	base flow
150982	0	0.59	849	15	3.1	0.039	base flow
220982	1.38	0.45	852	3	2.9	0.150	some direct flow
290982	0.07	0.68	880	28	3.1	0.024	some direct flow
061082	1.21	0.42	883	3	3.2	0.140	unsure ground water level
131082	0.04	0.21	896	13	3.4	0.014	transpiration loss
201082	1.63	0.30	917	21	3.5	0.014	transpiration loss
271082	0.15	0.09	924	7	3.7	0.013	transpiration loss
150683	1.44	1.58	763	6	2.4	0.263	some direct flow
220683	5.01	1.62	784	21	2.4	0.077	direct flow
290683	4.42	1.29	801	17	2.3	0.076	some direct flow
060783	1.64	1.08	821	20	2.4	0.054	little direct flow
130783	2.81	0.94	834	13	2.5	0.072	some direct flow
200783	2.13	0.80	849	15	2.6	0.053	little direct flow
270783	0.48	0.59	866	17	2.7	0.035	base flow
030883	2.21	0.39	878	12	2.8	0.033	base flow
100883	1.32	0.38	891	13	2.9	0.029	direct flow and transpiration loss
170883	1.14	0.28	902	11	3.1	0.025	transpiration loss
240883	0.11	0.15	914	12	3.3	0.013	transpiration loss
310883	4.07	0.23	924	10	3.3	0.023	direct flow and transpiration loss
070983	4.25	0.17	930	6	3.2	0.028	direct flow and transpiration loss
140983	1.34	0.22	938	8	3.3	0.028	direct flow and transpiration loss

* Soil suction in the root zone at the end of the week.

** Weekly discharge divided by drop in ground water level during that week.

TABLE 3.5 Selected days with mainly groundwater discharge for calculation of constants K and N in the discharge equation

Date	Gravity head (cm)		Storage (cm)	Discharge (mm/d)	Evaluation of discharge
	M0 *	M *			
180583	576	288	10.07	0.291	little direct flow
250583	544	272	9.52	0.246	base flow
010683	516	258	9.03	0.228	base flow
080683	486	243	8.49	0.522	direct flow
150683	474	237	8.28	0.182	base flow
220683	432	216	7.55	0.186	mainly base flow
290683	398	199	6.97	0.167	little direct flow
060783	358	179	6.26	0.129	mainly base flow
130783	332	166	5.80	0.179	some direct flow
200783	302	151	5.27	0.097	base flow
280783	268	134	4.70	0.066	base flow (transp.loss)
030883	244	122	4.28	0.072	mainly base flow
100883	218	109	3.82	0.069	little direct flow
170883	196	98	3.42	0.029	some transp. loss
240883	172	86	3.02	0.013	transpiration loss
310883	152	76	2.66	0.041	little direct flow

* M0 is representative head halfway between creeks,
M is representative average head (1000 - ZTr) (Appendix VI).

undisturbed base flow. With higher groundwater levels, the storage coefficient seems somewhat larger than when water-levels are deep. This agrees with the assumption of increasing storage coefficients higher in the profile (Table 3.3). It was concluded from Table 3.4, that the storage coefficient is 0.035 cm^3/cm^3. This low value is probably caused by the widespread occurrence of kaolinitic clay substratum which has very few large pores.

Several days for which discharge consisted mainly of base flow (Table 3.5) were selected for the calculation of the coefficients K and N in Equation 3.12.

From $S = M \times \mu$ and $Q = (S/K)^N$ follows $Q = (M \times \mu/K)^N$ and

$$\mathrm{Ln}\, Q = N \ln M + N \ln (\mu/K) \tag{3.14}$$

The relationship between ln M and ln Q is shown in Fig. 3.13. The line through the points has been drawn above points with transpiration loss and below points with direct flow following the remarks in Table 3.5. From the line K was found to be 22.6 and N 1.61. The equations for Q and S using these values for K and N have been introduced into the model WOFOST4. When discarding the value of 080683 (too much direct flow) and of 240883 (too much transpiration loss), linear regression gives approximately the same result; n=14, R^2=0.90, K=21.8 and

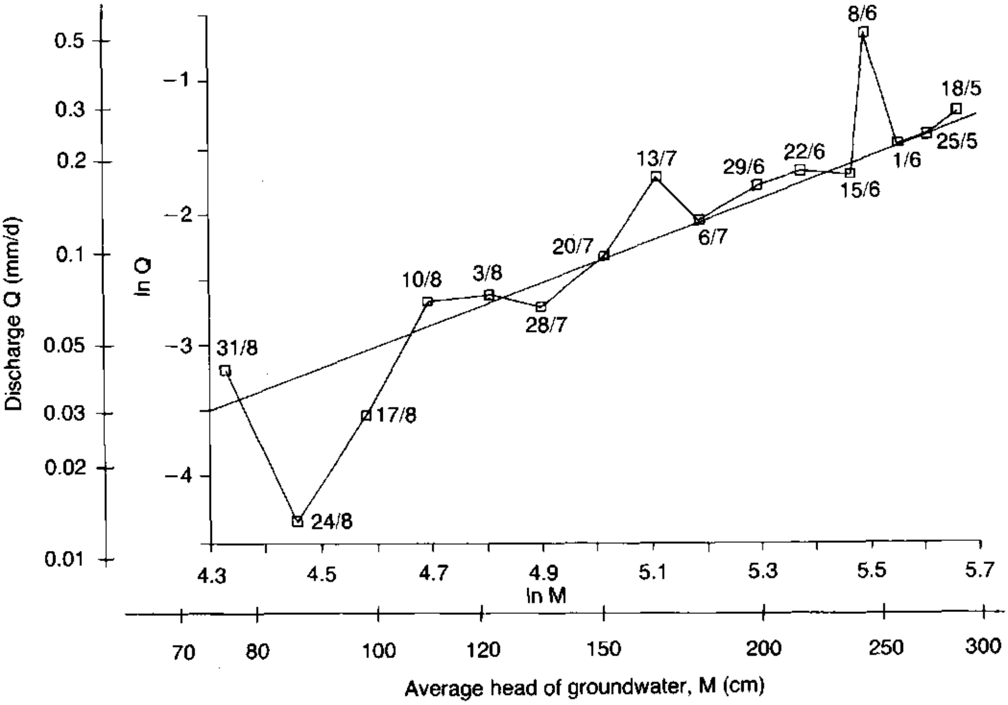


Fig. 3.13 Relationship between the discharge (Q) and the average head of the groundwater (M)

N=1.63. The line drawn by hand has been preferred because other dates were also influenced by direct flow or transpiration loss.

3.4.4 Relationship between soil suction and water content: pF curve

Driessen (1986) gives the relationship between soil suction and soil moisture content as

$$SM = SM0 \times e^{-t(\ln \psi)^2} \tag{3.15}$$

where

SM	is soil moisture content (cm^3/cm^3)
SM0	total pore space (cm^3/cm^3)
t	a texture specific constant
ψ	the matric suction (cm water)

Measured data from the project area did not fit this equation as the range in moisture content between pF2 and pF4.2 in these soils was too small when compared with the range in moisture content between saturation (SM0) and pF2.

The pF relationships are given in Table 3.3. Values of pF were not determined for the kaolinitic clay substratum but it is probable that at pF values from 2 to 4.2 the moisture content is higher than in the Zanderij sediment. However, for the water balance, the available moisture in the substratum is not as important as the storage coefficient, which was estimated to be 0.035. The combination of this storage coefficient for the substratum with the average available soil moisture contents for the top layers, gave a set of pF values for the entire depth of 0-1200 cm. These values, shown in the last line of Table 3.3, comply with Equation 3.15 for SM0 = 0.28 and t = 0.0063. This was incorporated in WOFOST4. The storage coefficient for the upper layers is much larger than 0.035 (Table 3.3). This did not cause problems in the simulations because these layers never became saturated.

3.4.5 Calculation of the position of the groundwater level

The WOFOST model was designed to calculate shallow groundwater tables in arable lands. The moisture content between the root zone and the groundwater level was calculated as the average of the moisture content in the root zone and the total pore space, that is the moisture content at saturation. When the water content in the root zone changed as a result of rainfall or evapotranspiration, the assumed amount below the root zone also changed. These changes were not accounted for in the model and resulted in unwanted loss or gain of water.

The water balance was corrected by adapting the groundwater level after each change in moisture content of the root zone, even when no transport of water through the lower boundary of the root zone or to drains had occurred. Later a new version of WOFOST was received (Wolf, 1985) in which calculation of the groundwater table was based on an equilibrium distribution of water above the groundwater level. This new version, which allows a much better determination of groundwater levels was incorporated in WOFOST4.

3.4.6 Evaporation and Transpiration

Potential evapotranspiration

To calculate transpiration and evaporation, WOFOST requires input of potential evapotranspiration and potential evaporation values. In the project area, data necessary for the calculation of potential evapotranspiration were incomplete but evaporation data from a Class A Pan were available. The following relationship was found between potential evapotranspiration (PET) from Zanderij and Epan data from Kabo (Fig. 2.10)

$$\mathrm{PET} = 0.816 \times \mathrm{Epan} + 1.28 \qquad \text{(mm/d)} \qquad (3.16)$$

As potential evapotranspiration according to Penman is considered to approach

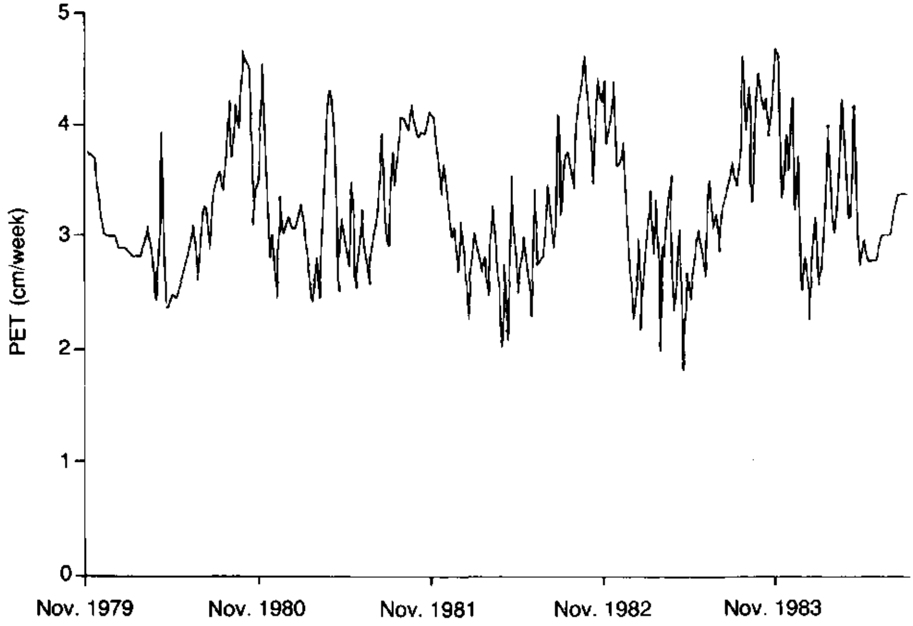


Fig. 3.14 Potential evapotranspiration (PET) for Kabo, calculated from Class A Pan evaporation data

the evapotranspiration of a forest better than Epan, daily Epan values were transformed to potential evapotranspiration values (Fig. 3.14). In the following section the three components of water use are discussed; evaporation from the soil surface, evaporation of interception water, and transpiration.

Evaporation from the soil surface

In the WOFOST model, soil evaporation is calculated from the open water evaporation using the equation

$$E = E0 \times e^{-0.4LAI} \times (SM\text{-}SMW/3)/(SM0\text{-}SMW/3) \qquad (3.17)$$

where

E	is evaporation from the soil surface (cm/d)
E0	is open water evaporation (cm/d)
LAI	is leaf area index (cm/cm)
SM	is the actual soil moisture content (cm^3/cm^3)
SMW	is the soil moisture content at the wilting point (cm^3/cm^3)
SM0	is total pore space (cm^3/cm^3)

Soil evaporation is reduced by leaves and by a soil moisture content that is lower than saturation. In the original model, soil evaporation continued until the moisture content of the root zone had fallen to one-third of that at wilting point. Application of the original model has led to unrealistic results. To survive the dry season, the forest needed a very large rooting depth of about 7 m and the amounts of water in the system appeared to be far too low at the end of the dry season.

Evaporation leads to the development of a mulch layer of dry soil at the soil surface which prevents further evaporation (Driessen, 1986). Such a mulch layer was not defined in the model. Furthermore in the forest there is a litter layer which largely prevents evaporation from the soil and the relative humidity of the air is high. It was decided therefore to set evaporation from the soil surface at zero.

Interception and Transpiration

Potential evapotranspiration (PET) is defined as the water use by evaporation and transpiration of a standard crop. This is defined as a short, dense, growing vegetation, well supplied with water. Evapotranspiration of a crop (ET) is related to the PET by a crop factor (CF), whereby CF=ET/PET. ET consists of soil evaporation, evaporation of interception water on the vegetation and of transpiration.

Evaporation remains an important cause of loss of water from the forest, even if soil evaporation is negligible. Evaporation of rain water, intercepted by the vegetation and the litter layer is a well-known process. Several small rain showers result in higher interception losses than one large storm which gives the same rainfall total. The interception store, that is the maximum amount of water adhering to vegetation, is larger in a forest than in a grassland or shrub vegetation. Tropical forests may have an interception store of about 5 mm.

Under equal evaporative circumstances, evapotranspiration from a forest with wet leaves exceeds that of a forest with dry leaves. This is because of the large stomatal resistance involved in transpiration. Evaporation from the interception store reduces the transpiration, but by a smaller amount than this evaporation. For the present purpose, it was not the total evaporation from the interception store which was important but the extra water losses which result from interception. Without interception evapotranspiration of the forest in the dry season would be much larger than in the wet season (Fig. 3.14). Interception losses reduce this difference.

In WOFOST4 interception loss is defined as the extra water loss of the forest to the air resulting from interception; actual ET minus T that would have occurred if vegetation had been dry. A maximum daily interception loss was introduced and this figure was subsequently substracted from each total daily rainfall to give the net rainfall. For days with a rainfall less than or equal to the maximum interception loss, net rainfall was set at zero.

Having defined interception losses, potential transpiration (T0) was defined as the transpiration of a dry forest (with no interception water), which is well supplied with water in the root zone and which has a LAI sufficiently high to intercept all light. The crop factor CF equals T0/PET. So the crop factor in WOFOST4 does not include evaporation. Potential transpiration supposes that all incoming light is intercepted (very high LAI) while maximum transpiration (Tm) is the transpiration of the dry vegetation, well supplied with water in the root zone, at the current LAI. For the evergreen tropical rainforest, Tm is almost equal to T0.

Transpiration and interception loss were determined as follows. The total amount of water present in the system was calculated for each day by totalling the amounts in the root zone, between the root zone and the groundwater level and between the groundwater level and the reference level at 12 m (Fig. 3.15). The situation was analysed for moments in a dry period when the creek discharge stopped or reached a particular low value, for example 0.5 mm/d. It is supposed that these moments characterize a well defined state of the system, more especially that the total amount of water stored on these dates is always the same. The dates at which these characteristic moments occurred varied considerably for the years investigated. A discharge of 0.5 mm/d was measured on the following dates:

1980: 21 May, 17 September
1981: 1 April, 28 October
1982: 27 January, 17 February, 10 March, 29 September
1983: 13 April, 3 August
1984: 30 May

Water amounts on these dates are indicated as dots in Fig. 3.15. If the simulated

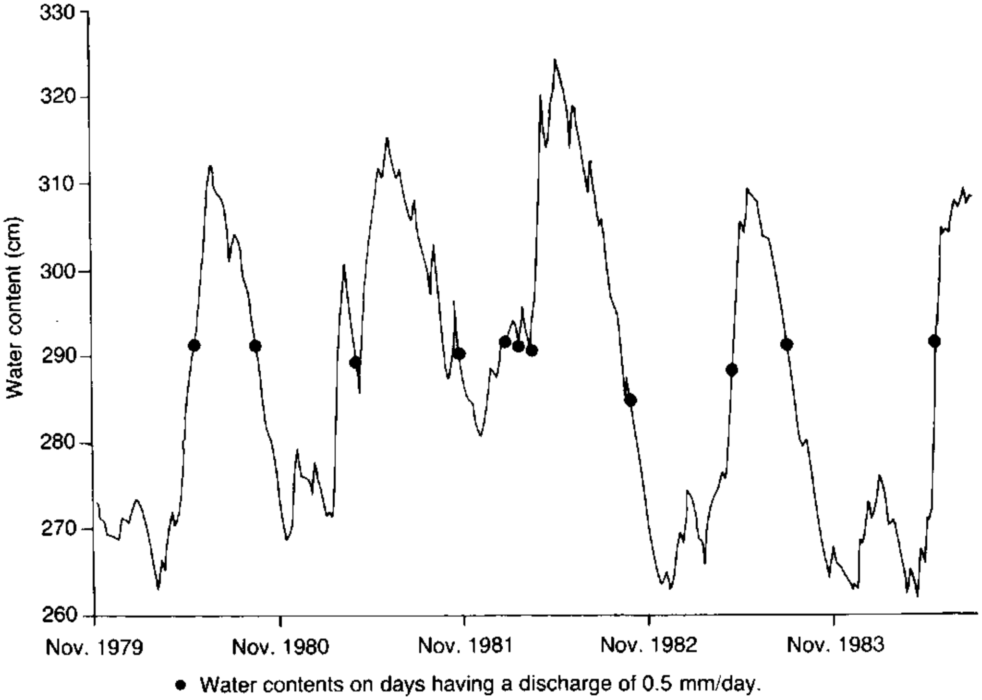


Fig. 3.15 Calculated water content of the representative soil profile to 12 m depth, indicating water contents on days having a discharge of 0.5 mm/d

total amounts of water for these comparable dates showed a rising trend in the simulation, it was concluded that the sum of interception and transpiration was set too low and vice versa. Increasing the crop factor (CF=T0/PET) or the maximum daily interception loss is needed then.

Transpiration and interception were separated by varying the crop factor (CF) and the maximum interception loss (INTC) per rain day. When CF was too large and INTC too small, simulated total water amounts, at comparable dates early in the dry season, were too high and those at the end of the dry season too low although over the years they still might remain stable. With correct CF and INTC values total water amounts on comparable days remained at about the same level during the whole period of simulation whether or not these days occurred at the beginning or at the end of the dry season. This stable total water amount on comparable days was the first requirement for a correct simulation. A second requirement was that calculated discharge corresponded with measured discharge.

3.5 Results of the simulations

Measured data of available soil moisture, the storage coefficient, and the discharge equation with independently determined K and N values were brought into the model. The rooting depth, the crop factor and the interception were then determined by simulation. Simulations were considered better when calculated discharges came closer to measured discharges, when total amounts of water in the system at "comparable moments" during the years approached the same level, and when calculated groundwater levels came closer to measured groundwater levels.

Transpiration and interception combined are not dependent on other variables, but on measured rainfall and discharge data. Simulation served to divide the water use between both components. Rooting depth and the division between interception and transpiration are partly related but as other measured factors govern the model, the values found were considered to be realistic. These values were; a representative rooting depth of 450 cm, a crop factor of 0.87 (T0/ET0), and a maximum interception loss (INTC) of 1.1 mm per rain day. The results of the final simulation are given below.

3.5.1 Total amount of water in the soil to 12 m depth

Total amounts of water in the system to 12 m depth can be seen in Fig. 3.15 to fluctuate at 290 cm. Calibration moments with a very small discharge (base flow) of 0.5 mm/d have been indicated. These were chosen instead of the fewer moments when the creek fell dry. In 1981, for instance, the creek did not stop flowing in the dry season. The stock of water on days with a discharge of 0.5 mm/d, remained about 290 cm throughout the period November 1979 to August 1984. When the base flow drops to a particular low value, groundwater levels and therefore amounts of water in the system can be expected to be about equal, provided the moisture contents in the root zone do not vary too much. The lowest storage at such a characteristic moment occurred at the beginning of the 1982 dry season, on 29 September with 283 cm of water. This happened during a very dry period with a soil moisture content much lower than at corresponding moments in other years. The extra dryness of the root zone may explain this low value. The conclusion is that the simulation run presented in Fig. 3.15 gives a total use of water, that is evaporation + transpiration + calculated discharge, that does not show trends over a period of several years.

3.5.2 Measured and calculated discharges

Measured and calculated discharges are shown in Fig. 3.16. Measured discharges varied more strongly and fell faster to zero in the dry season. Nevertheless, the calculated discharges resulting from groundwater flow, according to the adapted Ven equation, closely followed the measured creek flows. Peak discharges per week were in close agreement, but short discharge peaks that contain much superficial flow were not well represented. In the model they are regarded as being absorbed by the soil and later being discharged as groundwater flow.

Total annual discharges are given in Table 3.6. Small differences between these

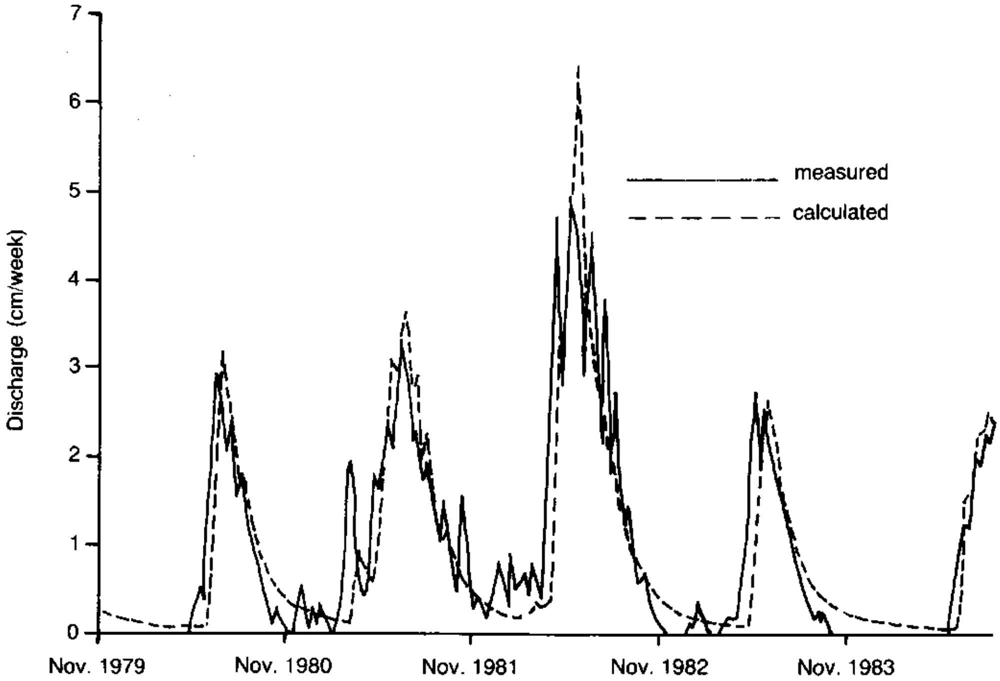


Fig. 3.16 Comparison of measured and calculated weekly discharges of the catchment area

and the totals in Table 3.1 are caused by the fact that the values in Table 3.6 are composed of weekly sums and week-ends and year-ends do not coincide. In two very dry periods, 1979-1980 and 1983-1984, calculated discharges continued while creeks were already dry. This gave over-estimations in the first and last year. Otherwise the annual balances were well simulated by the model.

3.5.3 Measured and calculated groundwater levels

Determination of the average or representative measured groundwater level
The measured groundwater levels cannot be compared directly with the calculated groundwater levels in a hydrological model. In the model a distance of 600 m is assumed between parallel creeks. Such a distance is considered representative for the catchment and it occurs in the field in the central area between Eastern and Western Creeks. The water-levels in this area were measured in deepborings nos. 9 to 13. The water-level as given by the model is the average groundwater depth below the (level) surface in such an area where the water-level in the creeks is 10 m below surface. The soil surface near deep borings has a varying elevation above creek level and deep borings are at varying distances from the creek.

The driving force for groundwater flow to the creeks is the gravity head (M). This is the average elevation of groundwater level above the water-level in the creeks. This average elevation has been taken as half the maximum elevation of the groundwater level halfway between the creeks (M0), with respect to creek water-level. This approaches the real situation as the shape of the phreatic surface resembles a triangle with a rounded top (Fig. 3.12). The triangular shape may be caused by a permeability which decreases with depth. A deep boring in the middle of the central area, like boring no 12, would allow M0 to be measured and M to be calculated. However, boring 12 could not be used for this purpose. It was dry for most of the time and only few observations were available. It was therefore necessary to compare the groundwater level calculated by the model with the level in holes that hold water during longer periods. Borings near creeks always had water but they were unable to provide reliable estimates of the groundwater level halfway between creeks because of their small amplitude. The most suitable borings were no 2, line 6, 400 West, no 7, line 0, 600 East, and no 14, line 0, 400 West.

Groundwater curves, like in Fig. 3.12, were drawn for a number of measurement dates. The elevation of groundwater level for the central area (M0) was determined graphically, extrapolating for dates with dry holes in the centre of the area. Measured water-levels in the 3 holes referred to above (nos 2, 7 and 14) were transformed to gravity heads (elevations above creek level). The following relationships were found between M0/2 (representative gravity head) and the gravity heads of the 3 borings: M(2), M(7) and M(14).

$$M0/2 = M(2) \times 0.82 - 0.59 \quad (m) \tag{3.18}$$
$$M0/2 = M(7) \times 0.89 - 0.22 \quad (m) \tag{3.19}$$
$$M0/2 = M(14) \times 0.64 + 0.36 \quad (m) \tag{3.20}$$

The representative gravity head M0/2 was calculated from the above equations giving equal weights to each. From these M0/2 values, representative groundwater depths were calculated: ZTr = 10 – M0/2. These depths below an idealized soil surface can be found in Appendix VI. They are only available for the period after August 1982.

Comparison of measured and calculated levels

Calculated and measured groundwater levels are presented in Fig. 3.17. Measured groundwater levels were only available after August 1982 and for this period measured and calculated levels agree rather well. Measured levels dropped quickly in the dry season to below drain depth (10 m). Calculated levels never reached this depth. In this respect reality is not well described by the model. The same effect was seen in Fig. 3.16, where the calculated discharge continued in the dry season because the groundwater level did not drop fast enough. This is another indication that the tree roots extract water from the groundwater reservoir in the dry season, a fact also suggested by the diurnal variations in the deep borings (Section 3.2.7). The deep rooting, which appeared in the simulation, was also found in the field. During the augering of the deep borings, occasionally pieces of straight live unbranched roots of a diameter of about 1 cm, were found below 4 m. Such finds were rare thus it is probably that only a few trees can develop roots to very deep layers. These deep roots seem able to survive periods of high groundwater tables in the wet season.

A minor part of this groundwater extraction is explained by the model as capillary rise, which occurs when soil suction becomes larger than the distance between the lower boundary of the root zone and the groundwater. Because the often large distance between the lower boundary of the root zone and the groundwater, especially during dry periods, capillary rise was obviously too small to explain all groundwater extraction by the trees. Increasing the rooting depth to reduce this distance and increase the capillary rise did not overcome this problem because then transpiration in the dry season became too large and discharge too low.

Although there is a reduction in transpiration in the dry season caused by water stress, reduction is less abrupt than in the simulated case with all roots confined to the top 450 cm. The model could not provide a clear picture of the processes involved in the extraction of water from great depth. Nonetheless, 450 cm seems a reasonable equivalent effective rooting depth for the whole catchment, bridging the strong concentration of roots in the upper layers and the very few roots that reach the groundwater.

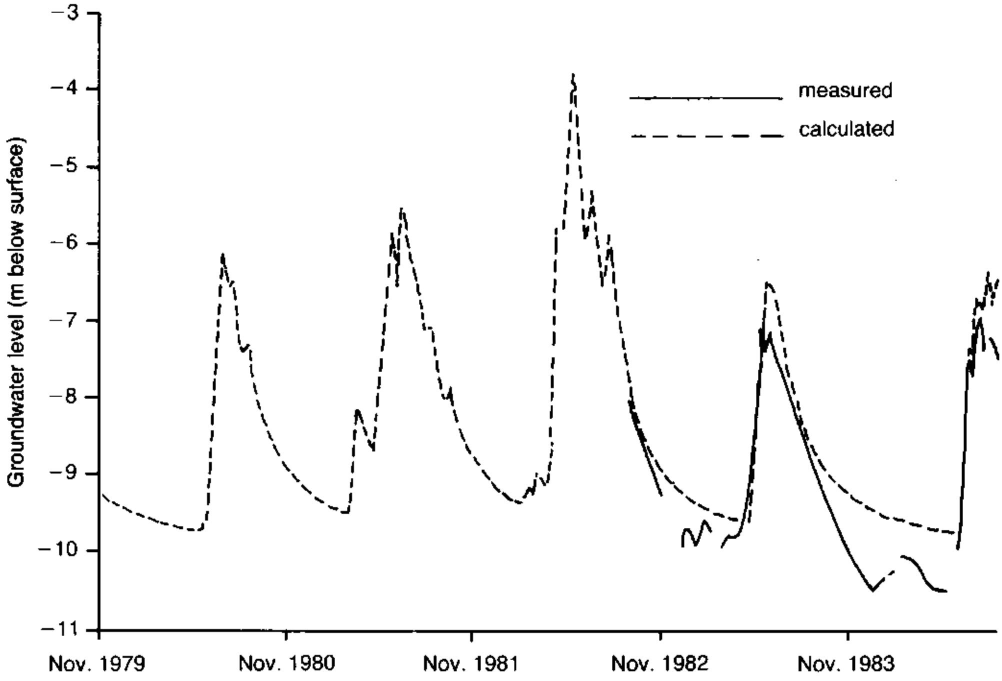


Fig. 3.17 Comparison of measured and calculated average groundwater levels

3.5.4 Soil suction and transpiration reduction

Calculated pF-values in the root zone and the ratios between actual and maximum transpiration rates are given in Fig. 3.18. Drought reduced transpiration in 1980, in two short periods before and after the rainy season. In 1981 no reduction occurred but in the 1982 dry season there was a strong reduction with transpiration falling to below half its maximum value. The same happened in 1983 and another dry period occurred at the beginning of 1984. Transpiration was reduced at a pF value of approximately 3.6. Reduction did not always start exactly at pF 3.6 as this value is dependent of Tm. The higher Tm, the larger is the critical soil moisture content and the earlier the transpiration reduction starts. Weekly total T/Tm values are related to pF values at the end of the week in Fig. 3.19. Transpiration reduction followed a roughly linear course from pF 3.6 to pF 4.2. Variations were caused by the varying critical soil moisture content and by differing weather conditions during the weeks of observation.

3.5.5 Transpiration and interception

Weekly transpiration and interception totals are given in Fig. 3.20. During periods

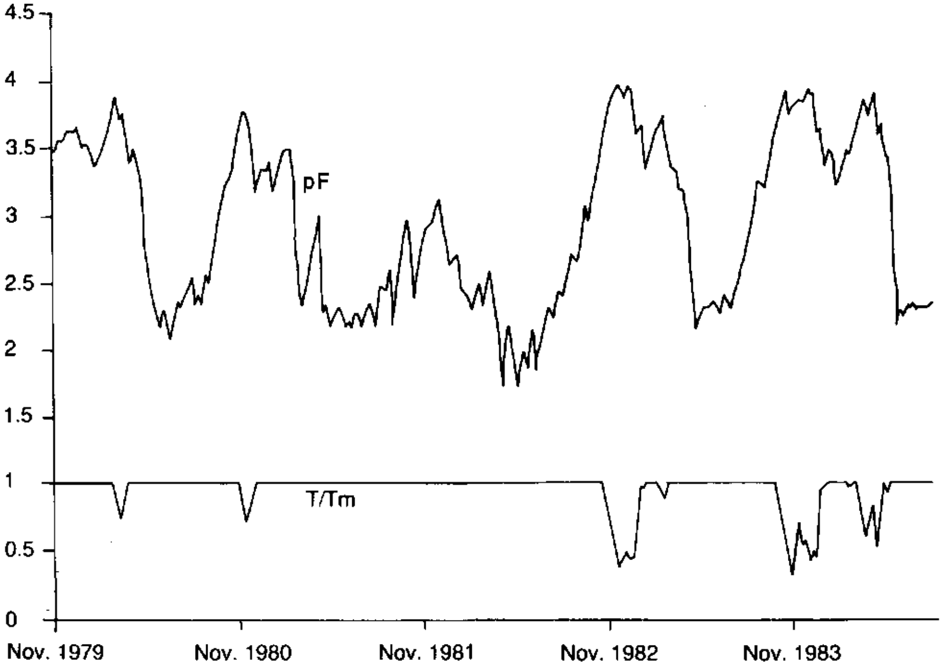


Fig. 3.18 pF values in the root zone and relationship between actual and maximum transpiration (T/Tm) calculated with WOFOST4

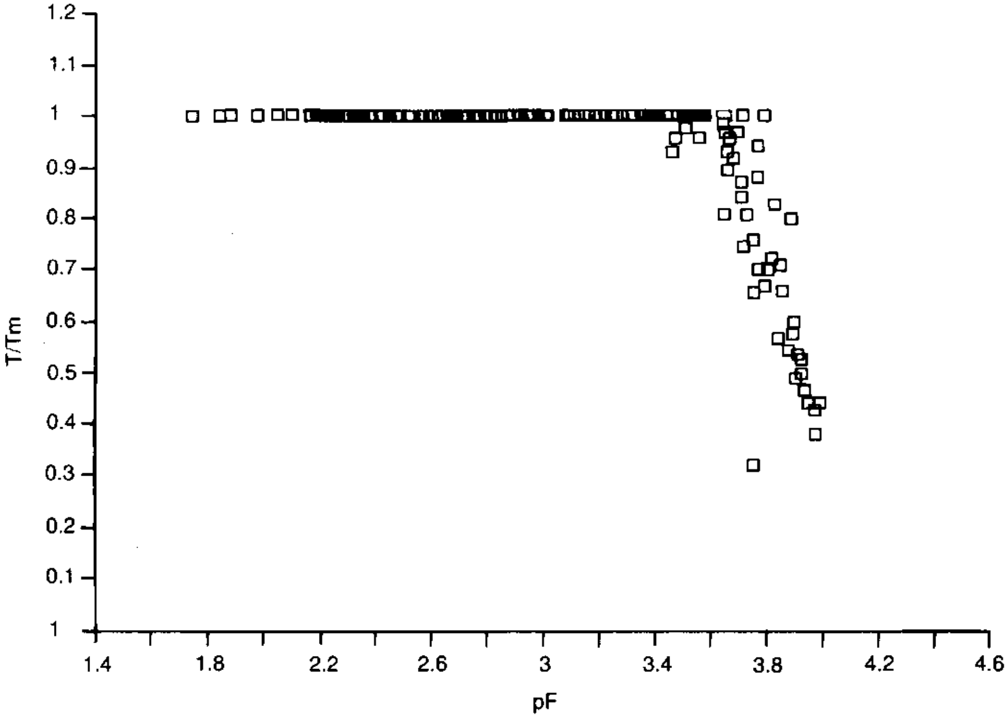


Fig. 3.19 Relationship between pF and transpiration reduction (T/Tm) used by WOFOST4

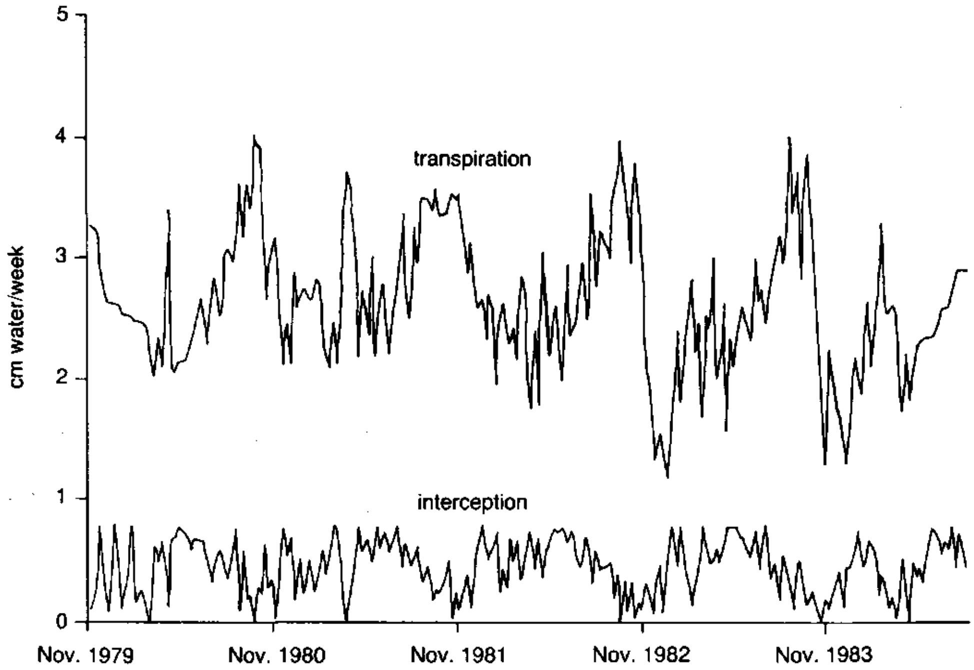


Fig. 3.20 Weekly amounts of transpiration and interception calculated by WOFOST4

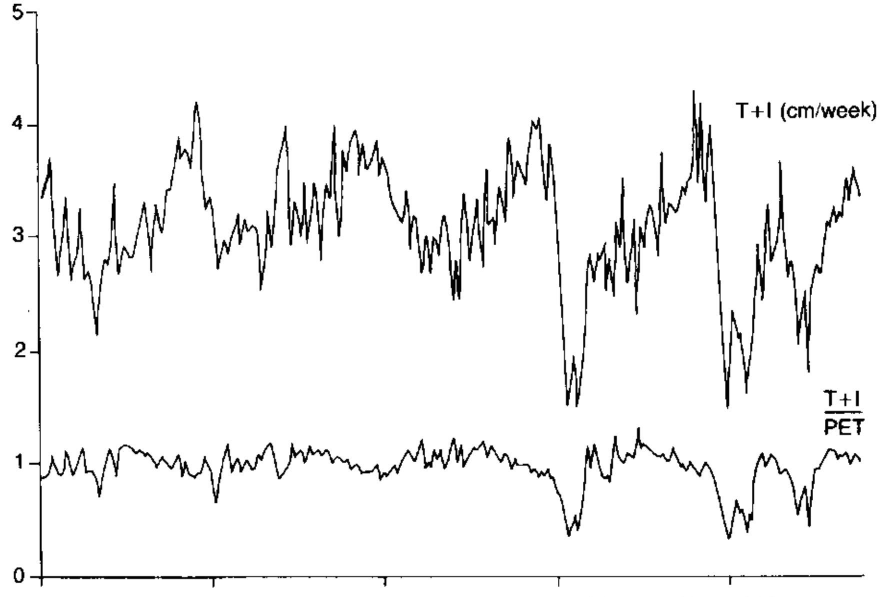


Fig. 3.21 Calculated total water use of the forest (transpiration + interception) and relationship between this total water use and potential evapotranspiration (PET)

without water stress, transpiration rates varied between 40 mm/week (5.7 mm/d) in very sunny periods and less than 20 mm/week (2.8 mm/d) in very wet weeks. Interception losses of up to 7.7 mm/week are higher in the rainy seasons but considerable losses also occur in the dry seasons. Fig. 3.21 shows the total water use of the forest, transpiration and interception, and compares this use with the potential evapotranspiration according to Penman, given in Fig. 3.14. Interception diminished the differences between the seasons when compared with transpiration alone but the water use in the dry season remained higher than in the wet season unless water stress occurred.

Maximum water use was about 40 mm/week in dry periods mainly during the sunny months of August-October. Periods of water stress can reduce total water use by about 50 %. As stated previously transpiration reduction might be slightly less abrupt (by the same total transpiration reduction) than shown in Figs. 3.18 and 3.21 because of some tree roots extracting groundwater. In spite of the crop factor being set at 0.87, the total water use of the forest was still approximately equal to PET because of the interception. Periods of water stress are clearly shown in Fig. 3.21.

3.5.6 Development of the vegetation

The simulated development of the vegetation and its growth to steady state is shown in Fig. 3.22. In the beginning the phytomass of the forest was at about half

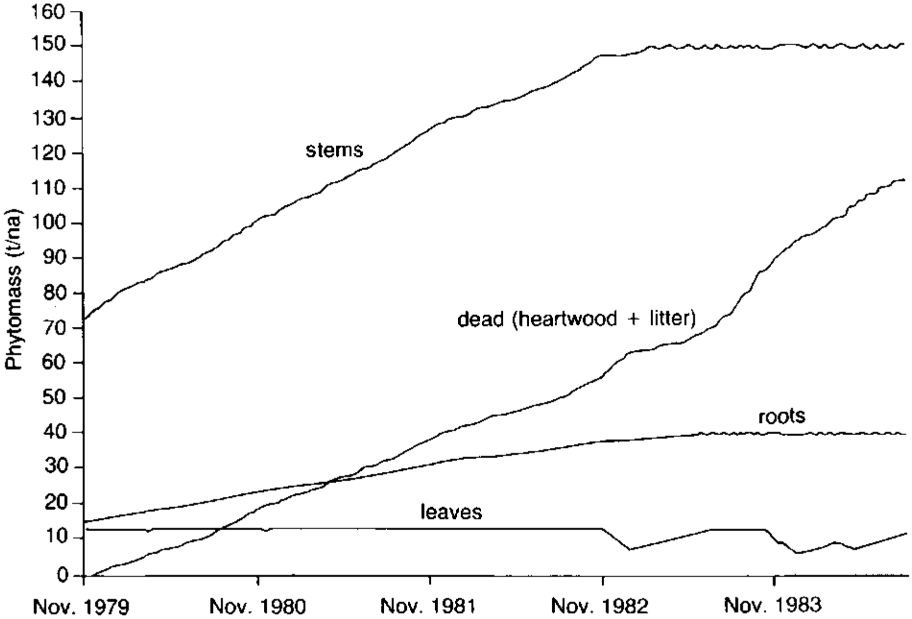


Fig. 3.22 Calculated weights of phytomass components during the growth of the forest

its steady state value but with full leaf cover, a situation that also occurs about two years after a vigorous refinement. According to the simulation it takes about 3 years under optimal nutritional conditions to reach the live weights of the steady state. The initial weights of roots, stems and leaves were 15, 72 and 12 t/ha live dry weights respectively. The weights of stems and roots in Fig. 3.22 apply only to sapwood.

The dry matter increase during the early period is apportioned to roots, leaves and stems for 15, 13 and 72 % respectively. The weights of live roots and stems increased to reach peak values of 40 and 150 t/ha respectively. The dry weight of leaves was bound to a maximum of 12.9 t/ha, corresponding with a LAI of 9. Ongoing leaf production was used to replace old leaves which were shed and transferred to the DEAD compartment. Therefore leaf weights remained at a steady 12.9 t/ha unless leaf mortality increased as a result of water stress. The periods of leaf mortality in Fig. 3.22 coincide with the periods of transpiration reduction in Fig. 3.18. A small and constant mortality rate affected the roots and stems, adding more material to the DEAD compartment, which grew steadily. Once the maximum weights had been reached (end 1982), the higher mortality of roots and stems did the DEAD compartment increase at a faster rate.

This DEAD compartment consists of fallen leaves that decompose quickly, of dead fine and coarse roots decomposing underground, of fallen twigs and small branches, but also of large dead logs both fallen and standing. The DEAD compartment also includes the heartwood of living trees. All these components

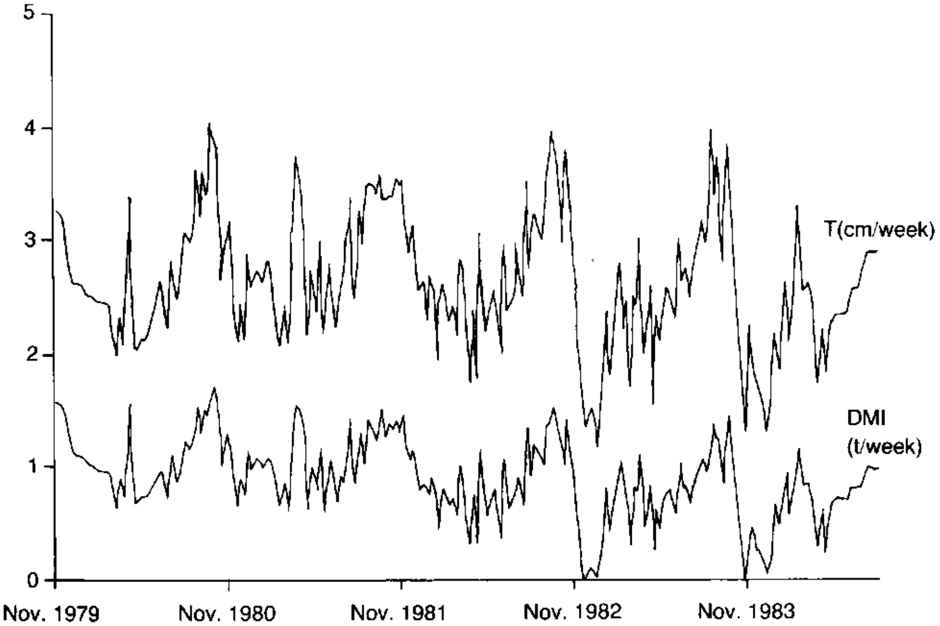


Fig. 3.23 Calculated weekly transpiration (T) and dry matter increase (DMI) of the forest

have different compositions and decomposition times. All dead material will eventually be mineralized and again incorporated in living biomass. In reality, the size of the DEAD compartment will level off and become constant at a point where addition of dead material is in equilibrium with decomposition. In this simulation the DEAD compartment was not subdivided and decomposition was not as yet considered. Litter production and decomposition will be discussed in Chapter 4.

Dry matter increase (DMI) in combination with the actual transpiration rate is shown in Fig. 3.23. There is a positive correlation. The gross assimilation rate is dependent on solar radiation, LAI and water availability, those factors which also control transpiration. As the large biomass requires a high maintenance respiration rate, dry matter increase (gross assimilation minus maintenance respiration) can drop to zero during very cloudy days and during periods of water stress. During the nearly 5 year period covered by the simulation exercise, there was an overall decrease in calculated DMI values because of the increasing biomass of the forest and correspondingly higher maintenance respiration rates. After the maximum biomass had been reached, the maximum DMI amounted to 1500 kg dry matter per week. The average dry matter increases per ha remained at about 35 t/y or 670 kg/week. Less attention was given to the growth of the vegetation than to the water balance during the simulation and a nutrient limited situation was not considered. Data given in Figs. 3.22 and 3.23 are therefore tentative.

3.5.7 Annual totals of water balance and vegetation

Measured and simulated annual totals of the water balance and the vegetation are given in Table 3.6 . The discharge deficits (rainfall minus discharge) varied considerably. This is mainly caused by changes in storage and to a lesser extent by transpiration reduction in drier years. The effect of drought is limited because of deep rooting. This can best be seen in the ratio transpiration/potential evapotranspiration that varied from 0.86 to 0.71, with an upper limit (crop factor) of 0.87.

Duynisveld and van der Weerd (1974), give as estimations of evapotranspiration average annual data of rainfall minus discharge for catchments of large rivers in Suriname. For six rivers these values vary between 1509 to 1784 mm, the average being 1619 mm/y. This study found an evapotranspiration of 6545 mm for a period of 4 years or 1636 mm/y (Table 3.6).

Dry matter increase (DMI) was about 50 t/ha during the first years. The start weight of 99 t/ha increased by 220 t during the simulation and its distribution over leaf, root, stem, storage organs and dead organic matter (heartwood + litter) is specified in Table 3.6.

TABLE 3.6 Water balance totals (mm) and dry matter increase of the vegetation (t/ha) per hydrological year, and dry weights of vegetation compartments (t/ha) at the end of each hydrological year

	1979/80	1980/81	1981/82	1982/83	1983/84*	Total
Measured						
rainfall	1967	2467	2348	1791	1703	10276
evaporation (EPan)	1461	1551	1478	1528	1143	7161
discharge	296	600	865	294	177	2232
rainfall-discharge	1671	1867	1483	1497	1526	8044
Simulated						
PET**	1659	1732	1673	1713	1292	8069
interception	218	239	245	232	177	1110
effective rainfall	1750	2228	2104	1559	1526	9167
transpiration	1423	1478	1441	1269	919	6531
discharge	345	586	855	319	201	2306
interception + transpiration	1641	1717	1686	1501	1096	7641
changes in storage	-19	164	-193	-29	406	329
transpiration/PET	0.86	0.85	0.86	0.74	0.71	0.81
Measured - simulated						
discharge	-49	14	10	-25	-24	-74
Simulated						
dry matter increase	56.9	54.8	46.9	35.5	25.9	220
weight leaf	12.9	12.9	12.9	9.7	11.6	
weight root	23.2	31.1	37.8	39.9	39.8	
weight stem	100	126	147	149	150	
weight storage organs	1	3	4	5	5	
weight dead organic matter	18	38	56	90	112	

* 9 months only.

** PET is potential evapotranspiration.

3.6 Summary of findings

A study of the hydrology of the forest on a catchment area scale was considered necessary in order to understand the way the ecosystem functions. For this purpose a catchment area of approximately 295 ha was investigated. The two small creeks in this area allow it to be subdivided into two catchments, the Eastern Creek catchment of 140 ha and the Western Creek catchment of 155 ha. The topography of the whole area is gently undulating with average slopes of about 4 %.

Data were collected on factors related to understanding the hydrological cycle. These included rainfall, evaporation, creek discharge, groundwater levels from deep borings, hydraulic conductivity and diurnal variations of water levels in creeks and deep borings. A computer model was used to predict water movements in the soil and to estimate evapotranspiration of the forest during wet and dry periods. The model was also used to gain insight into other aspects of the water balance, such as rooting depth and available soil moisture. Knowledge of these processes is needed to understand nutrient cycling. The model WOFOST4 was used. The findings of this hydrological study are summarized below.

- The measured average annual rainfall and discharge were approximately 2140 and 510 mm, respectively. Length and intensity of the dry season, that is less than 100 mm rain per month, varied between 2 and 5 months per year. The length of the dry period with no or very little discharge varied between 0 and 8 months per year.

- Groundwater flow was found to be the main contributor to discharge. Surface flow and lateral flow were important in the valley bottom and footslopes. Although these flows gave clear discharge peaks, they contributed relatively little to total discharge.

- In deep borings Zanderij sediment varied in depth from 0 to 4 m, overlying residual material, which generally consisted of kaolinitic clay with varying amounts of laterite and quartz gravel. The average depth of the Zanderij sediment is between 2 and 3 m.

- Average groundwater levels were found to be deep under plateaus and upper slopes and to fluctuate greatly throughout the year. The phreatic surface is triangular in shape with a rounded top under the plateaus.

- Hydraulic conductivities were high in upper layers and decreased with depth. Groundwater flow occurred mainly above drain level, that is creek level, and was non-steady in character.

- In the dry season, groundwater extraction by the vegetation appears to be widespread, not only in the swampy valley bottoms with shallow groundwater, but also on plateaus and upper slopes even when groundwater levels were more than 5 m deep. This has been concluded from diurnal variations in creek discharge, from groundwater levels in deep borings, and also from root observations and water balance simulations.

- Available soil moisture in the Zanderij soils was estimated to be approximately 10 % of volume. Amounts of air when the soil is at field capacity were large, more than 20 %. Water storage in the kaolinitic clay substratum, that is the amount of drainable water, was small. An average storage coefficient of 0.035 was calculated for the substratum of the whole catchment.

- The water balance during a period of 4 years and 9 months (1979-1984) was

simulated with the WOFOST4 model with inputs of measured climatic and soil data. Close agreement was obtained for measured and calculated discharge and for measured and calculated groundwater levels under the following conditions:
effective rooting depth of 450 cm
evaporation from the soil surface of zero
maximum extra interception loss of 1.1 mm per rain day
crop factor (potential transpiration/PET) of 0.87.

- Computer simulation showed that interception losses increased water use in rainy seasons but that in dry seasons water use was still higher. The extra water use caused by interception, not the total interception, was estimated to be 230 mm/y by a total water use of 1640 mm.

4 Nutrient balance in undisturbed and treated forests

4.1 Introduction

The soils in the study area are extremely poor and have a very low nutrient holding capacity and content. When considering any type of land use careful attention must be given to the nutrient supply available to the vegetation. Nutrient deficiencies can develop quickly or they may already exist. Under the Celos Silvicultural System (CSS, de Graaf, 1986), much phytomass is killed. When this decomposes it liberates large amounts of nutrients. Some might be removed from the ecosystem by drainage water, resulting in a cycle of less nutrients and more chance of nutrient deficiencies.

This chapter discusses the effects CSS had on nutrients in the biological or organic matter cycle and in the hydrological cycle in the study area. Nutrient cycles in the undisturbed area of the Eastern Creek are compared with those in the area of Western Creek, where a vigorous refinement according to CSS was carried out in 1981. The composition, and inflow and outflow of water were measured from 1980 to 1984.

Changes in the organic matter cycle were studied by determining amounts of nutrients in the phytomass and by measuring litter amounts and the composition of litter and soil in the undisturbed Eastern Creek area. This was then compared with a similar analysis carried out in the treated Western Creek area. Measured data were combined into a model of organic matter and nutrient flows.

Changes in the hydrological cycle were studied by measuring rainfall and creek discharges and also the composition of rain and creek water. Creek water from the Eastern and Western Creeks were sampled weekly for chemical analysis.

4.1.1 General nutrient cycle

In undisturbed climax forest, the production (growth) and consumption (including decomposition) of vegetative matter are equal, with steady state pools of biomass and dead organic matter. Biological activity is determined by this level of production. The amount of biomass (phytomass + animal biomass) is determined by the rate of production and the rate of consumption. The same level of biomass can result from either a high or low production of vegetative matter but in the latter case the rate of consumption is also slower. Both phytomass and the rate of vegetative production are important in a production forest. When the phytomass of a certain component has become sufficient, harvest is possible. If growth is too slow the lapse between harvests will be too long for exploitation to be economic.

Production of plant matter is governed by temperature, radiation and supply of water and nutrients. In the study area temperature, radiation and water supply were conducive to rapid growth. The supply of nutrients, however, was limited. The vegetation gets its nutrient supply principally from decomposing organic matter. The air and soil minerals can also supply nutrients. The supply from the air consists of nutrients brought from elsewhere by rain, dust, and smoke. The supply from the soil minerals was expected to be very small because of the strongly weathered status of the soil.

Assuming that the nutrient supply from soil minerals is negligible, there are two nutrient cycles, one in the biological cycle and the other in the hydrological cycle. The biological cycle has a large store, the biomass. The biomass produces litter; plant parts, dung and animal remains. Litter decomposition liberates the enclosed nutrients at the surface or in the soil. Plant roots can take up these nutrients, either directly from the litter or from the soil moisture, and incorporate them again in the biomass. Tropical forests are very efficient in this uptake. The nutrients in the hydrological cycle have also a store, the soil. There is an equilibrium between nutrients in the soil moisture and at the surface of soil particles. In this cycle, nutrients in the drainage water are losses and nutrients coming in from the air are gains. There is an exchange between the two cycles in both directions, which occurs mostly in the soil but also between the aerial parts of the vegetation and rain-water.

The drainage component of the hydrological cycle is responsible for most losses from the system. Losses are also possible as a result of harvesting biomass or by animal migration. There are two ways to minimize drainage water losses; minimizing drainage by high evapotranspiration, and minimizing nutrient concentration of the drainage water by avoiding nutrient transfer from the biological to the hydrological cycle.

4.1.2 The effect of silvicultural treatment

The Celos Silvicultural System, CSS (De Graaf, 1986) aims to increase the growth of commercial trees in the natural or semi-natural forest by diminishing competition by non-commercial trees and lianas. The objective of the system is to allow a modest harvest of quality timber every 20 to 25 years. To achieve this, commercial species have to accomplish a comparatively high growth rate. Competition is eliminated by poisoning trees and cutting lianas. The result is an increased supply of radiation and nutrients to the remaining vegetation and increased growth (De Graaf, 1986).

There is a danger of nutrient losses from the ecosystem when this type of silviculture is applied. Such losses are serious in the poor soils of the Zanderij area and it could take a very long period for the ecosystem to achieve the same nutrient levels as before. The nutrient pool in the biological cycle is greatly reduced and liberation of nutrients by decomposition of organic matter is equally enhanced. On the other hand the living vegetation that could take up these extra nutrients has become much smaller. Consequently, the chances that nutrients move from the biological to the hydrological cycle and are removed from the ecosystem with the drainage water are greatly increased. This risk is particularly high when the living vegetation is so reduced that evapotranspiration is lowered and the amount of drainage water raised. Therefore, the harsher the treatment, the greater the risk of nutrient loss.

4.2 The influence of harvest and refinement on the organic matter cycle

4.2.1 Methodology

The catchment of the western tributary (Fig. 4.1) is 155 ha which is about half the total catchment area. To test the influence of the silvicultural treatments according to CSS, it was decided to treat the Western Creek area and to leave the Eastern Creek area undisturbed. Treatment according to CSS consist of exploitation (harvesting) and refinement (De Graaf, 1986). Exploitation occurred in 1978 and 1979, before measurement of water and nutrients was started in 1980. Refinement was carried out in 1981.

Soil and litter samples were taken before and after refinement. Subsequently nutrients in different compartments of the organic matter cycle and in different soil compartments were determined. These data were used to make a model of organic matter and nutrient flows from which conclusions on the influence of CSS could be drawn.

Harvesting

Exploitation was not done systematically in the Western Creek area. Some parts, the plateaus and upper slopes, were more intensively logged than others, while the valley bottoms were not logged at all. It is estimated that two-thirds of the area was logged at an intensity of 20 m^3 stemwood per ha. According to Jonkers and Schmidt (1984), such a rate of logging kills about 50 t phytomass per ha of which 15 t in stemwood is removed. The phytomass for the whole catchment area is estimated to be 500 t/ha (Tables 2.7 and 4.9) and it can be concluded that the harvesting which took place in 1978 and 1979 killed about 7 % of all phytomass (10 % in two third of the area).

Refinement

This is the killing by poisoning of non-commercial trees to promote the growth of

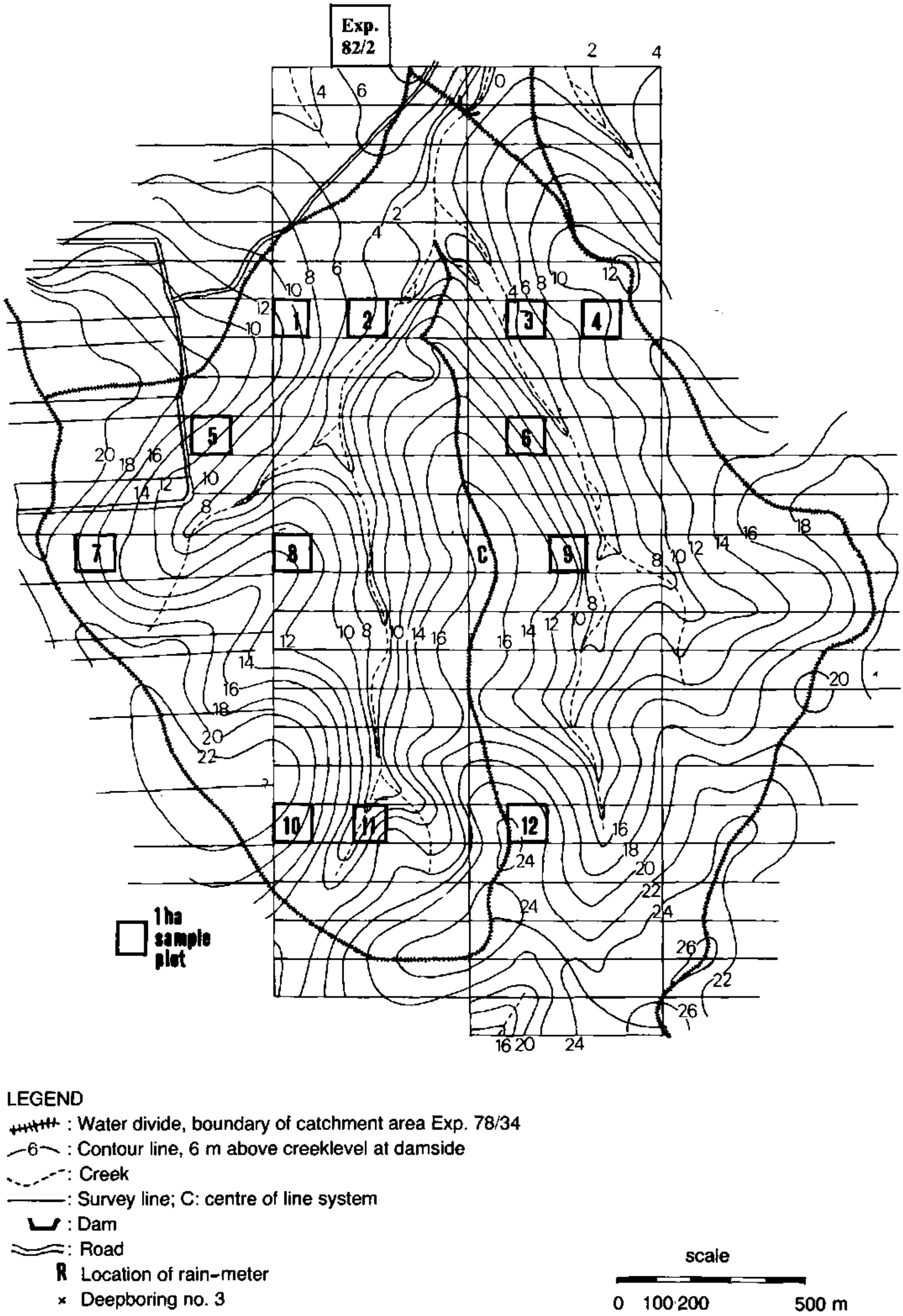


Fig. 4.1 Location of soil and litter sample plots

commercial trees. The poison, consisting of the herbicide 2.4.5 T in diesel oil (5 % solution), is applied to the foot of a tree after an incision has been made in the bark. Details of the treatment and a list of commercial species are given in de Graaf (1986) and Jonkers (in press). As a result of the treatment, the trees die slowly losing their leaves. The time between treatment and leaf drop depends on the species, size, vigour and the weather, but is usually between one month and one year.

Refinement of the Western Creek area was done between September and November 1981. About 144 ha were treated in the Western Creek area, the remaining 11 ha were valley bottoms with swamp forest. Such poorly drained areas have a very low proportion of commercial species and wood extraction is difficult there. Refinement causes unnecessary damage and little is achieved and there is the additional danger of contaminating the creek water with herbicide.

In the catchment area of the Western Creek a vigorous refinement was carried out. All trees of non-commercial species of a dbh > 20 cm were poisoned and all lianas of a diameter at ground level >3 cm were cut. A first estimate from stand composition and diameter class distribution was that about 60 % of the biomass would be killed. Jonkers (in press) however, measured the proportion of the vegetation killed in the nearby forestry experiment 78/5, on the water divide of the Western Creek area where treatment was the same and found that only 40 % was killed (190 out of 480 t). Experiment 78/5 is situated on plateau and upper slopes with the best forests and a high proportion of commercial species. Treatment on lower slopes was stronger because of the higher proportion of non-commercial trees. In the catchment area, the 25 % footslopes with a higher percentage killed and the 7 % untreated valley bottom (Table 2.2) may counterbalance each other. Of the total phytomass in the catchment, including valley bottoms, 40 % instead of 60 % is estimated to have been killed.

In Figs. 4.2 and 4.3 stereo-photographs are given of undisturbed and refined forests. In Fig. 4.2 the undergrowth of the undisturbed forest shows few large trees and numerous small trees, seedlings and palms. The undergrowth is rather open.

Fig. 4.2 Stereo-photograph of undisturbed forest
(courtesy: K.E. Neering)

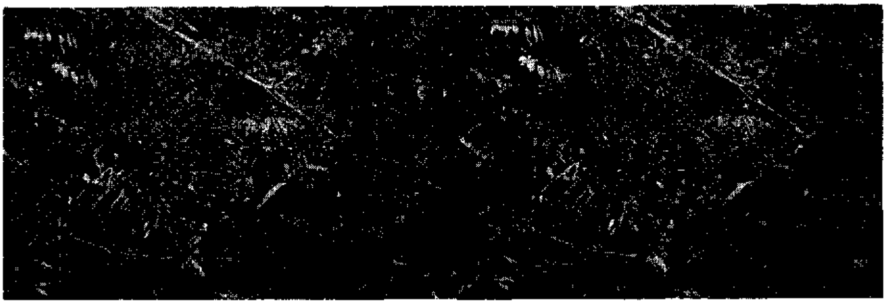


Fig. 4.3 Stereo-photograph of strongly refined forest, two years after treatment (courtesy: K.E. Neering)

Fig. 4.3 was taken two years after refinement on a spot where treatment was severe because of the absence of commercial trees. The canopy had largely disappeared and the increased amount of light on the forest floor, combined with extra supply of nutrients from decomposing litter, had resulted in vigorous growth. Photograph 4.2 was taken in Exp. 82/2 and photograph 4.3 in sample plot no. 2 (Fig. 4.1).

Soil and litter sampling

During the refinement in October 1981, litter and soil samples were taken from seven plots (100 x 100 m) in the Western Creek area and from five plots in the Eastern Creek area (Fig. 4.1). In August 1983 the same plots were sampled again. Most of the poisoned trees had died and the amount of litter, especially woody litter, on the forest floor in the Western Creek area was near its maximum.

During the October 1981 sampling, a line was cut along a diagonal of the plot and during the August 1983 sampling, a line was made from the middle of one side of the plot to the middle of the opposite side of the plot. Along the line 30 – 40 soil samples were taken with a sample auger of the layer 0 – 20 cm depth, and these were combined to a mixed topsoil sample. To analyse the soil at greater depth, a boring was made with an open blade auger near the middle of the line to a depth of 120 cm. Soil samples were collected from six layers each 20 cm in depth ranging from 0 – 120 cm. During the first sampling, one litter sample was taken from each plot on a representative location and during the second sampling two litter samples were taken with a square iron frame of 0.25 m^2 area. All litter within the frame was collected, except for hard woody litter of a diameter greater than about 3 cm.

The litter samples were dried at 60° C, weighed and ground and the contents of N, P, K, Ca, Mg and Na were determined. Extraction was done by wet combustion with H_2O_2 and H_2SO_4. Cations were analysed by spectrophotometer, N by the Kjeldahl and P by the molybdenum blue method. (For details see Boxman, in press). In the first sampling ash content was estimated and in the second sampling the ash content was measured. Ash content was used to calculate the amount of organic carbon in the litter. Carbon content was assumed to be 50 % of the organic matter. Ash contents was determined by ignition of a subsample. Soil particles (ash) in the samples were almost completely quartz sand. Nutrients contained in these soil particles, were considered to be negligible when compared with the nutrients in the organic part of the samples.

The soil samples were dried at 60° C and ground. They were then analysed for C (Walkley Black), N (Kjeldahl), CEC and cations after percolation with NH_4Ac, Al in KCl extract, K and P total in Fleischman's acid (concentrated HNO_3 and H_2SO_4) and available P with the Bray I method. The pH was measured in water and KCl extracts (for details see Boxman, in press). Total element analysis with the X-ray fluorescence method (Begheijn and van Schuylenborg, 1971) was carried out on soil samples of representative profiles. The results are given in Appendix III.

4.2.2 Results

Table 4.1 gives the mean and standard deviation of weights and compositions of the litter samples and Tables 4.2 and 4.3 give mean soil compositions of Eastern and Western Creek area before and after treatment. The data for the first sampling in Table 4.1 are not complete, Mg was not determined and the Ca figures seem to be too high and should possibly be reduced by a factor of 2 to bring them in line with other analysis results. The data for August 1983 are complete and appear to be reliable. The plots in the treated western catchment have higher amounts of litter with more nutrients (Table 4.1, Treated minus untreated area, August 1983). The difference is not entirely due to refinement, because before treatment the amounts of litter and nutrients in the litter of the western area were already higher than those of the eastern catchment.

The increases in elements in the litter which can be attributed to the refinement are given in Table 4.1 and Table 4.7 under Increase in treated minus increase in untreated area. These increases are 2000 kg organic C, 53 kg N, 26 kg Ca, 4 kg Mg, 1 kg K and 3 kg P per ha.

Analysis of variance of the original litter data, of which in Table 4.1 only the means and standard deviations are given, showed that the effects of treatment on litter amounts and on nutrients in the litter, were not statistically significant. This is probably caused by the small number of samples in October 1981 combined with the large variation in litter amounts. In August 1983 the litter amount in the Western Creek area was 35 % higher than in the Eastern Creek area. This litter is more woody and therefore concentrations of N, K, Mg and Na are slightly lower, and the concentration of Ca slightly higher.

The original values of each soil sampling plot (means given in Tables 4.2 and 4.3) have been used to calculate the amounts of organic carbon, total N, adsorbed cations, total K and P and of the available P in the profile up to 120 cm depth. The differences between both sampling periods were compared for the Eastern and Western Creek area and are given in Table 4.4. It appears that in August 1983 there was slightly more organic matter and K in the soil but less N, Ca and Mg than

TABLE 4.1 Amount and composition of litter in treated and untreated areas

Area and time	Treatment	No of samples	Data	Dry weight (g)	Weight (kg/ha)	Ash (%)	Elements in litter (kg/ha)						
							C	N	P	K	Ca	Mg	Na
Eastern Creek October 1981	untreated	5	mean	396	15 824	(40)	4747	139	2.3	3.6	80.3(40.2)*	n.a.	0.8
			SD	130	5 191	(0)	1557	70	2.7	3.6	53.9(27.0)	n.a.	0.7
Eastern Creek August 1983	untreated	10	mean	539	21 576	43	6107	179	6.5	14.1	46.4	15.9	4.2
			SD	135	5 400	11	2344	84	1.5	4.5	50.9	7.5	1.6
Western Creek October 1981	before treatment	7	mean	408	16 320	(40)	4896	173	3.2	6.6	70.2(35.1)	n.a.	1.5
			SD	205	8 207	(0)	2462	113	5.7	7.2	47.5(23.8)	n.a.	1.7
Western Creek August 1983	after treatment	14	mean	846	33 857	51	8258	266	10.0	17.9	67.5	20.0	4.6
			SD	466	18 621	15	4329	144	4.7	9.6	93.9	12.9	2.9
Western Creek minus Eastern Creek, October 1981			mean	12	496		149	34	0.9	3.0	-10.1(-5.1)	n.a.	0.7
Treated minus untreated area, August 1983			mean	307	12 281		2151	87	3.5	3.8	21.1	4.1	0.4
Increase in treated area minus increase in in untreated area			mean	295	11 785		2002	53	2.6	0.8	31.2(26.2)	(4.1)	-0.3

*

( ) estimated values

LE 4.2 Soil composition in the untreated Eastern Creek area (average of 5 profiles)

	OCTOBER 1981						AUGUST 1983					
th (cm)	0-20	20-40	40-60	60-80	80-100	100-120	0-20	20-40	40-60	60-80	80-100	100-120
tal (%)	1.31	0.89	0.52	0.31	0.24	0.23	1.37	0.74	0.56	0.40	0.33	0.25
tal (%)	0.093	0.070	0.044	0.038	0.030	0.032	0.096	0.056	0.042	0.032	0.030	0.025
	14	13	12	8	8	7	14	13	13	13	11	10
H_2O	4.4	4.7	4.8	4.8	4.9	4.8	4.4	4.4	4.4	4.7	5.0	4.7
KCl	3.9	4.1	4.1	4.0	4.1	4.1	3.5	3.7	3.8	3.8	3.9	3.9
C pH7 (me/100 g)	3.29	2.60	1.94	1.55	1.33	1.26	3.88	2.96	2.45	1.92	1.82	1.46
(me/100 g)	0.240	0.106	0.082	0.074	0.076	0.082	0.254	0.036	0.016	0.012	0.012	0.025
(me/100 g)	0.165	0.114	0.098	0.082	0.090	0.094	0.092	0.038	0.028	0.030	0.034	0.025
ne/100 g)	0.036	0.022	0.012	0.004	0.004	0.006	0.058	0.028	0.018	0.018	0.026	0.020
(me/100 g)	0.025	0.022	0.016	0.014	0.024	0.028	0.030	0.014	0.008	0.012	0.030	0.010
me/100 g)	1.20	1.09	0.89	0.74	0.64	0.57	1.33	1.11	1.04	0.93	0.77	0.65
l bases(me/100g)	0.466	0.264	0.208	0.174	0.194	0.210	0.434	0.116	0.070	0.072	0.102	0.080
C soil pH(me/100g)	1.67	1.36	1.10	0.91	0.83	0.78	1.76	1.23	1.11	1.00	0.87	0.73
aturation (%)	72	81	81	81	77	73	75	91	94	93	89	89
tal (ppm)	79.6	75.4	79.2	71.0	76.6	84.2	77.3	101.2	89.0	138.0	121.2	101.5
tal (ppm)	85.2	85.0	67.0	59.7	77.6	64.0	69.6	78.4	66.4	67.0	66.8	81.5
rayI (ppm)	3.4	7.3	2.1	2.1	1.1	3.0	4.2	3.3	1.3	1.4	1.2	1.3
al/PBray	25	12	32	28	71	21	17	24	50	49	55	65

BLE 4.3 Soil composition in the Western Creek area before and after refinement (average of 7 profiles)

	OCTOBER 1981						AUGUST 1983					
pth (cm)	0-20	20-40	40-60	60-80	80-100	100-120	0-20	20-40	40-60	60-80	80-100	100-120
otal (%)	1.53	0.88	0.53	0.30	0.23	0.20	1.45	0.99	0.54	0.39	0.26	0.21
otal (%)	0.103	0.064	0.044	0.031	0.029	0.026	0.099	0.067	0.040	0.030	0.023	0.023
	15	14	12	9	8	8	15	15	14	13	11	9
-H_2O	4.3	4.6	4.7	4.8	4.9	4.9	4.2	4.5	4.7	4.6	4.7	4.6
-KCl	3.8	4.0	4.1	4.1	4.1	4.1	3.5	3.8	3.8	3.8	3.8	3.8
C pH7 (me/100 g)	4.02	3.72	2.46	1.80	1.61	1.56	4.16	3.14	2.20	1.92	1.72	1.70
(me/100 g)	0.296	0.114	0.092	0.097	0.081	0.083	0.226	0.027	0.011	0.009	0.011	0.010
(me/100 g)	0.196	0.119	0.103	0.123	0.104	0.101	0.094	0.048	0.033	0.031	0.030	0.026
me/100 g)	0.043	0.020	0.010	0.014	0.010	0.020	0.048	0.036	0.016	0.020	0.014	0.020
(me/100 g)	0.033	0.023	0.021	0.029	0.013	0.033	0.027	0.026	0.014	0.023	0.019	0.008
(me/100 g)	1.40	1.25	0.96	0.85	0.77	0.81	1.43	1.22	1.02	0.90	0.87	0.84
al bases(me/100g)	0.568	0.276	0.226	0.263	0.208	0.237	0.395	0.137	0.074	0.083	0.074	0.064
C soil pH(me/100g)	1.97	1.53	1.19	1.12	0.98	1.04	1.83	1.36	1.09	0.98	0.94	0.90
saturation (%)	71	82	81	76	71	77	78	89	93	92	92	93
otal (ppm)	87.6	73.6	77.4	103.0	96.3	109.7	70.4	93.4	101.1	144.7	201.9	217.0
otal (ppm)	85.8	67.9	73.1	69.1	76.9	75.2	79.3	78.7	69.6	68.3	81.3	77.3
rayI (ppm)	3.5	3.9	2.1	3.2	3.8	1.7	5.0	5.4	5.2	2.0	2.4	2.5
tal/PBray	25	17	35	22	20	44	16	15	13	34	33	31

TABLE 4.4 Amounts of major elements in the soil before and after refinement (kg/ha)

Area and time	Treatment	Plot	Soil layer (cm)	C	N	Ca	Mg	K	K	P	P BrayI
				total		adsorbed			total		
Eastern Creek October 1981	Untreated	3	0-120	104 469	8888	405.7	325.3	91.6	1274	1211	50.0
		4	0-120	98 796	8968	558.3	244.9	87.4	1375	846	16.3
		6	0-120	105 717	9592	469.6	226.2	50.0	1220	1031	26.2
		9	0-120	83 632	8011	343.7	170.8	107.4	1114	1391	103.8
		12	0-120	104 894	8620	110.9	163.6	130.3	1840	1919	81.8
		mean		99 501	8816	377.7	226.2	93.4	1365	1280	55.6
		SD		8 303	513	151.1	58.6	26.4	252	367	33.0
Eastern Creek August 1983	Untreated	3	0-120	132 468	8700	211.1	41.7	229.4	1796	905	30.4
		4	0-120	100 002	7804	423.2	163.0	248.5	1991	1179	30.5
		6	0-120	106 072	6838	110.7	31.3	107.0	1230	1022	39.0
		9	0-120	93 802	8484	129.3	87.0	176.7	1461	1281	47.1
		12	0-120	87 977	8389	96.0	106.1	178.7	2778	1911	34.3
		mean		104 064	8043	194.1	85.8	188.1	1851	1260	36.2
		SD		15 437	672	121.3	47.5	49.3	533	350	6.3
Western Creek October 1981,	Before treatment	1	0-120	88 082	7303	888.7	282.7	148.8	2071	1275	36.4
		2	0-120	139 011	8288	403.4	224.5	120.2	1297	1454	83.6
		5	0-120	75 661	8558	412.3	256.0	55.1	2048	1458	75.4
		7	0-120	134 169	10154	456.3	305.6	111.8	1730	1503	22.4
		8	0-120	97 104	8907	382.5	183.5	91.8	1130	949	75.6
		10	0-120	104 700	9651	352.6	230.3	198.1	1364	1591	27.8
		11	0-120	88 997	6625	153.3	353.7	189.3	(17565)	931	47.8
		mean		103 960	8498	435.6	262.3	130.7	1607	1309	52.7
		SD		22 250	1148	205.9	52.6	47.8	367	249	23.4
Western Creek August 1983,	After treatment	1	0-120	102 560	8392	343.4	107.2	244.4	2364	1174	93.3
		2	0-120	138 313	7927	188.6	124.1	173.2	1224	1293	25.5
		5	0-120	117 169	9188	199.8	37.3	118.7	1666	1464	38.7
		7	0-120	99 843	6838	67.0	35.2	150.8	1332	1346	46.5
		8	0-120	95 712	6542	144.4	45.3	177.2	1258	935	46.5
		10	0-120	120 223	9843	80.8	167.2	179.5	1885	2364	32.3
		11	0-120	92 465	7692	92.6	120.9	160.9	(7459)	734	77.0
		mean		109 469	8060	159.5	91.0	172.1	1621	1330	65.7
		SD		15 239	1103	89.2	48.0	35.3	407	482	31.7
Western minus eastern creek area, October 1981		mean		4 459	-318	57.9	36.1	37.3	242	29	-2.9
Treated minus untreated area, August 1983		mean		5 405	17	-34.6	5.2	-16.0	-230	70	29.5
Increase in treated area, minus increase in untreated area		mean		946	335	-92.5	-30.9	-53.3	-472	41	32.4

( ) Very high total K values of plot 11 were not included in the calculation of the mean.

in October 1981. Measured Ca and Mg were then much higher than in August 1983. Whether or not these differences are due to systematic laboratory error or to varying amounts of these elements in the soil during different seasons (August is wetter than October) is not known.

The increases in carbon and major nutrient elements in the soil that can be attributed to the treatment are given in the last line of Table 4.4. No explanation can be given for the negative values of adsorbed Ca, Mg and K. Because adsorbed cations are relatively mobile and vary as a result of the rate of supply from decomposing organic matter and removal by roots or leaching, these negative values could be coincidental. For C, N, K and P total amounts in the soil have been determined. Most attention must be given to these total amounts. They showed a marked increase in the treated area with the exception of K. There is no explanation for the degree of increase of total K in the Eastern Creek area.

Analysis of variance of the original soil data showed that prior to treatment in 1981 there was no significant difference in soil composition between the Eastern and Western Creek areas. In 1983, amounts of adsorbed Ca, Mg and K were significantly lower than in 1981, but there were no significant changes in soil composition as a result of refinement.

It can be concluded that the extra nutrients released by refinement did not accumulate in the top 120 cm of the soil. Instead they had been taken up by the vegetation, leached to soil layers deeper than 120 cm, or passed into the groundwater.

4.2.3 Nutrients in different soil compartments

Nutrients in the soil can occur in several forms. They can occur in the soil solution or be adsorbed on soil particles and as such be readily available. They can be incorporated in the organic matter or can occur in the mineral fraction of the soil, either in clay or in coarser particles. When making a nutrient balance it is important to know how the nutrients are distributed over the various compartments. As only limited data were available, several assumptions had to be made with respect to the nutrient content of the soil compartments. Nevertheless, by doing so, it is possible to gain some insight in the order of magnitude of the compartments and their inter-relationships.

The composition of the organic fraction in the soil was not known. When soil samples were analysed, nutrients from both mineral and organic phases were extracted. A rough estimation of the nutrients in the organic matter was made as follows. It was assumed that the ratio between the nutrients in the soil organic matter was equal to the ratio of the nutrients in the litter. The amounts of nutrients in the soil organic matter were calculated from C and N contents, elements that occur only or mainly in the organic matter.

This assumption is based on the fact that in the Zanderij soil under forest no nutrient is relatively abundant. All nutrients, except perhaps N, seem to be in

TABLE 4.5 Calculated amounts of nutrients in the soil organic matter before and after refinement

Area and time	Depth (cm)	Bulk density	Total N (%)	N	Ca	Mg	K	P
				(kg/ha)				
Eastern Creek October 1981	0- 20	1.31	0.093	2424	242	73	170	48
	20- 40	1.48	0.070	2072	207	62	145	41
	40- 60	1.50	0.044	1320	132	40	92	26
	60- 80	1.50	0.038	1140	114	34	80	23
	80-100	1.50	0.030	900	90	27	63	18
	100-120	1.50	0.032	960	96	29	67	19
	Total			8816	882	264	617	176
Eastern Creek August 1983	0- 20	1.31	0.096	2515	252	75	176	50
	20- 40	1.48	0.056	1658	166	50	116	33
	40- 60	1.50	0.042	1260	126	38	88	25
	60- 80	1.50	0.032	960	96	29	67	19
	80-100	1.50	0.030	900	90	27	63	18
	100-120	1.50	0.025	750	75	23	53	15
	Total			8043	804	241	563	161
	Increase			-773	-78	-23	-54	-15
Western Creek October 1981	0- 20	1.31	0.103	2695	269	81	189	54
	20- 40	1.48	0.064	1903	190	57	133	38
	40- 60	1.50	0.044	1329	133	40	93	27
	60- 80	1.50	0.031	943	94	28	66	19
	80-100	1.50	0.029	857	86	26	60	17
	100-120	1.50	0.026	771	77	23	54	15
	Total			8498	850	255	595	170
Western Creek August 1983	0- 20	1.31	0.099	2601	260	78	182	52
	20- 40	1.48	0.067	1987	199	60	139	40
	40- 60	1.50	0.040	1200	120	36	84	24
	60- 80	1.50	0.030	900	90	27	63	18
	80-100	1.50	0.023	686	69	21	48	14
	100-120	1.50	0.023	686	69	21	48	14
	Total			8060	806	242	564	161
	Increase			-438	-44	-13	-31	-9
Increase in treated minus increase in untreated area				335	34	10	23	7

short supply, and will be taken up by the roots as soon as they become available by decomposition of organic matter. When not taken up, they will be removed from the soil by leaching. Taking together all litter samples of experiment 82/2 (54 samples), the following ratios of the elements were found:

C : N : Ca : Mg : K : P =
44 : 1 : 0.10 : 0.03 : 0.07 : 0.02

It was assumed that during decomposition the C:N ratio decreased to 10 to 15, that the ratios of C and the other elements decreased accordingly, and that the ratios between N, Ca, Mg, K and P remained constant. The calculated amounts of nutrients in the organic matter of the soil are given in Table 4.5. These amounts are based solely on the N content, which was lower in August 1983 than in October 1981. The same holds therefore for the calculated contents of Ca, Mg, K and P. The nutrients in the organic matter could also have been calculated from both the C and N contents with similar results.

Nutrients in soil minerals are not directly available for the plant roots and may therefore have little importance for agricultural crops with a short growing period. For a forest, however, they should be taken into account because slow exchanges between the mineral stock and more accessible nutrient pools, such as the exchange complex are possible. Concentrations of elements determined with the X-ray fluorescence method were used to estimate the magnitude of the mineral pools. In Appendix III the results of the total analysis of CaO, MgO, K_2O and P_2O_5 are given for Profiles 34, 35, 36 and 37, all under undisturbed forest. The mean values of these concentrations as well as the calculated total amounts in the soil up to 120 cm depth are given in Table 4.6.

In Table 4.7 the nutrient compartments discussed above have been combined; litter, soil organic matter, the exchange complex and the mineral soil compartment. Data for litter, soil organic matter and exchange complex have been summarized from Tables 4.1, 4.5 and 4.4 respectively. Total amounts of K and P, determined with Fleischman's acid are from Table 4.4, and results of total analysis with the X-ray fluorescence method from Table 4.6. These X-ray analyses were only performed on samples of profiles under undisturbed forest. Different amounts can be expected for the treated situation. For this reason data are listed

TABLE 4.6 Total amounts of nutrients in the soil based on average of undisturbed forest profiles 34, 35, 36, 37

Depth (cm)	Mean concentration (%)				Weight of soil layer (kg/ha)	Amounts of nutrients (kg/ha)			
	CaO	MgO	K_2O	P_2O_5		Ca	Mg	K	P
0- 20	0.014	0.080	0.011	0.009	2 620 000	262	1264	239	103
20- 40	0.010	0.078	0.013	0.014	2 960 000	212	1392	319	181
40- 60	0.013	0.078	0.018	0.011	3 000 000	279	1411	448	144
60- 80	0.010	0.065	0.018	0.014	3 000 000	214	1176	448	183
80-100	0.015	0.065	0.013	0.010	3 000 000	322	1176	324	131
100-120	0.015	0.065	0.018	0.015	3 000 000	322	1176	448	196
Total						1611	7595	2226	938

TABLE 4.7 Total amounts of elements in the soil profile to 120 cm depth in different organic and mineral compartments (kg/ha)

Area	Date	Element	Litter	Soil organic matter	Exchange complex a)	Total Fleisch b)	Total X-ray c)	Mineral d)
East	October 1981	C	4747	99 501	–			
		N	139	8 816	–			
		Ca	80(40)	882	378			
		Mg	(15)	264	226			
		K	4	617	93	1365		
		P	2	176	55	1280		
East	August 1983	C	6107	104 064	–			
		N	179	8 043	–			
		Ca	46	804	194		1611	613
		Mg	16	241	86		7595	7268
		K	14	563	188	1851	2226	1475
		P	6	161	36	1260	938	741
East	Increase 1981–83	C	1360	4 563	–			
		N	40	–773	–			
		Ca	–34(6)	–78	–184			
		Mg	1	–23	–140			
		K	10	–54	95	486		
		P	4	–15	–20	–20		
West	October 1981	C	4896	103 960	–			
		N	173	8 498	–			
		Ca	70(35)	850	436			
		Mg	(15)	255	262			
		K	7	595	131	1607		
		P	3	170	53	1309		
West	August 1983	C	8258	109 469	–			
		N	266	8 060	–			
		Ca	67	806	160			
		Mg	20	242	91			
		K	18	564	172	1621		
		P	10	161	66	1330		
West	Increase 1981–83	C	3362	5 509	–			
		N	93	–438	–			
		Ca	–3(32)	–44	–276			
		Mg	5	–13	–171			
		K	11	–31	42	14		
		P	7	–9	13	21		
Increase in treated minus increase in untreated area		C	2002	946	–			
		N	53	335	–			
		Ca	31(26)	34	–92			
		Mg	4	10	–31			
		K	1	23	–53	–472		
		P	3	7	32	41		

a) Easily available: adsorbed cations and P-Bray.
b) Extracted with Fleischman's acid.
c) Determined by X-ray fluorescence method.
d) In mineral fraction: Total (X-ray) amounts minus amounts in organic matter and easily available amounts.
( ) Estimated values.

for the Eastern Creek area only. The amounts of elements considered to be tightly bound in the soil minerals are given in the last column of Table 4.7. They result from subtracting the amounts in the organic matter and the exchange complex from the total amounts. These mineral reserves are very low, except for Mg. There is a discrepancy between the amounts found with the Fleischman method and the X-ray fluorescence method for P. With the first method 1260 kg P was found and with the latter (extracting theoretically 100 % of P present) only 938 kg. Probably the amount found with the first method is more accurate. With 0.01 % for P and Ca the X-ray fluorescence method is near the detection limit. Therefore the X-ray fluorescence data for total Ca and P are approximate.

It can be concluded from Table 4.7 that refinement resulted in an increase in organic matter in litter and soil with corresponding increases in amounts of carbon and nitrogen. An increase was measured for P but there were decreases in Ca, Mg and K.

4.3 Model of organic matter and nutrient flows

4.3.1 Organic matter amounts and flows

A simulation was made of the organic matter flows during harvest and refinement for a representative forest on plateau or upper slope. The results are shown in Table 4.8 where columns 1 to 3 represent the situation for an undisturbed forest on plateau with a phytomass of 540 t/ha. In the following columns organic matter amounts are given that might be expected to occur during exploitation and refinement in a situation where a harvest (extracting 20 m^3 stemwood per ha) is followed one year later by a refinement which kills 40 % of the phytomass. Several data in Table 4.8 have been adapted from Boxman et al. (1985) and the phytomass 82/2 was taken from Table 2.7.

- *Phytomass 82/2* (column 1): These are the amounts of phytomass occurring in experiment 82/2, situated on plateau land near the catchment and considered to be representative of the plateaus and upper slopes of the catchment.

- *Death rate* (column 2): This is the proportion of the vegetation, or the vegetation compartment that dies in one year. For trees in undisturbed forest, a death rate of 1.5 % was taken, and for trees in exploited and refined forest a slightly higher death rate of 2 % (De Graaf, 1986 and Boxman et al., 1985). The latter death rate has been used in calculating phytomasses in columns 5-10. Other death rates used are estimates, also taken from Boxman et al. (1985). Smaller plant parts have higher death rates than larger plant parts.

- *Litter production* (column 3): This was calculated from phytomass and death

TABLE 4.8 Simulation of organic matter pools (t/ha) and flows (t/ha/y) in undisturbed forest and changes during exploitation and refinement a)

		Phyto-mass 82/2	Death rate	Litter production	Killed in harvest	Phyto-mass	Killed in refinement	Phytomass			
Years after exploitation						1	1	2	3	4	5
Column number		(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
		t/ha	y^{-1}	t/ha/y	t/ha	t/ha	t/ha	t/ha	t/ha	t/ha	t/ha
Leaves	trees (dbh > 5cm)	7.6	1.0	7.6	1.0	7.0	3.0	5.	6.3	6.9	6.9
	trees (dbh < 5cm)	1.5	1.0	1.5	0.1	1.5		2.1	2.2	2.2	2.2
	palm	8.0	0.2	1.6	0.3	8.0		8.2	8.2	8.2	8.2
	liana	0.5	1.0	0.5	0.2	0.5	0.4	0.2	0.3	0.3	0.3
	total	17.6	0.64	11.2	1.6	17.0	3.4	15.5	17.0	17.6	17.6
Branches	large (> 3 cm)	94.0	0.015	1.41	13.3	81.0	32.4	50.9	56.8	63.7	69.6
	small (< 3 cm)	23.6	0.12	2.83	3.7	20.0	8.0	14.6	18.6	19.6	19.6
	liana	3.2	0.12	0.38	0.3	3.0	2.5	0.6	0.7	0.8	0.9
	total	120.8	0.038	4.63	17.3	104.0	42.9	66.1	76.1	84.1	90.1
Stems	trees (dbh > 5cm)	283.5	0.015	4.25	24.4	259.0	105.0	155.2	164.8	179.7	198.4
	trees (dbh < 5cm)	1.0	0.015	0.015	0.1	1.0		1.4	1.6	1.7	1.7
	palm	4.5	0.015	0.068	0.6	4.0		4.2	4.7	5.0	5.2
	liana	6.6	0.015	0.099	1.0	6.0	5.0	1.3	1.5	1.6	1.7
	total	295.6	0.015	4.43	26.1	270.0	110.0	162.1	172.6	188.0	207.0
Total above ground phytomass		434.0	0.047	20.26	45.0	391.0	156.3	243.7	265.7	289.7	314.7
Roots	(> 3 cm)	84.4	0.015	1.27	7.0	78.0	31.2	49.8	56.8	62.8	67.8
	(< 3 cm)	24.1	0.12	2.89	2.0	22.0	8.8	17.2	20.2	21.2	21.2
	total	108.5	0.038	4.16	9.0	100.0	40.0	67.0	77.0	84.0	89.0
Total living phytomass		542.5	0.045	24.42	54.0	491	196.3	310.7	342.7	373.7	403.7
Litter	coarse woody (> 3 cm)	21.5		28.6 c)	23.5 d)	47.5	137.4 e)	175.4	149.5	117.9	90.4
b)	decomposed wood	3.3									
	fine woody (< 3 cm))			6.7 c)	4.9 d)	9.1	15.5 e)	22.2	16.4	8.6	6.7
	leaf)	13.3		5.6 c)	1.6 d)	5.6	3.4 e)	5.3	4.5	5.2	5.5
	total	38.1		40.9 c)	30.0 d)	62.2	156.3 e)	202.9	170.4	131.7	102.6
Total phytomass without soil		580.6				553.2		513.6	513.1	505.4	506.3
Soil	0-120 cm	172.7				179.3		216.9	207.5	195.4	186.7
organic	120-170 cm	16.4				16.4		16.4	16.4	16.4	16.4
matter	170-300 cm	27.0				27.0		27.0	27.0	27.0	27.0
	total	216.1				222.7		260.3	250.9	238.8	230.1
Total phytomass		796.7				775.9		773.9	764.0	744.2	736.4

a) For explanation, see Section 4.3.1.

b) Decomposition time for coarse woody (>3cm), fine woody (<3cm), and leaf litter is 5, 2, and 0.5 y respectively.

c) Equilibrium amounts of litter by this litter production and decomposition times as mentioned under b.

d) Increase in litter amount resulting from harvest.

e) Increase in litter amount resulting from refinement.

rates. The equilibrium amounts of litter given are calculated from litter production and decomposition times. These amounts agree reasonably well with the measured litter amounts in undisturbed forest (1), which means that average decomposition times were appropriately chosen.

- *Phytomass killed by harvest* (column 4): This is the phytomass killed by harvest and extraction of 20 m^3 stem wood (15 t) per ha. Increases in litter amounts resulting from this operation can be observed. In the year after harvesting there was some regrowth and the extra litter amount decreased somewhat by decomposition.

- *One year after harvest* (column 5): These are the phytomass amounts one year after harvesting. This was the time of refinement.

- *Phytomass killed by refinement* (column 6): Refinement killed 40 % of the phytomass. The total increase in litter resulting from this refinement is given but this amount did not reach the litter compartment at the time of refinement. Trees died slowly and lost their leaves during the first year. It is proposed that half of the leaves fell after 6 months and the remainder after 12 months. Further, woody litter was available for decomposition after about one year, it is proposed that half began to decompose after 12 months and the remainder after 18 months. Coarse woody litter decomposes slower (5 years) than fine woody litter (2 years).

- *Phytomass 1 to 4 years after refinement* (column 7 – 10): The estimated situation in the years following refinement is given and this is based on the following assumptions. Living phytomass increased at half its usual rate in the first year, when a large proportion of sunlight still fell on leaves of dying trees, so reaching a low of 310 t/ha one year after refinement. All treated trees had died at that time. The living phytomass increased at normal rate thereafter. This was estimated to be about 30 t/ha/y, according to the calculations with WOFOST4 (Table 3.9). In 3 years, living phytomass increased to 400 t/ha.

- *Litter*. The litter amounts result both from as yet undecomposed exploitation and refinement material and from annual litter fall and decomposition. Litter amounts increased from 40 t/ha in the undisturbed situation to 70 t/ha directly after harvest (60 t/ha one year later) and to 200 t/ha one year after refinement. In the subsequent three years the amount then decreases to 100 t/ha.

  The spatial distribution of the litter from exploitation and refinement is uneven. Very large amounts of nutrients can be released locally during decomposition of such concentrations of organic material. Leakage to the groundwater is to be expected because such damaged places have also little vegetation to take up the nutrients.

- *Soil organic matter*. In this simulation decomposition of above ground litter did not increase the soil organic matter content. This is a simplification but the increase was expected to be small. The extra mortality of roots caused by exploitation and refinement was added to the soil organic matter. The resulting higher organic matter content decreased again with decomposition of these roots. Large roots decomposed in five years, fine roots in two years.

- *Total phytomass*. The strongest decreases in total phytomass occurred during the first year after exploitation and in two to three years after refinement. In the year after exploitation this loss was mainly due to wood extraction (15 t/ha). The danger of nutrient loss by leaching may be largest in the latter year but then the vegetation was already recuperating vigorously from refinement and nutrient uptake was high.

Some changes in the amount of organic matter are also illustrated in Fig. 4.4, which shows the changes in living phytomass, litter amounts, soil organic matter and the total of these components over a period of 5 years. It was assumed that all poisoned trees had already died in year 2 and moved to the litter compartment. Danger of nutrient loss seems highest at that time. But as leaves of poisoned trees

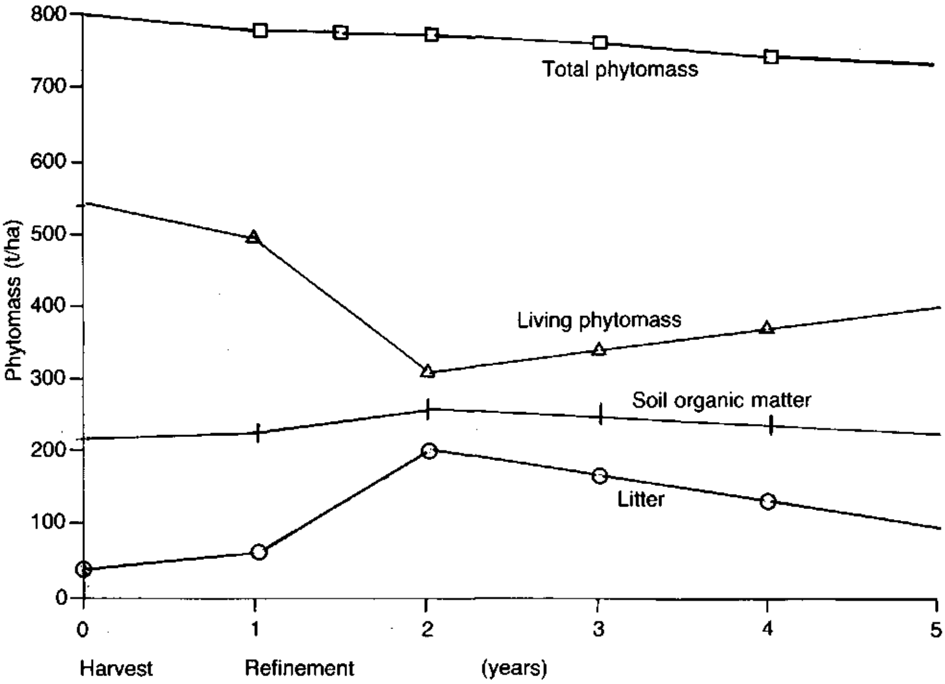


Fig. 4.4 Simulated changes in total and living phytomass in soil organic matter and in litter amounts resulting from harvest and refinement

TABLE 4.9 Calculated effects of treatment on living phytomass for various parts of the catchment area

Physiography	Proportion of catchment (%)	Before treatment (t/ha)	Killed by harvest (t/ha)	Killed by refinement (t/ha)	1 year after refinement (t/ha)
Plateau/upper slopes	68	540	54	196	311
Lower slopes	25	415	0	267	163
Valley bottoms	7	415	0	0	415
Total catchment area	100	500	37	200	281

still fell to this moment and as decomposition of wood was just beginning, the most crucial moment is probably between six months and one year later (near Year 3).

The treatment effects on footslopes and on the whole catchment differ from those on plateaus and upper slopes. Refinement was more radical in the lower footslopes than on plateaus and upper slopes because of the smaller proportion of commercial trees. The effects of treatment on phytomass on the lower slopes and for the whole catchment were calculated (Table 4.9) assuming that exploitation took place only on plateaus and upper slopes, that 40 % of the living phytomass was killed in the refinement and that valley bottoms remained unchanged.

4.3.2 *Changes in nutrient amounts*

Changes in nutrient amounts in the phytomass can be calculated by combining the organic matter amounts and nutrient contents. In Table 4.10 they are given for three situations; undisturbed forest, two years after refinement, and four years after refinement. Nutrient amounts are also given for annual litter fall in undisturbed forest and in the phytomass killed by harvest and by refinement.

The annual litter fall in undisturbed forest contained about 10 % of all nutrients in the living phytomass (5 % for Ca), and between 1.8 % (N) and 6.5 % (K) of all nutrients in the total phytomass including soil organic matter. Nutrient levels in the standing amount of litter (measured amounts given under undisturbed forest or equilibrium amounts given under annual litter fall) were approximately the same as in the annual litter fall, K having a faster turnover and Ca a slower turnover. Harvest killed phytomass containing nutrients equivalent to the amount in the annual litter fall. The Ca amounts were not the same because Ca occurs mainly in the wood which has a slower turnover. Refinement killed phytomass which has a little more than three times the amount of nutrients than the annual litter fall.

Nutrients in harvested and extracted stemwood are lost from the ecosystem. The amounts of nutrients in 15 t extracted stemwood per ha from plateaus and upper

TABLE 4.10 Nutrients in phytomass and soil organic matter before and after treatment (kg/ha)

	Element	Leaves	Branches	Stems	Roots	Total living phytomass	Litter	Soil organic matter	Total
Undisturbed forest (82/2)	N	234	454	826	857	2371	392	12 086	14 848
	P	14	34	49	58	154	12	242	409
	K	175	378	714	380	1646	52	841	2 539
	Ca	95	745	1633	445	2918	200	1 203	4 321
	Mg	30	72	134	79	316	35	362	712
Annual litter fall in undisturbed forest	N	174	28	12	54	269	318 a)		
	P	9	2	1	4	16	12 a)		
	K	106	23	11	24	164	54 a)		
	Ca	79	33	24	21	157	237 a)		
	Mg	23	4	2	5	35	37 a)		
Killed by exploitation	N	25	65	74	71	235	123 b)		
	P	1	5	4	5	15	8 b)		
	K	16	55	63	32	165	95 b)		
	Ca	11	108	149	37	305	187 b)		
	Mg	3	11	12	7	32	19 b)		
Killed by refinement	N	57	164	311	315	849	532 b)		
	P	3	12	18	21	55	33 b)		
	K	30	134	265	140	569	430 b)		
	Ca	27	262	634	164	1087	927 b)		
	Mg	8	26	50	29	113	84 b)		
Treated forest, 2 y after refinement	N	222	299	481	642	1644	680	12 336	14 660
	P	13	23	29	44	109	11	259	378
	K	173	252	420	285	1129	49	952	2 130
	Ca	90	480	928	321	1819	210	1 342	3 371
	Mg	28	49	78	59	215	33	385	633
Treated forest, 4 y after refinement	N	232	343	576	719	1869	476	12 163	14 507
	P	13	26	34	49	123	11	247	381
	K	177	288	502	318	1286	50	875	2 211
	Ca	94	562	1114	368	2137	213	1 255	3 604
	Mg	30	56	94	66	245	35	369	649

a) Nutrients in equilibrium amount of litter in undisturbed forest.
b) Nutrients in increase in litter amount resulting from treatment.

slopes are given in Table 4.11. Nutrients are released from the phytomass killed either by exploitation (but not extracted) or by refinement, when the organic matter gradually decomposes. They are then taken up by the vegetation, absorbed by the soil or removed. Rapid nutrient uptake by the vegetation is necessary to minimize losses by leaching, because the nutrient holding capacity of the soil is small (Tables 4.2 to 4.4). Table 4.10 in fact shows that three to five years after exploitation, nutrients in the phytomass (except N) were already increasing, even

TABLE 4.11 Nutrients in extracted wood and nutrients released by extra decomposition of organic matter (kg/ha) in the 3-year period after harvesting

	N	Ca	Mg	K	P
Plateaus and upper slopes					
Extracted in harvest	40	81	7	34	2
Extra release	148	869	72	375	29
Total catchment					
Extracted in harvest	30	60	5	25	1
Extra release	148	838	70	362	28

though the total amount of organic matter was still decreasing (Table 4.8).

Nutrient amounts in the phytomass were lowest three years after exploitation or two years after refinement. These amounts were compared with levels in undisturbed forest (Table 4.11). Amounts for plateaus and upper slopes were taken from Table 4.10 (differences between forest undisturbed and forest two years after refinement). Average amounts for the catchment as a whole were derived from these data and from the data shown in Table 4.9, assuming a living biomass of 311 t/ha for the whole catchment area 3 years after exploitation.

Is it not clear whether the amounts of extra nutrients released were held by the soil. Table 4.7 shows that refinement increased the total amounts of N and P in the upper 120 cm by about 400 and 40 kg respectively, but decreased the total amount of K and the adsorbed amounts of Ca, Mg and K. It seems that the soil did not take up the released amounts of Ca, Mg and K. Compared with the total amounts of nutrients in the upper 120 cm of the soil (Tables 4.7 and 4.11) these losses from the phytomass were 56 % for Ca, 1 % for Mg, 19 % for K and 3 % for P. This means that there is reason for concern about the nutrient status of Ca and K. N is considered to be plentiful and because it is not mobile, P will not leach from the soil. Mg is already relatively abundant in the soil minerals.

4.4 Sampling and analysis of rain and creek water

In this section, sampling of rain-water, and water in the untreated Eastern Creek and the treated Western Creek is discussed and also the analysis of samples to determine the nutrient balance in the hydrological cycle. Most samples were analysed in Suriname and some were sent to the Netherlands for analysis.

4.4.1 Methodology

The weekly sampling of rain-water and of creek water at the dam site and at the

Eastern and Western Creek produced respectively 77, 173, 154 and 162 water samples between the end of 1979 to the end of 1983. Only 77 rain-water samples were collected because samples were only taken when sufficient water had collected in the rainfall recorder. The number of creek water samples differs slightly. At the dam site, sampling started somewhat earlier whereas the Eastern Creek was dry for slightly longer periods than the Western Creek. The samples were taken in plastic bottles (0.5 or 1 litre) with screw caps. Prior to analysis samples were kept in the dark, they were not cooled and no preservatives were added.

The water samples for the whole period were analysed in the laboratory of the Centre for Agricultural Research (CELOS) in Paramaribo, Suriname. This laboratory was able to carry out the following analyses. The electrical conductivity (EC) at 20° C in μS/cm, the Ca, Mg, K and Na contents in mg/l, and pH and P contents of a small number of samples. Cations were determined with a spectrophotometer and P with the molybdenum blue method (Begheijn, 1980).

Determining the composition of creek water was simpler than that of rain-water, partly because there were more creek water samples, also from the drier months. The concentrations in creek water were higher and could be determined more accurately. Moreover, it was much easier to avoid contamination of these samples. The sampling bottles were only used for rain and creek water samples. They never came into contact with more concentrated solutions because phosphorus especially tends to be absorbed by the bottle wall.

A limited number of water samples taken in 1982 and 1983, from the dam site, Eastern and Western Creeks, and also 14 rain-water samples, 29 water samples from deep borings, and seven water samples for soil moisture, surface flow, lateral flow, reservoir in front of the dam and leakage water from under the dam were also analysed in the laboratory of the Department of Soil Science and Geology of the Agricultural University, Wageningen, The Netherlands. This laboratory is well equipped to analyse water samples with very low concentrations of elements. The

TABLE 4.12 Number of water samples and year of sampling

Location	Analysed only in Paramaribo*	Analysed only in Wageningen**	Analysed in Paramaribo and Wageningen
Dam	167 (1979-83)	4 (1983)	2 (1982)
Eastern Creek	133 (1980-83)	3 (1983)	18 (1982-83)
Western Creek	139 (1980-83)	4 (1983)	19 (1982-83)
Rain meter	63 (1980-83)	3 (1983)	11 (1982-83)
Groundwater	2 (1983)	0	29 (1981+83)
Soil moisture	0	1 (1983)	1 (1981)
Other samples	8 (1979-80)	5 (1983)	0

* Samples analysed at CELOS, Paramaribo, Suriname.

** Samples analysed at the Agricultural University, Wageningen, the Netherlands.

numbers of water samples and the distribution of the samples over the laboratories are given in Table 4.12 .

In Wageningen the same components were analysed as had been analysed in Suriname, but additional entities were determined: organic and inorganic carbon, SiO_2, Al, Fe, Mn, NH_4, F, Cl, NO_3, SO_4, H_2PO_4 and HCO_3. The totals of mmols(c) of anions and of cations were calculated. The methods used in Wageningen followed Begheyn (1980). In mmol(c), (c) means charge, one mmol(c) is equal to the mass corresponding with Avogadro's number of elementary electrical charges. One mmol(c) equals meq used previously. When mmol appears in the text, mmol(c) is meant, unless otherwise stated.

4.4.2 Results of the analysis

The Paramaribo laboratory data are too extensive to be given here. The Wageningen laboratory data are presented in Appendix VII.

The results from both laboratories show that the composition of rain and creek water was not constant. During drier periods higher concentrations were measured. The Suriname results show deviations for some periods, considering time of the year and creek discharge. The results for these periods have been assumed to be incorrect. The compositions for these periods were reconstructed with the aid of data from corresponding periods in others years. These adaptations are discussed in Appendix VIII.

Results from both laboratories showed a rather good agreement for electrical conductivity (EC), and contents of Mg, K and Na. Ca contents found in the Wageningen laboratory, however, were considerably higher than those obtained in Suriname.

Rain-water

The mean monthly values of elements in all rain-water samples are given in Table 4.13. Samples taken in wet periods generally have lower values than those taken in dry periods. The years have been taken together and the results grouped into months. The density of observation was largest in April, May and June, the main rainy season. In this period EC of rain-water was lowest (about 10 μS/cm), and the variation in EC was slight. For the remainder of the year the EC values were generally higher and there was a large variation between the samples. Values of more than 100 μS/cm were occasionally found.

Two factors could account for the low EC values during the rainy season and the higher values during the drier periods:

- real differences in composition of the rain-water between wet and dry periods;
- contamination of the water samples, especially during the dry periods.

In drier periods when rain showers are far apart, the falling rain drops can absorb

TABLE 4.13 Mean monthly EC (μS/cm), Ca, Mg, K, Na and P (mg/l) in rainwater samples

Month	Number of samples		EC		Ca		Mg		K		Na		P	
	P	W	P	W	P	W	P	W	P	W	P	W	P	W
Jan	5	0	45	–	0.83	–	0.11	–	0.91	–	1.02	–	–	–
Feb	6	1	27	77	0.56	0.86	0.15	0.26	0.82	1.37	0.98	1.61	–	0.557
Mar	8	2	39	38	0.44	0.75	0.14	0.18	0.64	0.72	0.57	0.91	–	0.170
Apr	11	2	9	12	0.33	0.63	0.09	0.10	0.36	0.25	0.33	0.44	0.050	0.031
May	10	2	16	13	0.25	0.59	0.10	0.06	0.39	0.29	0.25	0.23	0.138	–
Jun	9	3	21	16	0.28	0.59	0.08	0.08	0.41	0.46	0.14	0.24	0.125	0.062
Jul	6	1	10	22	0.18	0.56	0.11	0.09	0.39	0.63	0.11	0.34	0.125	0.031
Aug	5	1	12	45	0.20	0.56	0.09	0.11	0.41	1.02	0.16	0.39	0.150	0.031
Sep	4	0	17	–	0.39	–	0.09	–	0.58	–	0.24	–	0.175	–
Oct	1	1	8	60	0.40	0.62	0.10	0.13	0.20	1.17	0.20	0.46	0.100	0.093
Nov	1	1	14	30	0.32	0.60	0.06	0.13	1.22	0.98	0.31	0.34	–	0.062
Dec	8	0	38	–	0.85	–	0.12	–	1.09	–	0.78	–	–	–

P Analysis carried out at CELOS, Paramaribo, Suriname.
W Analysis carried out at the Agricultural University, Wageningen.

more dust and smoke from the air than during periods when rainfall is almost daily and therefore reach a higher conductivity and concentration of various elements. This factor may be of limited importance in the study area which is part of a vast forest and where the air is quite clear in the dry season.

The other possible reason for the variation in EC values is that the rain-water samples were contaminated. During wet periods sampling was generally once a week but in dry periods emptying and sampling was usually done after several weeks and sometimes after two months. The risk of contamination is therefore much greater in the dry seasons. Contamination was possible via the large funnel of the rain-gauge (about 2500 cm^2), which had its rim 10 cm above a soil surface covered with sparse grass vegetation. Insects and dust were able to fall into the funnel. Contamination by humans was also possible. As with emptying of the rain-gauge also most of the contamination was removed, following samples were progressively more pure.

All rain-water samples with a conductivity of more than 50 μS/cm have arbitrarily been considered to be contaminated. These samples have not been included in calculating the mean rain-water concentrations per month or in nutrient balance calculations. The correction of rain-water data is given in Appendix VIII. The resulting corrected mean monthly values are given in Table 4.14.

Creek water

Both time of year and discharge influence the composition of creek water. The results of the analysis of creek water samples from the Wageningen and Suriname

TABLE 4.14 Estimated mean monthly EC µS/cm) and Ca, Mg, K, Na and P (mg/l) in rainwater samples *

Month	EC	Ca	Mg	K	Na	P
Jan	20	1.10	0.15	1.10	0.90	0.05
Feb	18	1.00	0.14	1.05	0.80	0.05
Mar	16	0.90	0.12	0.70	0.70	0.05
Apr	10	0.65	0.11	0.50	0.45	0.03
May	10	0.55	0.09	0.40	0.30	0.03
Jun	10	0.55	0.09	0.40	0.20	0.03
Jul	10	0.55	0.09	0.50	0.25	0.03
Aug	12	0.55	0.09	0.60	0.30	0.03
Sep	14	0.75	0.10	0.70	0.35	0.05
Oct	16	0.90	0.11	0.80	0.40	0.05
Nov	18	1.00	0.13	1.00	0.60	0.05
Dec	20	1.10	0.15	1.10	0.70	0.05

* Derived from Appendix VIII; Table VIII.1.

laboratory also showed some differences especially in Ca content. Data for some periods from the Suriname laboratory were considered to be incorrect. Instead of discarding these data, an attempt was made to reconstruct the correct values using concentrations measured in corresponding periods in other years. These adjustments are described in Appendix VIII. The corrected cation concentrations of the Eastern and Western Creek waters are given in Figs. 4.5 and 4.6. The measured P concentrations had also to be adapted (Appendix VIII). The corrected monthly P concentrations are given in Fig. 4.7

The composition of the creek water was established with reasonable accuracy. There was a relatively close agreement between the measured values obtained in Suriname and in Wageningen. The ionic balance and the agreements between measured and calculated conductivities according to Stuifzand (Section 4.4.4) were generally good.

4.4.3 Cation and anion charge balance

The contents of Ca, Mg, K, Na and P in rain and creek water have been discussed in the preceding section. Attention is now given to the other components in the water samples.

Water analysis data from the Wageningen laboratory (Appendix VII) often showed a sum of cations which was higher than the sum of anions. It was thought that organic anions, which were not determined, were responsible for this imbalance. The creek water samples generally had a slightly brown colour and a total carbon content generally between 700 and 1000 mmol/m^3 (Appendix VII).

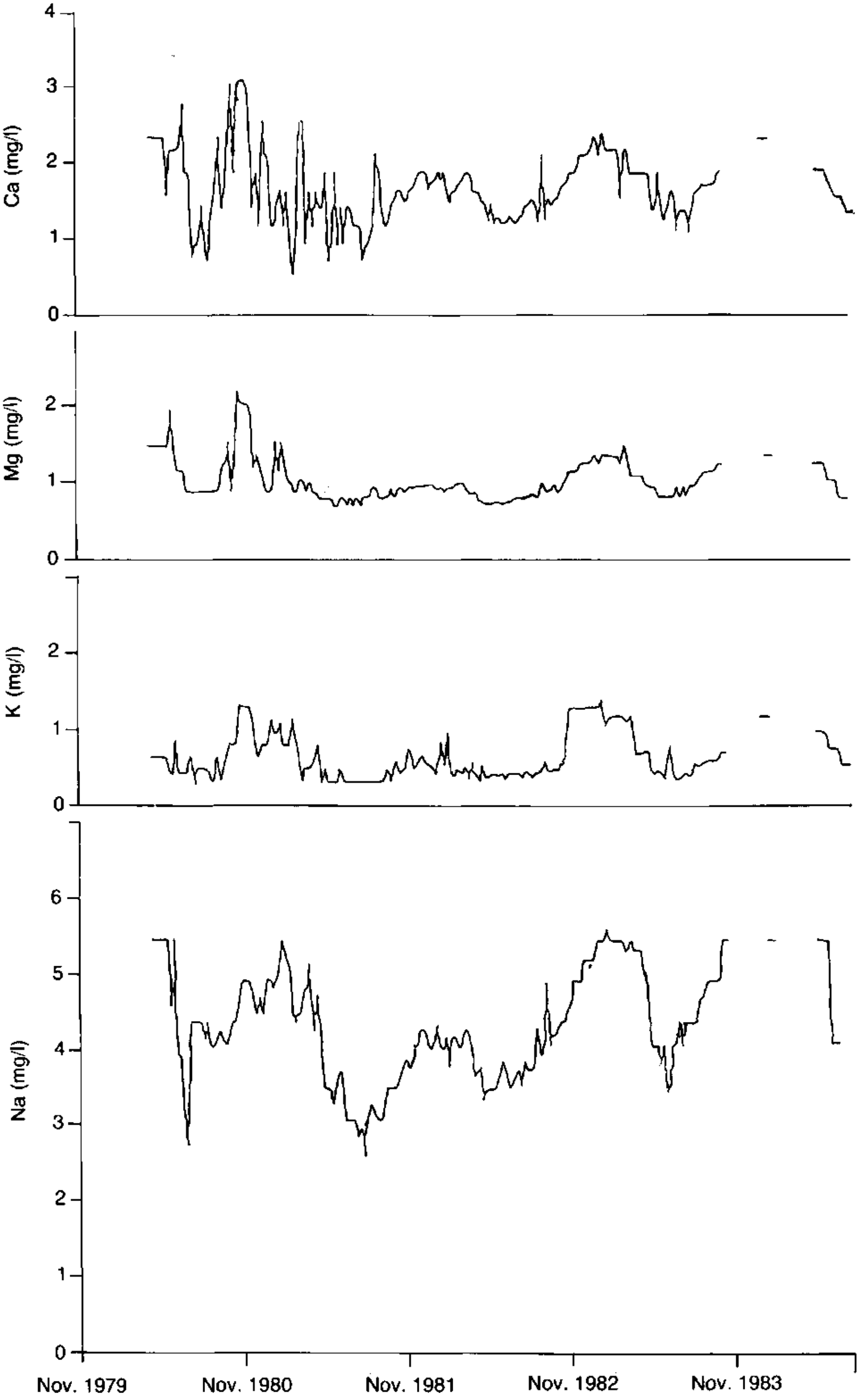


Fig. 4.5 Concentrations of Ca, Mg, K and Na in discharge water from Eastern Creek area in the period 1979 – 1984

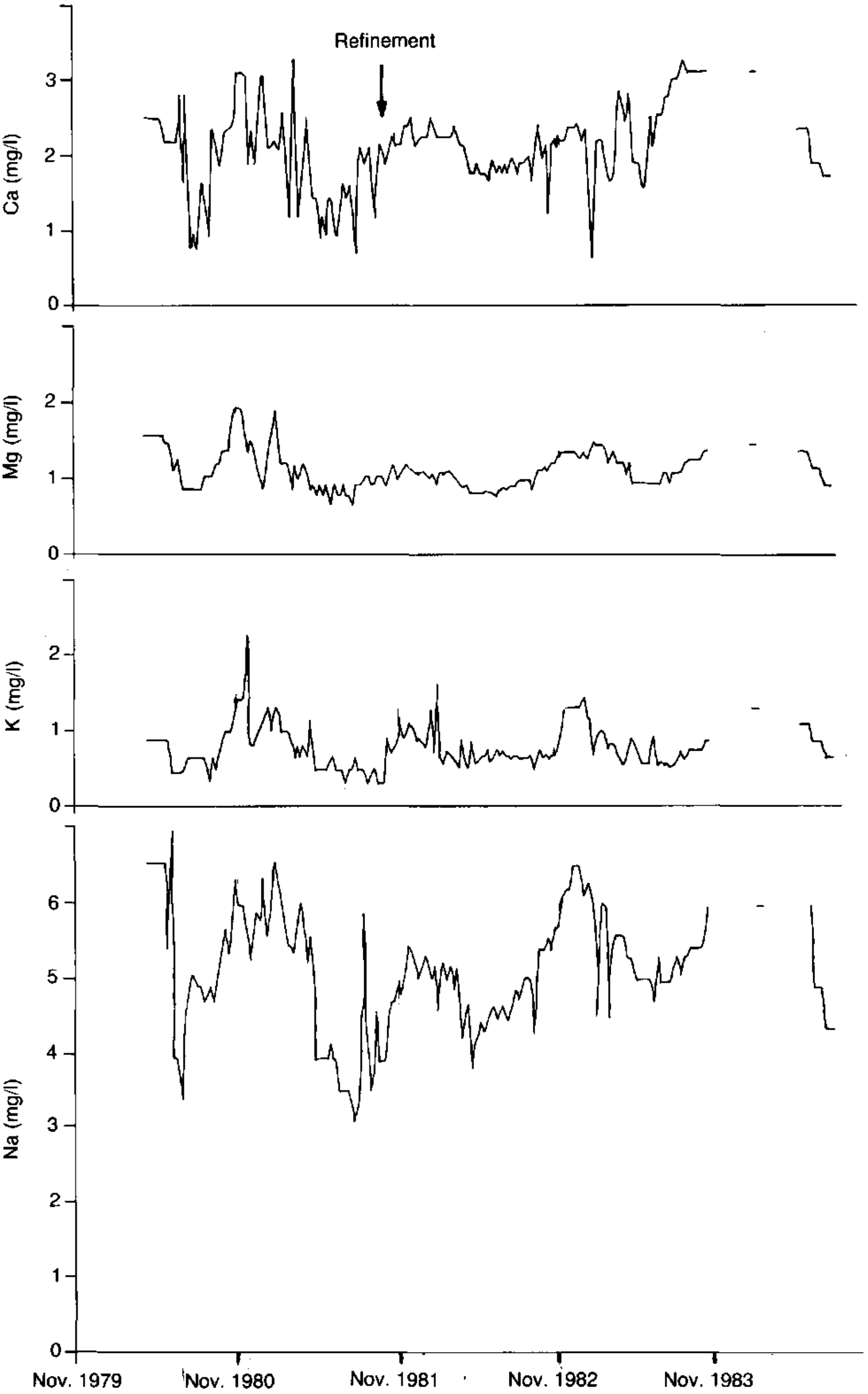


Fig. 4.6 Concentrations of Ca, Mg, K and Na in discharge water from Western Creek area in the period 1979 to 1984

TABLE 4.15 Mean concentrations for main groups of water samples analysed in Wageningen a)

	pH	EC	EC' (calc)	C total	C an-organic	SiO_2	H	K	Na	Ca	Mg	Al	Fe	Mn	N (NH_4)	Cl	N (NO_3)	S (SO_4)	P (PO_4)	C (HCO_3)	SOA b)	SUM+ c)	SUM- d)
		(µS/cm)		(mmol/m³)																			
Dam	6.79	44	38	961	327	321	0	20	214	98	91	2	6	1	0	118	4	18	1.5	228	45	432	414
Eastern Creek	6.81	40	35	1074	268	326	0	15	200	87	84	0	9	1	1	128	2	22	1.2	187	56	398	396
Western Creek	6.97	49	42	981	333	292	0	18	231	117	92	1	4	1	4	136	8	21	1.3	260	46	468	472
Rainwater e)	6.32	20	13	434	121	7	6	14	16	31	8	0	5	0	26	20	26	16	1.0	72	21	106	156
Groundwater f)	6.00	37	29	260	95	57	8	10	151	36	39	1	9	2	5	156	47	15	0.0	43	10	262	271
Soil moisture g)	8.17	700	649	16000	3240	511	0	624	638	5130	264	13	171	4	366	342	219	3100	9	3160	919	7210	7749
Surface flow	5.27	153	91	3180	56	71	5	281	219	126	97	3	15	5	174	138	335	178	8	4	184	925	847
Lateral flow	3.89	152	121	1395	72	22	133	211	187	45	37	34	33	5	120	217	377	137	10	0	48	805	788

a) Derived from data in Appendix VII.
b) Sum organic anions.
c) Sum of cations.
d) Sum of anions.
e) Not included sample nos. 52, 53 and 63.
f) Not included sample nos. 67 and 93.
g) Only sample no. 95.

24% for the rain-water samples but they were in some cases as high as 60%.

The EC values measured in Suriname and Wageningen are compared with the calculated EC values according to Stuifzand in Table 4.16. Values differed somewhat from those in Table 4.15 because a slightly different group of samples was considered. All samples measured in Wageningen (with a few exceptions) are given in Table 4.15 while Table 4.16 only gives those which were analysed both in Suriname and Wageningen. The Suriname values were slightly lower, and for the creek waters they showed a very good agreement with the calculated conductivities.

The conductivities calculated according to Stuifzand's method were lower for all groups than the conductivities measured in the Wageningen laboratory. As for creek waters the ionic balance was generally good, indicating correct values for cations and anions, it was concluded that conductivities measured in Suriname were correct and that the Wageningen laboratory had overestimated conductivities by about 12 %.

If the conductivities of rain-water samples have been measured correctly in Suriname (mean 14 µS/cm), the calculated value of 10 µS/cm indicates that too low concentrations of ions have been measured in Wageningen. As cation concentrations are lower than anion concentrations, cation concentrations are therefore probably too low. This conclusion should be drawn with caution because the concentrations of the rain-water samples are near the lower limit of the range given for the Stuifzand method. Several samples have a sum of cations + anions below 0.2 meq/l. It is not certain how accurate the Stuifzand method is in this range. However, when conductivities were calculated according to Robinson and Stokes (1970) a similar result to that of the Stuifzand method was obtained.

Of the anions in the rain-water, 46 % consisted of HCO_3, 17% of NO_3, 13% of

TABLE 4.16 Comparison average measured and calculated electrical conductivities (µS/cm) of water samples

	Measured EC		Calculated EC
	Suriname*	Wageningen**	
Creek at dam	35	38	35
Eastern creek	35	40	35
Western creek	42	48	42
Rain-water	14	16	10
Groundwater	37	38	30
Soil moisture	–	700	649
Surface flow	–	153	91
Lateral flow	–	152	121

* Results of analysis carried out at CELOS, Paramaribo, Suriname.

** Results of analysis carried out at the Agricultural University, Wageningen, the Netherlands.

organic anions, 13% of Cl, 10% of SO_4 and 0.6% of H_2PO_4. It is possible that carbon contents were somewhat overestimated, resulting in too high HCO_3 and SOA values. Part of the NH_4 in the samples may also have been oxidized to NO_3. These effects could largely explain the ionic imbalances. However, as the calculated EC is lower than the measured EC, it is more likely that cation concentrations were underestimated.

4.4.5 Calculation of missing values of total carbon and anorganic carbon

Values for total carbon and anorganic carbon are given in brackets for 25 samples in Appendix VII. These values were not determined in the laboratory but calculated afterwards.

Anorganic carbon was calculated from pH and HCO_3^- in the opposite direction as HCO_3^- was calculated in the laboratory from pH and anorganic carbon. The equation is:

$$HCO_3^- = \text{C-anorg} \times F \qquad (4.7)$$

F is taken from Fig. 4.8 for pH values between pH 4.5 and pH 8.4, and is a function of the dissociation factor K and the pH. It approaches 0 for pH < 4.5. For pH

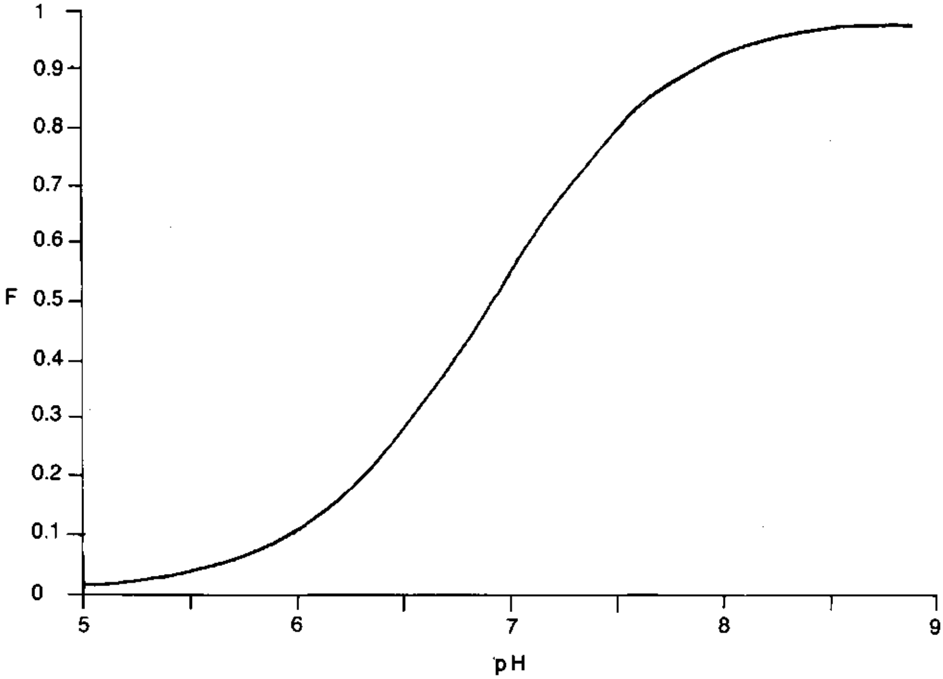


Fig. 4.8 Relationship between dissociation factor F from carbonate equilibrium and pH, for the calculation of bicarbonate from total anorganic carbon

values above 8.4, HCO_3^- is largely replaced by CO_3^{2-}, but such high pH values did not occur in the samples. The calculated values were in line with the measured values of the other samples.

Missing total carbon values have been calculated according to the method for calculating the amount of organic anions. This is given in Section 4.4.3. An iterative procedure was used in which the total carbon was varied until the value was found at which the organic anions (SOA) reached the level that equalled approximately the sum of cations (SUM+) and the sum of anions (SUM-). This was acceptable for the creek water samples, as the other creek water samples showed a relatively good balance between cations and anions. The calculated total carbon values agreed rather well with the measured values of the other creek water samples. A different approach was used for the rain-water samples because the other samples had a negative ion balance. A reasonable agreement with the other samples was reached by introducing a mean total carbon content of 400 mmol/m^3.

4.5 Nutrient balances in the hydrological cycle

4.5.1 Annual nutrient input by rain-water

The rainfall inputs per hydrological year (1 November – 31 October) for the period 1979 – 1984 are given in Table 4.17. Nutrient inputs were calculated by multiplying the monthly rainfall amounts by the estimated concentrations given in Table 4.14. Mean inputs (expressed as kg/ha/y) with rain were 16 for Ca, 2 for Mg, 14 for K, 10 for Na and 0.8 for P.

The composition of the rain-water samples was not established with the same accuracy achieved for the creek water samples (see Section 4.4.2). This was because concentrations were often near the detection limit, particularly for the Suriname laboratory, and because the sampling was not perfect. Also, the number of rain-water samples was low compared with the samples of creek water. The inputs with rain-water may be better understood by comparing measured rain-water composition and data from the literature. The rain composition is compared with data from other places in Table 4.18.

There is a large variation in the composition of rain-water throughout the world. Parker (1983) collected approximately 120 rain-water compositions world-wide. Average concentrations are higher than those found in the present study, except for K, which was relatively high. The concentrations in the study area, with the exception of P, correspond rather well with those found in Amapa, eastern Amazon area, Brazil (Russell, 1983). Many other locations have similar rain-water compositions. Input of Ca with rain-water was 16 kg/ha/y in Amapa (Russell, 1983) and in Malaysia 14 kg/ha/y (Kenworthy, 1970) which is very similar to the values in this study. However Manaus, more than 1000 km from the sea, in the centre of the Amazon area, received only 4 kg Ca/ha/y (Klinge and Fittkau, 1972).

TABLE 4.17 Rainfall and discharge and corresponding flow of nutrients in the project area for the period 1979 - 1984

Year (Nov-Oct)	Rainfall (mm)	Discharge (mm)	Catchment	Ca	Mg	K	Na	P
				(kg/ha/y)				
1979/80	1967			14.3	2.1	12.5	8.5	0.7
		296	Eastern	5.2	3.2	1.5	12.2	0.2
		296	Western	5.6	3.2	1.7	14.0	0.2
1980/81	2467			18.8	2.8	17.1	11.7	1.0
		601	Eastern	7.9	4.9	2.7	21.5	0.3
		601	Western	9.5	5.5	3.7	25.4	0.3
1981/82	2351			17.9	2.6	15.8	11.5	0.9
		864	Eastern	12.4	6.9	3.7	32.3	0.5
		864	Western	16.5	7.7	6.0	39.8	0.5
1982/83	1788			13.7	2.0	12.0	8.9	0.7
		294	Eastern	4.7	2.7	1.6	12.4	0.2
		294	Western	6.5	3.0	2.0	15.0	0.2
1983/84*	1667			12.1	1.8	10.6	7.4	0.6
		164	Eastern	2.5	1.5	1.1	6.5	0.1
		164	Western	3.0	1.7	1.3	7.8	0.1
Average	2143			16.2	2.4	14.4	10.2	0.8
		514	Eastern	7.6	4.4	2.4	19.6	0.3
		514	Western	9.5	4.9	3.4	23.6	0.3
Inflow minus	1629		Eastern	8.6	-2.0	12.0	-9.4	0.5
outflow	1629		Western	6.7	-2.5	11.1	-13.4	0.5

* 9 months only.

The source of the rain-water is probably very important and partly explains the level of variation reported in these studies. The Suriname study area is about 80 km from the sea. Rain is brought from the sea by north-easterly winds for almost the whole year. The rain-water is probably mainly derived from sea evaporation with a relatively high nutrient concentration. Bruynzeel (1982) states that the origin of the precipitation in his area, particularly during the rainy season, was terrestrial rather than maritime. This would explain the low concentration of elements observed. The same may apply for the interior of New York State, USA, as cited by Borman and Likens (1977). Sources of rain-water for the Central Amazon area, Brazil are described in several studies (Klinge and Fittkau, 1972; Sioli, 1985). It has been concluded that only half of the rain-water in this area comes from the sea and the remainder from evapotranspiration from the vast land mass. Concentrations in the rain-water are therefore much lower than near the coast at Amapa and in Suriname.

There is no reason to doubt the general level of these concentrations after comparing the composition of rain-water in Suriname and in other areas (Table 4.18). It can be concluded that these estimated net inputs of nutrients into the ecosystem as given in Table 4.17 are possible. Another factor which leads to the

TABLE 4.18 Comparison of measured composition of the rain water with data from elsewhere

	Country	Annual rainfall (mm)	Ca	Mg	K	Na	P	N	Cl	S	Si	Al	Fe	Mn
			(mg/l)											
Present study	Suriname	2143	0.74	0.12	0.64	0.44	0.037	0.88	0.87	0.30	0.25	0	0.16	0.01
Russell (1983)	Brazil	2352	0.67	0.14	0.43		0.006							
Bruynzeel (1982)	Indonesia	4768	0.21	0.09	0.20	0.28					<0.11	<0.034		
Bruynzeel (1985)	Indonesia	4670	0.21	0.09	0.31	0.28	<0.03	0.33	0.87	0.31				
Kenworthy (1970)	Malaysia	2500	0.56	0.13	0.50									
Nye (1961)	Ghana	1850	0.69	0.61	0.95		0.022	0.88						
Van Breemen (1987)	Netherlands	706	1.11	0.36	0.15	2.87	0.044	3.43	2.26	2.95				0.02
Borman/Likens (1977)	USA	1320	0.17	0.05	0.07	0.12	0.003		0.47	0.96				
Klinge/Fittkau (1972)	Brazil	2545	0.15	0.12			0.003[a]	0.39					0.08	
Manokaran (1978)	Malaysia		0.18	0.03	0.29	0.98		0.58						
Brasell (1980)	Australia	2520	0.11	0.11	0.18	0.83								
Jordan (1972)	Puerto Rico	3760	0.58	0.12	0.48	1.52								
Dalal (1979)	Trinidad	1595	2.18	0.47	1.21	2.57		1.0	3.9	0.67				
Mathieu (1976)	Ivory Coast	1320	<1.0	<0.1	<0.5	<0.5								
Henderson (1978)	USA		0.2	0.05	0.1	0.2								
Sollins (1980)	USA	2370	0.15	0.05	0.04	0.25								
Cryer (1976)	UK	1850	1.4	0.35	0.1	2.2								
Parker (1983)	World average		0.82	0.40	0.52	1.27	0.12[b]	0.98[b]	1.01	1.43				
	SD		0.94	1.02	0.58	2.50	0.19	0.92	0.66	1.10				

a PO_4-P, total P 0.012.

b P or N total.

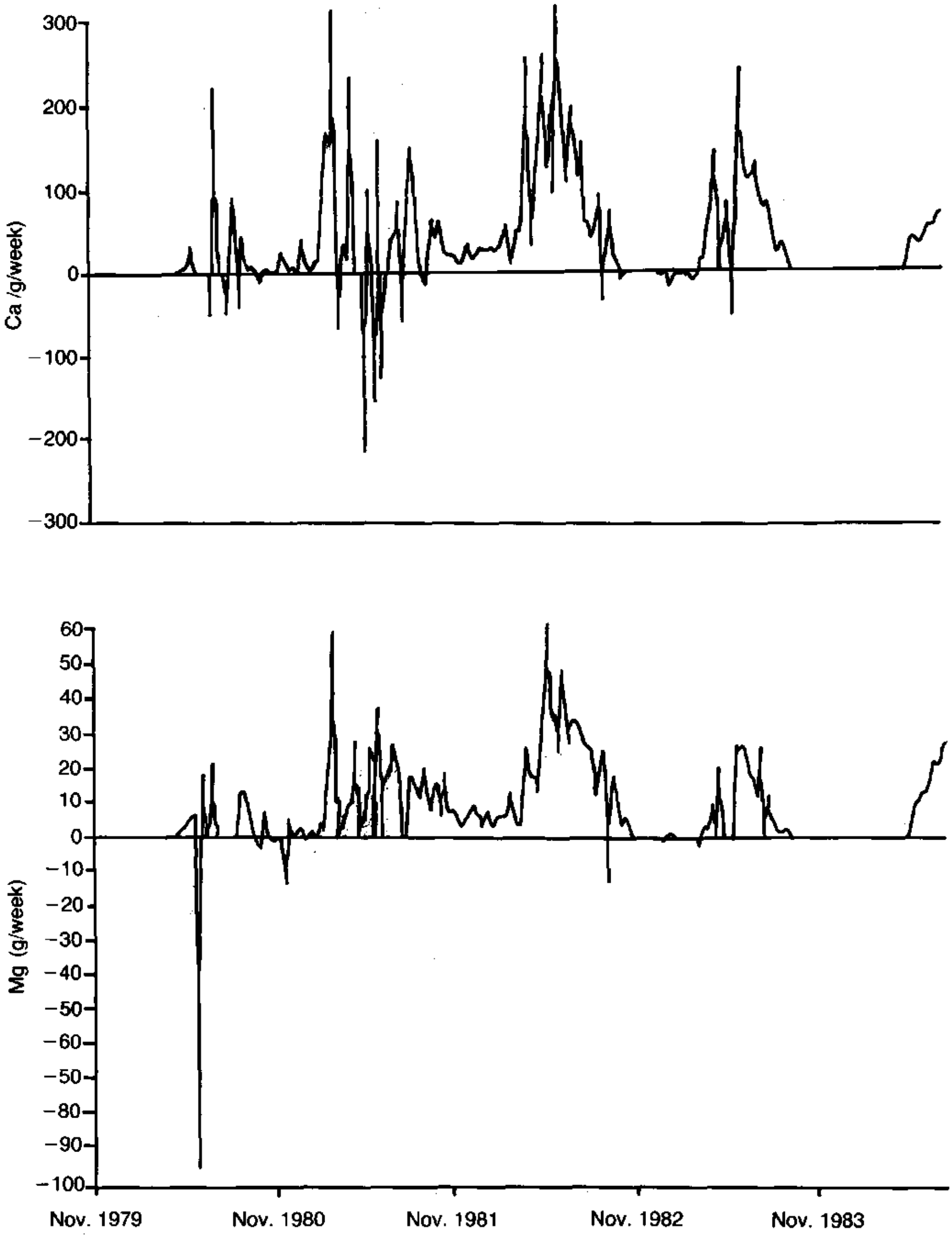


Fig. 4.9 Additional outflow of Ca and Mg in Western Creek area (concentration in Western Creek minus that in Eastern Creek multiplied by discharge)

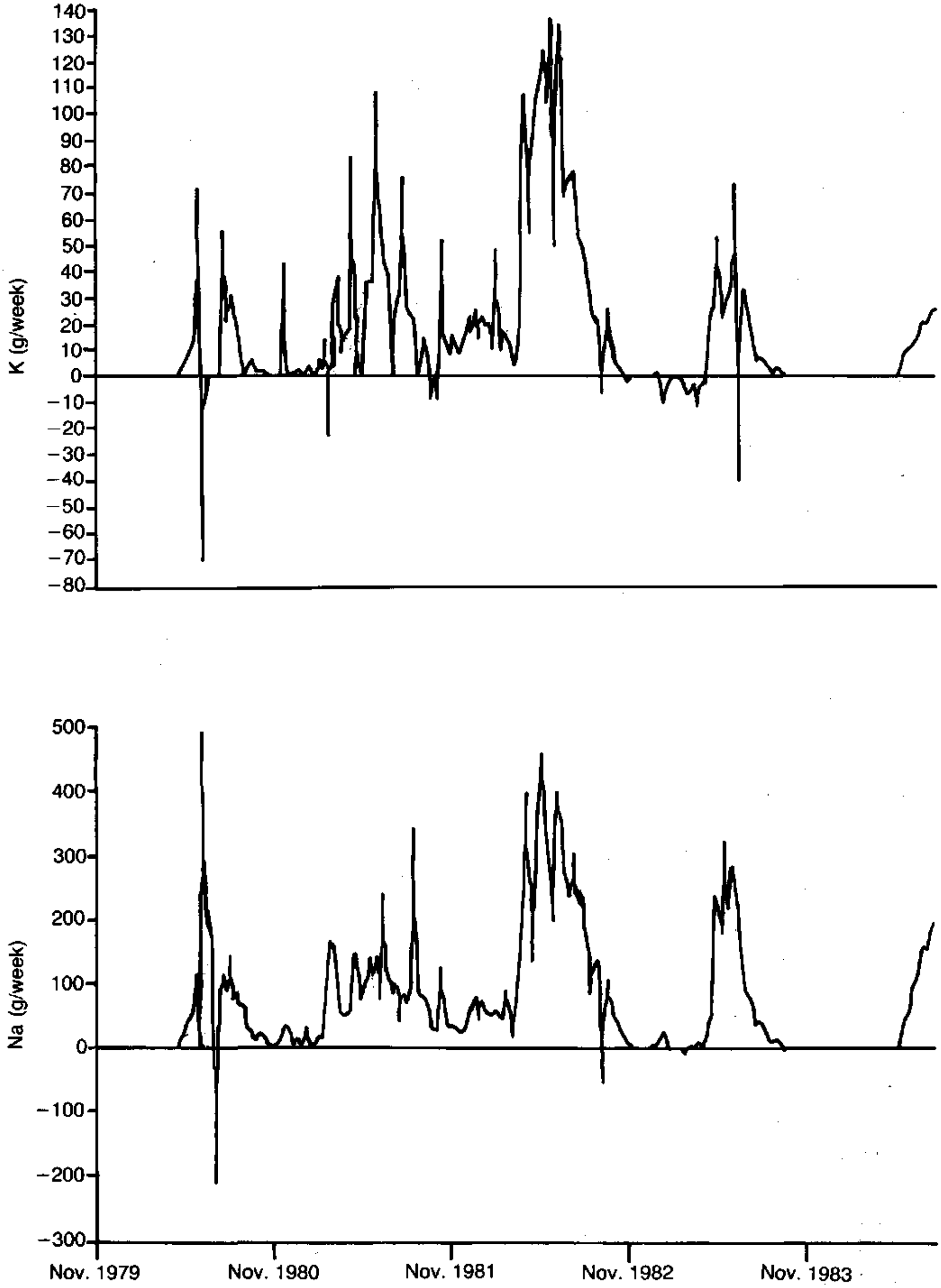


Fig. 4.10 Additional outflow of K and Na in Western Creek area (concentration in Western Creek minus that in Eastern Creek multiplied by discharge)

suggestion that these net inputs are minimum estimates is the influence of dry deposition. Although dry deposition occurs also on the rain gauge, where it is partly responsible for the higher concentrations of the rain-water in the drier periods, the amount will be larger on the forest because of its height and structure.

4.5.2 Annual nutrient outflow in creek water

The nutrient outflow for both the Eastern Creek area of undisturbed forest and the Western Creek area of selectively harvested and refined forest was calculated per week. Amounts of cations and P in the drainage water were found by multiplying the weekly discharge by the concentration of elements. The reconstructed figures were used for these calculations (Figs. 4.5 to 4.7).

The nutrient input in rainfall and the nutrient output in creek water for period 1979 – 1983 are compared in Table 4.17. There is only a small difference in output between the two catchments. The undisturbed catchment accumulated annually about 9 kg Ca, 12 kg K and 0.5 kg P, while it lost 2 kg Mg and 9 kg Na. The treated catchment lost annually 2 kg Ca, 0.5 kg Mg, 1 kg K and 4 kg Na per ha more than the undisturbed catchment. These figures are small and indicate that losses as a result of exploitation and forest refinement were not substantial, at least during the early years. An initial impression is that refinement has not had much influence on the outflow in the treated area (time of refinement indicated with an arrow on Fig. 4.6). The cations generally showed a higher concentration in the treated catchment, both before and after refinement.

Effect of refinement

The refinement of the forest was carried out in September – November 1981. Leaf fall from the poisoned trees occurred mostly in 1982 and the decomposition of fallen leaves was expected to have peaked in the rainy season of 1982 (March-July), liberating large amounts of nutrients. As the coarser parts of the killed trees (branches, stems and roots) decompose even more nutrients will be liberated. This process is slower to begin with and will extend over many years. The decomposition of the leaves and fine roots is of primary importance in this study because it gives a peak in the liberation of nutrients at a moment when the vegetation has been greatly reduced by treatment and has therefore a lower uptake capacity. Although the total difference in nutrient discharge between the two catchments was small, the difference needs to be examined more closely both in the most vulnerable period shortly after treatment and over the total observation period.

The extra amounts of cations discharged from the treated compared with the untreated area are given in Figs. 4.9 and 4.10. The data points in these graphs consist of the concentration in the water of Western Creek minus the concentration of Eastern Creek water multiplied by the discharge in the corresponding week. High peaks generally coincided with weeks of high

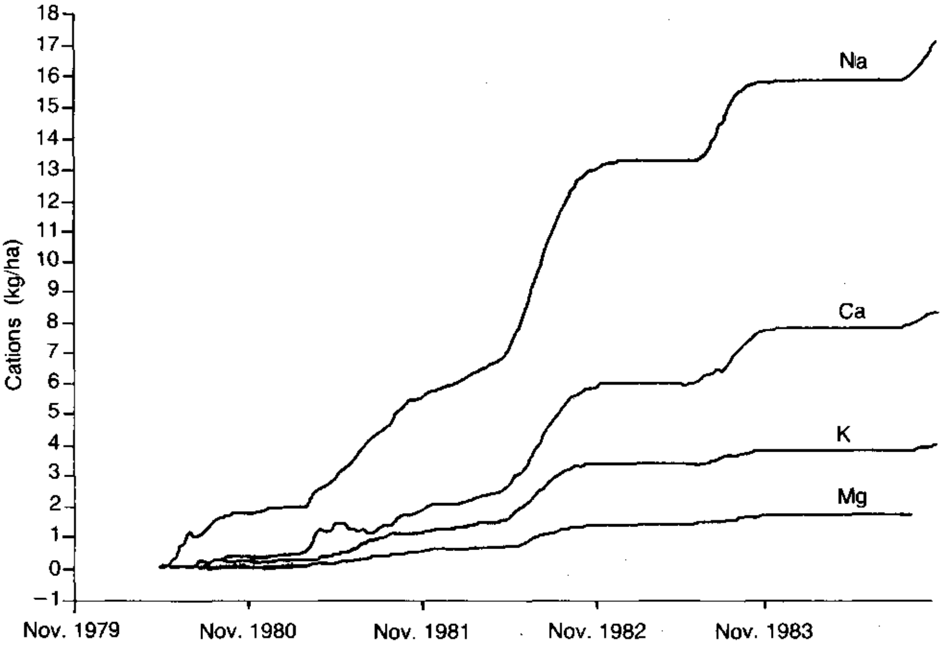


Fig. 4.11 Cumulative additional outflow of cations in Western Creek (concentration in Western Creek minus that in Eastern Creek multiplied by discharge)

discharge. Values were mostly positive because of the higher concentrations in the Western Creek. The largest extra loss of cations occurred in 1982 during the first rainy season after refinement indicating that there was indeed an extra loss just after treatment. K in particular was lost in relatively large amounts. There was no extra loss of P as no difference in P concentration was measured between the creeks.

Negative values were also found particularly in the beginning. They indicate weeks in which the measured concentration in the Eastern Creek was higher. Some of these negative values may result from analytical errors. Combining weeks as in Fig. 4.11 smooths out these peaks.

Cumulative extra losses in the Western Creek are given for all four cations in Fig. 4.11. The differences between creeks increased greatly during the rainy season of 1982 for Na, Ca and K. The effect for Mg is small. Losses continued in the rainy season of 1983, two years after refinement. Comparing the mobile cations Na and K, both had a high extra outflow in 1982 but in 1983 only Na had a high extra outflow, K was already lower. It is possible that in the second year the vegetation retained K more efficiently while Na continued to be discharged. Potassium predominates in the leaves and is therefore liberated quickly. Calcium, on the contrary, is mainly bound in the wood and is therefore released much slower than K. The extra discharge of Ca was still quite evident in the second year.

Analysis of the variations during the years in annual outflow amounts for the Eastern and Western Creeks, given in Table 4.17, showed that:

- Ca outflows were higher each year in Western Creek and refinement resulted in clear extra outflow during 1981-82 and 1982-83.
- Mg outflows were slightly higher in Western creek but there was no clear effect of refinement on Mg outflow.
- K outflows were slightly higher in the Western Creek and refinement greatly increased potassium outflow in Western Creek but only for 1981-82.
- Na-outflows were higher in the Western Creek throughout the period, and refinement had little extra effect on the sodium level in Western Creek. The extra outflow of sodium in 1981-82 seems large in Fig. 4.11, but this was mainly caused by the high discharge during that year. The concentration is in line with other years. Only a small proportion of this extra outflow can be attributed to refinement.

It seems that most of the extra nutrients released have disappeared. Analysing the groundwater concentrations in Appendix VII shows no clear difference between groundwater composition in deep borings between the Eastern and Western Creek areas. Thus 22 months after treatment the upper groundwater layer also did not show the effect of refinement.

Effect of exploitation

Even before refinement in 1981 all cations showed higher levels in the Western Creek than in Eastern Creek. Outflow was 15 % higher for Ca, 7 % for Mg, 29 % for K and 17 % for Na in the Western Creek during the years 1979-80 and 1980-81.

It is unfortunate that exploitation was done in 1978 and 1979, before the creek water sampling programme had begun in 1980. It is not possible now to show that exploitation has caused the higher nutrient outflow in the Western Creek although this is probably the main cause. Exploitation may have killed less phytomass than refinement and released less nutrients (Tables 4.8 and 4.10), but the killed phytomass was highly concentrated in felling gaps and skid trails. Vegetation, litter layer and topsoil were very disturbed, particularly on skid trails. The high concentration of decomposing phytomass, combined with a much greater disturbance than takes place during refinement, may well have caused the differences observed in outflow during 1979-80 and 1980-81.

The time taken for rain-water infiltrating the soil to travel through the groundwater reservoir and to be discharged as creek water is unknown. There is a large difference in travel time between rain-water falling at the centres of plateaus and rain falling on footslopes or creek valleys. The travel time for rain falling some distance away from the creek valleys is expected to be several years. It is probable that small differences in creek water composition will continue for several years. The first effects of treatment on creek water composition must have come from leaching of nutrients in footslopes near the creek.

4.5.3 Export or accumulation of main elements

The outflow of Na and Mg from the ecosystem was larger than the inflow from rain. This contrasted with amounts of Ca, K and P (see Section 4.5.2). This would indicate that weathering of soil and substratum yields more Na and Mg than is needed by the vegetation but insufficient Ca, K and P. The soil and substratum were therefore expected to have Na and Mg containing minerals. The soil analyses (Appendix III) showed that the deeper subsoil always had extremely low total Ca and P concentrations in the soil and in the clay fraction. The content of Mg was much higher although still at a low level and the content of K and Na was somewhere in between. Obviously Ca was well retained by the ecosystem because of scarcity, P was retained because of scarcity and low mobility, and K was retained because it is much needed by the vegetation. There were slightly larger amounts of Na than of K in the soil (Appendix III). Na is less retained because it is needed less by the vegetation. Mg was liberated in such large amounts that the vegetation was satisfied and a net outflow occurred. Possibly the very low Ca:Mg ratio prevented the vegetation from taking up more Mg.

Of the elements studied, Ca and P seemed to be in minimum supply. There is probably little P fixation in these soils (Boxman, in press) as soils have low iron contents and a low activity clay fraction. Hence the low availability of P is caused purely by the near absence of this element. N is considered to be plentiful. Amounts were high in the litter and in the soil organic matter. The forest is expected to have considerable potential for fixation of atmospheric nitrogen.

The nutrient balance for the Western Creek area is given in Table 4.19. As in Table 4.17, Ca, K and P accumulated throughout the whole period and Mg and Na showed a net output. In the first year after refinement (1981-82), accumulations were reduced. The conclusion can be drawn from these data that silvicultural treatment does not result in losses of essential elements, such as Ca, K and P. There was only a slow down in the accumulation of these elements lasting one or two years. The losses of Mg and Na appear to be of little importance because they were sufficiently liberated by weathering of minerals and therefore available in excess.

TABLE 4.19 Nutrient balance of the Western Creek area; input in rainfall minus output in creek water (kg/ha/y)

Year (Nov-Oct)	Ca	Mg	K	Na	P
1979/80	8.7	-1.1	10.8	-5.5	0.5
1980/81	9.3	-2.7	13.4	-13.7	0.7
1981/82	1.4	-5.1	9.8	-28.3	0.4
1982/83	7.2	-1.0	10.0	-6.1	0.5
1983/84 *	9.1	0.1	9.3	-0.4	0.5

* 9 months only.

4.5.4 Calculation of mean weighted concentrations of minor elements

In this section, an attempt is made to use the mean concentrations in rain and creek waters obtained in the Wageningen analyses to predict the inflow and outflow of elements other than the main ones discussed above. Concentrations of these elements C, N, Si, Al, Fe, Mn, Cl, and S were not determined in the Suriname laboratory and therefore they were not available for most of the study period. The samples analysed in Wageningen were from the later part of the period (Appendix VII). It was necessary to find out whether the results could be extrapolated over the whole period in order to estimate the fluxes of these other elements.

The mean concentrations of elements analysed in the Wageningen laboratory are not necessarily the weighted mean concentrations of the incoming rain-water and the outflowing creek water (weighted for water amounts per week). Because of this, mean concentrations obtained in Wageningen were compared with the mean weighted water balance concentrations for the main cations and P. Concentrations were available for the whole period for these particular constituents. By comparing these two sets of data, the relationship between them was established. It was then assumed that the same relationship applied also to the other elements. The weighted average concentrations of the "minor elements" were calculated as follows.

- The weighted mean concentrations of Ca, Mg, K, Na and P were calculated from Table 4.17 and are given in Table 4.20.

- The mean concentrations obtained in the Wageningen analyses (Table 4.15) were compared with the concentrations given in Table 4.20 in order to find the multipliers needed to obtain the weighted mean concentrations of the main cations and P from the mean concentrations in the Wageningen analyses. In Table 4.21 the mean concentrations of these elements are given together with these multiplying factors.

- After discarding the factors for P (P determinations were few and inaccurate in the Suriname analyses) there was a good agreement in factors for rain and creek water. The mean factor for rain-water is 1.21 and the mean factor for creek water in both creeks is 0.85. A factor of 0.85 for the creek water means that the

TABLE 4.20 Weighted mean concentrations of the main cations and P (mg/l) in rainfall and discharge, derived from Table 4.17)

	Ca	Mg	K	Na	P
Rainfall	0.76	0.11	0.67	0.48	0.037
Eastern creek	1.48	0.86	0.47	3.81	0.058
Western creek	1.85	0.95	0.66	4.59	0.058

LE 4.21 Mean concentrations of the main cations and P in the Wageningen samples (derived from le 4.15) and the factor between these concentrations and the weighted average concentrations table 0)

	Ca			Mg			K			Na			P		
	mmol /m3	mg /l	factor	mmol /m3	mg /l	factor	mmol /m3	mg /l	factor	mmol /m3	mg /l	factor	mmol /m3	mg /l	factor
nfall	31	0.62	1.23	8	0.10	1.10	14	0.55	1.22	16	0.37	1.30	1.00	0.031	1.19
tern Creek	87	1.74	0.85	84	1.02	0.84	15	0.59	0.80	200	4.60	0.83	1.24	0.038	1.53
stern Creek	117	2.34	0.79	92	1.12	0.85	18	0.70	0.94	231	5.31	0.86	1.35	0.042	1.38

mean concentration in samples analysed in Wageningen is higher than the mean weighted concentrations of constituents in creek water. As shown in Section 4.4.2 and Appendix VIII, concentrations of elements in creek water increase with decreasing discharge. Higher concentrations in the Wageningen analyses indicate a lower than average discharge for the period in which the samples were taken. This is in agreement with the facts. The samples analysed in Wageningen were mainly from 1983; less rain fell during the rainy season in that year than in the same season in 1981 and 1982. Discharges were correspondingly lower (Table 4.17). Moreover, many samples were from the later part of the rainy season when discharges were small.

- Factors for rain-water samples were also expected to be below 1. Concentrations in the rain-water were found to be lower in wetter than in drier periods. The cation concentrations in the Wageningen analyses were, however, below the mean weighted concentrations of the nutrient balance. The reason could be either too high weighted concentrations or too low Wageningen concentrations. The measured mean Wageningen concentrations are about 30% lower than the expected concentrations that would have given the same factors as found for the creek water samples. It is stated in Section 4.4.4 that cation concentrations in the Wageningen rain-water samples are probably too low, because the ionic balance is negative and because the calculated conductivity according to Stuifzand is lower than the measured conductivity. It is therefore concluded that the cation concentrations in the Wageningen rain-water samples are too low.

When a factor of 1.21 has to be applied to bring the concentration of the main cations of the Wageningen rain-water samples to the level of the weighted rain-water concentration, then the best estimate for the weighted concentration of the other elements is also the Wageningen concentration multiplied with the same factor. The same applies to the creek water for a factor of 0.85. The calculated weighted mean concentrations for rain and creek water used for element balances are shown in Table 4.22. They have been derived from the Wageningen concentrations (Table 4.15) by applying factors for rain and creek water of 1.21

active soil layers but still had to travel some distance through the deeper substratum to the creek. Roots have explored this water for nutrients and thus their concentrations are lowest in the upper groundwater layers. Most of the uptake of Si, Na and Mg will occur during the passage through the substratum.

The higher concentration of Cl in the groundwater compared with the creek water can be explained in terms of a "bypass mechanism". Not all the water is concentrated to the same extent. Part of the discharge is generated from rainfall on creek beds, valley bottoms and neighbouring land. This water becomes discharge relatively quickly without having intensive contact with soil or vegetation. It will retain a composition similar to rain-water and be discharged with lower Cl and higher nutrient concentrations than water falling on the plateaus.

Another bypass mechanism occurs on a smaller scale in the soil profile. Concentrations of all elements were much higher in soil moisture samples than in rain, creek and groundwater samples. The exact level of the soil moisture concentrations in Table 4.15 and 4.22, should not be given too much weight because the data are for a single soil moisture sample extracted in the rainy season by suction from a plateau soil at 100 cm depth. Few other soil moisture samples were available and these were only partly analysed because of a limited sample volume. However they showed concentrations of the same order of magnitude. The bypass mechanism implies that most of the percolating water follows certain preferred pathways, such as large pores and that other moisture 'bodies‘ remain in situ in smaller pores, intensively in contact with soil and biological activity. Generally they contain more nutrients, being in close contact with the exchange complex of the soil, and so conserve nutrients for the ecosystem, leaching water having lower concentrations of elements than the soil moisture. Soil morphology does not give strong indications for "by-passing". There are no large cracks and few large pores. The soil gives a rather isotropic impression. Structure is granular and water movement could be largely through the small pores around the granules.

The first "bypass mechanism" mentioned, the quicker discharge of part of the rain-water falling near the creeks compared with rain falling on plateaus, problably does not save nutrients, but rather looses them. If this water runs off in the rain-water composition, there is already a relative loss because rain-water on the well drained areas gives a net supply of nutrients to the system. The rain-water composition cannot be maintained, however, when this water comes into contact with vegetation, litter and, sometimes, in the case of lateral flow, with the topsoil. The litter layer and these upper soil layers were much richer in nutrients than lower layers (Appendix III). Shallow lateral flow was detected on a slope near the creek and soil profile characteristics indicate that such flow is probable.

The composition of one surface flow sample and the average composition of two lateral flow samples is included in Table 4.22. Again the small number of samples makes assumptions about the exact level of these concentrations unreliable. It is clear, however, that the concentrations of nutrients in these samples are much higher than in water from rain, creeks or deep borings. The bypass in the soil profile seems to save nutrients, the bypass on a larger scale, direct surface flow to the creeks and the somewhat slower lateral flow along the valley slopes on the other hand, results in a loss of nutrients.

The concentrations of Table 4.22 have been combined with water amounts to give the element balance in Table 4.24. This element balance is supplementary to Tables 4.17 and 4.19. Values for P and the main cations (Ca, Mg, K, Na) should be taken from Tables 4.17 and 4.19 because they are more accurate. An annual loss of about 25 kg Si per ha indicates desilication taking place in the soil or in the substratum. Silica could be released by dissolution of quartz or it could come from transformations in the clay fraction where kaolinite is formed from 2:1 lattice clays or gibbsite from kaolinite. Weathering is responsible for the annual export of 10 kg Na and 2 kg Mg per ha. The net annual influxes of 12 kg K, 9 kg Ca, 5 kg S and 0.5 kg P in the undisturbed Eastern Creek area and slightly less in the treated Western Creek area are very important. The fluxes of C and N are not so important because amounts are very small compared with amounts in the ecosystem. The fluxes of H and Mn are minute with Mn being just near the limit of detection. The infux of Fe is small and unsure. It is also near the detection limit.

The data indicate an ecosystem that is accumulating nutrients. This is unexpected. The general opinion about tropical rain forest areas is that they suffer from weathering and leaching and therefore become increasingly poor in nutrients. It is suggested that the enrichment which has been observed here is the result of the very poor soil and substratum, which delivers extremely small amounts of nutrients to the creek. Impoverishment of the soil is thought to have taken place during former, drier periods such as the last glacial period, when the area was covered by a savannah vegetation. It is not possible however, that nutrient accumulation has continued at the current rate over the 10 000 years since the end of the last glacial period. There must have been periods in which the ecosystem was reduced to a lower nutrient status by forest destruction caused for example, by fires or storms.

A certain amount of nutrients comes with the rain and when there is a well developed vegetation cover which is able to use most of the water and the elements in it, a slow increase in nutrient status of the ecosystem is possible. This continues until forest destruction reduces the nutrient status back to a lower level. At times when well developed forests exist a slow accumulation of nutrients can occur. An equilibrium can be reached if such periods lasts long enough. This equilibrium probably means a larger phytomass and/or a higher nutrient concentration in the phytomass.

4.6 Summary of findings

The soils in the study area are extremely poor and with a low nutrient holding capacity. Nutrient deficiencies, if not existing, can develop easily. The Celos Silvicultural System (CSS) aims to increase the growth of commercial trees in natural and semi-natural forests. This is done by diminishing competition, non-commercial trees are poisoned and lianas are cut. Under this system much phytomass is killed and as it decomposes large amounts of nutrients are released. Some will be removed from the ecosystem by drainage water. This results in a cycle having less nutrients in which nutrient deficiencies could occur.

The effects of the CSS on the nutrient cycle have been studied in two small catchments; Eastern Creek, an area of 140 ha of undisturbed forest, and Western Creek, an area of 155 ha of forest under CSS. Changes in the nutrients in the organic matter cycle were studied by determining the amounts of nutrients in the phytomass and by measuring litter amounts and the composition of litter and soil. Measured data were combined into a model of organic matter and nutrient flows. Changes in nutrients in the hydrological cycle were studied by measuring rainfall and creek discharges and also the composition of rain and creek water. The findings of this nutrient study are summerized below.

- After harvest and before refinement litter amounts and nutrients in litter and soil were slightly higher in the treated western catchment area than in the untreated eastern area.

- Even though 22 months after refinement litter amounts in the treated area had increased further the nutrient amounts in the litter had increased only slightly. Nutrient amounts in the soil had not increased at all, and even decreases were measured. Refinement did not cause significant changes in nutrient amounts in litter or soil.

- A computer simulation was made of the amounts, flows and decomposition of organic matter in a plateau soil bearing 540 t living phytomass per ha, in which a harvest of 15 t stemwood per ha was followed one year later by a refinement during which 40 % of the phytomass was killed. In the three- year period after the harvest there was an extra release of about 150 kg N, 900 kg Ca, 70 kg Mg, 400 kg K and 30 kg P per ha. These nutrients were not retained in the upper 120 cm of the soil.

- Where the vegetation after refinement has a higher mean nutrient concentration than the undisturbed vegetation, which is possible because of the increased production of fresh leaves and twigs combined with a larger nutrient supply than without treatment, the extra release of nutrients would have been less than the amounts quoted above.

- According to this simulation, the weight of the living phytomass reached its lowest level one year after refinement. The amounts of nutrients in living and dead phytomass were at their lowest levels about two years after refinement. The amount of total phytomass both living and dead was still decreasing four years after refinement.

- From a comparison of the amounts of nutrients coming in by rain-water and flowing out by creek water, it appeared that there was a small net accumulation of Ca, K and P in the untreated catchment area of 9, 12 and 0.5 kg/ha/y respectively. In the treated catchment the accumulation was slightly less. This means that of the large release of nutrients by treatment, only a very small proportion was exported by creek water, at least during the first two years after refinement. If evapotranspiration of the catchment had been reduced by the treatment, the difference in outflow would be somewhat larger.

- Almost two years after refinement, groundwater samples from deep borings in the treated catchment area did not have higher concentrations of nutrients than groundwater samples from the untreated catchment area. It seems therefore that most of the extra nutrients released by refinement had already passed through the soil and the upper groudwater layers on their way to the creek where some will be extracted by the swamp vegetation.

- Nutrients leaching to the groundwater can still be picked up by deep roots from several metres depth and probably can even be regained from the groundwater by such roots. A certain loss of nutrients from the plateaus and upper slopes is still to be expected as a result of treatment. Nutrient enrichment of footslopes and valley bottoms will then occur and only small amounts will leave the catchment via the creek water.

- Comparison of concentrations of elements in rain-water and creek water showed that there was a nett export from the catchment of Si, Na and Mg and a nett accumulation of Ca, K, P, N and S.

- The undisturbed forest ecosystem, and to a lesser extent also the treated forest, is accumulating nutrients. There is no equilibrium at present. The area was covered with a savannah vegetation during the last glacial period. It is thought that during that period the soil was intensively leached under a climate with definite wet and dry seasons and that during periods with forest vegetation a slow nutrient accumulation takes place.

5 Conclusions

The extreme chemical poverty of the soil is the result of a long history of leaching. The Zanderij sediment was already weathered before deposition in a braided river and alluvial fan system during the Pliocene era. Part of the clay fraction was lost during transport. Wheathering continued after deposition and large white sand areas were formed in places with coarse texture and impeded drainage. During periods of savannah vegetation nutrient export from the area has probably taken place.

In the study area a thin layer of Zanderij sediment (2 – 4 m) of generally brown sandy clay loam overlies weathered Precambrian material of kaolinitic clay and laterite gravel. Main soil forming processes active in the area are hydrolysis and leaching of silica and basic cations, and podzolization. Hydrolysis and leaching are the main processes in the better drained parts where oxisols with a sandy topsoil occur. A slight podzolization occurs in the sandy topsoil of the oxisols and the process intensifies downslope where profiles become progressively more sandy and grey in colour.

Groundwater levels were found to be several metres deep under the plateaus and groundwater flow is the main contributor to discharge. Although roots are concentrated in the topsoil some very deep roots were observed in deepborings. Groundwater extraction in the dry season by the vegetation appeared to be widespread. An effective average rooting depth of 4.5 m was found in water balance simulations. Evaporation of interception water on the vegetation was found to have increased the evapotranspiration of the forest by 230 mm per year but water use in dry seasons was still higher than in wet seasons.

In the forest ecosystem studied, nutrients, especially Ca and K, were found to be stored mainly in the living phytomass. The soil which consists of quartz and kaolinitic clay, contains very low amounts of nutrients and has also an extremely low nutrient holding capacity. Forest destruction accompanied by liberation of large amounts of nutrients has resulted in considerable leaching losses because the soil can only hold limited amounts of nutrients. Such losses are not easily replaced by nutrient release by weathering of these extremely poor materials.

The deep roots extracting groundwater from depths of 5 m and more are essential for the ecosystem. They also form a nutrient saving mechanism by increasing transpiration and decreasing concentrations in groundwater and discharge. It is doubtful whether other vegetations such as forest plantations could develop such deep root systems. Agricultural crops on these soils are known for their shallow rooting and drought susceptibility (Janssen, in press). Lower evapotranspiration in the dry season leads to higher annual discharges with higher nutrient losses.

It seems unlikely that the Celos Silvicultural System results in an unacceptable loss of nutrients from the ecosystem. In both the undisturbed and the treated catchments investigated nutrient gains were measured between 1980 and 1984. These gains were the result of higher inputs with rain-water than losses with drainage water. However, as gains were lower in the treated catchment there was a relative loss of nutrients as a result of treatment.

From a nutrient point of view the ecosystem seems able to maintain its long-term productivity under the CSS. The effect of harvesting was not directly measured, because harvesting preceded the measurements of water flows and its composition. However, the higher nutrient concentrations in the Western Creek compared with the undisturbed Eastern Creek indicate clearly the effect of harvesting on the composition of creek water. This effect may even be higher than that of refinement.

It is essential that soil, litter layer and vegetation are disturbed as little as possible during harvest and also that the intensity of refinement is limited as much as possible. Strong refinement in places with few commercial trees such as footslopes should be avoided.

The first principle in CSS should be to maintain the biomass at as high a level as possible, because there is a close link between biomass and nutrients. A high level of biomass should be maintained especially on plateaus and upper slopes where most of the commmercial species grow. It is fairly evident that heavy refinement results in the movement of nutrients from the higher to lower slopes and swamp forest with no or little timber. While the amount of biomass may easily be decreased, the biomass increases very slowly again on these soils. The nutrients required for building up new organic matter have to be brought in mainly by rain-water.

It can be concluded that silviculture based on the natural forest on the brown loamy and sandy soils of the Zanderij Formation, is a land use from which sustained yields can be expected. As this land use also leads to economic returns (de Graaf, 1986) this or similar forestry systems could also be of value in other parts of the tropical forest areas where comparable conditions exist.

Summary

Background

Suriname, on the north coast of South America, is about 16 million ha in area and has a population of less than half a million inhabitants with a low population density. The climate is warm and humid and most of the country is covered with tropical forest. The population is largely concentrated on the moderately fertile, low lying marine alluvial soils of the northern coastal plain. More than 80 % of the country consists of undulating to hilly uplands of predominantly residual soils. The Zanderij formation is between the marine sediments in the north and the residual soils of the Guiana Shield. This is a strip of old continental alluvia covering about 9000 km^2.

Development plans for the interior have concentrated initially on the area of the Zanderij formation, which is easily accessible and nearest to the population centres. The gently undulating surface, the sandy soils and the generally good drainage make road building and forest exploitation easy. These conditions offer also possibilities for mechanized agriculture. However, the extreme poverty of the strongly leached, sandy soils causes many problems when these soils are developed for agriculture. In this study a forestry alternative is considered. The natural forest is adapted to the nutrient-poor environment. However, after selective logging of the natural forest, regrowth of commercial trees in the remaining stand appeared to be very low. A silvicultural system known as the CELOS Silvicultural System (CSS), based on natural regeneration, is under study in the Zanderij area and in part of the adjoining residual hill area. In this system a selective harvest is scheduled every 20 to 30 years.

CELOS Silvicultural System (CSS)

CSS aims to increase the growth of commercial trees in natural and semi-natural forests by a treatment known as refinement. This is done by reducing competition by poisoning non-commercial trees and cutting lianas. While this results in increased growth of commercial trees, the effects of the treatment on the nutrient status of the ecosystem are not known. The treatment may kill up to half of the tree biomass in the forest and on decomposition large amounts of nutrients are released. The amount of nutrients at one time may be to high for the remaining vegetation to take up and some nutrients may be removed from the ecosytem by drainage water. Therefore it is important to find out whether CSS results in unacceptable losses from the ecosystem which may endanger the long-term productivity of these forests.

Study area

The study area comprises two hydrological catchment areas each of approximately 150 ha. One catchment known as Eastern Creek area was under undisturbed forest and the other known as Western Creek area was being treated according to CSS. Soils in both catchments were surveyed, amounts and composition of rainfall and creek discharge were measured. These data were collected over a period of 4 years and 9 months (1979–1984). Additional data on factors related to the hydrological cycle were collected. Nutrient amounts and flows were studied in both catchments.

Physical environment

The study area is slightly undulating, with well to moderately well drained plateaus graduating via convex and concave slopes to poorly drained narrow valley bottoms. The Pliocene Zanderij sediment is shallow (2 to 4 m), and overlies deeply weathered Precambrian rock. The Zanderij sediment mainly consists of yellowish brown moderately coarse sandy clay loam, while the Precambrian substratum is more clayey, redder in colour and often gravelly (with laterite and quartz gravel).

The soils of the Zanderij formation can be broadly divided into white sands (40%), brown sands (30%) and brown loams (30%). The study area is on the least infertile of these soils: the brown loams. Main soil forming processes, active in the project area are; hydrolysis and leaching of silica and bases, and podzolization. The first process is most important in the better drained parts and the latter in the lower parts where groundwater occurs at shallow depth during wet periods.

Plateaus and upper slopes generally have a thin topsoil of loamy sand to sandy loam on a sandy clay loam subsoil. Thickness of the sandier top layer increases progressively downslope and clay content decreases. Lower footslopes often consist of grey sand or loamy sand to more than 1 m depth. Valley bottoms are also mostly sandy, and are covered in some places with thin peaty layers. It is concluded that podzolization is active in the topsoil of all soils, but that the process is more intense on the lower slopes with impeded drainage. Podzolization is possible by the sandy texture of the topsoil, the extremely poor nutrient status and the acidity. Not all mobile organic matter formed in topsoils is precipitated elsewhere in the profile. Creek water is light brown coloured. Groundwater in sandy footslopes is also coloured by organic matter while groundwater from well drained loamy soils is colourless.

Rainfall and evaporation were measured in the project area and additional data were collected from a nearby meteorological station. The relationship found between evaporation of a Class A Pan and the potential evapotranspiration (PET) according to Penman was used in the calculation of forest transpiration.

The vegetation consists of high forest, high dryland forest on plateaus and slopes and high swamp forest in the valleys. Phytomass of the high dry land forest was calculated from the diameters at breast height of all trees, using correlations between such diameter and weights of stems, branches and leaves, determined in similar forests by destructive sampling.

Hydrology

A study of the hydrology of the forest on a catchment area scale was considered necessary in order to understand the way the ecosystem functions. For this purpose a catchment area of approximately 295 ha was investigated. The two small creeks in this area allow it to be subdivided into two catchments; the Eastern Creek catchment of 140 ha and the Western Creek catchment of 155 ha. The topography of the whole area is gently undulating with average slopes of about 4 %.

Data were collected on factors related to understanding the hydrological cycle. These included rainfall, evaporation, creek discharge, groundwater levels from deep borings, hydraulic conductivity and diurnal variations of water levels in creeks and deep borings. A computer model was used to predict water movement in the soil and to estimate evapotranspiration of the forest during wet and dry periods. The model was also used to gain insight into other aspects of the water balance, such as rooting depth and available soil moisture. Knowledge of these processes is needed to understand nutrient cycling. The model WOFOST4 was used. The findings of the hydrological study were as follows:

The measured average annual rainfall and discharge were approximately 2140 and 510 mm, respectively. Length and intensity of the dry season that is less than 100 mm rain per month, varied between 2 and 5 months per year. The length of the dry period with no or very little discharge varied between 0 and 8 months per year.

In the simulations, long dry periods gave a reduction in actual transpiration below its potential value. Such a reduction occurred during less than 20 % of the time, and mainly during the months October to December, the later part of the dry season. In one year (1981) no transpiration reduction occurred. During the whole simulation period of 4 years and 9 months, the actual transpiration was 94 % of the potential value.

Groundwater flow was found to be the main contributor to discharge. Surface flow and lateral flow were important in valley bottoms and footslopes. Although these flows gave clear discharge peaks they contributed relatively little to total discharge.

Average groundwater levels were found to be deep under plateaus and upper slopes and to fluctuate greatly throughout the year. The phreatic surface is triangular in shape with a rounded top under the plateaus.

Hydraulic conductivities were high in upper layers and decreased with depth. Groundwater flow occurred mainly above drain level, that is creek level, and was non-steady in character.

In the dry season, groundwater extraction by the vegetation appears to be widespread, not only in the swampy valley bottoms with shallow groundwater, but also on plateaus and upper slopes even when groundwater levels were more than 5 m deep. This has been concluded from diurnal variations in creek discharge, from groundwater levels in deep borings, and from root observations and water balance simulations.

Available soil moisture in the Zanderij soils was estimated to be approximately 10 % of volume. Amounts of air when the soil is at field capacity were large, more than 20 %. Water storage in the kaolinitic clay substratum, that is the amount of drainable water, was small. An average storage coefficient of 0.035 was calculated for the substratum of the whole catchment.

The water balance during a period of 4 years and 9 months was simulated with the WOFOST4 model with inputs of measured climatic and soil data. Close agreement was obtained for measured and calculated discharge and for measured and calculated groundwater levels under the following conditions:

- effective rooting depth of 450 cm
- evaporation from the soil surface of zero
- maximum extra interception loss of 1.1 mm per rain day
- crop factor (potential transpiration/PET) of 0.87.

Computer simulation showed that interception losses increased water use in rainy seasons but that in dry seasons water use was still higher. The extra water use caused by interception, not the total interception, was estimated to be 230 mm/y by a total water use of 1640 mm.

Nutrients

The effects of CSS on the nutrient cycles have been studied in the Eastern Creek area and the Western Creek area. Changes in nutrients in the organic matter cycle were studied by determining the amounts of nutrients in the phytomass and by measuring litter amounts and the composition of litter and soil. Measured data were combined into a model of organic matter and nutrient flows. Changes in the hydrological nutrient cycle were studied by measuring rainfall and creek discharges and also the composition of rain and creek water. The findings of this nutrient study were as follows:

After harvest and before refinement litter amounts and nutrients in litter and soil were slightly higher in the treated western catchment area than in the untreated eastern area.

Even though 22 months after refinement litter amounts in the treated area had increased further, the nutrient amounts in the litter had increased only slightly. Nutrient amounts in the soil had not increased at all, and even decreases were measured. Refinement did not cause significant changes in nutrient amounts in litter or soil.

A computer simulation was made of the amounts, flows and decomposition of organic matter in a plateau soil, bearing 540 t living phytomass per ha, in which a harvest of 15 t stemwood per ha was followed one year later by a refinement during which 40 % of the phytomass was killed. In the three- year period after the harvest there was an extra release of about 150 kg N, 900 kg Ca, 70 kg Mg, 400 kg K and 30 kg P per ha. These nutrients were not retained in the upper 120 cm of the soil.

Where vegetation after refinement has a higher mean nutrient concentration than the undisturbed vegetation, which is possible because of the increased production of fresh leaves and twigs combined with a larger nutrient supply than without treatment, the extra release of nutrients would have been less than the amounts quoted above.

According to this simulation, the weight of the living phytomass reached its lowest level one year after refinement. The amounts of nutrients in living and dead phytomass were at their lowest levels about two years after refinement. The amount of total phytomass both living and dead was still decreasing four years after refinement.

From a comparison of the amounts of nutrients coming in by rain-water and flowing out by creek water, it appeared that there was a small net accumulation of Ca, K and P in the untreated catchment area of 9, 12 and 0.5 kg/ha/y respectively. In the treated catchment the accumulation was slightly less. This means that of the large release of nutrients by treatment, only a very small proportion was exported by creek water, at least during the first two years after refinement. If evapotranspiration of the catchment had been reduced by the treatment, the difference in outflow would be somewhat larger.

Almost two years after refinement, groundwater samples from deep borings in the treated catchment area did not have higher concentrations of nutrients than groundwater samples from the untreated catchment area. It seems therefore that most of the extra nutrients released by refinement had already passed through the soil and the upper groudwater layers on their way to the creek where some will be extracted by the swamp vegetation.

Nutrients leaching to the groundwater can still be picked up by deep roots from several metres depth and probably can even be regained from the groundwater by such roots. A certain loss of nutrients from the plateaus and upper slopes is still to be expected as a result of treatment. Nutrient enrichment of footslopes and valley bottoms will then occur and only small amounts will leave the catchment via the creek water.

Comparison of concentrations of elements in rain-water and creek water showed that there was a nett export from the catchment of Si, Na and Mg and a nett accumulation of Ca, K, P, N and S.

The undisturbed forest ecosystem, and to a lesser extent also the treated forest, is accumulating nutrients. There is no equilibrium at present. The area was covered with a savannah vegetation during the last glacial period. It is thought that during that period the soil was intensively leached under a climate with definite wet and dry seasons and that during periods with forest vegetation a slow nutrient accumulation takes place.

Conclusions
It is concluded that forest treatment according to the CELOS Silvicultural System does not result in an unacceptable loss of nutrients from the ecosystem. Silviculture based on the natural forest on the brown loamy and sandy soils of the Zanderij formation, is a land use of which sustained yields can be expected. As this land use also leads to economic returns (de Graaf, 1986), this or similar forestry systems could also be of value in other parts of the tropical forest areas, where comparable conditions exist.

Samenvatting

BODEM, WATER EN NUTRIËNTEN IN EEN BOSECOSYSTEEM IN SURINAME

Achtergrond

Suriname, gelegen aan de noordkust van Zuid Amerika, heeft een oppervlakte van 16 miljoen ha en minder dan een half miljoen inwoners en daardoor een geringe bevolkingsdichtheid. Het klimaat is warm en vochtig en het meerendeel van het land is bedekt met tropisch regenbos. De bevolking is geconcentreerd in de kustvlakte, een matig vruchtbaar, laag gelegen zeekleigebied. Meer dan 80 % van het land is golvend tot heuvelachtig met residuaire bodems. De Zanderij formatie is gelegen tussen de mariene sedimenten in het noorden and de residuaire gebieden van het Guianese schild. Het is een strook land met continentale afzettingen, ongeveer 9000 km^2 in oppervlak.

Ontwikkelingsplannen voor het binnenland richtten zich vanaf het begin op het Zanderij gebied dat gemakkelijk toegankelijk was en het dichtste bij de bevolkingscentra lag. Het glooiende oppervlak, de zandige bodems en de meestal goede drainage maken wegaanleg en bosexploitatie gemakkelijk. Deze eigenschappen boden ook vooruitzichten voor gemechaniseerde landbouw. De extreme armoede van de sterk uitgeloogde zandige gronden veroorzaakt echter veel problemen wanneer deze gronden ontgonnen worden voor landbouw. In deze studie komt een bosbouw alternatief aan de orde. Het natuurlijke bos is aangepast aan de nutriënten (plantevoedende stoffen) armoede van de bodem. Het bleek echter dat de bijgroei van waardehout in het natuurbos na selectieve kap erg laag was. Een bosteeltsysteem voor natuurlijke verjonging, het “CELOS Silvicultural System” ontwikkeld bij het CELOS, het Centrum voor Landbouwkundig Onderzoek in Suriname, wordt onderzocht in het Zanderij gebied en het aangrenzende residuaire gebied. In dit syteem vindt elke 20 tot 30 jaar een selectieve kap plaats.

“CELOS Silvicultural System” (CSS)

De bedoeling van CSS is om de groei van waardehoutsoorten, boomsoorten waarvan het hout marktbaar is, in natuurlijke of semi-natuurlijke bossen te vergroten door middel van een behandeling die zuivering genoemd wordt. Deze zuivering bestaat uit het vergiftigen van niet-waardehoutsoorten en het kappen van lianen. Deze behandeling heeft inderdaad een gunstig effect op de groei van de waardehoutsoorten, maar het was niet bekend welke invloed het heeft op de voedingstoestand van het ecosysteem. Door de behandeling kan ongeveer de helft van de biomassa gedood worden waaruit bij decompositie grote hoeveelheden nutriënten vrijkomen. De op een bepaald moment vrijkomende hoeveelheid nutriënten kan te hoog zijn om door de overgebleven vegetatie te worden opgenomen waardoor een deel kan uitspoelen met het drainage water. Het is daarom belangrijk om uit te vinden of CSS onacceptabele verliezen veroorzaakt, die de productiviteit op lange termijn in gevaar brengen.

Het studie gebied

Het studiegebied omvat twee hydrologische stroomgebieden van elk ongeveer 150 ha. Het ene, genaamd het Oostkreekgebied, werd onder ongestoord bos gelaten en het andere, het Westkreekgebied werd behandeld volgens CSS. De bodems in beide gebieden werden gekarteerd en de hoeveelheid en samenstelling van neerslag en afvoer werden gemeten. Deze gegevens werden verzameld over een periode van 4 jaar en 9 maanden (1979–1984). Aanvullende hydrologische gegevens werden verzameld en nutriënt hoeveelheden en stromingen werden bestudeerd in beide stroomgebieden.

Natuurlijke gesteldheid

Het studiegebied is zwak golvend, met goed tot matig goed gedraineerde plateaus die geleidelijk overgaan via convexe en concave hellingen in slecht gedraineerde smalle beekdalen. Het Pliocene Zanderijsediment is dun (2 tot 4 m), en ligt op diep verweerd Precambrisch gesteente. Het Zanderij sediment bestaat voornamelijk uit geelbruine matig grofzandige zware leem, de Precambrische ondergrond bevat meer klei, is roder van kleur en vaak rijk aan lateriet en kwarts grind.

De bodems van het Zanderij gebied kunnen verdeeld worden in witte zanden (40 %), bruine zanden (30 %) en bruine lemen (30 %). Het studiegebied is gelegen op de minst onvruchtbare van deze gronden: de bruine lemen. De belangrijkste bodemvormende processen zijn: hydrolyse en uitspoeling van silica en basen, en podzolisatie. Het eerste proces is het belangrijkste op de beter gedraineerde delen en het tweede in de lage delen waar in natte perioden grondwater op geringe diepte voorkomt.

De plateaus en de convexe hellingen hebben meestal een dunne bovengrond van lemig zand tot zandige leem op een zware zandige leem ondergrond. De dikte van de zandige bovengrond neemt toe hellingafwaarts en de kleigehalten nemen af. De voethellingen bestaan vaak uit grijs zand of lemig zand tot meer dan 1 m diepte. De beekdalen zijn ook meestal zandig en op sommige plaatsen bedekt met dunne veenlaagjes. Geconcludeerd is dat podzolisatie actief is in de bovengrond van alle bodems, maar dat het proces sterker is op de lagere hellingen met slechtere drainage. Podzolisatie is mogelijk door de zandige textuur van de bovengrond, de extreem arme voedingstoestand en de lage pH. Niet alle beweeglijke organische componenten uit de bovengrond slaan elders neer in het profiel. Het water in de kreken is licht bruin gekleurd door organische stof. Grondwater in zandige hellingvoeten is ook gekleurd door organische stof terwijl grondwater in goed gedraineerde lemige gronden kleurloos is.

Neerslag en verdamping werden gemeten in het projectgebied en aanvullende gegevens werden verzameld van een nabijgelegen meteo-station. Het verband gevonden tussen evaporatie van een Class A Pan en de potentiele evapotranspiratie volgens Penman werd gebruikt in de berekening van de verdamping van het bos.

De vegetatie bestaat uit hoog bos, hoog drooglandbos op plateaus en hellingen en zwampbos in de dalen. De phytomassa van het drooglandbos werd berekend uit de diameters op borsthoogte van alle bomen, gebruik makend van correlatieve verbanden tussen deze diameters en de gewichten van stammen, takken en bladeren, bepaald in overeenkomstige bossen door middel van destructive bemonstering.

Hydrologie

De bestudering van de hydrologie op het niveau van stroomgebieden werd noodzakelijk geacht om het functioneren van het ecosysteem te begrijpen. Hiertoe werd een stroomgebied van ongeveer 295 ha onderzocht. De twee kleine kreken in dit gebied maken het mogelijk dit onder te verdelen in twee stroomgebiedjes; het Oostkreekgebied van 140 ha en het Westkreekgebied van 155 ha. De topografie is zwak golvend met hellingen van gemiddeld 4 %.

De volgende hydrologische gegevens werden verzameld: neerslag, verdamping, kreekafvoer, grondwaterstanden in diepboringen, doorlatendheden en gegevens over dagelijkse schommelingen in waterstanden in kreken en boringen. Een computermodel werd gebruikt om water bewegingen in de bodem te voorspellen en om de verdamping van het bos te schatten gedurende natte en droge perioden. Het model werd ook gebruikt om inzicht te verkrijgen in andere aspecten van de waterbalans zoals bewortelingsdiepte en beschikbaar bodemvocht. Kennis van de processen is nodig om de kringlopen van nutriënten te begrijpen. Het computermodel WOFOST4 werd gebruikt. De uitkomsten van het hydrologisch onderzoek waren als volgt:

De gemeten gemiddelde jaarlijkse neerslag en afvoer waren ongeveer 2140 en 510 mm. De lengte en intensiteit van de droge tijd, dat is de periode met minder dan 100 mm neerslag per kalendermaand, varieerde van 2 tot 5 maanden per jaar. De lengte van de droge periode met geen of zeer weinig kreekafvoer varieerde van 0 to 8 maanden per jaar.

Volgens de simulatie gaven lange droge perioden een verdampingsreductie te zien. Zo'n reductie kwam voor gedurende minder dan 20 % van de tijd en wel voornamelijk gedurende de maanden October tot December. In 1981 kwam geen verdampingsreductie voor. Tijdens de gehele studie periode van 4 jaar en 9 maanden kwam de actuele verdamping op 94 % van de potentiele verdamping.

Afvoer kwam tot stand voornamelijk als gevolg van grondwaterstroming. Oppervlakkige en laterale waterstromingen waren van belang in de beekdalen en de voethellingen. Ofschoon deze stromingen duidelijke afvoerpieken veroorzaakten, droegen ze toch weinig bij aan de totale afvoer.

Gemiddelde grondwaterstanden waren diep onder de plateaus en schommelden sterk gedurende het jaar. De vorm van de grondwaterspiegel tussen twee kreken is min of meer driehoekig met een afgeronde top onder het plateau.

Waterdoorlaatfactoren waren hoog in de bovenste bodemlagen en namen af met de diepte. Grondwaterstroming vond voornamelijk plaats boven het drainage niveau of kreekniveau en was niet-stationair van karakter.

In de droge tijd bleek grondwateronttrekking door de vegetatie voor te komen, niet alleen in de kreekdalen met ondiep grondwater, maar ook op plateaus en de bovenste delen van de hellingen, zelfs bij grondwaterstanden dieper dan 5 m. Dit werd geconcludeerd uit de dagelijkse schommelingen in kreekafvoeren en in grondwaterstanden en ook uit waarnemingen aan wortels en uit waterbalans simulaties.

De beschikbare hoeveelheid vocht in de Zanderij gronden werd geschat op ongeveer 10 volumepercent. Luchthoeveelheden bij veldcapaciteit zijn meer dan 20 %. De waterberging in de kaolinitische klei ondergrond is gering. Een gemiddelde bergingscoefficient van 0.035 werd berekend voor het gehele stroomgebied.

De waterbalans werd gesimuleerd met WOFOST4 gedurende een periode van 4 jaar en 9 maanden. Een goede overeenkomst werd gevonden voor gemeten en berekende afvoer en voor gemeten en berekende grondwaterstanden onder de volgende condities:

- een effectieve bewortelingsdiepte van 450 cm
- geen verdamping van het bodemoppervlak
- een maximum extra interceptieverlies van 1.1 mm per regendag
- een gewasfactor (potentiele transpiratie/PET) van 0.87

Computersimulatie toonde aan dat interceptieverliezen zorgden voor een toegenomen waterverbruik in het regenseizoen, maar dat in het droge seizoen het waterverbruik toch nog hoger was. De toename in het waterverbruik ten gevolge van interceptie (niet de totale interceptie) werd geschat op 230 mm/jaar bij een totaal waterverbruik van 1640 mm/jaar.

Nutriënten

De effecten van CSS op nutriënten kringlopen werden bestudeerd in het Oostkreek- en het Westkreekgebied. Veranderingen in nutriënten in de organische stofkringloop werden bestudeerd door bepalingen van de hoeveelheden nutriënten in de phytomassa en door metingen van strooisel hoeveelheden en van de samenstelling van strooisel en bodem. Gemeten waarden werden ingebracht in een model van organische stof en nutriëntenbewegingen. Veranderingen in de nutriënthoeveelheden in de hydrologische kringloop werden bestudeerd door metingen van hoeveelheid en samenstelling van neerslag en afvoer. De bevindingen van deze nutriëntenstudie waren als volgt:

Na de houtoogst en vóór de zuivering waren de strooiselhoeveelheden en de nutriënten in strooisel en bodem iets hoger in het behandelde Westkreekgebied dan in het Oostkreekgebied.

Hoewel de strooiselhoeveelheden 22 maanden na zuivering in het behandelde gebied verder waren toegenomen, waren de hoeveelheden nutriënten in het strooisel slechts weinig gestegen. Nutriënt hoeveelheden in de grond waren niet toegenomen, zelfs afnames werden gemeten. Zuivering veroorzaakte geen significante veranderingen in nutriënt hoeveelheden in strooisel en bodem.

Een computersimulatie werd gemaakt van de hoeveelheden, stromingen en omzettingen van organische stof in een plateau grond met 540 t biomassa per ha, waarin een houtoogst van 15 t stamhout een jaar later werd gevolgd door een zuivering waarbij 40 % van de biomassa gedood werd. In de drie jaar na de oogst was er een extra vrijkomende hoeveelheid nutriënten van ongeveer 150 kg N, 900 kg Ca, 70 kg Mg, 400 kg K, en 30 kg P per ha. Deze nutriënten werden niet vastgehouden door de bovenste 120 cm van de bodem.

Indien de vegetatie na zuivering een hogere concentratie aan nutriënten heeft, wat mogelijk is door de toegenomen productie van blad en twijgen en een verhoogd aanbod van nutriënten, zijn de extra vrijkomende hoeveelheden minder dan hierboven vermeld.

Volgens deze simulatie bereikte het gewicht van de levende phytomassa zijn laagste niveau één jaar na zuivering. De hoeveelheden nutriënten in de organische stof bereikten hun laagste niveau ongeveer 2 jaar na zuivering. De hoeveelheid totale phytomassa daalde 4 jaar na zuivering nog steeds.

Vergelijking van hoeveelheden nutriënten die inkomen met de neerslag en uitstromen met het kreekwater, toonde aan dat er een kleine netto accumulatie van Ca, K en P in het onbehandelde stroomgebied voorkwam van 9, 12 en 0.5 kg/ha/jaar respectievelijk. In het behandelde gebied was deze toename iets geringer. Dat betekent dat van de grote hoeveelheid door behandeling vrijgekomen nutriënten, slechts een zeer klein deel werd afgevoerd met het kreekwater, tenminste gedurende de eerste twee jaar na zuivering. In het geval dat de evapotranspiratie door de behandeling verminderd is, zou het verschil in uitstroom wat groter zijn.

Bijna twee jaar na zuivering had het grondwater in diepboringen in het behandelde gebied geen hogere concentraties aan nutriënten dan in het onbehandelde gebied. Het schijnt daarom dat het grootste deel van de extra vrijgekomen nutriënten toen al de bodem en de bovenste grondwaterlagen gepasseerd was op weg naar de kreek, waar de moerasvegetatie er wel een deel van zal opnemen.

Nutriënten die uitspoelen naar het grondwater kunnen nog door diepe wortels opgenomen worden van vele meters diepte en waarschijnlijk zelfs uit het grondwater. Een zeker verlies aan nutriënten van de plateaus en bovenste hellingdelen ten gevolge van de behandeling is echter te verwachten en een toename aan nutriënten in de voethellingen en beekdalen. Slechts geringe hoeveelheden verlaten het stroomgebied met het kreekwater.

Vergelijking van concentraties van elementen in regen- en kreekwater toonde aan dat er een netto transport was uit het stroomgebied van Si, Na en Mg en een netto accumulatie van Ca, K, P, N en S.

Het ongestoorde bosecosysteem, en in mindere mate ook het behandelde bos, accumuleert nutriënten. Er is momenteel geen evenwicht. Het land was bedekt met een savanne vegetatie gedurende de laatste ijstijd. Het is waarschijnlijk dat gedurende die periode de bodem sterk uitgeloogd is tijdens een klimaat met duidelijke natte en droge seizoenen en dat tijdens perioden met een bosbedekking er een langzame nutriënt accumulatie optreedt.

Conclusie

De conclusie is dat bosbehandeling volgens het "CELOS Silvicultural System" niet resulteert in een onaanvaardbaar verlies van nutriënten uit het ecosysteem. Bosteelt gebaseerd op het natuurbos op de bruine lemige en zandige gronden van de Zanderij formatie is een landgebruik waarvan blijvende opbrengsten verwacht kunnen worden. Aangezien dit landgebruik ook economisch gunstig is (de Graaf, 1986), zou het ook van waarde kunnen zijn in andere delen van de tropische bosgebieden, waar overeenkomstige omstandigheden bestaan.

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APPENDIX I: AVERAGE MONTHLY METEOROLOGICAL DATA FROM ZANDERIJ AND KABO/TONKA STATIONS *)

Month	Temp Zand		Temp Kabo		Rel Hum Zand			RH min	Rain Zand	Rain Tonka	Wind(m/s)			Sun frac	Sun frac	Angot	EPan Kabo	EPan Kabo	EPan Zand	PET Penman	PET Penman
	max	min	max	min	8	14	18	Kabo	(mm)	(mm)	8	14	18	Zand	Kabo	J/m2/d	(day)	month			corr
1179	34.0	23.2			87	54	78		70		0.82	2.17	0.76	0.56		33950122			4.31	4.96	4.41
1279	31.6	22.8			93	66	85		204		0.64	1.49	1.30	0.47		32979867			3.31	4.26	3.65
0180	31.8	21.9			92	59	74		64		0.27	2.79	2.63	0.57		33749324			3.55	4.83	4.32
0280	32.5	20.1	32.2	20.6	90	52	66	41	21	27	0.42	3.34	2.60	0.66	0.76	35649393	3.38	98	2.29	5.48	5.51
0380	30.9	22.0	29.1	21.6	90	67	76	58	181	203	0.42	3.55	2.49	0.37	0.39	37134054	3.39	105	3.53	4.66	4.11
0480	31.3	22.7	31.4	22.9	91	70	83	60	277	244	0.65	2.54	1.79	0.46	0.38	37128363	3.30	99	3.26	4.77	4.27
0580	31.8	23.4	31.6	23.6	92	73	87	61	278	266	1.06	2.63	1.16	0.43	0.44	35998686	3.19	99	3.95	4.65	3.96
0680	32.2	23.1	31.5	23.0	91	69	85	57	320	339	0.93	2.35	1.43	0.57	0.56	35130885	3.53	106	3.87	4.89	4.44
0780	32.8	22.7	32.5	22.5	90	59	85	48	344	156	0.80	2.00	1.22	0.66	0.71	35419057	4.10	127	3.10	5.31	4.85
0880	33.6	22.7	32.5	22.7	87	55	77	46	160	195	1.68	2.38	1.58	0.75	0.76	36426926	4.90	152	5.45	5.91	5.72
0980	35.0	23.1			84	46	72	43	61	64	2.76	2.31	1.73	0.82	0.86	36801495	5.87	176		6.40	6.29
1080	34.1	22.7	32.1	22.4	85	54	79	44	126	71	2.17	2.87	1.68	0.74	0.77	35746087	4.94	153	5.31	5.89	5.62
1180	32.8	23.0	32.2	22.9	88	63	83	52	173	189	1.93	2.40	1.13	0.63	0.70	33950122	4.37	131	4.37	4.99	4.67
1280	32.1	22.5	31.5	22.4	91	61	81	53	149	108	0.78	2.50	1.03	0.63	0.67	32979867	3.71	115	3.84	4.83	4.23
0181	31.7	21.6	31.4	21.7	93	62	78	50	161	116	0.33	2.85	1.44	0.60		33749324	3.87	120		4.79	4.24
0281	30.9	22.7	30.1	22.6	93	68	82	58	220	328	0.59	2.46	1.72	0.37		35617697	3.00	84		4.38	3.90
0381	33.4	21.9	32.3	22.1	90	53	71	44	52	145	0.84	2.43	2.03	0.66		37134054	4.94	153		5.64	5.35
0481	33.1	23.6	31.8	23.8	88	62	86	51	269	324	1.18	2.16	0.84	0.46		37128363	3.87	116		4.95	4.41
0581	32.6	23.3	31.3	23.1	89	70	86	62	287	356	1.22	2.03	1.10	0.48		35998686	3.52	109		4.76	4.22
0681	32.3	22.9	31.1	22.9	90	64	88	55	356	249	1.42	2.40	1.23	0.54		35130885	3.60	108		4.75	4.31
0781	32.3	22.4	31.1	22.3	89	60	81	52	250	218	1.10	2.03	1.49	0.65		35419057	4.19	130		5.16	4.82
0881	33.7	23.0	32.5	22.6	87	55	77	47	226	174	1.33	2.41	1.20	0.71		36426926	4.97	154		5.75	5.43
0981	34.5	22.5	33.0	22.3	85	51	72	42	164	63	1.97	2.78	1.40	0.81		36801495	5.53	166		6.23	5.90
1081	33.8	22.8	33.2	22.5	89	53	79	44	248	196	1.11	2.33	1.11	0.77		35746087	5.42	168		5.87	5.36
1181	33.7	23.1	33.0	23.0	89	54	79	45	131	80	1.37	1.82	0.92	0.71		33950122	4.57	137		5.33	4.71

(continued)

Month	Temp Zand		Temp Kabo		Rel Hum Zand			RH min Kabo	Rain Zand (mm)	Rain Tonka (mm)	Wind(m/s)			Sun frac Zand	Sun frac Kabo	Angot J/m2/d	EPan Kabo (day)	EPan Kabo month	EPan Zand	PET Penman	PET Penman corr
	max	min	max	min	8	14	18				8	14	18								
1281	31.9	22.8	31.6	22.4	92	65	86	55	193	227	0.90	2.33	1.00	0.52		32979867	3.58	111		4.48	3.99
0182	30.9	21.9	30.5	21.8	94	66	78	56	156	158	0.36	2.18	1.60	0.47		33749324	3.42	106		4.26	3.84
0282	30.7	22.3	29.6	21.9	93	67	80	58	111	164	0.62	2.30	1.68	0.30		35617697	3.18	89		4.09	3.68
0382	30.7	22.6	30.6	22.2	92	72	83	60	274	285	0.43	2.83	1.87	0.30	0.28	37134054	3.06	95		4.21	4.00
0482	31.3	22.9	30.6	22.6	91	72	83	64	397	402	1.06	2.37	1.19	0.34	0.26	37128363	3.30	99		4.43	3.95
0582	31.5	23.1	30.8	22.8	91	74	87	61	306	319	1.08	2.42	1.26	0.39	0.37	35998686	3.39	105		4.43	3.77
0682	31.9	22.9	31.4	22.4	89	64	87	55	364	252	1.02	2.25	1.54	0.46	0.45	35130885	3.57	107		4.47	4.08
0782	32.4	22.4	31.5	23.1	90	58	83	50	318	252	1.10	1.97	1.20	0.66	0.66	35419057	4.29	133		5.24	4.75
0882	33.5	22.4	32.0	22.7	88	50	74	45	205	108	1.29	2.68	1.07	0.75	0.74	36426926	4.94	153		5.87	5.60
0982	34.4	22.7	32.9	22.9	84	48	67	42	84	75	2.07	1.96	1.26	0.74	0.80	36801495	5.73	172		5.95	5.77
1082	34.3	22.6	32.9	22.9	86	49	74	41	97	32	2.02	2.52	1.25	0.75	0.67	35746087	5.58	173		5.82	5.65
1182	33.3	23.2	32.1	22.5	87	51	78	41	110	54	2.18	2.96	1.44	0.71	0.69	33950122	5.17	155		5.37	5.17
1282	32.1	22.8	30.0	22.3	93	66	85	57	261	132	1.24	2.27	1.05	0.56	0.51	32979867	3.87	120		4.53	4.05
0183			28.6	21.6				60		140					0.45	33749324	3.32	103			
0283			28.9	21.2				61		144					0.50	35649393	3.36	94			
0383			29.2	22.6				63		173					0.44	37134054	3.39	105			
0483			28.5	22.9				67		413					0.29	37128363	2.87	86			
0583			29.6	22.4				53		273					0.47	35998686	3.32	103			
0683			31.3	22.4				50		173					0.47	35130885	3.97	119			
0783			30.4	21.5				44		67					0.63	35419057	4.42	137			
0883			31.4	21.9				40		83					0.80	36426926	5.45	169			
0983			31.5	21.7				41		79					0.85	36801495	5.37	161			
1083			32.8	21.9				36		63					0.87	35746087	6.10	189			
1183			32.3	22.4				38		58						33950122	5.13	154			
1283			31.5	21.9				50		194					0.55	32979867	3.61	112			
0184			30.5	21.5				53		164					0.54	33749324	3.32	103			
0284			30.9	20.9				48		77					0.63	35649393	4.28	124			
0384			31.0	20.8				52		65					0.56	37134054	4.61	143			

(continued)

Month	Temp Zand		Temp Kabo		Rel Hum Zand			RH min Kabo	Rain Zand (mm)	Rain Tonka (mm)	Wind(m/s)			Sun frac Zand	Sun frac Kabo	Angot J/m2/d	EPan Kabo (day)	EPan Kabo month	EPan Zand	PET Penman	PET Penman corr
	max	min	max	min	8	14	18				8	14	18								
0484			30.7	21.6				53		171					0.54	37128363	4.13	124			
0584										372						35998686	3.29	102			
0684										325						35130885	3.70	111			
0784										269						35419057	4.29	133			

*) Month 1179 : November 1979
Zand : Zanderij
Temp max (min) : maximum (minimum) daily temperature in °C
Rel Hum (RH) : relative air humidity (%); 14: at 14 hours
RH min : minimum daily relative air humidity
Sun frac : actual/maximum sunshine hours
Angot : extra terrestrial radiation in Joule/m^2/day
EPan : evaporation of a Class A Pan in mm/day
PET : potential evapotranspiration in mm/day

APPENDIX II: GENERAL CHARACTERISTICS OF THE SOIL MAP UNITS

PW 1 : Well drained, brown or yellow soils with a sandy loam to sandy clay loam topsoil and a sandy clay loam subsoil

This is the most common soil of the study area, it occurs on plateaus and upper slopes covered with Zanderij sediment, covering in total 118 ha. Subsoil colours are 10 YR or 7.5 YR. The groundwater is generally deeper than 5 m, but may rise to about 2 m in very wet periods. The vegetation is high forest and the soils are covered with a thin litter layer which decomposes quickly. Numerous small roots occur in the top few centimetres and in the litter. The texture in the topsoil is generally considerably sandier than in lower horizons. The first few centimetres often contain pockets of bleached sand. Rooting is deep to very deep, with a strong concentration of roots in the upper decimetres. Below the topsoil the amount of roots decreases rapidly but gradually. At 1 m depth few roots occur, but at depths of 4 to 7 m some active roots have been encountered. Two representative profiles are described in Appendix III. Profile 36 is a representative of the smaller plateaus where the Zanderij sediment is relatively thin (about 2 m). The texture is sandy clay loam from a depth of 30 cm. Profile 11 is a representative of the larger plateaus where the Zanderij sediments are deeper (more than 3 m), and is located on an almost level plateau with rather slow external drainage. The topsoil is sandier than in profile 36, sandy clay loam texture beginning at 108 cm depth.

PW 2 : Well drained, brown or yellow soils with a sand to loamy sand topsoil and a sandy loam subsoil

This soil also occurs on plateaus and upper slopes but generally in more level positions, and covers in total 6 ha. In comparison with PW 1 these soils are lighter in texture, have more bleached sand in the topsoil, a more definite root mat, and are covered with a slightly lighter forest. Profile 37 (Appendix III) shows that under well-drained conditions the podzolization process can also be active, provided the substratum is very poor and sandy.

PM 1 : Moderately well drained, brown or yellow, loamy soils with a loamy sand to sandy loam topsoil and a sandy clay loam subsoil

This soil occurs on generally poorer drained sites adjacent to and below PW 1 and covers a total area of 66 ha. This poorer drainage is mostly caused by lateral water supply from higher areas.

Characteristics of wetness occur in the topsoil that is generally grey in colour. Subsoil horizons are often well oxidized because groundwater levels are several metres deep. Probably because of the slope and the occurrence of this unit generally on the shoulders of plateaus, the Zanderij sediments are often rather shallow in this unit, and therefore the shallow phase of the Pliocene sediments is quite extensive.

These soils also occur on extensive plateaus of little slope with less than optimal external drainage, where groundwater levels are deep. Compared with PW 1, the profiles are grey (chromas 3 or less) to 60 cm or more in depth, have a Hue of 2.5 Y in the subsoil or rusty mottles between 50 and 100 cm. Topsoil textures are generally sandier than those of PW 1 and the topsoil has more bleached sand pockets. The forest vegetation is almost as tall as on PW 1. In Profile 35 (Appendix III) the Zanderij packet is rather thick (about 2 m) and Profile 25 is developed on the shallow phase with a lateritic clay beneath.

PM 2 : Moderately well drained, brown or yellow, loamy soils with a sand to loamy sand topsoil and a sandy loam subsoil

This soil occurs on similar or slightly lower sites than PM 1 and covers an area of 3 ha in the catchment. Grey colours in the topsoil and the pockets of bleached sand are well pronounced. This soil has generally more fine roots in the topsoil and in the litter than do the more clayey profiles. The forest is somewhat lower and there is less biomass.

PM 3 Moderately well drained, grey, loamy soils with a sand to loamy sand topsoil and a sandy loam to sandy clay loam subsoil

This soil covers 1.3 ha and occurs only in the south-eastern corner of the study area at a high elevation. Elsewhere, the moderately well drained soils have a brown to yellow subsoil, which means that within auger depth (120 cm) chroma reaches 4 or more. The soil is rather sandy, sand to loamy sand extends to about 70 cm, and sandy loam to sandy clay loam below. Colours are 10 YR 3/4 or 4/4 in the top 20 cm, about 10 YR 4/3 and 4/2 up to about 80 cm, and about 10 YR 6/3 in the subsoil with common rusty and grey mottles. The flatness of the plateau combined with the difference in texture between topsoil and subsoil are considered to be the reason for the impeded drainage. Groundwater level is always very deep. The vegetation cover is forest, but without very large trees.

PI 1.1 Imperfectly drained, grey soils with a sand to sandy loam topsoil and a sandy clay loam subsoil

This loamy soil, which occurs over an area of 13 ha in the catchment, has a subsoil comparable in texture with PW 1 and PM 1 (SCL) but generally the topsoil is sandier. These soils occur on the lower slopes, below loamy variants of plateau and upper slope soils (PW 1 and PM 1). The PI map units cover the Pliocene sediments between plateaus/upper slopes (PW and PM units) and the poorly drained valley bottoms. The PI units are mostly sandy, except for the loamy soils PI 1.1 and PI 1.2, which occur on the highest sites, adjacent to loamy soils upslope, where there is little seepage water. Soil chromas are grey (3 or less) throughout within 120 cm, with hues of 10 YR or 2.5 Y. Mottling may occur within 50 cm depth. Characteristics of wetness occur in the topsoil through supply of lateral water from higher areas and also in the subsoil where the highest groundwater level is about 1 m. Moderate amounts of bleached sand pockets occur in the topsoil. Rooting depth is restricted, and the forest is moderately high and somewhat open.

PI 1.2 Imperfectly drained, grey soils with a sand to sandy loam topsoil, a sandy clay loam subsoil and a thick dark grey to black layer between 20 and 80 cm depth

This map unit occupies only a very small area of 0.25 ha. The dark layer is more common in the sandier imperfectly drained soils and consists mostly of sandy material which is slightly brittle and has values and chromas of 4/1, 3/2 or darker. This layer occurs directly below the top 20 or 30 cm and may extend below 80 cm. The dark layer is only considered as such when it is at least 30 cm thick. The soils with a dark layer occur in the lower footslopes, immediately adjacent to the poorly drained valley bottom soils. The topsoil has many bleached sand pockets and the subsoil is grey, graduating into light grey. There are many roots in the topsoil and in the litter on the soil, but below the topsoil there are few roots and rooting depth is restricted by the groundwater level which is around 1 m depth. The forest is moderately high and somewhat open.

PI 2.1 Imperfectly drained, grey soils with a sand to loamy sand topsoil and a sandy loam subsoil

This map unit, which covers 17 ha, is about as extensive as PI 1.1 and soils are similar. PI 2.1 is sandier as indicated by the subsoil not attaining a texture of sandy clay loam (SCL) within a depth of 120 cm. Also, the topsoil is somewhat sandier. This unit often occurs next to and downslope of unit PI 1.1, and therefore drainage is slightly poorer but this may be balanced by the sandier texture.

PI 2.2 **Imperfectly drained, grey soils with a sand to loamy sand topsoil and a sandy loam subsoil and with a thick dark grey to black layer**

This unit, which covers 6 ha of the catchment area, is more extensive than PI 1.2 because the dark layer is restricted to lower slopes where sandier textures prevail. Except for the texture, soil properties are similar to those of unit PI 1.2. The vegetation of units PI 2.1 and 2.2 is slightly lower than that of units PI 1.1 and 1.2 but is still high dry land forest. Profile 34 (Appendix III) is a representative for this map unit.

PI 3.1 **Imperfectly drained, grey soils with a sand to loamy sand texture throughout**

These soils occur on lower slopes in relatively low lying sites as compared with PI 1.1 and 2.1 and cover about 15 ha of the catchment area. Locally they occur below PI 2.1 but also in the extension of creek heads, thus they occur where there is considerable lateral water flow. Soils are heavily leached and contain bleached sand in the top layers. Vegetation is still high dry land forest.

PI 3.2 **Imperfectly drained, grey soils with a sand to loamy sand texture throughout and with a dark grey to black layer**

These soils cover 9 ha of the catchment area and are comparable with PI 2.2 but sandier and more leached. They occur on sites similar as PI 2.2, on places where the higher land has a more sandy texture. The physiographic position is always the lower footslope of a rather level topography, where laterally supplied water or groundwater may rise by capillarity to upper horizons and may be withdrawn there by roots. Organic residues left may cause the dark layer. Vegetation is relatively low and open but, as on PI 3.1, is high dry land forest.

PI 3.3 **Imperfectly drained, grey soils with a sand texture throughout and a light grey coloured subsoil starting at shallow depth (within 50 cm)**

These soils occur in the north-east, outside the catchment area and in a small area at the head of the Western creek (1 ha only in the catchment). This soil is very common elsewhere in the Zanderij area and known as savannah soil. The physiography of the area in the north-eastern corner of the soil map is a flat plain, only 1 or 2 m above the water level in adjacent creeks, not directly bordering higher land so that additions of lateral drainage do not occur.
The soil profile consist of a raw humus layer intertwined with roots on pure bleached quartz sand. The profiles are brown (10 YR 3/3 to 5/4) in

the upper 10 cm, graduating to light grey to white (10 YR 7/1, 7/2, 8/1 or 8/2) within 50 cm, but generally directly below 10 cm. The groundwater level varies considerably; in the dry season, groundwater is not encountered within a depth of 120 cm and in the rainy season, levels are about 50 cm deep but may rise to the surface. The soils consist of pure bleached sand and are extremely poor chemically. Litter decomposes slowly, which leads to the formation of a raw humus layer several centimetres thick. The physical condition of the soil is also very poor because roots have to withstand drought conditions alternated with saturation. The natural vegetation reflects these conditions: the savannah forest is very open and low with thin-stemmed trees, and the relatively high light intensity on the forest floor does not result in luxurous undergrowth.

In contrast, the small area at the head of the Western Creek with the same bleached sandy soil is covered with high dry land forest comparable with the vegetation in unit PI 3.2, where the humus layer is absent or almost absent. At the head of the Western creek, the bleached sand borders on higher ground with loamy soils, but in the north-eastern corner, it is not in contact with higher land. It is assumed that the lateral and groundwater flow from the higher land to the creek provide more favourable conditions here for the vegetation than in the savannah area.

This unit has two separate areas of bleached soil in different physiographic positions, one having savannah vegetation and the other forest. Two map units would have been appropriate but because of the small area of the bleached soils only one has been distinguished. Profile 40 in the north-eastern savannah area is representative for this map unit (Appendix III).

PI 3.4 Imperfectly drained, grey soils with a sand to loamy sand texture throughout and with a light grey subsoil below 80 cm depth

These soils, which extend over 8 ha in the catchment, are similar to those of PI 3.1 except for the colour which reaches a value of at least 7 combined with a chroma of 2 or less within 120 cm depth. These soils occur on rather level footslopes where groudwater levels are rather high. The light grey colour of the subsoil is attributed to varying groundwater levels, having removed iron components from the soil after reduction. The vegetation is a rather light high dry land forest.

PI 3.5 Imperfectly drained, grey soils with a sand to loamy sand texture throughout, with a thick dark grey to black layer and with a light grey subsoil

These soils, which extends over about 3 ha in the catchment area, combines the properties of PI 3.2 and 3.4. They occur on very low footslope positions where lateral inflow of water brings the organic components which have build up the dark layer and where groundwater levels are so high that bleaching of the subsoil is possible. These soils occur especially where relatively sandy areas are located in higher positions above this unit. The vegetation is a meagre "high dry land forest", in some places approaching the size of savannah forest. Around Profile 26 (Appendix III) unit PI 3.5 is so narrow that it could not be shown on the map (Fig. 2.12) and has been incorporated in unit PI 3.4.

L 1 Excessively to imperfectly drained, clayey soils with laterite outcrops or massive laterite within 30 cm

These soils with Precambrian material at or near the surface are found over an area of 1.3 ha within the catchment. Augering deeper than 30 cm is not possible because of the laterite. Soils are clayey and reddish generally. In this map unit, the steepest slopes are found, of more than 45 % at outcrops. The forest is a high dry land forest, indicating that some roots extend through the laterite into deeper layers, but generally root development is restricted as may be concluded from the frequent occurrence of windthrown trees with shallow large roots.

L 2 Well and moderately well drained, clayey (texture of clay or sandy clay within 60 cm depth) soils with or without laterite gravel or hard laterite

These well and moderately well drained soils with Precambrian material at shallow depth occupy about 4 ha in the catchment area. On top there may still be some Zanderij material. The topsoil in Zanderij material has a texture of sandy clay loam or sandier and a colour hue of 10 YR. The subsoil is clayey and mostly reddish in colour (7.5 YR or redder). Mottling is rather common as temporary water stagnation can occur on the transition of the lighter topsoil and the clayey subsoil, the latter being less but still reasonably permeable. The vegetation is a normal high dry land forest.

L 3 Imperfectly drained, clayey soils (texture of clay or sandy clay within 60 cm depth) with or without laterite gravel or hard laterite

There is only one occurrence of about 2 ha of this map unit in the upstream part of the Western creek area, a rather level plateau about 5 m above creek level. The profile consists of a sandy loam to sandy clay loam topsoil and a mottled sandy clay loam to clay subsoil of matrix colour 10 YR 8/3. Quartz and laterite gravels occur at varying depths in the profile. The vegetation cover is a somewhat open, high dry land forest.

H Poorly and very poorly drained grey soils, mostly with a sandy texture, often with a thin peaty layer on top and rarely with clayey textures within 120 cm depth

These soils are on the valley bottoms and are saturated most of the year. They occupy an area of about 21 ha within the catchment area of which 1.2 ha is an artificial lake. The valley bottoms are not completely flat, but slope in longitudinal and lateral directions. In the longitudinal direction, the slope is about 0.6 %, varying from 0.3 % near the dam to more than 1.5 % at the headwaters. Perpendicular to the creek the valley is concave, with slopes of zero in the middle to a few percent at the sides, and normally with a gradual transition to the imperfectly drained footslopes. The boundary between footslope and valley bottom is clearly indicated in a few places only.

In the valley bottom, the groundwater level is above or reaches the surface in the wet season, while in the dry season it varies between the surface to about 1 m depth and also the creeks which are generally less than 50 cm deep are then dry. In about half of the years the dry season is less severe and the creeks continue to flow and the valley bottoms remain saturated, thus resulting in a completely different vegetation in the valley bottoms to that on the higher land. Trees with aerial roots and swamp palm species occur.

The valley may be considered to be a gully, filled with sand from displaced Zanderij material, a few metres thick and resting on older formations of a clayey texture, sometimes within a depth of 120 cm. The creek meanders in this sand and in quiet places some distance from the creek, a thin peaty layer may be present. Because of the many tree roots and other obstacles, the longitudinal slope of the creek is rather steep (0.6 %). In the dry season, when the water level drops below the creek bottom, the sandy aquifer below the creek bed remains filled with water for a long time and the water continues to flow slowly. The subsoil is therefore heavily leached. Iron components have been reduced and removed, leaving a sand of pale colours and in some places with dark organic remnants. Soil colours are 10 YR 3/3 in the top decimetres, and below 10 YR 5/2 or 5/3; below 100 cm, the colour may be 10 YR 7/1. These soils are extremely poor but the vegetation has a large biomass, supported probably by nutrients supplied by the moving groundwater. The vegetation is a high swamp forest with a biomass comparable with the somewhat poorer representatives of the high dry land forest growing on adjacent footslopes. Profile 27 (Appendix III) is a representative for this map unit.

APPENDIX III: SELECTED SOIL PROFILE DESCRIPTIONS

Profile 36

(representative for map unit PW 1)

Information on the site

Location: Kabo area Suriname, LH/UvS 01 project area Tonka creek, hydrological experiment 78/34, line 2 north, 15 m east of Central Line. Coordinates 5°15′ N, 55°43′ W
Described by R.L. Catalan Febrero on 24 May 1983.
Elevation: approximately 27 m above mean sea level.
Physiographic position of the site: plateau.
Landform of surrounding country: undulating.
Microtopography: even.
Slope: almost flat (1%).
Vegetation: undisturbed high dryland forest.
Climate: Tropical rainforest climate (Af), see further Profile 11 and Chapter 2.3: Climate

General information of the soil

Parent material: Zanderij sediment of sandy clay loam texture, derived from granites and associated rocks.
External drainage: medium.
Internal drainage: medium.
Drainage class: well drained.
Moisture condition of the profile: moist throughout.
Depth of groundwater table: below profile throughout the year.
Depth of gley/pseudogley: not encountered.
Presence of surface stones/rock outcrops: none.
Evidence of erosion: none.
Presence of salt or alkali: none.
Human influence: none.
Map unit: PW 1, well drained brown or yellow soils with a sandy loam to sandy clay loam topsoil and a sandy clay loam subsoil.

Brief description of the profile

Deep, well drained profile with a brown to light yellowish brown sandy loam topsoil and a yellow sandy clay loam subsoil; structure is weak throughout, but finer aggregates are fairly stable; the whole profile is friable, porous and permeable. Apparently there is a very weak podzolic differentiation in the topsoil.

Description of individual soil horizons

O2	3- 1 cm	Litter of leaves and other plant remains which ranges from recently deposited material to not yet humified matter; gradual boundary.
O1	1- 0 cm	Partly decomposed and humified organic material, intensively mixed with many fine and very fine roots growing above the mineral soil; clear boundary.
Ah1	0- 3 cm	Dark yellowish brown (10 YR 3/4), moist, sand, 10% bleached; weak fine to very fine subangular blocky structure, breaking easily into crumbs; non-sticky and non-plastic consistence when wet, very friable to loose when moist; many very fine and fine tubular and interstitial pores; abundant very fine to medium and few coarse roots; penetrometer: 0.75 kg/cm^2; clear smooth boundary.
Ah2	3- 10 cm	Brown (10 YR 5/3), moist, loamy sand; moderately weak fine to medium subangular blocky structure, breaking easily into fine crumbs and single grains; non-sticky and slightly plastic consistence when wet, friable when moist; common very fine to medium tubular and interstitial pores; abundant very fine to medium and few coarse roots; penetrometer: 1.75 kg/cm^2; clear smooth boundary.
E	10- 27 cm	Light yellowish brown (10 YR 6/4), moist, sandy loam; moderately weak medium subangular blocky structure; slightly sticky and plastic consistence when wet, friable when moist; common fine and medium tubular and interstitial pores; some charcoal particles; many very fine to medium roots; penetrometer: 2.25 kg/cm^2; clear smooth boundary.
Bhs	27- 48 cm	Brown to pale brown (10 YR 5.5/3), moist, sandy loam; moderate medium subangular blocky structure, breaking easily into fine subangular blocky elements; sticky and plastic consistence when wet, friable when moist; common fine to medium tubular and interstitial pores; many very fine to medium and few large roots; penetrometer: 3.25 kg/cm^2; gradual smooth boundary.
Bws1	48- 63 cm	Light yellowish brown (10 YR 6.5/4), moist, sandy clay loam; moderate medium to coarse subangular blocky

		structure, breaking easily into fine subangular blocky elements; sticky and very plastic consistence when wet, friable when moist; no cutans detectable; few fine to medium tubular and common fine interstitial pores; common fine to medium and few large roots; penetrometer: 3.25 kg/cm^2; gradual smooth boundary.
Bws2	63-87/ 95 cm	Yellow (10 YR 7/6), moist, sandy clay loam; moderate medium to coarse subangular blocky structure, breaking easily into fine subangular blocky elements; sticky and very plastic when wet, friable when moist; no cutans detectable; few fine to medium tubular and common fine interstitial pores; common fine to medium and few large roots; penetrometer: 3.5 kg/cm^2; gradual wavy boundary.
Bws3	87/ 95- 102/115 cm	Yellow (10 YR 7/6), moist, sandy clay loam; common, medium to coarse, faint, diffuse, reddish yellow (7.5 YR 7/8) mottles; moderately weak medium subangular blocky structure, breaking easily into fine crumbs;; sticky and very plastic when wet, friable when moist; no cutans detectable; few fine to medium tubular and common interstitial pores; common fine to medium roots; penetrometer: 3.5 kg/cm^2; diffuse, wavy boundary.
Bws4	102/115- 130/115 cm	Yellow (10 YR 7/6), moist, sandy clay loam; many coarse, faint, diffuse, reddish yellow mottles; moderately weak, medium subangular blocky structure, breaking easily into fine crumbs; sticky and plastic consistence when wet, friable when moist; no cutans detectable; few fine tubular and common fine interstitial pores; few medium roots; penetrometer: 3.75 kg/cm^2; diffuse wavy boundary.
Bws5	130/150- 180 cm	Yellow (10 YR 8/6), moist, sandy clay loam; many coarse, distinct, diffuse and clear, reddish yellow (7.5 YR 6/8) mottles; very weak coarse subangular blocky to massive structure; sticky and plastic consistence when wet, firm when moist; no cutans detectable; few fine tubular and common fine interstitial pores; few medium roots; penetrometer: 4.0 kg/cm^2.
BCws	180-200 cm (Boring)	Like Bws5, but with laterite gravels.

Classification (USDA): Ultic Haplorthox
(FAO) : Xanthic Ferralsol

Results of analyses of Profile 36 carried out in Paramaribo, Suriname

Horizon	Depth (cm)	Sand (%)	Silt (%)	Clay (%)	Texture class	C (%)	N (%)	C/N	pH-H_2O	pH-KCl	CEC pH7 (me/100g)	CEC/100g clay	Ca	Mg	K	Na
													me/100 g			
Ah1	0-3	75.2	21.7	3.2	LS	1.52	0.11	14	4.0	3.8	3.48	108.8	0.46	0.10	0.06	0.07
Ah2	3-10	75.6	16.4	8.0	SL	0.86	0.08	11	4.0	3.6	2.66	33.3	0.06	0.05	0.03	0.03
E	10-27	61.6	18.8	19.7	SL	0.41	0.04	10	4.4	3.8	2.00	10.2	0	0.02	0.02	0.03
Bhs	27-48	57.8	17.1	25.2	SCL	0.41	0.05	8	4.6	3.9	1.96	7.8	0	0.02	0.01	0.01
Bws1	48-63	56.9	14.6	28.6	SCL	0.28	0.03	9	4.8	4.0	1.72	6.0	0	0.03	0.02	0
Bws2	63-87	54.8	15.0	30.3	SCL	0.18	0.03	6	4.8	4.0	1.44	4.8	0	0.04	0.01	0
Bws3	87-102	57.2	12.7	30.1	SCL	0.15	0.02	8	4.9	4.0	1.16	3.9	0.03	0.04	0	0.01
Bws4	102-130	58.9	13.3	27.8	SCL	0.16	0.01	16	5.0	4.1	1.00	3.6	0.03	0.03	0.01	0
Bws5	130-180	59.3	13.4	27.4	SCL	0.07	0.01	7	5.2	4.2	0.92	3.4	0	0	0.01	0.01

(continued)

Horizon	Depth (cm)	Bases	Al	ECEC	Al sat (%)	K total	P total	P-Bray I	Ptot/P Bray	Bulk density (kg/l)	pF 1	pF 1.5	pF 2	pF 3.4	pF 4.2
		me/100 g				ppm					vol %				
Ah1	0-3	0.69	0.71	1.40	51	41	54	2.1	26	1.38					
Ah2	3-10	0.17	1.10	1.27	87	59	60	1.4	43	1.47	42.8	27.7	20.4	11.3	8.9
E	10-27	0.07	0.90	0.97	93	76	66	0	-	1.51	37.2	31.8	27.6	22.3	17.2
Bhs	27-48	0.04	1.07	1.11	96	72	82	0	-		37.0	32.7	29.6	21.8	16.9
Bws1	48-63	0.05	0.92	0.97	95	41	71	0.7	101	1.49					
Bws2	63-87	0.05	0.71	0.76	93	103	76	0	-	1.53	35.7	33.2	30.2	27.0	22.1
Bws3	87-102	0.08	0.72	0.80	90	48	47	0.5	94	1.57	35.5	32.9	29.2	24.9	21.8
Bws4	102-130	0.07	0.61	0.68	90	44	54	0.5	108	1.58	33.8	31.9	28.8	24.5	19.9
Bws5	130-180	0.02	0.33	0.35	94	40	56	1.8	31		34.1	31.9	28.7	19.9	19.3

Results of analyses of Profile 36 carried out in Wageningen, the Netherlands

Horizon	Depth (cm)	C (%)	N (%)	Free iron (%)	Amorphous iron (%)	pH-H_2O	pH-$CaCl_2$	Ca	Mg	Na	K	Al	H	Sum cations	CEC
								me/100 g							
Ah1	0-3	1.91	0.09	0.24	0.05	4.1	3.6	0.5	0.3	0	0	0.8	0.6	2.2	6.4
Ah2	3-10	1.09	0.05	0.43	0.08	3.8	3.6	0	0.1	0	0	1.3	0.2	1.6	4.7
E	10-27	0.62	0.03	0.72	0.12	4.3	3.9	0	0	0	0	1.0	0.2	1.2	3.6
Bhs	27-48	0.57	0.02	0.88	0.10	4.5	4.0	0	0	0	0	0.9	0.2	1.1	3.9
Bws1	48-63	0.27	0.01	0.91	0.08	4.6	4.1	0	0	0	0	0.9	0.2	1.1	4.1
Bws2	63-87	0.31	0.01	1.07	0.04	4.9	4.2	0	0	0	0	0.6	0.2	0.8	2.1
Bws3	87-102	0.11	0.01	1.06	0.02	4.9	4.2	0	0	0	0	0.6	0.2	0.8	1.8
Bws4	102-130	0.34	0.01	1.00	0.02	4.9	4.2	0	0	0	0	0.5	0.1	0.6	1.3
Bws5	130-180	0.29	0.01	0.39	0.02	5.0	4.3	0	0	0	0	0.3	0.1	0.4	1.5

Proportion of soil and clay (%) in Profile 36

Horizon	SiO_2		Al_2O_3		Fe_2O_3		FeO		MgO	
	soil	clay	soil	clay	soil	clay	soil	clay	soil	clay
Ah1	93.95	43.14	2.33	36.81	0.47	2.24	0.20	1.11	0.05	0.13
Ah2	92.83	43.14	4.22	36.81	0.65	3.30	0.05	0.13	0.05	0.12
E	86.01	41.71	8.08	37.02	1.14	3.43	0.05	0.20	0.06	0.09
Bhs	81.52	41.46	12.00	37.18	1.39	3.63	0.06	0.03	0.08	0.13
Bws1	77.29	41.67	12.49	37.89	1.24	3.56	0.04	0.05	0.08	0.10
Bws2	81.70	40.43	12.01	37.36	1.55	3.06	0.02	0.20	0.07	0.09
Bws3	79.16	41.40	12.80	37.66	1.55	3.54	0	0.07	0.07	0.09
Bws4	81.28	41.39	11.76	37.64	1.49	3.56	0.01	0.16	0.08	0.10
Bws5	90.55	40.43	8.72	31.75	0.70	4.22	0.22	1.02	0.08	0.21

Horizon	CaO		Na_2O		K_2O		TiO_2		P_2O_5		MnO
	soil	clay	soil	clay	soil	clay	soil	clay	soil	clay	soil and clay
Ah1	0.03	0.01	0.03	0	0	0.07	0.16	1.79	0.01		0
Ah2	0.01	0.01	0.03	0	0.01	0.07	0.30	1.79	0.01	0.21	0
E	0.01	0.01	0.03	0	0.01	0.06	0.50	1.70	0.01		0
Bhs	0.01	0	0.03	0.02	0.02	0.05	0.71	1.70	0.01		0
Bws1	0.01	0	0.03	0.09	0.02	0.05	0.69	1.67	0.01		0
Bws2	0.01	0.01	0.03	0.05	0.02	0.06	0.63	1.62	0.01	0.21	0
Bws3	0.02	0.01	0.03	0.06	0.02	0.06	0.70	1.54	0.01		0
Bws4	0.01	0	0.03	0.07	0.03	0.06	0.65	1.59	0.02		0
Bws5	0.02	0.03	0.03	0.09	0.01	0.13	0.08	2.29	0.03		0

Profile 11

(representative for map unit PW 1 on large flat plateau; transition to PM 1 with deep sandy topsoil)

Information on the site

Location: Kabo area, Suriname, LH/UvS 01 project area Tonka creek, natural regeneration experiment 78/5, repetition II, centre of central field. Coordinates 5°15'N, 55°43'W.
Described by J.A. de Fretes and R.L.H. Poels on 10-8-1978.
Elevation: approximately 34 m above mean sea level.
Physiographic position of the site: plateau.
Landform of surrounding country: level to undulating.
Microtopography: slightly uneven.
Slope: almost flat (1%).
Vegetation: undisturbed high dry land forest with Bolletri (*Manilkara bidentata*), Bergi Gronfoeloe (*Qualea rosea*), Basralocus (*Dicorynia guianensis*), Grootbladig Tingimonie (*Protium insigne*), Djadidja (*Sclerolobium melinonii*), Barklak (*Esweilera sp*), Kassavehout (*Didymopanax morototoni*), Salie (*Tetragastris sp*), Goebaja (*Jacaranda copaia), Swietboontje (*Inga sp*), Maripa palm (*Attalea regia*), Agrobigi (*Parkia nitida*), and Spijkerhout (*Mouriria crassifolia*); rather open canopy because of fallen trees; undergrowth of young trees and common Paramakka (Astrocaryum paramaca)* palms, few lianas.
Climate: Tropical rainforest climate (Af) with two wet and two drier periods; average precipitation 2200 mm/y; mean temperature 27 ° C; three months with an average rainfall below 100 mm (between 50 and 100 mm); for details see section 2.3: Climate.

General information of the soil

Parent material: Zanderij sediment of sandy clay loam texture, derived from granites and associated rocks.
External drainage: slow to medium.
Internal drainage: medium.
Drainage class: well drained.
Moisture condition of the profile: moist throughout.
Depth of groundwater table: below profile throughout the year.
Depth of gley/pseudogley: not encountered.
Presence of surface stones/rock outcrops: none.
Evidence of erosion: none.
Presence of salt or alkali: none.

Human influence: none.
Map unit: PW 1, well drained brown or yellow soils with a sandy loam to sandy clay loam topsoil and a sandy clay loam subsoil, near transition to PM 1, moderately well drained brown or yellow loamy soils with a loamy sand to sandy loam topsoil and a sandy clay loam subsoil.

Brief description of the profile

Very deep, well drained profile with a dark brown sandy topsoil and a yellow to reddish yellow subsoil of sandy loam to sandy clay loam texture; large quantities of charcoal occur at 113 cm depth; structure is weak throughout, but finer aggregates are fairly stable. The whole profile is friable, porous and permeable; some bleached sand pockets occur in the topsoil.

Description of individual soil horizons

O2	2- 1 cm	Undecomposed and slightly decomposed litter of leaves and other plant remains; gradual boundary.
O1	2- 0 cm	Partly decomposed and humified organic material, with many fine and very fine live roots growing above the mineral soil; clear boundary.
A11	0- 7 cm	Dark brown (7.5 YR 3/3 and 10 YR 3/3) sand; moderate fine and medium crumb structure; loose consistence when moist, non-sticky and non-plastic when wet; many medium and fine pores; abundant fine, common medium and large roots; high organic matter content, partly decomposed; little earthworm activity; few sand pockets with bleached sand grains; clear smooth boundary.
A12	7- 14 cm	Dark brown (7.5 YR 3/4) loamy sand; moderate fine subangular blocky and fine and medium crumb structure; loose consistence when moist, non-sticky and non-plastic when wet; many fine and medium pores; abundant fine, common medium and large roots; moderate organic matter content almost decomposed, often concentrated in small balls (diameter 5 mm); few sand pockets with bleached sand grains; gradual smooth boundary.
A13	14- 27 cm	Dark yellowish brown (10 YR 4/4) loamy sand; moderate fine and medium subangular blocky structure; very friable consistence when moist, slightly sticky and non-plastic when wet; common fine and medium pores; abundant to many

Proportion of soil and clay (%) in Profile 11

Horizon	Depth (cm)	SiO_2 (%)	Al_2O_3 (%)	Fe_2O_3 (%)
A11	0- 7	87.94	2.34	0.81
A12	7- 14	95.98	1.40	0.55
A13	14- 27	88.11	5.06	1.16
A 3	27- 49	88.24	7.12	1.44
B 1	49- 73	87.88	6.21	1.28
B21	73-108	89.24	6.08	1.24
B22	108-180	87.45	7.72	1.46
B 3	220-300	82.12	9.60	1.77

(continued)

P_2O_5 (%)	K_2O (%)	CaO (%)	MgO (%)	TiO_2 (%)	MnO (%)
≤0.01	0.02	≤0.01	≤0.01	0.20	≤0.01
≤0.01	0.01	≤0.01	≤0.01	0.14	≤0.01
≤0.01	0.02	≤0.01	≤0.01	0.38	≤0.01
≤0.01	0.03	≤0.01	≤0.01	0.50	≤0.01
≤0.01	0.02	≤0.01	≤0.01	0.42	≤0.01
≤0.01	0.02	≤0.01	≤0.01	0.41	≤0.01
≤0.01	0.03	≤0.01	≤0.01	0.47	≤0.01
≤0.01	0.03	≤0.01	≤0.01	0.62	≤0.01

Profile 37

(representative for map unit PW 2)

Information on the site

Location: Kabo area, Suriname, LH/UvS 01 project area Tonka creek, hydrological experiment 78/34, between line 12 and 13 south, approximately 400 m east of the Central Line. Coordinates 5°15′ N, 55°43′ W.
Described by R.L. Catalan Febrero on 2 June 1983.
Elevation: approximately 39 m above mean sea level.
Physiographic position of the site: almost level plateau.
Landform of surrounding country: undulating.
Microtopography: even.
Slope: 0-1%.
Vegetation: undisturbed moderately high dryland forest.
Climate: see Profile 11 and Chapter 2.3: Climate.

General information of the soil

Parent material: Zanderij sediment of sandy clay loam texture, derived from granites and associated rocks.
External drainage: slow to medium.
Internal drainage: medium to fast.
Drainage class: well drained.
Moisture condition of the profile: slightly moist throughout.
Depth of groundwater table: at all times deep below profile; presumed highest level: 4-5m.
Depth of gley/pseudogley: not encountered.
Presence of surface stones/rock outcrops: none.
Evidence of erosion: none.
Presence of salt or alkali: none
Human influence: none.
Map unit: PW 2, well drained brown or yellow loamy soils with a sand to loamy sand topsoil and a sandy loam subsoil.

Brief description of the profile

Very deep, well to somewhat excessively drained soil with a dark yellowish brown loamy sand topsoil and a brownish yellow sandy loam subsoil; the soil has a very clear crumb type of structure and also a darker layer with brittle consistence at a depth of 24-47 cm; Roots are very abundant in the topsoil, decreasing to common at 180 cm depth.

Description of individual soil horizons

O2	4- 2 cm	Litter of leaves and other plant remains ranging from recently deposited material to not yet humified matter; gradual boundary.
O1	2- 0 cm	Partly decomposed and humified organic material, intensively mixed with many fine and very fine roots that are growing above the mineral soil; clear boundary.
Ah1	0- 4 cm	Dark brown (7.5 YR 3/3), moist, sand, 70 % bleached; weak, fine subangular blocky structure; non-sticky and non-plastic consistence when wet, very friable when moist; many very fine and fine tubular and interstitial pores; abundant very fine to medium, common large roots; penetrometer: 0.25 kg/cm^2; clear smooth boundary.
Ah2	4- 15 cm	Dark yellowish brown (10 YR 4/4), moist, sand, 60 % bleached; very weak fine subangular blocky structure; non-sticky and non-plastic consistence when wet, very friable when moist; common very fine to medium tubular and interstitial pores; abundant very fine to medium and common large roots; penetrometer: 0.75 kg/cm^2; gradual smooth boundary.
E	15- 24 cm	Dark yellowish brown (10 YR 4/5), moist, sand, 40 % bleached; moderately weak fine subangular blocky structure; non-sticky and non-plastic consistence when wet, very friable when moist; common very fine to medium tubular and interstitial pores; abundant very fine to medium and common large roots; penetrometer: 1.25 kg/cm^2; clear smooth boundary.
Bhs	24- 41/ 47 cm	Dark yellowish brown (10 YR 4/5) moist, loamy sand; moderate medium subangular blocky structure, breaking into fine and medium crumbs; non-sticky and non-plastic consistence when wet, friable and brittle when moist; common fine tubular and interstitial pores; many fine to medium and common coarse roots; penetrometer: 2.75 kg/cm^2; gradual wavy boundary.
Bws1	41/ 47- 52/ 65 cm	Yellowish brown (10 YR 5/6), moist, loamy sand; moderate fine to medium crumb structure; slightly sticky and non-plastic consistence when wet, very friable when moist; no

		cutans detectable; common very fine and fine tubular and interstitial pores; common fine to medium and few large roots; penetrometer: 3.25 kg/cm^2; gradual wavy boundary.
Bws2	52/ 65- 87/ 97 cm	Brownish yellow (10 YR 6/6), moist, sandy loam; moderate fine to medium crumb structure; slightly sticky and slightly plastic consistence when wet, very friable when moist; no cutans detectable; common very fine and fine tubular and interstitial and few coarse tubular pores; common fine to medium and few large roots; penetrometer: 3.00 kg/cm^2; gradual wavy boundary.
Bws3	87/ 97- 112/120 cm	Brownish yellow (10 YR 6/6), moist, sandy loam; moderate fine to crumb structure; slightly sticky and slightly plastic consistence when wet, friable when moist; no cutans detectable; common very fine and fine interstitial and tubular pores; common fine to medium and few large roots; penetrometer: 3.75 kg/cm^2; gradual wavy boundary.
Bws4	112/120- 143/160 cm	Brownish yellow (10 YR 6/8), moist, sandy loam; moderate fine to medium crumb; sticky and slightly plastic consistence when wet, friable when moist; no cutans detectable; few fine tubular and common fine interstitial pores; common fine to medium and few large roots; penetrometer: 4.00 kg/cm^2; diffuse, wavy boundary.
Bws5	143/160- 180 cm	Reddish to brownish yellow (8.75 YR 6/8), moist, sandy loam; moderate fine to medium crumb; sticky and slightly plastic consistence when wet, firm when moist; no cutans detectable; few fine tubular and common fine interstitial pores; common fine to medium and few large roots; penetrometer: 4.25 kg/cm^2.

Classification (USDA): Quartzipsammentic Haplorthox
(FAO) : Xanthic Ferralsol

Results of analyses of Profile 37 carried out in Paramaribo, Suriname

Horizon	Depth (cm)	Sand (%)	Silt (%)	Clay (%)	Texture class	C (%)	N (%)	C/N	pH-H_2O	pH-KCl	CEC pH7 (me/100g)	CEC/100g clay	Ca	Mg	K	Na	Bases
													me/100 g				
Ah1	0- 4	80.1	18.8	1.1	LS	1.51	0.09	17	4.0	3.8	3.10	281.8	0.11	0.21	0.03	0.03	0.38
Ah2	4- 15	90.3	6.9	2.8	S	0.81	0.05	16	4.4	3.8	1.30	46.4	0.03	0.02	0.01	0.01	0.07
E	15- 24	87.1	8.1	4.8	LS	0.45	0.05	9	4.5	3.8	1.30	27.1	0.03	0.01	0.01	0.01	0.06
Bhs	24- 41	83.4	6.9	9.8	LS	0.63	0.04	16	5.0	4.0	1.64	16.7	0	0	0.01	0	0.01
Bws1	41- 52	79.8	7.7	12.6	SL	0.32	0.01	32	4.9	4.1	1.32	10.5	0.03	0.01	0.01	0	0.05
Bws2	52- 87	81.5	6.1	12.4	SL	0.13	0.01	13	4.9	4.1			0.03	0.03	0.01	0.02	0.09
Bws3	87-112	77.9	7.5	19.6	SL	0.09	0.02	4	5.0	4.0	0.78	4.0	0	0	0.01	0	0.01
Bws4	112-143	70.7	8.4	21.0	SCL	0.09	0.02	4	4.8	4.0	0.92	4.4	0.03	0.01	0.01	0.01	0.06
Bws5	143-180	72.7	8.8	18.6	SL	0.06	0.02	3	5.0	4.2	0.72	3.9	0	0	0.01	0	0.01

(continued)

Horizon	Depth (cm)	Al	ECEC	Al saturation	K total	P total	P-Bray I	Bulk density (kg/l)	pF 1	pF 1.5	pF 2	pF 3.4	pF 4.2
		me/100 g		(%)	ppm				vol %				
Ah1	0- 4	0.28	0.66	42	20	24	2.1						
Ah2	4- 15	0.56	0.63	89	30	42	1.1	1.32	42.0	16.3	11.4	4.7	3.5
E	15- 24	0.70	0.76	92	30	42	0.8	1.38	41.5	17.2	11.5	6.8	4.7
Bhs	24- 41	0.95	0.96	99	40	64	0.7	1.45	38.5	22.3	16.6	9.9	7.9
Bws1	41- 52	0.92	0.97	95	54	66	1.1	1.50	31.7	21.1	15.9	10.6	8.7
Bws2	52- 87	0.33	0.42	79	48	59	0.8	1.45	34.3	21.2	14.9	10.2	8.4
Bws3	87-112	0.33	0.34	97	64	68	0.8	1.49	31.0	25.0	20.4	11.3	9.5
Bws4	112-143	0.75	0.81	93	92	96	0.2	1.49	31.3	21.9	16.2	16.3	13.4
Bws5	143-180	0.47	0.48	98	88	103	0.3	1.53	31.0	23.5	18.3	14.2	11.2

Results of analyses of Profile 37 carried out in Wageningen, the Netherlands

Horizon	Depth (cm)	C (%)	N (%)	Free iron (%)	Amorphous iron (%)	pH-H_2O	pH-$CaCl_2$	Ca	Mg	Na	K	Al	H	Sum cations	CEC
								me/100 g							
Ah1	0- 4	3.00	0.12	0.98	0.02	4.2	3.2	0.5	0.5	0	1	0.7	0.8	2.6	4.5
Ah2	4- 15	0.46	0.08	0.62	0.08	4.1	4.0	0	0	0	0	0.7	0.2	0.9	1.5
E	15- 24	0.82	0.11	0.52	0.04	4.0	3.9	0	0	0	0	0.6	0.3	0.9	0.7
Bhs	24- 41	0.59	0.02	0.67	0.06	4.5	4.3	0	0	0	0	0.9	0.1	1.0	1.3
Bws1	41- 52	0.50	0.02	1.06	0.04	4.7	4.3	0	0	0	0	0.5	0.2	0.7	0.9
Bws2	52- 87	0.36	0.01	0.91	0.02	4.7	4.2	0	0	0	0	0.4	0.2	0.6	1.2
Bws3	87-112	0.30	$\leq$0.01	1.01	0.03	4.6	4.3	0	0	0	0	0.3	0.2	0.5	1.1
Bws4	112-143	0.37	$\leq$0.01	0.73	0.02	5.0	4.3	0	0	0	0	0.4	0.2	0.6	1.5
Bws5	143-180	0.12	$\leq$0.01	1.24	0.02	5.0	4.3	0	0	0	0	0.3	0.1	0.4	1.4

Proportion of soil and clay (%) in Profile 37

Horizon	SiO_2		Al_2O_3		Fe_2O_3		FeO		MgO	
	soil	clay	soil	clay	soil	clay	soil	clay	soil	clay
Ah1	82.29	38.74	11.31	35.61	1.14	6.44	0.04	0.12	0.07	0.15
Ah2	94.97	40.01	2.49	34.83	0.99	6.23	0.03	0.34	0.08	0.13
E	95.36	40.80	1.62	34.67	0.68	6.03	0.06	0.05	0.08	0.17
Bhs	94.32	42.07	3.70	36.89	1.17	3.10	0.19	0.17	0.08	0.10
Bws1	89.24	39.03	6.41	36.02	1.57	6.43	0.04	0.12	0.06	0.13
Bws2	89.95	39.21	6.06	36.55	1.54	6.60	0.05	0.17	0.07	0.13
Bws3	92.08	39.20	5.22	36.04	1.72	5.86	0.04	0.60	0.08	0.10
Bws4	90.38	39.21	6.63	36.14	1.96	6.75	0.04	0.03	0.08	0.10
Bws5	91.64	39.32	5.21	36.40	1.99	6.74	0.02	0.06	0.08	0.14

Horizon	CaO		Na_2O		K_2O		TiO_2		P_2O_5	MnO	
	soil	clay	soil	clay	soil	clay	soil	clay	soil	soil	clay
Ah1	0	0.01	0.03	0.07	0.02	0.10	0.67	2.23	0.01	0	0.01
Ah2	0.01	0.01	0.04	0.05	0.02	0.11	0.26	2.24	0.01	0	0.01
E	0.01	0.02	0.03	0.08	0.01	0.12	0.17	2.38	0.01	0	0.01
Bhs	0.01	0.01	0.03	0.02	0.01	0.05	0.28	2.03	0.01	0	0
Bws1	0.02	0.01	0.02	0.03	0.02	0.09	0.48	2.11	0.01	0	0.01
Bws2	0.01	0.01	0.02	0.09	0.03	0.10	0.47	2.17	0.02	0	0.01
Bws3	0.02	0.01	0.03	0.07	0.01	0.11	0.38	2.08	0.01	0	0.01
Bws4	0.02	0.01	0.03	0.03	0.02	0.12	0.44	2.02	0.01	0	0.01
Bws5	0	0.01	0.03	0.03	0.02	0.11	0.36	2.02	0.01	0	0.01

Profile 35

(representative for map unit PM 1, deep phase)

Information on the site

Location: Kabo area, Suriname, LH/UvS 01 project area Tonka creek, hydrological experiment 78/34, line 2 north, 215 m east of Central Line. Coordinates 5°15′ N, 55°43′ W.
Described by R.L. Catalan Febrero on 27 May 1983.
Elevation: approximately 20 m above mean sea level.
Physiographic position of the site: Lower part convex slope.
Landform of surrounding country: undulating.
Microtopography: even.
Slope: gently sloping (6%).
Vegetation: undisturbed high dryland forest.
Climate: see Profile 11.

General information of the soil

Parent material: Zanderij sediment of sandy clay loam texture, derived from granites and associated rocks.
External drainage: slow to medium.
Internal drainage: medium.
Drainage class: moderately well drained.
Moisture condition of the profile: moist throughout.
Depth of groundwater table: highest level in wet season around 170 cm depth.
Depth of gley/pseudogley: not encountered.
Presence of surface stones/rock outcrops: none.
Evidence of erosion: none.
Presence of salt or alkali: none
Human influence: none.
Map unit: PM 1, moderately well drained brown or yellow loamy soils with a loamy sand to sandy loam topsoil and a sandy clay loam subsoil.

Brief description of the profile

Deep, moderately well drained profile with a brown loamy sand topsoil and a very pale brown sandy clay loam subsoil; this soil shows a darker layer in the topsoil, a so called gray layer, which seems related to some degree of podzolization; structure is moderately weak throughout.

Description of individual soil horizons

O2	4- 2 cm	Litter of leaves and other plant remains ranging from recently deposited material to not as yet humified matter; gradual boundary.
O1	2- 0 cm	Partly decomposed and humified organic material, intensively mixed with many fine and very fine roots growing above the mineral soil; clear boundary.
Ah1	0- 4 cm	Brown (7.5 YR 4/3), moist, sand; weak , very fine subangular blocky structure; non-sticky and non-plastic consistence when wet, very friable when moist; many fine and common medium tubular and interstitial pores; abundant very fine to medium and few large roots; penetrometer: 0.25 kg/cm^2; clear smooth boundary.
Ah2	4- 9 cm	Brown (8.75 YR 4/3), moist, loamy sand; moderately fine to medium subangular blocky structure; non-sticky and slightly plastic consistence when wet, very friable when moist; common very fine and fine tubular and interstitial and few coarse pores; abundant very fine to medium and common large roots; penetrometer: 1.75 kg/cm^2; clear smooth boundary.
E	9- 24 cm	Brown (10 YR 5/3), moist, loamy sand; moderate medium subangular blocky structure; slightly sticky and slightly plastic consistence when wet, friable when moist; common very fine and fine and few coarse tubular and interstitial pores; many very fine to medium and common large roots; penetrometer: 2.75 kg/cm^2; gradual smooth boundary.
Bhs	24- 50/ 63 cm	Grayish brown (10 YR 5/2) moist, sandy loam; moderate weak coarse subangular blocky structure; slightly sticky and slightly plastic consistence when wet, very friable and brittle when moist; common fine and medium tubular and interstitial and few coarse tubular pores; common very fine to medium and few coarse roots penetrometer: 3.25 kg/cm^2; gradual wavy boundary.
Bws1	50/ 63- 66/ 77 cm	Pale brown (10 YR 6/3), moist, sandy clay loam; moderate medium subangular blocky structure; sticky and plastic consistence when wet, friable when moist; no cutans detectable; common fine and medium tubular and interstitial

and few coarse tubular pores; common very fine to medium and few large roots; penetrometer: 3.75 kg/cm^2; gradual wavy boundary.

Bws2	66/ 77-104/109 cm	Very pale brown (10 YR 7/4), moist, sandy clay loam; moderate medium subangular blocky structure; sticky and plastic consistence when wet, friable when moist; no cutans detectable; common fine and medium tubular and interstitial pores; common fine to medium and very few large roots; penetrometer: 4.00 kg/cm^2; diffuse wavy boundary.
Bws3	104/109-134/160 cm	Very pale brown to pale yellow (1.25 Y 7.5/4), moist, sandy clay loam; common fine to coarse, distinct, clear, bright brown and bright yellowish brown mottles; moderately weak medium subangular blocky structure; sticky and plastic consistence when wet, friable when moist; no cutans detectable; common fine and medium interstitial and few fine tubular pores; few fine to medium roots; penetrometer: 4.00 kg/cm^2; diffuse wavy boundary.
Bws4	134/160-170 cm	Very pale brown to pale yellow (1.25 Y 7.5/4), moist, sandy clay loam, many medium and coarse, distinct, clear and diffuse, yellow orange (7.5 YR 7/8) mottles; very weak coarse subangular blocky structure; sticky and plastic consistence when wet, friable when moist; no cutans detectable; common fine and medium interstitial and few fine tubular pores; few fine to medium roots; penetrometer: 4.25 kg/cm^2.
Bws5	170-180 cm (boring)	Very pale brown (10 YR 8/3), moist,sandy clay; many coarse, prominent, sharp, red (2.5YR4/8) mottles.
BCws	180-190 cm	Pale yellow (5 Y 8/3), moist, sandy clay; many coarse, prominent, sharp, dark yellowish brown (10 YR 4/4) mottles.
C	190-197 cm	Similar to BCws but with laterite gravels (more than 50 % of volume).

Classification (USDA): Ultic Haplorthox
(FAO) : Orthic Ferralsol

Results of analyses of Profile 35 carried out in Paramaribo, Suriname

Horizon	Depth (cm)	Sand (%)	Silt (%)	Clay (%)	Texture class	C (%)	N (%)	C/N	pH-H_2O	pH-KCl	CEC pH7 (me/100g)	CEC per 100g clay	Ca	Mg	K	Na	Bases
													me/100 g				
Ah1	0- 4	83.5	13.6	2.9	LS	1.17	0.08	15	4.0	3.3	2.60	89.7	0.25	0.23	0.04	0.02	0.54
Ah2	4- 9	76.2	17.6	6.3	LS	1.20	0.09	13	3.7	3.4	2.84	45.1	0.08	0.10	0.03	0.05	0.26
E	9- 24	68.5	17.9	13.6	SL	0.82	0.06	14	4.4	3.8	2.32	17.1	0.03	0.05	0.01	0.03	0.12
Bhs	24- 50	63.8	18.8	17.6	SL	0.56	0.04	14	4.8	4.0	2.28	13.0	0.03	0.03	0.01	0.02	0.09
Bws1	50- 66	62.8	14.2	23.1	SCL	0.25	0.02	12	4.8	3.8	1.44	6.2	0.03	0.02	0	0.02	0.07
Bws2	66-104	64.2	12.4	23.6	SCL	0.14	0.03	5	4.8	4.0	1.22	5.2	0.03	0.01	0	0.01	0.05
Bws3	104-134	62.3	12.5	25.4	SCL	0.07	0.01	7	5.0	4.0	1.08	4.3	0	0	0.01	0	0.01
Bws4	134-170	58.1	14.3	27.8	SCL	0.06	0.01	6	5.0	4.1	0.98	3.5	0.03	0	0	0.01	0.04

(continued)

Horizon	Depth (cm)	Al	ECEC	Al sat (%)	K total	P total	P-Bray I	Bulk density (kg/l)	pF 1	pF 1.5	pF 2	pF 3.4	pF 4.2
		me/100 g			ppm				vol %				
Ah1	0- 4	0.38	0.92	41	20	32	2.2						
Ah2	4- 9	1.24	1.50	83	24	49	2.2	1.41	41.2	30.5	23.2	17.9	8.8
E	9- 24	1.18	1.30	91	24	54	1.1	1.28	37.3	27.4	22.4	14.1	10.6
Bhs	24- 50	1.23	1.32	93	30	47	0.6	1.56	32.7	29.5	25.2	20.3	16.6
Bws1	50- 66	0.90	0.97	93	34	52	0.2	1.60	32.1	29.7	26.0	20.5	15.8
Bws2	66-104	0.77	0.82	94	30	49	0.5	1.65	31.3	29.1	25.9	20.3	16.9
Bws3	104-134	0.69	0.70	99	40	37	1.1	1.69	31.5	29.9	27.1	25.0	15.7
Bws4	134-170	0.67	0.71	94	34	37	0.8	1.69	32.8	31.4	29.7		

Results of analyses of Profile 35 carried out in Wageningen, the Netherlands

Horizon	Depth (cm)	C (%)	N (%)	Free iron (%)	Amorphous iron (%)	pH-H_2O	pH-$CaCl_2$	Ca	Mg	Na	K	Al	H	Sum cations	CEC
								me/100 g							
Ah1	0- 4	1.45	0.07	0.23	0.05	4.3	3.6	0.4	0.4	0	0	0.6	0.5	1.9	4.1
Ah2	4- 9	1.30	0.06	0.34	0.09	3.9	3.6	0	0.1	0	0	1.2	0.4	1.7	3.5
E	9- 24	0.43	0.03	0.52	0.18	4.1	4.0	0	0	0	0	1.2	0.3	1.5	4.3
Bhs	24- 50	0.74	0.03	0.63	0.19	4.7	4.2	0	0	0.1	0.10	1.0	0.1	1.3	3.1
Bws1	50- 66	0.68	0.02	0.76	0.12	4.7	4.2	0	0	0	0	0.7	0.2	0.9	3.3
Bws2	66-104	0.32	<0.01	0.60	0.06	5.0	4.2	0	0	0	0	0.6	0.1	0.7	2.3
Bws3	104-134	0.21	<0.01	0.59	0.04	5.3	4.4	0.5	0	0	0	0.4	0.1	1.0	2.9
Bws4	134-170	0.20	<0.01	0.79	0.03	6.5	6.1	1.3	0	0	0	0.1	0	1.4	3.0

Proportion of soil and clay (%) in Profile 35

Horizon	SiO_2		Al_2O_3		Fe_2O_3		FeO		MgO	
	soil	clay	soil	clay	soil	clay	soil	clay	soil	clay
Ah1	96.62	44.18	1.57	35.17	0.20	2.08	0.19	0.09	0.06	0.16
Ah2	92.78	44.20	3.30	36.43	0.31	1.86	0.15	0.18	0.05	0.12
E	87.34	43.50	8.63	36.52	0.61	2.47	0.15	0.04	0.14	0.12
Bhs	88.41	42.81	5.72	36.55	1.00	2.67	0.01	0.10	0.07	0.10
Bws1	84.75	44.19	10.11	38.55	1.24	1.26	0	0.02	0.08	0.10
Bws2	85.29	43.15	10.08	36.91	1.09	2.73	0.12	0.18	0.05	0.08
Bws3	82.65	43.56	12.04	37.64	0.97	3.89	0.18	0.19	0.05	0.10
Bws4	82.36	43.29	12.03	35.98	1.18	2.29	0.14	0.08	0.06	0.07

(continued)

Horizon	CaO		Na_2O		K_2O		TiO_2		P_2O_5 soil	MnO soil and clay
	soil	clay	soil	clay	soil	clay	soil	clay		
Ah1	0.02	0.02	0.03	0	0	0.11	0.13	2.16	0.01	0
Ah2	0.02	0.01	0.03	0.02	0.02	0.07	0.24	2.17	0	0
E	0.01	0.01	0.03	0.02	0.01	0.06	0.65	2.17	0.01	0
Bhs	0.01	0.01	0.03	0.03	0.01	0.05	0.47	2.17	0.02	0
Bws1	0.01	0.01	0.03	0	0.02	0.08	0.71	1.82	0.01	0
Bws2	0.01	0.01	0.03	0	0.01	0.05	0.71	2.05	0.01	0
Bws3	0.02	0.01	0.03	0	0.01	0.05	0.88	2.12	0.02	0
Bws4	0.05	0.01	0.03	0	0.01	0.08	0.86	1.74	0.02	0

Profile 25

(representative of map unit PM 1, shallow phase, on lateritic clay)

Information on the site

Location: Kabo area, Suriname, LH/UvS 01 project area Tonka creek, hydrological experiment 78/34, line 0, 250 m east of the Central Line; coordinates 5°15′ N, 55°43′ W.
Described by M. van Leeuwen on 1 October 1982.
Elevation: approximately 24 m above mean sea level.
Physiographic position of the site: midway on long slope about 5 m above creek level.
Landform of surrounding country: undulating.
Microtopography: even.
Slope: gently sloping (6%).
Vegetation: undisturbed high dryland forest.
Climate: see Profile 11.

General information of the soil

Parent material: Zanderij sediment of sandy clay loam texture, derived from granites and associated rocks.
External drainage: medium.
Internal drainage: slow to medium.
Drainage class: moderately well drained.
Moisture condition of the profile: moist throughout.
Depth of groundwater table: deep below profile; maximum level estimated at 2 m below surface.
Depth of gley/pseudogley: not encountered.
Presence of surface stones/rock outcrops: none.
Evidence of erosion: none.
Presence of salt or alkali: none
Human influence: none.
Map unit: PM 1 shallow, moderately well drained brown or yellow loamy soils with a loamy sand to sandy loam topsoil and a sandy clay loam subsoil. Precambrian parent material starts between 60 and 120 cm depth and consist of laterite (gravel) or clayey material.

Brief description of the profile

Deep, moderately well drained profile with a brown loamy sand topsoil and a brown to brownish yellow sandy clay loam subsoil to 78 cm, below which a reddish yellow sandy clay occurs with a layer of laterite gravel which appears practically impenetrable for roots, above a horizon with dark red mottles. This horizon probably contains a fair amount of plinthite.

Description of individual soil horizons

O2	4- 2 cm	Dry leaves, twigs and other plant remains, clearly recognizable as such, cover approximately 70 % of the surface; mean leave size 15 x 5 cm; gradually boundary.
O1	2- 0 cm	Humified leaves and other plant remains; intertwined by many very fine to fine roots; clear boundary.
AE	0- 7 cm	Brown (7.5 YR 4/3) sand, with common fine bleached sand grains (occurring probably in vague sand pockets); weak medium to fine subangular blocky structure, breaking into fine granules; very friable consistence when moist, non-sticky and non-plastic when wet; many fine and very fine pores; abundant very fine and medium, common large roots; clear wavy boundary.
EA	7- 20 cm	Brown (10 YR 4/3) sand, with faint coarse (2 cm^2) brown (10 YR 5/3) loamy sand pockets; common very faint diffuse, medium to coarse dark brown (7.5YR4/6) mottles; few coarse black soft charcoal particles; moderately weak medium subangular blocky structure, breaking into medium granules; slightly sticky and non-plastic consistence when wet, very friable when moist; many very fine, common fine and few medium pores; common fine, medium and large roots; gradual smooth boundary.
Bh	20- 40 cm	Dark yellowish brown (10 YR 4/4) sandy clay loam; few faint diffuse, fine to medium, reddish yellow (7.5 YR 6/6) mottles; moderately weak coarse angular blocky structure, breaking into coarse granules; slightly sticky and plastic consistence when wet, very friable when moist; thin patchy cutans on largest structure elements, mainly around pores, consisting probably of organic matter and clay; few fine and many very fine pores; few fine, common coarse roots; few medium to coarse soft black charcoal concretions; diffuse smooth boundary.
Bt1	40- 62 cm	Brown (10 YR 5/3) sandy clay loam; common coarse clear distinct yellow (10 YR 7/6), and few medium faint diffuse dark brown (7.5 YR 4/6) mottles; thin patchy cutans

		(probably of clay and humus); moderate medium subangular blocky structure; slightly sticky and plastic consistence when wet, firm when moist; few fine and medium, common very fine pores; few medium and large roots; very few, medium gravel sized angular quartz fragments; diffuse smooth boundary.
Bt2	62- 78 cm	Brownish yellow (10 YR 6/6) sandy clay; up to 50% brown (10 YR 5/3) colour; few medium faint diffuse red (2.5 YR 5/8) mottles; moderately weak fine subangular blocky structure, breaking into coarse granules, structure tending to very weak thin platy; slightly sticky and plastic consistence when wet, firm when moist; thin patchy cutans (organic matter and clay); many very fine and few fine pores; few coarse and medium roots; very few fine (diameter 2-5 mm) hard concretions, mainly of angular quartz and iron; abrupt smooth boundary.
Bcs	78- 92 cm	Reddish yellow (7.5 YR 7/8) sandy clay; common medium distinct clear red (2.5 YR 5/8) mottles; structure dominated by the stoniness of the horizon, probably moderately weak medium to fine subangular blocky (apart from the stones), breaking into coarse granules; slightly sticky and plastic consistence when wet, firm when moist; weakly cemented; thin patchy cutans (probably of organic matter and clay); common very fine and fine, few medium pores; very few fine roots (practically none); frequent gravel sized quartz particles; frequent to very frequent dark red (7.5 R 3/6 to 4/8) nodules, with quartz deposited on the outside, diameter 4-8 cm, consisting probably of Fe_2O_3, $Al(OH)_3$ and quartz; the layer is continuous and pisolithic; clear smooth boundary.
Bs	92-115 cm	Reddish yellow (5 YR 6/6) sandy clay, with 30% pinkish gray (7.5 YR 6/3) colour; common medium to coarse, dark red ((7.5 R 3/6) mottles and soft nodules; weak fine to medium subangular blocky structure, breaking into coarse granules, structure tending to thick platy; slightly sticky and plastic consistence when wet, firm when moist; thin patchy cutans, especially on aggregates of mineral nodules; common very fine, few fine and medium pores (well porous); apparently no roots; few fine, medium and coarse, mottlelike concretions (Fe_2O_3?); soft, gravel sized quartz fragments (mean diameter 6 mm), angular, whitish inside; bottom pit at 115 cm; this and following horizons are considered to contain some plinthite.

colour is light gray to white; groundwater and seepage on the sandy clay loam subsoil keep this soil wet below 90 cm during most of the year.

Description of individual soil horizons

O2	4- 2 cm	Litter of leaves and other plant remains ranging from recently deposited material to not as yet humified matter; gradual boundary.
O1	2- 0 cm	Partly decomposed and humified organic material intensively mixed with many very fine and fine roots growing above the mineral soil; clear boundary.
Ah1	0- 7 cm	Brown (7.5 YR 4/3) sand, 40 % bleached; very weak, fine and medium subangular blocky structure; non-sticky and non-plastic consistence when wet, very friable when moist; many very fine and fine tubular and interstitial pores; abundant very fine to medium and common large roots; penetrometer: 0.75 kg/cm^2; gradual smooth boundary.
E	7- 20 cm	Brown (7.5 YR 4/2) sand, 10 % bleached; very weak fine subangular blocky structure, breaking easily into very fine subangular blocky elements and into single grains; non-sticky and non-plastic consistence when wet, very friable to loose when moist; common very fine and fine tubular and interstitial pores; common fine to medium and few coarse roots; penetrometer: 2.00 kg/cm^2; clear smooth boundary.
Bhs1	20- 30 cm	Very dark grayish brown (10 YR 3.5/2) loamy sand; very weak coarse subangular blocky structure, breaking easily into fine granules; non-sticky and non-plastic consistence when wet, very friable and somewhat brittle when moist; common fine tubular and interstitial pores; common fine to medium and few large roots; penetrometer: 3.50 kg/cm^2; gradual smooth boundary.
Bhs2	30- 60 cm	Dark gray (10 YR 4/1) loamy sand; massive structure; non-sticky and non-plastic consistence when wet, very friable and brittle when moist; few fine tubular and common fine interstitial pores; common fine to medium and few large roots; penetrometer: 4.25 kg/cm^2; gradual smooth boundary.

Bhs3	60-70/ 80 cm	Gray (10 YR 5/1) loamy sand; very weak coarse subangular blocky structure, breaking easily into very fine subangular blocky elements; slightly sticky and slightly plastic consistence when wet, very friable when moist; few fine tubular and common fine interstitial pores; few fine and medium roots; penetrometer: 4.00 kg/cm^2; gradual wavy boundary.
Bws	70/ 80-88 cm	Gray (10 YR 6/1) sandy loam; many medium distinct, clear, light gray (10YR 7/2) mottles and some gray (10 YR 5/1) horizontal strips which are approximately 3 cm thick and 10 to 50 cm long, which consists probably of organic matter deposited in very thin horizontal layers; many spherical mottles of lighter colours than the matrix which are 15 to 20 mm in diameter; moderately weak coarse subangular blocky structure; sticky and plastic consistence when wet, friable when moist; no cutans detectable; common fine to medium tubular and interstitial pores; few fine to coarse roots; penetrometer: 3.75 kg/cm^2; gradual smooth boundary.
2Bwsg1	88-102 cm	Light gray (10 YR 7/1) sandy loam; many medium and coarse, distinct, clear, light gray (10 YR 7/2) and common, fine, prominent, sharp, bright olive yellow (2.5 Y 6/6) mottles; gray (10 YR 5/1) strips (3 cm thick and 10-15 cm long); very weak coarse subangular blocky structure; sticky and plastic consistence when wet, friable when moist; iron cutans visible on vertical channels and on some vertical ped surfaces; very few fine tubular and common fine interstitial pores; few fine to medium and few coarse roots; penetrometer: 3.5 kg/cm^2; gradual smooth boundary.
2Bwsg2	102-136 cm	White (2.5 Y 8/2) sandy clay loam; many fine to coarse, distinct, clear, cm gray (10 YR 6/1) and many fine and medium, prominent, sharp, olive yellow (2.5 Y 6/6) mottles; very weak coarse subangular blocky structure; sticky and very plastic consistence when wet, friable when moist; iron cutans are visible on vertical channels and in some vertical ped surfaces; very few fine tubular and common fine interstitial pores; very few fine to coarse roots; penetrometer: 3.00 kg/cm^2.
2Bwsg3	136-180 cm	Similar to 2Bwsg2 but colour is now white (2.5Y8/1).

2BCwsg1	180-220 cm	Similar to 2Bwsg3 but without mottles and with fine quartz gravels beginning at 200 cm.
2BCwsg2	220-240 cm	Similar to 2BCwsg1, but colour is now white (7.5Y8/1).

Classification (USDA): Aquic quartzipsamment or Tropohumod
(FAO) : Humic podzol

Results of analyses of Profile 34 carried out in Paramaribo, Suriname

Horizon	Depth (cm)	Sand (%)	Silt (%)	Clay (%)	Texture class	C (%)	N (%)	C/N	pH-H_2O	pH-KCl	CEC pH7 (me/100g)	CEC 100g clay	Ca	Mg	K	Na	Bases
													me/100 g				
Ah1	0- 7	81.2	14.4	4.4	LS	1.31	0.13	10	4.0	3.6	3.10	70.5	0.16	0.12	0.04	0.03	0.35
E	7- 20	80.4	11.1	8.6	LS	0.97	0.08	12	4.0	3.8	2.56	29.8	0	0.05	0.02	0.04	0.11
Bhs1	20- 30	73.9	14.4	11.8	SL	0.83	0.06	14	4.5	4.0	2.96	25.1	0	0.02	0.01	0.01	0.04
Bhs2	30- 60	76.9	10.1	13.2	SL	0.39	0.03	13	4.8	4.2	1.72	13.0	0	0.04	0.02	0.05	0.11
Bhs3	60- 70	75.4	10.5	14.3	SL	0.31	0.02	16	4.8	4.0	1.36	9.5	0	0.03	0.01	0.03	0.07
Bws	70- 88	73.2	11.7	15.2	SL	0.22	0.02	11	5.0	4.0	1.12	7.4	0	0.01	0.01	0.02	0.04
2Bwsg1	88-102	72.0	12.3	16.0	SL	0.21	0.01	21	5.0	4.0	1.10	6.3	0	0.03	0.01	0.04	0.08
2Bwsg2	102-136	65.7	15.6	19.0	SL	0.08	0.02	4	4.6	3.8	1.14	6.0	0	0.02	0.01	0.03	0.06

(continued)

Horizon	Depth (cm)	Al	ECEC	Al sat (%)	K total	P total	P-Bray I	Bulk density (kg/l)	pF 1	pF 1.5	pF 2	pF 3.4	pF 4.2
		me/100 g			ppm				vol %				
Ah1	0- 7	1.15	1.50	77	38	43	2.1	1.29	48.3	25.6	16.6	8.4	6.6
E	7- 20	1.19	1.30	92	38	36	2.1	1.37	44.0	28.3	19.4	12.5	5.4
Bhs1	20- 30	1.18	1.22	97	45	49	3.5	1.41	40.9	29.3	20.5	14.7	10.6
Bhs2	30- 60	0.82	0.93	88	48	28	1.4	1.53	36.4	27.1	18.9	10.6	7.6
Bhs3	60- 70	0.81	0.88	92	38	30	1.2	1.56	31.3	25.7	19.3	14.1	11.2
Bws	70- 88	0.68	0.72	94	45	30	0.7	1.55	31.5	26.2	19.7	14.3	11.5
2Bwsg1	88-102	0.69	0.77	90	52	28	0.7	1.58	31.3	26.7	21.1	20.8	15.1
2Bwsg2	102-136	0.63	0.69	91	79	32	0	1.60	35.4	33.0	27.1		

Results of analyses of Profile 34 carried out in Wageningen, the Netherlands

Horizon	Depth (cm)	C	N	Free iron	Amorphous iron	pH-H_2O	pH-$CaCl_2$	Ca	Mg	Na	K	Al	H	Sum cations	CEC
				%								me/100 g			
Ah1	0- 7	1.80	0.08	0.11	0.04	3.9	3.7	0	0.2	0	0	1.3	0.6	2.1	4.4
E	7- 20	0.77	0.02	0.13	0.03	4.1	4.0	0	0.1	0	0	1.3	0.4	1.8	3.1
Bhsl	20- 30	0.48	0.04	0.12	0.03	4.3	4.2	0	0.1	0	0	1.2	0.3	1.6	3.8
Bhs2	30- 60	0.51	0.02	0.13	0.02	4.8	4.3	0	0	0	0	0.8	0.1	0.9	3.3
Bhs3	60- 70	0.43	0.01	0.15	0.02	4.9	4.3	0	0	0.2	0.3	0.6	0.2	1.3	3.0
Bws	70- 88	0.38	≤0.01	0.11	0.03	5.0	4.3	0	0	0	0	0.6	0.3	0.9	3.5
2Bwsgl	88-102	0.32	≤0.01	0.15	0.03	5.2	4.4	0	0	0	0	0.4	0.2	0.6	3.0
2Bwsg2	102-136	0.32	≤0.01	0.13	0.02	4.8	4.2	0	0	0	0	0.5	0.2	0.7	2.2

Proportion of soil and clay (%) in Profile 34

Horizon	SiO_2		Al_2O_3		Fe_2O_3		FeO		MgO	
	soil	clay	soil	clay	soil	clay	soil	clay	soil	clay
Ah1	93.13	44.33	1.83	36.08	0.11	1.32	0.05	0.04	0.17	0.23
E	93.48	42.65	3.51	36.59	0.39	1.15	0.07	0.12	0.12	0.13
Bhsl	88.52	43.31	5.35	37.52	0.22	1.27	0.07	0.18	0.09	0.13
Bhs2	91.48	43.36	5.68	37.70	0.21	1.50	0.05	0.02	0.08	0.12
Bhs3	91.26	43.50	5.71	38.27	0.26	1.17	0	0.03	0.07	0.12
Bws	91.03	42.46	6.46	37.28	0.30	0.97	0	0.18	0.06	0.13
2Bwsgl	93.81	43.36	5.09	38.41	0.23	1.05	0.07	0.02	0.06	0.10
2Bwsg2	85.46	42.53	10.07	37.61	0.24	3.52	0.08	0.02	0.05	0.07

(continued)

Horizon	CaO		Na_2O		K_2O		TiO_2		P_2O_5		MnO
	soil	clay	soil	clay	soil	clay	soil	clay	soil	clay	soil and clay
Ah1	0.02	0.01	0.03	0.08	0.01	0.14	0.12	1.91	0.01		0
E	0.02	0.01	0.03	0.03	0	0.07	0.25	1.90	0.01		0
Bhsl	0.01	0.02	0.03	0.03	0.01	0.07	0.35	1.89	0.01		0
Bhs2	0.01	0.02	0.03	0.03	0.01	0.06	0.36	1.86	0.02	0.27	0
Bhs3	0.01	0.02	0.03	0.05	0.01	0.07	0.38	1.87	0.01		0
Bws	0.01	0.02	0.03	0.03	0.01	0.06	0.43	1.82	0.02		0
2Bwsgl	0.01	0.02	0.03	0.05	0.01	0.06	0.33	1.79	0.01		0
2Bwsg2	0.01	0.02	0.04	0.02	0.01	0.06	0.63	1.71	0.01		0

Profile 40

(Boring 29) (representative for map unit PI 3.3, under savannah forest)

Information on the site

Location: Kabo area, Suriname, LH/UvS 01 project area Tonka creek, hydrological experiment 78/34, line 12 north, 370 m east of Central Line; coordinates 5°15′ N, 55°43′ W.
Described by R.L. Catalan Febrero and R.L.H. Poels on 25 May 1983.
Elevation: approximately 15 m above mean sea level.
Physiographic position of the site: almost level plain slightly above creek level.
Landform of surrounding country: undulating.
Microtopography: even.
Slope: nearly flat (1%).
Vegetation: low savannah forest.
Climate: see Profile 11.

General information of the soil

Parent material: Zanderij sediment of sandy clay loam texture derived from granites and associated rocks.
External drainage: slow.
Internal drainage: fast.
Drainage class: imperfectly drained.
Moisture condition of the profile: moist on top and wet below.
Depth of groundwater table: highest level in wet season near the surface, lowest level approximately 2 m depth, during examination at 42 cm.
Depth of gley/pseudogley: subsoil is not mottled probably because iron content of the pure quartz sand is too low.
Presence of surface stones/rock outcrops: none.
Evidence of erosion: none.
Presence of salt or alkali: none
Human influence: none.
Map unit:PI 3.3, imperfectly drained gray soils with a sand texture throughout and a light gray coloured subsoil starting at shallow depth (within 50 cm).

Brief description of the profile

Shallow, imperfectly drained profile in deep quartz sand with a shallow dark brown to yellowish brown topsoil containing raw humus, and a light gray to white structureless subsoil.

Description of individual soil horizons

O2	2- 0 cm	Litter of leaves and other plant remains.
A1	0- 10 cm	Yellowish brown (10 YR 5/4) medium sand with much brown, raw, partly decomposed organic matter, intensively mixed with abundant roots.
AC	10- 30 cm	Light gray (10 YR 7/2) medium sand; some organic matter; common roots.
C	30-120+cm	White (10 YR 8/1) medium sand; loose; structureless; very few roots, decreasing with depth.

Classification (USDA): Typic Quartzipsamment
(FAO) : Albic Arenosol

(No analysis results)

Profile 26

(representative for map unit PI 3.5)

Information on the site

Location: Kabo area, Suriname, LH/UvS 01 project area Tonka creek, hydrological experiment 78/34, line 0, 320 m east of the Central Line; coordinates 5°15′ N, 55°43′ W.
Described by M. van Leeuwen on 1 October 1982.
Elevation: approximately 20 m above mean sea level.
Physiographic position of the site: on the lower footslope of a long slope, directly bordering the poorly drained valley bottom.
Landform of surrounding country: undulating.
Microtopography: even.
Slope: gently sloping (4%).
Vegetation: undisturbed high dryland forest, moderately high and with a relatively low basal area.
Climate: see Profile 11.

General information of the soil

Parent material: Zanderij sediment of sandy clay loam texture, derived from granites and associated rocks.
External drainage: slow.
Internal drainage: medium.
Drainage class: imperfectly to poorly drained.
Moisture condition of the profile: moist on top and wet below 60 cm.
Depth of groundwater table: approximately 75 cm.
Depth of gley/pseudogley: water carrying subsoil below 75 cm is not mottled, presumably because iron components are absent.
Presence of surface stones/rock outcrops: none.
Evidence of erosion: none.
Presence of salt or alkali: none
Human influence: none.
Map unit: PI 3.5, imperfectly drained gray soils with a sand to loamy sand texture throughout, with a thick dark gray to black layer and with a light gray subsoil.

Brief description of the profile

Rather shallow, imperfectly drained gray profile with a sandy texture throughout; the topsoil is very dark grayish brown to 75 cm, below which a light gray coloured structureless sandy subsoil occurs, that apparently carries water.

Description of individual soil horizons

O2	3- 1 cm	Dry leaves, flowers, fruits, twigs and other plant remains, clearly recognizable as such, covering approximately 95 % of the surface; mean leave size 20 x 7 cm, leaves glabrous with entire margins; gradually boundary.
O1	1- 0 cm	Rotten and partly decomposed leaves and other plant remains; intertwined by very many, very fine and fine roots; clear boundary.
AE1	0- 3 cm	Dark brown (10 YR 3/4 dry, 3/3 moist) medium sand, with up to 50 % white (10 YR 8/1) bleached sand grains; very weak medium to coarse granular structure; loose consistence when moist, non-sticky and non-plastic when wet; many medium, fine and very fine pores, continuous, mainly horizontal; many very fine, fine, medium and large roots; clear smooth boundary.
AE2	3- 12 cm	Very dark grayish brown (10 YR 3/2) medium sand, with up to 20 % white (10 YR 8/1) bleached sand grains, occurring also in larger pockets; colour of the horizon smeared is dark yellowish brown (10 YR 4/4 moist); the sand is poorly sorted; very weak medium to fine subangular blocky structure, breaking into medium granules; non-sticky and non-plastic consistence when wet, very friable when moist; many very fine and few fine pores; many fine, medium and large roots; clear smooth boundary.
BE	12- 30 cm	Very dark grayish brown (10 YR 3/2 moist) medium sand, with few white (10 YR 8/1) bleached sand grains; moderately weak medium subangular blocky structure, breaking into medium granules; non-sticky and non-plastic consistence when wet, very friable when moist; few fine and many very fine pores; common fine, medium and coarse roots; diffuse smooth boundary.
Bh1	30- 60 cm	Very dark brown (10 YR 2/3 moist) sand, slightly loamy, and appearing grayer than BE; moderately weak coarse subangular blocky structure, breaking into fine subangular blocky elements and into medium granules; non-sticky and non-plastic consistence when wet, very friable when moist; few fine and many very fine pores; few fine and medium, common large roots; diffuse smooth boundary.

Bh2 60- 75 cm Very dark brown (10 YR 2/2 moist) medium sand, slightly loamy; moderately weak coarse subangular blocky structure, breaking into fine subangular blocky elements and into medium granules; non-sticky and non-plastic consistence when wet, very friable when moist; common very fine pores; few coarse and medium roots; few gravel sized quartz fragments, angular, diameter 4 mm; abrupt smooth boundary.

Bg 75 + cm Light gray (2.5 Y 7/2) medium sand, with few gravel fragments (2-3 mm); apparently structureless; non-sticky and non-plastic consistence when wet, loose when moist; probably well porous (fine and very fine pores); apparently no roots; difficult to investigate because of water seepage in this horizon; bottom pit at 85 cm.

Classification (USDA): Aquic Quartzipsamment or Tropohumod
(FAO) : Humic Podzol

Results of analysis results Profile 26

Horizon	Depth (cm)	Sand (%)	Silt (%)	Clay (%)	C tot (%)	N (%)	C/N	pH-H_2O	pH-KCl	CEC pH7	Ca	Mg	K	Na	Al	Bases	ECEC	Al sat (%)
										me/100 g								
AE1	0- 3	91.4	6.0	1.0	1.97	0.11	18	4.2	3.2	2.30	0.13	0	0.05	0.06	0.36	0.24	0.60	60
AE2	3- 12	90.3	6.7	2.2	1.20	0.08	15	4.4	3.6	1.90	0.03	0.06	0.03	0	0.43	0.12	0.55	78
BE	12- 30	-	-	-	1.18	0.07	17	4.4	3.8	2.04	0.03	0.04	0.01	0	1.11	0.80	1.19	93
Bh1	30- 60	86.6	5.1	8.0	0.29	0.03	10	4.8	4.0	1.52	0.03	0.08	0	0.01	0.86	0.12	0.98	88
Bh2	60- 75	88.9	2.6	7.8	0.49	0.03	16	5.0	4.2	1.30	0.01	0.06	0.01	0.03	0.90	0.10	1.00	90
Bg	75- 85	95.9	1.1	2.5	0.07	0.02	4	5.4	4.4	0.34	0.03	0.06	0	0.03	0.10	0.12	0.22	46

(continued)

Horizon	Depth (cm)	K total	P total	P-Bray I	Bulk density (kg/l)	pF 1	pF 1.5	pF 2	pF 3.4	pF 4.2	pF 2-4.2	Pores	Air at pF 1	Air at pF 2
		ppm				vol %								
AE1	0- 3	76	78	2.6	1.10	41.8	20.7	12.9	8.1	4.4	8.5	58.5	16.7	45.5
AE2	3- 12	72	36	1.1	1.22	42.7	20.1	11.7	6.6	3.4	8.3	54.0	11.3	42.3
BE	12- 30	84	60	1.7	1.54	41.6	30.8	20.1	11.2	6.2	13.9	41.9	0.3	21.8
Bh1	30- 60	133	237	0.3	1.66	33.5	26.8	18.8	9.8	7.8	11.0	37.4	3.9	18.6
Bh2	60- 75	80	64	6.0	1.64	34.7	27.1	13.4	7.9	5.9	7.5	38.1	3.4	24.7
Bg	75- 85	38	14	1.5										

Profile 27

(Boring) (representative for map unit H)

Information on the site

Location: Kabo area, Suriname, LH/UvS 01 project area Tonka creek, hydrological experiment 78/34, line 0, 350 m east of Central Line; coordinates 5°15′ N, 55°43′ W.
Described by M. van Leeuwen in September 1982.
Elevation: approximately 18 m above mean sea level.
Physiographic position of the site: swampy valley bottom near creek.
Landform of surrounding country: undulating.
Microtopography: even.
Slope: almost flat (<1%).
Vegetation: swamp forest.
Climate: see Profile 11.

General information of the soil

Parent material: Sandy sediment, probably deposited in the Holocene, derived from Zanderij sediment of surrounding slopes.
External drainage: very slow.
Internal drainage: fast.
Drainage class: poorly to very poorly drained
Moisture condition of the profile: wet throughout.
Depth of groundwater table: at or near the surface mostly all year around; in very dry years the ground water table can drop to about 1 m depth for one or two months. Depth of gley/pseudogley: subsoil is not mottled, probably because iron content of the pure quartz sand is too low.
Presence of surface stones/rock outcrops: none.
Evidence of erosion: none.
Presence of salt or alkali: none
Human influence: none.
Map unit: H, poorly and very poorly drained gray soils, mostly of a sandy texture, often having a thin peaty layer on top and rarely with clayey texture within 120 cm depth.

Brief description of the profile

Poorly drained gray sandy profile with a peaty layer of 20 cm thickness on top.

computed as negative rainfall. They could have three causes: the, mostly weekly, emptying of the reservoir; evaporation from the reservoir; and possible errors in the data. The cause of each decrease was established and occurring errors were corrected. All highest levels before and all lowest levels after emptying were also checked with the field book. Evaporation from the reservoir occurred only during sunny rainless periods and then only in very small

TABLE IV.1: Monthly rainfall data, evaporation of Class A Pan (EPan) at Kabo and discharges from the catchment

Month	Rainfall* (mm)				EPan	Discharge **	Month	Rainfall* (mm)				EPan	Discharge **
	A	B	C	D	(mm)	(mm)		A	B	C	D	(mm)	(mm)
1179		(95)			(144)	0	0482	394	402	396	336	99	165
1279		(165)			(115)	0	0582	311	319	320	319	105	194
0180		(144)			(108)	0	0682	245	252	254	257	107	147
0280		(27)			(98)	0	0782	246	252	247	277	133	117
0380		(203)		195	(105)	0	0882	103	108	107	126	153	67
0480		(244)		244	99	0	0982	72	75	74	86	172	29
0580		(266)		266	99	19	1082	29	32	32	35	173	10
0680		(339)		339	106	106	1182	50	54	51	78	155	0
0780		(156)		156	127	84	1282	126	132	132	128	120	1
0880		(195)		195	152	61	0183	135	140	146	158	103	6
0980		(64)		64	176	20	0283	138	144	151	168	94	2
1080		(71)		71	153	5	0383	166	173	178	161	105	7
1180	183	189		211	131	6	0483	405	413	405	401	86	63
1280	104	108		133	115	6	0583	265	273	279	266	103	97
0181	111	116		90	120	6	0683	166	173	174	151	119	68
0281	322	328		320	84	27	0783	62	67	73	85	137	34
0381	141	145		138	153	49	0883	78	83	83	78	169	13
0481	317	324	332	403	116	57	0983	75	79	80	83	161	4
0581	348	356	356	305	109	97	1083	61	63	60	29	189	0
0681	241	249	252	268	108	124	1183	55	58	59	74	154	0
0781	211	218	223	238	130	92	1283	188	194	226	160	112	0
0881	169	174	175	168	154	63	0184	157	164	166	156	103	0
0981	60	63	62	82	166	37	0284	74	77	78	88	124	0
1081	193	196	191	170	168	37	0384	62	65	69	80	143	0
1181	76	80	77	55	137	12	0484	167	171	171	177	124	0
1281	219	227	226	234	111	24	0584	366	372	376		102	18
0182	152	158	159	174	106	24	0684	317	325	332		111	62
0282	157	164	161	184	89	27	0784	261	269	270		133	95
0382	278	285	288	300	95	46							

(   ) estimated values.

* A: Data from rainfall gauge Recover, operated from November 1980

B: Corrected Recover data

C: Data from rainfall gauge Hand Tonka

D: Data from rainfall gauge Hand Kabo.

** Measured discharges from the catchment including leakage losses.

amounts. On very dry days water-levels could drop by 1 or 2 mm. As these water-level decreases were not counted as negative rainfall, this evaporation is not a cause of errors.

For the hydrological model, rainfall data (from the RECOVER gauge), and discharge data were totalled into daily figures, days running from 0.00 hours to 24.00 hours. The hand operated rain-meters, however, give daily totals which run from one measurement to the next. Measurement was mostly done around 08.00 hours. The measured amount at 08.00 hours on day x is the amount contributed to day x-1. On days with rainfall between 0.00 hours and measurement time, the amounts of RECOVER and Hand Tonka do not agree. As the rain generally falls in convective showers, which have a peak occurrence at about 16.00 hours, the period from midnight to measurement time is usually dry. This made a comparison between RECOVER and Hand Tonka possible for most days.

Comparison rainfall data for Hand Tonka and RECOVER
For days with no rain in the morning, the RECOVER values are generally lower than Hand Tonka. When the Hand Tonka recorded very low rainfall, often no rain was recorded in RECOVER. For days on which Hand Tonka registered rain, RECOVER recorded on average 0.28 mm less. The difference is attributed to evaporation from the large funnel of the RECOVER, the surface of which was not completely smooth. Thus, for the days on which Hand Tonka registered rain, the amounts recorded by RECOVER were increased by 0.28 mm. These corrected RECOVER values were used in the hydrological models. Monthly data of rainfall, evaporation (Class A Pan) and creek discharge including leakage losses are given in Table IV.1.

Total annual (1 November-31 October) rainfall, evaporation and discharge data for the period 1979-1984 are given in Table IV.2. The years studied were quite

TABLE IV.2: Total annual rainfall, evaporation of Class A Pan at Kabo and discharges from the catchment

Year (1 Nov-31 Oct)	Rainfall* (mm)				Evaporation Class A Pan (mm)	Discharge* (mm)
	A	B	C	D		
1979/80		(1976)			(1482)	(295)
1980/81	2400	2466		2526	1554	601
1981/82	2282	2354	2341	2383	1480	862
1982/83	1727	1794	1812	1786	1541	295
1983/84**	(1647)	(1695)	(1747)		(1106)	(175)
Mean	2136	2205	(2077)	2232	1525	586

( )estimated values.
* see Table IV.1.
** *9 months* only.

different, the rainfall varying from 1794 to 2466 mm and discharges from 295 to 862 mm. The agreement between B: RECOVER corrected and C: Hand Tonka is good (difference $< 3\%$).

IV.2 Discharge and leakage losses

Dam and measuring weir

Discharge was measured with a sharp-crested triangular weir, commonly called a V-notch or Thomson weir. Initially, the vertex of the V-notch, that is the lowest point of the V-shape, was 60 cm above the creek bottom ($p = 0.6$ m).

In November 1980, the thin aluminium strips were removed because they were too thin and therefore bent too easily. The opening of the weir was lowered by sawing a new V-shape 0.21 m below the old opening. After that a rigid aluminium plate in one piece, 3 mm thick sharpened at the rim to 2 mm was nailed to the upstream side of the wooden planks which formed the V-shape. As a result of this lowering, there was less danger of downstream erosion by a smaller force of the falling water, a smaller lake in front of the weir, and less leakage through the sandy underground. Still the weir remained high enough to avoid submergence in wet periods. The creek bottom was lowered about 10 cm after which the distance between the vertex and the creek bottom (p) became 0.5 m instead of 0.6 m as it was before November 1980. This change influences slightly the discharge equation for high discharges. The weir has a maximum overflow height of 1 m with a resulting Qmax of about 1.4 m^3/s.

Measuring of water head

The discharge is calculated from the water head, that is the height of the water above the vertex or the overflow height, which was recorded at 15 minutes interval with a Fisher and Porter digital recorder (van Walsum, 1980). The water-level is transferred from a float in a stilling well with a metal band to the recorder. The stilling well is situated 4 m upstream of the weir. Readings are given in millimetres. Calibration is necessary to determine the reading of the recorder when h is zero. The water-level is then just at the vertex of the V-notch. Calibration has been carried out at intervals of about one year according to the method given by Pitlo (1969). The records, consisting of a roll with punched holes, were taken once in every few months from the recorder and transferred manually to lists from which they were entered on computer disk.

Measuring of leakage losses

Leakage losses were determined on four occasions: on 5 November 1980 in the old situation ($p = 0.6$ m), and on 29 September, 5 October and 6 October 1983 in the new situation with the apex 21 cm lower and p equal to 0.50 m. In wet years leakage losses could not be measured. Leakage losses were determined in the creek bed 23 m behind the weir by collecting the flow in buckets without changing the water-level of the flow. At this point it can be assumed that all leakage passes the creek bed, except the flow that occurs underground in the fine to medium sandy subsoil. Because of the high resistance, these underground flows are considered to be negligible compared with the creek bed flow. The measured flows were as follows:

5 November 1980 : 0.2376 l/s ($h = -0.091$m)
29 September 1983 : 0.1954 l/s ($h = -0.052$m)
5 October 1983 : 0.07843 l/s ($h = -0.161$m)
6 October 1983 : 0.03197 l/s ($h = -0.227$m)

The measured leakage losses are shown in Fig. IV.1. Assuming that Darcy's law applies (linear relationship between water head and laminar flow), which is reasonable for water flow through soil layers, the leakage losses for the period after November 1980 follow the line through the three observation points. For the period after 12 November 1980 the leakage losses become zero when $h < -0.25$ m and the water-level is 0.25 m above the creek bottom. The relationship between Q and h is:

$$Q = 0.98\,h + 0.245 \qquad \text{l/s (h in m)} \qquad \text{(IV.1)}$$

For the period before 12 November 1980 there is only one observation. Assuming

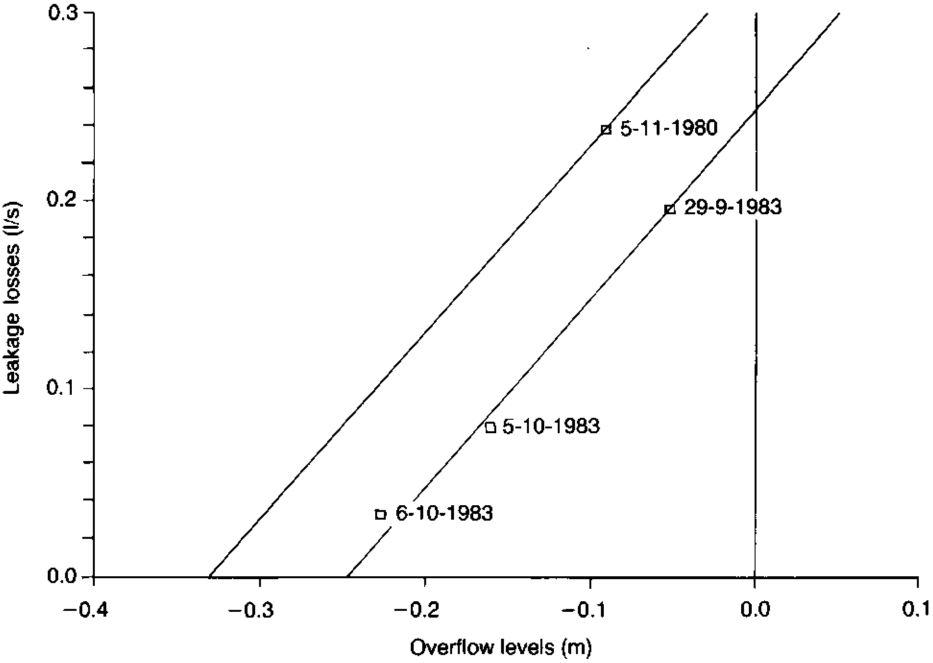

Fig. IV.1 Relationship between leakage losses (l/s) under and through dam and weir, and overflow levels (m).

the same steepness of the relationship between h and Q, the equation for this period is:

$$Q = 0.98\,h + 0.326 \qquad \text{l/s (h in m)} \qquad \text{(IV.2)}$$

Before November 1980 leakage stops at a water-level of 0.33 m below the vertex or 0.27 m above the creek bottom. This means that the creek bottom and the deeper subsoil contribute very little to the leakage, but that leakage occurs above ground level, through the dam and through the weir. Leakage losses for selected overflow levels calculated from Fig. IV.1 are given in Table IV.3. In the old situation when the apex was 0.60 m above the creek bottom, the leakage losses were higher than in the new situation, after 12 November 1980, when the apex was 0.50 m above the creek bottom. At the same overflow level leakage losses are 0.08 l/s lower after 12 November 1980 than before that date.

Leakage losses were relatively low. The average annual discharge was 586 mm (Table IV.2) corresponding to an average discharge of 55 l/s. At an overflow level of 27.5 cm, which produced a discharge of 55 l/s, leakage was 0.51 l/s. Thus leakage was about 1 % of the discharge. This calculation is approximate, as weir discharges do not have a linear dependence on the overflow level. However, it remains valid for the bulk of the discharges, which occur at overflow levels between 20 and 30 cm. In calculation of discharges, correction for leakage losses was made for each 15 minutes period, depending on the overflow level. The resulting leakage was added

TABLE IV.3: Leakage losses for selected overflow levels

Overflow levels (m)	Leakage losses (l/s)	
	Before 12-11-1980	After 12-11-1980
-0.40	0.000	0.000
-0.30	0.032	0.000
-0.20	0.130	0.049
-0.10	0.228	0.147
0	0.326	0.245
0.10	0.424	0.343
0.20	0.522	0.441
0.30	0.620	0.539
0.40	0.718	0.637
0.50	0.816	0.735
0.60	0.914	0.833
0.70	1.012	0.931
0.80	1.110	1.029
0.90	1.208	1.127
1.00	1.306	1.225

to the discharge over the weir for the same period. Weir discharge and leakage were totalled per day and then used for water balance calculations.

IV.3 Determination of the size of the catchment area by topographic survey

A topographic survey was carried out of the catchment area and surroundings. From the resulting contour map the boundaries of the catchment were constructed. First a system of main lines was cut by slashing the undergrowth for a width of about 2 m along a straight compass line. Wooden pickets were then placed at regular intervals. A few large trees which were exactly on the main lines had to be cut down. The main line system consisted of three north-south lines, 500 m apart, of which the central line runs over the dam (Fig. 3.4); and also three east-west lines, 1200 m apart.

Subsequently, a sub-line system was made of smaller lines in the undergrowth. Hereby no large trees were cut down. They are 100 m apart, lying in east-west direction (see Fig. 3.4). Some lines in the western part of the area follow the boundaries of a silvicultural experiment on natural forest regeneration (Exp. 78/5).

The main line system and the sub-line system were surveyed with the aid of theodolite and levelling instrument (van Walsum, 1980; Oliemans, 1982; and Boer, 1982). Observations were made at intervals of 25 m and on almost level areas sometimes at 50 m intervals. Extra observations were made, for instance at valley boundaries, creek beds and the highest points of a water divide. Cross-sections of all lines were made at a horizontal scale of 1:5000 and a vertical scale of 1:100.

From these cross-sections a contour map was constructed (Fig. 3.4). The location of the water divide was drawn on the countour map after which the size of the catchment area was calculated. Extra lines were cut over the water divide to check its location. The area of the catchment, that is the size of the area that drains through the dam, was calculated to be 295 ha, 140 ha for the Eastern creek area and the area east of the main creek, after the confluence of both tributaries, and 155 ha for the Western creek area and the area west of the main creek after the same confluence.

However, the question remains whether the topographic water divide coincides with the hydrologic water divide, that is whether the highest point in the terrain separates the flows of water into the creeks. Oblique impermeable layers in the subsoil may separate the topographic and hydrologic water divides and areas with deep permeable layers could receive water from or loose water to neighbouring catchments. The deep borings indicate that topographic and hydrologic water divides coincide, because generally sandy and loamy permeable top layers gradually merge into a more impermeable, clayey substratum.

IV.4 Measurement of groundwater levels in deep borings

In the project area 18 deep borings, to a depth of 7.5 m, were made with a hand operated auger set. Firstly, a hole was made with an open blade auger of 7 cm diameter. Other implements were used if necessary, such as auger heads for stony soils and thick spiral wire to break through cemented layers.

The first measurements of groundwater depth were taken in the unprotected holes but later the holes were protected with perforated plastic pipes after having been widened and restored to a depth of 7.5 m with auger heads of 11 cm diameter. Plastic pipes, 4 m long, outer diameter of 11 cm, were perforated with 0.5 cm holes about 20 cm apart. Two pipes were joined by widening one side of a pipe by heating and then the other pipe was inserted about 10 cm. The resulting pipe of almost 8 m length was placed in the hole with its upper end about 40 cm above the surface.

The pipes were covered with a plastic bag to prevent particles from falling into the holes. The upper meter of the 8 m long pipes was not perforated, also to prevent the entrance of particles. This appeared to be of value at one location (boring no. 3) where, because of artesian conditions, water-levels above the soil surface were recorded. Here the water head of the deeper groundwater was well above the dry soil surface.

One borehole was made in June 1981, 15 in June and July 1982 and two in September 1982. Regular recording started on 25 August 1982 and continued until 10 August 1984. The water-levels were measured with a chain and sounder generally once a week. Deepening of the holes and placing of the protecting plastic pipes was done in December 1982. In July and August 1983 the holes were cleaned again. Groundwater samples from the holes were taken twice for chemical analysis, on 1 June and on 16-17 August 1983. On 16-17 August 1983 also estimations of hydraulic conductivity of soil layers below the groundwater table were made by recording the rate of the rise of the water-table in the holes after taking out part of the water.

IV.5 The measurement of hydraulic conductivity

The hydraulic conductivities of the soil layers below the groundwater table to the bottom of the boreholes were measured on 16 and 17 August 1983 using the Hooghoudt method (van Beers, 1958). The rise of the groundwater table was measured with the same chain and sounder used to measure the weekly groundwater levels.

The accuracy of the measurements was affected by the long period of time needed for every measurement, water-levels being often more than 5 m deep. Generally, one observation per minute was made and the first observation about 3.5 minutes after the start of bailing. A second complication was the varying width of the boreholes. The sandier the soil the more vulnerable the walls were to collapse particularly before the plastic pipes were installed. After several cleanings of the boreholes with bailers, the original depths were restored but varying hole diameters remained. To determine the diameter the number of bailers taken out was recorded and the volume of one bailer was established.

The water depth was measured, then a number of bailers full of water were removed and the water depth was measured again every minute for a period of 10 to 20 minutes. Then the depth of the hole was measured.

To calculate the hydraulic conductivity, the logarithm of the drawdown of the groundwater table was plotted against time. In most cases a linear relationship was found and a straight line could be drawn through the points until t=0, the moment of bailing. At the intersection y_0 can be read, the maximum drawdown just after bailing. The graph for deep boring no. 3 is given in Fig. 3.6.

From the y_0 and the volume of water bailed out, the radius r of the hole over the distance y_0 is calculated. If the slope of ln y against time changes with time, then the line is drawn through the first, generally steepest, part of the points. In one case, borehole no. 5, the curve through the points changes very suddenly in steepness during the measurements. This can be attributed to a changing borehole diameter encountered by the rising water-table or to a sudden collapse of the borehole wall.

Values on the best fit line through the points were chosen to calculate the hydraulic conductivity rather than the measured values. As much as possible the condition was respected, that for analysis only the period in which y remains larger than 3/4 y_0 is considered.

The Nomogram of Hooghoudt-Ernst for the impermeable layer at great depth (van Beers, 1958) was used if possible to calculate the conductivity. To use this nomogram which is made for a borehole diameter of 4 cm, both H (initial water depth in borehole) and y are adapted to the calculated radius r. H corrected equals H multiplied by 4/(borehole diameter), y corrected equals y multiplied by 4/(borehole diameter). When the adapted H or y falls outside the reach of the nomogram the conductivity is calculated with the equation of Ernst (van Beers, 1958)

$$K = \frac{4000\ r^2}{(H + 20r)(2 - y/H)y} \frac{dy}{dt} \qquad \text{(IV.3)}$$

In Fig. 3.6 a line is drawn through the first 4 points, the observation points from 3.5 to 6.5 minutes after the start of bailing. The curve through later points flattens out, indicating loss of hydraulic head. The latter part is therefore not usable for conductivity determination. Extension of the line to t = 0 minutes gives ln y_0 = 6.21 and y_0 = 498 cm. Ten bailers were taken out corresponding with 20 600 cm^3 water. This combined with a y_0 of 498 cm gives a borehole radius of 3.63 cm. H, the water depth in the borehole before bailing, is 366 cm. Because of this large depth the Nomogram of Hooghoudt-Ernst cannot be used. The conductivity is therefore calculated with the equation of Ernst. Calculation had to be done before y has reached 3/4 y_0 or 373 cm. This is shortly after one minute. With y = 411 cm after 45 sec and y = 361 cm after 75 sec a K-factor of 0.54 m/day is calculated.

IV.6 Air and water in a representative soil profile

Physical and chemical properties of the soils of the Kabo area were determined on 28 soil profiles. Bulk density, total pore space and moisture contents at pF values 1, 1.5, 2 and 2.7 were determined from undisturbed core samples of 100 ml. Moisture content at pF values 1, 1.5 and 2 was determined on fine sand boxes to which suction was applied. Moisture contents at pF 2.7 were also determined on such boxes whereby the fine sand was covered with a thin layer of kaoline. This was done for only eight profiles. Two to four soil cores were taken from every soil horizon for these analyses. Moisture contents at pF 3.5 and pF 4.2 were determined with a pressure membrame apparatus for all horizons of all profiles. For these analyses bulk samples were used instead of core samples.

An average pF profile was made for the most common soil unit, that is the well to moderately well drained sandy clay loam soil of the plateaus and the upper slopes. Of the 28 profiles, 13 belong to this category. The equations describing this average pF profile are given in Table IV.4. From Table IV.4 the values in Table 3.3 were calculated.

Variations of moisture contents with depth, at a given pF-value, appear to change rapidly in the topsoil but more gradually in the subsoil. For the higher pF values there is a constant increase in moisture content with depth along with the increase in clay content. For the lower pF values the relationship with depth is more complicated because not only clay content, but also organic matter content, structure and bulk density become important. For pF 2, moisture contents increase up to about 60 cm depth and remain constant deeper in the profile. For pF 1 there is a decrease over the whole depth and for pF 1.5 an initial increase is followed by a decrease going from topsoil to subsoil.

TABLE IV.4: Mean relationship between porosity (Y; vol %) and depth (X; cm), and relationship between moisture content at different soil suctions (Z; vol %) and depth (X; cm), for loamy plateau soils under forest at Kabo

Soil suction	Profile section	
	0-35 cm	35-300 cm
pF -oo (total porosity)	$Y = 59.7 - 4.24 \ln X$	$Y = 42.2 + 0.714 \ln X$
pF 1	$Z = 42.0 - 2.03 \ln X$	$Z = 39.6 - 1.27 \ln X$
pF 1.5	$Z = 28.2 + 0.504 \ln X$	$Z = 31.4 - 0.340 \ln X$
pF 2	$Z = 18.7 + 1.42 \ln X$	$Z = 24.1 + 0.0476 \ln X$
pF 2.7	$Z = 12.5 X^{0.0838}$	$Z = 14.9 + 0.624 \ln X$
pF 3.5	$Z = 7.21 X^{0.204}$	$Z = 11.5 X^{0.0753}$
pF 4.2	$Z = 5.15 X^{0.240}$	$Z = 7.59 + 1.41 \ln X$

APPENDIX V: DETERMINATION OF THE DISCHARGE EQUATION

In Bos (1976) the following equation is given to calculate the discharge of a sharp crested triangular weir:

$$Q = Ce \times 8/15 \times (2g)^{0.5} \times \tan a/2 \times h_e^{2.5}\ \mathrm{m^3/s} \qquad \text{(V.1)}$$

where

Q	: discharge	(m^3s^{-1})
g	: gravitational acceleration	(ms^{-2})
h_e	: effective upstream head over crest (h+Kh)	(m)
h	: water head	(m)
Kh	: head coefficient	(m)
Ce	: coefficient of discharge	–
a	: weir notch angle	(°)
p	: water depth in front of weir when h = 0	(m)
B	: channel width	(m)

The classification and the limits of application for such a weir are given in Table V.1. Difficulties were encountered in establishing values of some factors, especially Ce and g.

Bos (1976, Table 5.4) gives discharges resulting from overflow levels (h, water heads) between 0.05 and 0.38 m. The table, which is assumed to give the most accurate discharges at given h, has two disadvantages. Firstly the tabulated format is difficult for a computer to read, and secondly no values for discharges at heads below 0.05 and above 0.38 m are given.

Further, discharges calculated with the equation did not agree with those given in the table. It was difficult to establish values for Ce. The International Organization for Standardization (ISO, 1980) gives the same table as Bos (1976) but also includes values of Ce. These two tables are summarized in Table V.2.

In the subsequent sections, equations to calculate Ce are developed and the value of g for the experiment area is discussed.

V.1. The Coefficient of discharge: Ce

There are a number of simple discharge equations for a thin-plate triangular weir with a weir notch angle of 90°, all of the form:

$$Q = c1 \times h^{c2} \qquad (V.2)$$

where h = overflow level (m)
Q = discharge (m^3/s)
c1, c2 are constants

In this equation different constants are used:

	c1	c2	
Cone (1916)	1.34	2.48	
Hydraulica Laboratorium (1966)	1.354	2.483	($h > 4$ cm)
Hydraulica Laboratorium (1966)	1.41	2.5	($h < 4$ cm)
Kraijenhoff and Pitlo (1977)	1.38	2.48	

When comparing discharges computed with one of these simple equations and experimentally determined discharges at given overflow level h, there are always discrepancies between the two with some or all values of h. The relationship between h and Q appears to be more complicated than it is in these simple equations. Equation V.1 contains two other variables, Ce and h_e, to improve the relationship between h and Q. Bos (1976) gives for Kh in $h_e = h + Kh$ the value 0.0008 m. Kh varies with the notch angle, the given value is for a angle of 90°. ISO (1980) gives for Kh a value of 0.00085 m, but it also uses the equation with $Kh = 0$ and $h_e = h$. However, in a given situation Kh is constant.

The value of Ce varies with the overflow level h. When assuming that $Kh = 0$, Ce is high at low heads, it decreases with increasing h to a minimum value, whereafter it increases again. For every assumed value of Kh, a new set of values for Ce is required to correct the relationship between h and Q. The Ce values have been determined experimentally. ISO (1980) gives a graph with values of Ce depending on h: the overflow level, p: the water depth in front of the weir if $h=0$, and B the channel width. For low values of h, Ce reaches a small and constant value of about

TABLE V.1: Classification and limits of application of V-notch sharp crested (thin plate) weirs

Partially contracted weir	Fully contracted weir
$h/p \leqslant 1.2$	$h/p \leqslant 0.4$
$h/B \leqslant 0.4$	$h/B \leqslant 0.2$
$0.05 < h \leqslant 0.6m$	$0.05 < h \leqslant 0.38$
$p \geqslant 0.1m$	$p \geqslant 0.45m$
$B \geqslant 0.6m$	$B \geqslant 0.9m$

Source: After ISO, 1971 in Bos, 1976

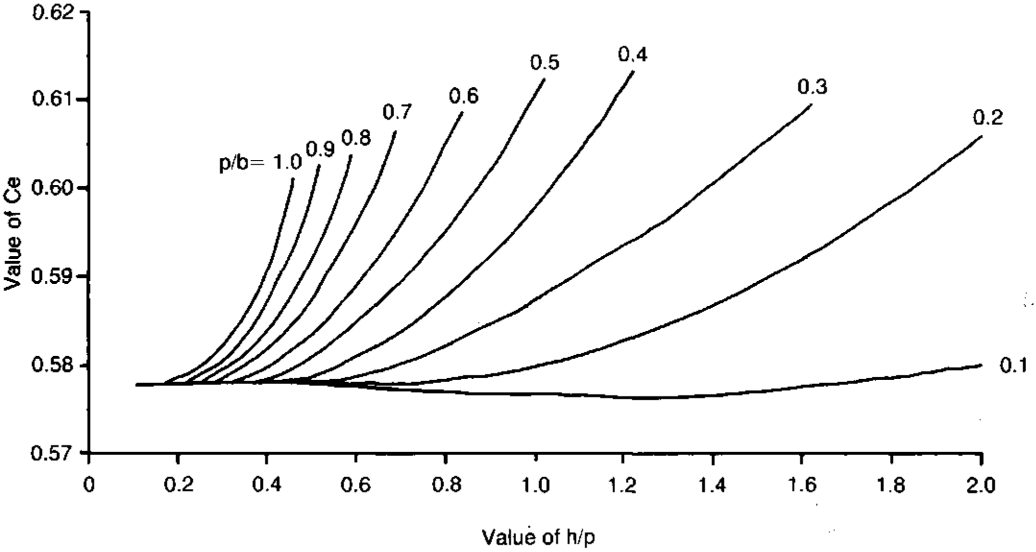

Fig. V.1 Coefficient of discharge Ce for a thin-plate triangular weir with a weir notch angle of 90° (Kh = 0.00085 m).
(After ISO, 1980)

0.578, when Kh is set at 0.00085 m. For higher values of h, Ce increases depending on p and B (Fig. V.1).

Bos (1976) distinguishes between a partially contracted and a fully contracted weir:

- partially contracted weir that is a weir, the contractions of which along the sides of the V-notch are not fully developed because of the proximity of the walls and/ or bed of the approach channel.
- fully contracted weir that is a weir which has an approach channel whose bed and sides are sufficiently remote from the edges of the V-notch to allow for a sufficiently great approach velocity component parrallel to the weir face so that the contraction is fully developed.

The limits of application of partially and fully contracted weirs are given in Table V.1. From this table it appears that a weir may be fully contracted at low heads while at increasing h it becomes partially contracted. In the case of p = 0.6 or 0.5 m, the weir is fully contracted till h = 0.24 or 0.20 m. For h between 0.24 and 0.72 m, respectively 0.20 and 0.60 m the weir is partially contracted, and for overflow levels of more than 0.72 and 0.60 m respectively, the weir is outside the limits of application. This applies also for overflow levels of less than 0.05 m.

In the fully contracted situation, Bos (1976) and ISO (1980) assume a low and

TABLE V.2: Water head, coefficient of discharge and discharges of water over a "V-notch" with tan a/2 = 1 and Kh = 0

Head (m)	Coefficient of discharge	Discharge (l/s)	Head (m)	Coefficient of discharge	Discharge (l/s)	Head (m)	Coefficient of discharge	Discharge (l/s)
0.050		0.803	0.165	0.5855	15.297	0.280	0.5847	57.306
0.055		1.015	0.170	0.5853	16.477	0.285	0.5847	59.899
0.060	0.6032	1.257	0.175	0.5851	17.709	0.290	0.5847	62.560
0.065	0.6012	1.530	0.180	0.5851	19.001	0.295	0.5848	65.303
0.070	0.5994	1.836	0.185	0.5850	20.345	0.300	0.5848	68.106
0.075	0.5978	2.176	0.190	0.5850	21.748	0.305	0.5848	70.980
0.080	0.5964	2.551	0.195	0.5849	23.203	0.310	0.5849	73.936
0.085	0.5950	2.961	0.200	0.5849	24.719	0.315	0.5849	76.954
0.090	0.5937	3.409	0.205	0.5848	26.288	0.320	0.5850	80.057
0.095	0.5927	3.895	0.210	0.5848	27.921	0.325	0.5850	83.222
0.100	0.5917	4.420	0.215	0.5847	29.607	0.330	0.5850	86.459
0.105	0.5906	4.985	0.220	0.5847	31.359	0.335	0.5850	89.772
0.110	0.5898	5.592	0.225	0.5846	33.168	0.340	0.5851	93.175
0.115	0.5891	6.242	0.230	0.5846	35.039	0.345	0.5851	96.638
0.120	0.5885	6.935	0.235	0.5846	36.974	0.350	0.5852	100.91
0.125	0.5880	7.673	0.240	0.5846	38.973	0.355	0.5852	103.81
0.130	0.5876	8.458	0.245	0.5846	41.034	0.360	0.5853	107.52
0.135	0.5872	9.289	0.250	0.5846	43.160	0.365	0.5853	111.30
0.140	0.5868	10.167	0.255	0.5846	45.350	0.370	0.5854	115.17
0.145	0.5865	11.093	0.260	0.5846	47.606	0.375	0.5855	119.11
0.150	0.5861	12.066	0.265	0.5846	49.928	0.380	0.5855	123.13
0.155	0.5859	13.093	0.270	0.5846	52.317			
0.160	0.5857	14.169	0.275	0.5846	54.772			

Source: ISO (1980, Table 1) and Bos (1976, Table 5.4)

constant value of Ce (about 0.578) and for a partially contracted situation the values of Ce as given in Fig. V.1.

Table V.2 gives a number of Ce values from ISO (1980) and also experimentally determined discharges. The given Ce values assume that Kh = 0, and that therefore the following equation applies:

$$Q = Ce \times 8/15 \times (2g)^{0.5} \times \tan(a/2) \times h^{2.5}\ \mathrm{m^3/s} \qquad (V.3)$$

The value for g, the gravity constant, is assumed here to be 9.8111. The fact that no head coefficient Kh was used in this equation is confusing. Values of Ce differ therefore from Ce values given in Fig V.1. The coefficient of discharge is lowest when h = 0.25 m.

Discharges calculated using various simple equations are compared with discharges determined experimentally in Table V.3. For low values of h (<0.20m), $Q = 1.34 \times h^{2.48}$ agrees best with the experimental values, while for higher values of h, $Q = 1.354 \times h^{2.483}$ agrees best. The latter can be used to illustrate that it is not possible to calculate the discharge accurately with a simple equation. In Table V.4, variable coefficients are given, but only with the introduction of a discharge coefficient dependent on h, can the discharge be calculated accurately. The lowest coefficient of discharge occurs at h = 0.15m.

The dimensions of the weir at Tonka are such that at higher discharges partially contracted flow occurs. The channel width B is 2.85 m. The water depth in front of the weir when h = 0 (p) was 0.60 m for the period between 15-4-1980 and 12-11-1980, after which p was 0.50 m. Before 12-11-1980 partially contracted flow with corresponding higher values of Ce (Fig V.1) occurred when h > 0.24 m; and after 12-11-1980 when h > 0.20 m.

TABLE V.3: Experimentally determined discharges (ISO, 1980; and Bos, 1976) and discharges calculated with a simple discharge equation (l/s)

Head (m)	Experiment. determined discharge	$Q = a \times h^b$				
		a = 1.4 b = 2.5	a = 1.34 b = 2.48	a = 1.354 b = 2.483	a = 1.41 b = 2.50	a = 1.38 b = 2.48
0.001		.000044	.000049	.000048	.000045	.000050
0.002		.000250	.000271	.000269	.000252	.000280
0.003		.000690	.000742	.000737	.000695	.000764
0.004		.00142	.00151	.00150	.00143	.00156
0.005		.00247	.00263	.00262	.00249	.00271
0.01		.01400	.01469	.01464	.01410	.01513
0.02		.0792	.0820	.0819	.0798	.0844
0.03		.2182	.2241	.2240	.2198	.2307
0.04		.448	.457	.458	.451	.471
0.05	.803	.783	.795	.796	.788	.819
0.10	4.420	4.427	4.437	4.453	4.459	4.570
0.15	12.066	12.200	12.129	12.186	12.287	12.491
0.20	24.719	25.044	24.755	24.893	25.223	25.494
0.25	43.160	43.750	43.052	43.322	44.063	44.337
0.30	68.106	69.013	67.665	68.126	69.506	69.685
0.35	100.19	101.46	99.173	99.894	102.19	102.13
0.40		141.67	138.11	139.17	142.68	142.23
0.45		190.18	184.96	186.44	191.54	190.48
0.50		247.49	240.19	242.19	249.26	247.36
0.55		314.08	304.23	306.86	316.32	313.31
0.60		390.40	377.50	380.86	393.19	388.77
0.65		476.88	460.39	464.60	480.29	474.14
0.70		573.95	553.28	558.47	578.05	569.80
0.75		682.00	656.53	662.82	686.87	676.13
0.80		801.41	770.49	778.02	807.13	793.49
0.85		932.56	895.50	904.41	939.22	922.23
0.90		1075.8	1031.9	1042.3	1083.5	1062.7
0.95		1231.5	1179.9	1192.1	1240.3	1215.2
1.00		1400.0	1340.0	1354.0	1410.0	1380.0

TABLE V.4: Variable coefficients of a simple discharge equation ($Q = a \times h^b$) for various values of h

Head (m)	Q measured (l/s)	a in $Q = a\ h^{2.483}$	b in $Q = 1.354h^b$	Ce in $Q = Ce\ 1.354h^{2.483}$
0.05	0.803	1.3651	2.480	1.0082
0.10	4.420	1.3441	2.486	0.9927
0.15	12.066	1.3407	2.488	0.9902
0.20	24.719	1.3445	2.487	0.9930
0.25	43.160	1.3490	2.486	0.9963
0.30	68.106	1.3536	2.483	0.9997
0.35	100.19	1.3580	2.480	1.0030
0.38	123.13	1.3607	2.478	1.0049

To obtain a correct discharge equation for the Tonka weir, the relationship between Ce and h for the situations p = 0.60 m and p = 0.50 m was established. The equation for Ce was deduced from Fig. V.1. When p = 0.60 m (before 12-11-1980) p/B is 0.211 and when p = 0.50 m (after 12-11-1980) p/B is 0.175. Table V.5

TABLE V.5: Coefficients of discharge for the lines p/B=0.211 and p/B=0.175 of Fig. V.1

h/p	p = 0.6 p/B = 0.211			p = 0.5 p/B = 0.175		
	h	Ce	Cé	h	Ce	Cé
0.1	0.06	0.5780	0.5780	0.05	0.5780	0.5780
0.2	0.12	0.5780	0.5780	0.10	0.5780	0.5780
0.3	0.18	0.5780	0.5780	0.15	0.5780	0.5780
0.4	0.24	0.5780	0.5780	0.20	0.5780	0.5780
0.5	0.30	0.5780	0.5780	0.25	0.5780	0.5780
0.6	0.36	0.5781	0.5781	0.30	0.5779	0.5779
0.7	0.42	0.5784	0.5784	0.35	0.5780	0.5780
0.8	0.48	0.5789	0.5790	0.40	0.5781	0.5782
0.9	0.54	0.5796	0.5798	0.45	0.5784	0.5786
1.0	0.60	0.5808	0.5808	0.50	0.5791	0.5792
1.1	0.66	0.5821	0.5822	0.55	0.5799	0.5800
1.2	0.72	0.5838	0.5838	0.60	0.5812	0.5811
1.3	0.78	0.5856	0.5858	0.65	0.5824	0.5824
1.4	0.84	0.5884	0.5880	0.70	0.5844	0.5839
1.5	0.90	0.5906	0.5905	0.75	0.5861	0.5857
1.6	0.96	0.5939	0.5933	0.80	0.5885	0.5878
1.7	1.02	0.5967	0.5964	0.85	0.5906	0.5901
1.8	1.08	0.5999	0.5999	0.90	0.5930	0.5926
1.9	1.14	0.6042	0.6036	0.95	0.5962	0.5955
2.0	1.20	0.6079	0.6077	1.00	0.5993	0.5986

gives values for Ce derived by interpolation from Fig. V.1 for the relationships between p and B. The lowest value for Ce is reached for values of $h = 0.30$ m and lower. Entering the Ce values for $h > 0.30$ m in the general equation

$$Ce - 0.5780 = a\,(h\text{-}0.30)^{b} \qquad \text{(V.4)}$$

gave as the best fit line for $p = 0.6$ m

$$Ce = 0.5780 + 0.03718\,|h\text{-}0.30|^{2.136} \qquad (R^2\text{=}1.00) \qquad \text{(V.5)}$$

and for $p = 0.5$ m

$$Ce = 0.5779 + 0.04531\,|h1\text{-}0.30|^{2.201} \qquad (R^2\text{=}0.99) \qquad \text{(V.6)}$$

With these equations Ce′ was calculated. When the Ce or Ce′ values of Table V.5 are used in Equation V.1, the resulting discharges are lower than the experimentally determined discharges given in Table V.2. Discharges calculated with this equation are given in Table V.6.

Assuming that the experimentally determined discharges given by Bos (1976) and ISO (1980) are correct, it was concluded that the values for Ce in Figure V.1, which were derived from ISO (1980; Fig 7) are too low at least in the range $0.05 < h < 0.38$ m.

TABLE V.6: Overflow levels, coefficients of discharge according to Fig. V.1 and calculated discharges (Kh = 0.00085 m) compared with experimentally determined discharges

Head (m)	p = 0.6m		p = 0.5m		Experimentally determined discharge (l/s)
	Ce'	Q(l/s)	Ce'	Q(l/s)	
0.05	0.5780	0.796	0.5780	0.796	0.803
0.10	0.5780	4.411	0.5780	4.411	4.420
0.15	0.5780	12.069	0.5780	12.069	12.066
0.20	0.5780	24.688	0.5780	24.688	24.719
0.25	0.5780	43.036	0.5780	43.036	43.160
0.30	0.5780	67.791	0.5779	67.780	68.106
0.35	0.5781	99.581	0.5780	99.564	100.19
0.38	0.5782	122.27	0.5781	122.25	123.13
0.40	0.5783	138.99	0.5782	138.96	
0.45	0.5786	186.57	0.5786	186.57	
0.50	0.5792	242.92	0.5792	242.92	
0.60	0.5808	383.98	0.5811	384.18	
0.70	0.5833	566.67	0.5839	567.25	
0.80	0.5865	795.28	0.5878	797.04	
0.90	0.5905	1074.5	0.5926	1078.4	
1.00	0.5954	1409.6	0.5986	1417.2	

The differences between the calculated discharges and the experimentally determined discharges are small (< 1 %). They are, however, in the wrong direction. The calculated discharges should be higher and not lower, especially at the higher overflow levels. A fully contracted situation is assumed for the experimental discharges (Table V.2). In reality a partially contracted situation exist whereby the increasing influence of sides and bottom is reflected in increasing values of Ce at higher overflow levels (partially contracted flow if $h > 0.24$ m, resp $h > 0.20$ m).

In ISO (1980), the statement that in the fully contracted situation, Ce depends on the weir notch only and the influence of h/p and p/B is negligible, contradicts Table V.2, which gives the fully contracted situation where Ce varies over the whole range of h. ISO (1980) also states that in the discharge equation a Kh of 0.00085 m should be used while Bos (1976) gives Kh a value of 0.0008 m, and then gives Ce values for a discharge equation with Kh = 0. These values are shown in Table V.2.

The following procedure was taken to obtain correct values of Ce. For $0.05 < h < 0.38$ m the Ce values of Table V.2 were assumed to be correct, and for $h > 0.38$ m the Ce values of Table V.5 were assumed to be correct. An attempt was made to develop equations for the relationship between h and Ce. No satisfactory equation could be developed for the data in Table V.2 (Kh = 0). The Ce values in Table V.2 were then changed to give the same Q in discharge equations with Kh = 0.0008 and Kh = 0.00085 m. The best relationship between h and Ce was obtained when a Kh equal to 0.0008 m was used in the discharge equation. This gave generally lower Ce values and the lowest Ce value at an overflow level h of 0.15 m instead of 0.30 m. Four Ce equations were necessary: for $h \leqslant 0.08$ m, $0.08 < h < 0.15$ m, $0.15 \leqslant h < 0.19$ m and for $h \geqslant 0.19$ m.

For $h \geqslant 0.19$ m the influence of the partially contracted situation was introduced as follows. For the period before 12-11-1980 (p = 0.60 m) the value of Ce = 0.5967 for h = 1.02 m was added before computing the Ce equation and for the period after 12-11-1980 (p = 0.50 m) the value of Ce = 0.5993 for h = 1.00 m, derived from Fig V.1 and Table V.5, was added. Because of the smaller p the influence of the bottom of the approach channel is stronger after 12-11-1980. This is reflected in the higher value of Ce (less contracted). By introducing these extra Ce values the difference is brought into the equations.

The reliability of the high Ce values in Fig. V.1 is not known. No large differences are expected between them and the exact Ce values because also for the lower overflow levels the differences of Ce values from Fig. V.1 and from Table V.2 were only small. The discharge equation is given below together with five equations to calculate Ce

$$Q = Ce \times 2.35877 \times (h+0.0008)^{2.5} \quad \mathrm{m^3s^{-1}}\ (h>0) \qquad (V.7)$$

$$Ce = 0.57835 + 0.2226\,|h-0.15|^{1.56} \quad \text{for } h \leqslant 0.08\text{m} \qquad (V.8)$$
$$Ce = 0.57835 + 8.423\times10^{-5} \times e^{57.14|h-0.15|} \quad \text{for } 0.08<h<0.15\text{m} \qquad (V.9)$$
$$Ce = 0.57835 + 4.034\times10^{-5} \times e^{63.61|h-0.15|} \quad \text{for } 0.15 \leqslant h<0.19\text{m} \qquad (V.10)$$
$$Ce = 0.57835+0.02178\times|h-0.15|^{1.134} \quad \text{for } h \geqslant 0.19\text{m (before 12-11-80)} \qquad (V.11)$$
$$Ce = 0.57835+0.02402\times|h-0.15|^{1.176} \quad \text{for } h \geqslant 0.19\text{m (after 12-11-80)} \qquad (V.12)$$

These equations do not give the same discharges as are given in Table V.2, because the gravity factor g is smaller at Tonka than assumed in Table V.2. In Table V.2,

TABLE V.7: Coefficients of discharge (Ce), calculated from experimental discharges at full contraction, calculated coefficients (Ce') for the fully and partially contracted situation and calculated discharges (Q) for selected overflow levels (Kh = 0.0008 m, g = 9.78 m/s²)

Head (m)	|h-0.15|	Ce (fully contracted)	Ce-0.57835	Ce' before 12-11-80	Ce' after 12-11-80	Q (l/s) before 12-11-80	Q (l/s) after 12-11-80
0.05	0.10	0.58437	0.00602	0.58448	0.58448	0.802	0.802
0.06	0.09	0.58372	0.00537	0.58355	0.58355	1.255	1.255
0.07	0.08	0.58266	0.00431	0.58268	0.58268	1.833	1.833
0.08	0.07	0.58185	0.00350	0.58186	0.58186	2.547	2.547
0.09	0.06	0.58082	0.00247	0.58095	0.58095	3.404	3.404
0.10	0.05	0.57996	0.00161	0.57982	0.57982	4.412	4.412
0.11	0.04	0.57922	0.00087	0.57918	0.57918	5.583	5.583
0.12	0.03	0.57877	0.00042	0.57882	0.57882	6.925	6.925
0.13	0.02	0.57860	0.00025	0.57861	0.57861	8.445	8.445
0.14	0.01	0.57851	0.00016	0.57850	0.57850	10.151	10.151
0.15	0.00	0.57835	0.00000	0.57839	0.57839	12.048	12.048
0.155	0.005	0.57843	0.00008	0.57841	0.57841	13.072	13.072
0.16	0.01	0.57843	0.00008	0.57843	0.57843	14.146	14.146
0.165	0.015	0.57846	0.00011	0.57845	0.57845	15.273	15.273
0.17	0.02	0.57848	0.00013	0.57849	0.57849	16.451	16.451
0.175	0.025	0.57846	0.00011	0.57855	0.57855	17.684	17.684
0.18	0.03	0.57864	0.00029	0.57862	0.57862	18.970	18.970
0.185	0.035	0.57872	0.00037	0.57872	0.57872	20.313	20.313
0.19	0.04	0.57890	0.00055	0.57892	0.57890	21.714	21.714
0.20	0.05	0.57909	0.00074	0.57908	0.57906	24.679	24.678
0.22	0.07	0.57942	0.00107	0.57942	0.57940	31.309	31.309
0.24	0.09	0.57976	0.00141	0.57977	0.57977	38.912	38.912
0.26	0.11	0.58012	0.00177	0.58013	0.58014	47.532	47.532
0.28	0.13	0.58054	0.00219	0.58050	0.58053	57.212	57.214
0.30	0.15	0.58092	0.00257	0.58088	0.58093	67.994	67.999
0.32	0.17	0.58136	0.00301	0.58127	0.58134	79.919	79.928
0.34	0.19	0.58167	0.00332	0.58166	0.58176	93.026	93.041
0.36	0.21	0.58203	0.00368	0.58206	0.58218	107.35	107.38
0.38	0.23	0.58243	0.00408	0.58246	0.58262	122.94	122.97
1.00	0.85	(0.59930)	0.02095	0.59646	0.59819	1409.7	1413.8
1.02	0.87	(0.59670)	0.01835	0.59695	0.59874	1482.4	1486.9

TABLE V.8: Discharges, calculated with different equations and experimentally determined discharges ($g=9.8111 ms^{-2}$)

Head (m)	Experimentally determined discharge (l/s)	Discharges (l/s) calculated with		
		$Q=1.354h^{2.483}$	Fig.V.1 (p = 0.5m)	Equations 7-12 (p = 0.5m)
0.001		0.000048	0.000201	0.000192
0.005		0.00262	0.00357	0.00357
0.01		0.01464	0.01674	0.01686
0.05	0.803	0.796	0.796	0.803
0.10	4.420	4.453	4.411	4.419
0.15	12.066	12.186	12.069	12.067
0.20	24.719	24.893	24.688	24.717
0.25	43.160	43.322	43.036	43.160
0.30	68.106	68.126	67.780	68.107
0.35	100.19	99.894	99.564	100.21
0.38	123.13	122.52	122.25	123.17
0.40		139.17	138.96	140.09
0.45		186.44	186.57	188.31
0.50		242.19	242.92	245.44
0.60		380.86	384.18	388.49
0.70		558.47	567.25	573.31
0.80		778.02	797.04	803.72
0.90		1042.3	1078.4	1083.4
1.00		1354.0	1417.2	1416.1

$8/15 \times (2g)^{0.5} = 2.3625$ or $g = 9.8111$. At Tonka $g = 9.78$ (Appendix V.2) and therefore $8/15 \times (2g)^{0.5} = 2.359$.

Ce values and discharges for the periods before and after 12-11-1980 are given in Table V.7 .

Discharges calculated with various equations are compared with the experimental discharges in Table V.8. The discharges computed with Equations V.7 to V.12 agree very well with the experimental values. At overflow levels above 0.30 m these calculated discharges begin to exceed the experimental discharges because of the effect of sides and bottom (partially contracted flow).

At low levels of h, there is good agreement between the discharges calculated with Fig. V.1 and with Equations V.7 to V.12 in spite of the fixed Ce according to Fig.V.1 and the increasing Ce by decreasing h according to Equation V.8. This agreement is caused by the difference in Kh being 0.00085 and 0.0008m respectively.

Thus it may be concluded that:

- a discharge coefficient Ce is necessary to compute the discharge accurately;
- Ce varies over the whole range of h when no head coefficient Kh is used;
- a different set of Ce values is necessary for each value of Kh;

- for a Kh of 0.00085 m, Ce is almost constant at low overflow levels;
- Fig. V.1, derived from ISO (1980), gives too low values for Ce, but the deviation is slight;
- for a Kh of 0.0008 m, Ce can be described accurately by a set of four equations.

V.2. Gravitational acceleration g

Discharges resulting from overflow levels assuming that $g = 9.811$ m/sec^2 are given in ISO (1980). This value may be applicable for parts of Europe but not for Suriname. Generally speaking, g is highest at the poles and decreases towards the equator. A number of local factors influence the value of g for a certain place, for example, elevation, topography and geology. The weir at Tonka is at latitude 5°15′N and at an elevation of 13.5 m above NSP (MSL).

Van Boeckel (1968) uses the equation of the International Union of Geodesy and Geophysics to calculate the theoretical gravity at sea level:

$$g_o = 978.049 \times (1 + 0.0052884 \sin^2 L - 0.0000059 \sin^2 2L) \qquad (V.13)$$

For Tonka ($L = 5.25$) this gives $g_o = 978.09211$ cm/sec^2.

Two standard corrections can be applied to arrive at the real gravity g from the theoretical gravity g_o. These are a correction for elevation above a reference plain (mostly sea level) and a correction for the weight of the mass between the point of observation and the reference level. Both corrections are combined in the Bouguer reduction (after Pierre Bouguer (1698-1758))

$$g_B = (0.3086 - 0.0420\, d)\, h \qquad \text{(mgal)} \qquad (V.14)$$

d is the density of the mass between observation point and reference level. The unit mgal is 10^{-3} cm/sec^2. For Tonka ($h = 13.5$ m, $d = 2.67$) g_B reaches a value of 2.65 mgal, therefore g should be

$$978.09211 - 0.00265 = 978.08946 \text{ cm/s}^2 \qquad (V.15)$$

A number of other factors can effect the gravity of a certain location; these include the geology of the area, particularly the density of the geological formations to a depth of several tens of kilometres, the topography of the surrounding area; and the curvature of the earth.

Van Boeckel (1968) has found relatively large differences in measured and theoretical gravities at many locations throughout northern Suriname, including the Zanderij area. For all 439 locations he gives the observed gravity g and the theoretical or normal gravity g_o and tries to bridge the gap between the two with the aid of the Bouguer correction. He presents a map of the Bouguer Gravity

Anomalies of northern Suriname for the remaining differences. These anomalies vary from +30 mgal in Nickerie to -85 mgal in the area south of the Goliath Mountain along the Saramacca river. The Kabo area which is to the north-west of the Goliath Mountain is in the area of a strong negative anomaly; a value of -77 mgal can be read from the map for Kabo/Tonka.

Based on the work of Veldkamp (1960), van Boeckel (1968) gives a closer approximation of theoretical gravity values by calculating the Isostatic correction for the northern part of Suriname. This correction is based on a model cross-section of the crust, in which the thickness of the continental and oceanic crust are 28 and 7.56 km respectively, the density of crustal and subcrustal rocks being 2.85 and 3.30 respectively. Based on this model the expected gravity at the coast increases with a certain value. This decreases inland reaching about zero near Kabo/Tonka. This means that the value of the Bouguer correction and the "expanded" Bouguer correction which includes the isostatic correction are the same in the area of Kabo. Van Boeckel (1968) gives two maps the Bouguer Gravity Anomaly map and the Isostatic Anomaly map. In the first map Bouguer anomaly contours are given at intervals of 5 mgal. These anomalies (dg_B) were computed for every station with the equation:

$$dg_B = g - g_o + (0.30857 - 0.00021 \cos 2L - 0.0420\ d)h \text{ mgal} \qquad (V.16)$$

d being the density of the mass determined from analysing more than 200 samples of rock.

In the second map isostatic anomaly contours are given at intervals of 5 mgal. These anomalies are the differences between the measured gravities and the theoretical gravities adjusted with the Bouguer correction and the isostatic correction explained above.

Both maps show that the whole of northern Suriname, except part of Nickerie, has negative anomalies, gravities being smaller than the theoretical gravities. This large area of negative anomalies is explained by assuming in the negative belt a large granite batholith, that is the plutonic core of an old Precambrian orogeny. Whatever the reason for the negative anomalies, from the Bouguer Gravity Anomaly map the anomaly of the Kabo area can be read as -77 mgal. The real gravity of the Tonka weir can be calculated as

$$g = g_o - g_B - 77 \text{ mgal} = 978092.11 - 2.65 - 77 = 978012.46 \text{ mgal} = 9.7801 \text{ m/s}^2 \qquad (V.17)$$

APPENDIX VI: MEASURED GROUNDWATER LEVELS IN DEEP BORINGS (CM BELOW SURFACE)

Boring	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	REPR.
Line	6	6	6	6	6	0	0	0	0	0	0	0	0	0	0	0	0	4	LEVEL
Place	600W	400W	200W	CENTR	400E	900E	600E	400E	280E	200E	150E	CENTR	200W	400W	700W	900W	1100W	700W	(Ztr)*
Date																			
050681																		450	
100682																120			
170682	200																		
230682		130	+60	140	400		290										650		676
280682						320		15		510									
070782												650	155	250	90				710
250882	450	280	+15	230	550	500	425	48		550		420?	230	399	87	244	450?		800
010982	700?	300	+16	230	590	(467)	440	42		(643)		(666)	236	436	85	263	(637)		818
080982	700?	324	+6	244	600	(434)	455	42		(643)		(666)	250	460	93	289	(637)		834
150982	(450)	357	6	260	(600)	(434)	455?	56		(643)		(666)	260	488	100	319	(637)		849
220982	(450)	360	6	262	(600)	(434)	455?	56		(643)		(666)	265?	494	102	324	664		852
290982	(450)	405	8	270	(560)	(430)	(455)	64		(610)		(666)	280	525	104	(360)	(659)		880
061082	(450)	410	10	270	(560)	(430)	(455)	58		(610)		(666)		528	108	(360)	(659)		883
121082	(450)	442	21	282	(560)	(430)	(455)	61		(610)		(666)	295	528	111	(360)	(659)		896
201082	(450)	457	26	288	(560)	(430)	(455)	72		(610)		(666)	300	(528)	115	(360)	(659)		917
271082	(450)	(466)	36	295	(560)	(430)	(455)	71		(610)		(666)	304	(528)	115	(360)	(659)		925
041182	(450)	(466)	41	300	(560)	(430)	(455)	81		(610)		(666)	312	(528)	124	(360)	(659)		
101182	(450)	(466)	48	330	(560)	(430)	(455)	85		(610)		(666)	319	(528)	128	(360)	(659)		
171182	(450)	(466)	58	330	(560)	(430)	(455)	91		(610)		(666)	324	(528)	132	(360)	(659)		
231182	(450)	(466)	64	337	(560)	(430)	(455)	93		(610)		(666)	(324)	(528)	135	(360)	(659)		
011282	(450)	(466)	64	333	(560)	(430)	(455)	87		(755)		(666)	(324)	(528)	137	(360)	(659)		
101282	(724)	541	75	342	(737)	(668)	711?	107	434	(720)	(758)	(666)	338	(528)	138	(360)	(659)		986
181282	(724)	517	73	343	(737)	(668)	(711)	94	(677)	(720)	(758)	(666)	333	(528)	145	(360)	(659)		966
221282	(724)	519	74	346	(737)	(668)	(711)	95	(677)	(720)	(758)	(666)	334	(528)	146	(360)	(659)		968
301282	(724)	540	61	325	(737)	(668)	(711)	70	422	(720)	(758)	(666)	326	(528)	141	(360)	(659)	719	985
060183	(739)	549	59	323	(744)	(701)	606	77	420	(733)	611	(670)	322	(546)	147	392	678	754	988
120183	(739)	539	41	310	631?	(701)	(573)	(44)	400	(733)	643	(670)	318	(546)	137	(392)	(678)	(754)	969
200183	(739)	519	46	300	701	(701)	569	71	397	(733)	(673)	(670)	321	(546)	142	(392)	(678)	(754)	959
260183	(739)	519	51	303	706	(701)	593	78	405	(733)	(673)	(670)	323	(546)	150	(392)	(678)	(754)	970

(continued)

Boring Line Place	1 6 600W	2 6 400W	3 6 200W	4 6 CENTR	5 6 400E	6 0 900E	7 0 600E	8 0 400E	9 0 280E	10 0 200E	11 0 150E	12 0 CENTR	13 0 200W	14 0 400W	15 0 700W	16 0 900W	17 0 1100W	18 4 700W	REPR. LEVEL (ZTr)*
160283	(739)	560	72	327	725	(701)	607	102	433	(750)	(698)	(666)	334	(553)	170	(360)	(659)	(754)	993
230283	(739)	550	66	321	729	(701)	613	79	430	(750)	(698)	(666)	326	(553)	176	(360)	(659)	(754)	991
030383	(739)	549	50	307	700	(701)	591	67	413	684	(673)	(657)	320	(551)	167	(381)	(645)	(754)	981
090383	(739)	542	51	299	722	(701)	605	74	405	700	(673)	(637)	316	(513)	172	(359)	(645)	(754)	985
160383	(739)	534	48	293	721	(701)	605	72	405	(700)	(673)	(637)	314	(513)	165	(359)	(645)	(754)	981
230383	(739)	537	39	291	719	(701)	601	57	398	(700)	(673)	(637)	310	(513)	154	(359)	(645)	(754)	981
020483	(739)	533	37	257	711	(701)	597	58	387	(700)	(673)	(637)	309	(513)	158	(359)	(645)	(754)	977
060483	(739)	507	30	261	721	(701)	(586)	60	367	(700)	(673)	(637)	290	(513)	140	(359)	(645)	(754)	962
130483	(739)	469	0	223	718	(701)	545	44	334	(700)	(673)	(637)	260	(513)	121	(359)	(645)	(754)	928
200483	(739)	395	+18	200	701	(701)	500	27	310	(700)	(673)	(637)	240	(513)	101	(359)	(645)	(754)	878
270483	(739)	294	+34	170	632	(701)	356	13	277	518	570	(637)	194	337	89	(359)	(645)	(754)	770
040583	(739)	231	+42	136	513	(701)	276	34	260	526	503	(637)	152	239	82	(359)	(645)	(754)	708
080583	440	244	+35	160	517	572	318	39	287	527	508	624	166	253	90	(384)	(659)	(754)	727
120583		257	+34	170	521		351	34	295	563	573		176	278	85			(721)	
180583	360	203	+49	143	461	368	313	18	277	468	573	633	156	242	76	354	(659)	581	712
250583	372	211	+42	150	481	472	340	32	287	517	618	647	165	268	75	347	(659)	539	728
010683	391	212	+39	157	498	465	364	32	292	554	556	(670)	176	299	78	340	(659)	546	742
080683	405	239	+44	170	506	471	381	13	297	527	513	(670)	156	313	56	344	(659)	561	757
150683	440	249	+34	180	521	448	388	38	298	563	573	(670)	185	319	86	319	(659)	561	763
220683	469	265	+21	189	553	478	406	35	302	569	579	(670)	195	371	82	333	(659)	566	784
290683	499	287	+27	201	561	488	423	44	309	603	602	(670)	210	397	88	350	(718)	596	801
060783	528	311	+17	213	582	503	443	52	317	630	(673)	(670)	226	435	96	362	(718)	629	821
130783	553	332	+21	222	613	518	453	30	316	590	548?	(670)	238	456	94	381	(718)	646	834
200783	568	356	+ 8	234	607	540	466	46	322	640	(713)	(670)	247	478	100	401	(718)	665	849
280783	603	381	1	247	622	560	481	52	325	664	(713)	(670)	260	502	104	423	(718)	692	866
030883	623	398	5	260	634	576	497	54	328	(700)	(713)	768	256	514	112	444	(718)	713	878
100883	648	423	4	264	650	598	506	52	334	681	(765?)	(757)	274	531	109	473	(718)	735	891
140883	667	442	20	273	661	616	515	62	337	705	764	760m	282	548	113	496	(715)	756	902
240883	689	461	27	280	676	636	525	70	344	714	(757)	(760)	288	564	118	520	(715)	776	914
310883	704	476	25	284	688	657	535	55	344	726	720	(760)	297	579	118	542	(715)	787m	924
070983	716	486	27	286	700	672	541	69	350	732	777	(760)	300	587	120	559	(715)	(787)	930

(continued)

Boring	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	REPR.
Line	6	6	6	6	6	0	0	0	0	0	0	0	0	0	0	0	0	4	LEVEL
Place	600W	400W	200W	CENTR	400E	900E	600E	400E	280E	200E	150E	CENTR	200W	400W	700W	900W	1100W	700W	(Ztr)*
140983	731	497	31	291	711	694	547	68	358	742	777	(760)	302	599	124	583	(715)	(787)	938
210983	745	504	40	299	717	701m	553	79	371	750	(777)	(760)	309	609	127	595	(715)	(787)	943
280983	757	516	46	310	730	(701)	564	83	380	764	(777)	(760)	312	622	130	618	(715)	(787)	953
051083	772	529	53	319	741	(701)	576	92	394	(773)	(777)	(760)	319	639	134	636	(715)	(787)	963
121083	(777)	554	67	335	759	(701)	589	109	417	(773)	(777)	(760)	336	666	142	664	(715)	(787)	980
191083	(777)	571	78	345	761	(701)	604	121	426	(773)	(777)	(760)	344	682	152	681	(715)	(787)	992
261083	(777)	580	96	354	(765)	(701)	621	127	436	(773)	(777)	(760)	354	700	163	704	(715)	(787)	1004
031183	(777)	586	90	354	(765)	(701)	622	121	444	(773)	(777)	(760)	358	705	174	730	(715)	(787)	1007
091183	(777)	588	92	356	(765)	(701)	625	120	449	(773)	(777)	(760)	362	704	176	730	(715)	(787)	1008
171183	(777)	599	103	364	(765)	(701)	635	131	461	(773)	(777)	(760)	370	719	186	(736)	(715)	(787)	1017
231183	(777)	608	110	371	(765)	(701)	644	137	470	(773)	(777)	(760)	376	730	194	(736)	(715)	(787)	1024
301183	(777)	621	119	380	(765)	(701)	658	149	480	(773)	(777)	(760)	386	744	206	(736)	(715)	(787)	1035
081283	(777)	638	131	392	(765)	(701)	676	161	499	(773)	(777)	(760)	399	757		(736)	(715)	(787)	1048
141283	(777)	639	135	395	(765)	(701)	676	159	504	(773)	(777)	(760)	401	760		(736)	(715)	(787)	1049
211283	(777)	638	135	395	(765)	(701)	(677)	150	509	(773)	(777)	(760)	402	748		(736)	(715)	(787)	1046
291283	(777)	628	121	388	(765)	(701)	676	139	506	(773)	(777)	(760)	397	734		(736)	(715)	(787)	1040
120184	(777)	601	100	362	(765)	(701)	668	118	481	(773)	(777)	(760)	376	710		(736)	(715)	(787)	1025
170184	(777)	600	96	293?	(765)	(701)	669	110	483	(773)	(777)	(760)	372	708		(736)	(715)	(787)	1025
020284	(777)	571	66	337	(765)	(701)	648	77	451	(773)	(777)	(760)	323	678		(736)	(715)	(787)	1004
070284	(777)	570	72	337	(765)	(701)	648	95	449	(773)	(777)	(760)	320	672		(736)	(715)	(787)	1003
160284	(777)	578	86	347	(765)	(701)	650	112	-	(773)	(777)	(760)	329	669		(736)	(715)	(787)	1005
210284	(777)	578	86	349	(765)	(701)	650	109	-	(773)	(777)	(760)	328	667		(736)	(715)	(787)	1005
290284	(777)	582	93	357	(765)	(701)	656	117	466	(773)	(777)	(760)	332	668		(736)	(715)	(787)	1008
080384	(777)	594	104	365	(765)	(701)	663	129	474	(773)	(777)	(760)	342	672		(736)	(715)	(787)	1014
130384	(777)	608	115	377	(765)	(701)	669	137	484	(773)	(777)	(760)	348	685		(736)	(715)	(787)	1022
220384	(777)	633	135	399	(765)	(701)	682	153	505	(773)	(777)	(760)	365	708		(736)	(715)	(787)	1038
270384	(777)	636	137	403	(765)	(701)	676	157	511	(773)	(777)	(760)	372	712		(736)	(715)	(787)	1038
050484	(777)	643	146	410	(765)	(701)	683	161	516	(773)	(777)	(760)	375	723		(736)	(715)	(787)	1044
180484	(777)	646?	149	410	(765)	(701)	681m	159	524	(773)	(777)	(760)	380	725		(736)	(715)	(787)	1045
260484	(777)	646	151	415	(765)	(701)	(688)	159	530	(773)	(777)	(760)	385	730		(736)	(715)	(787)	1048
170584	(777)	546	25	306	(765)	(701)	639	31	425	(773)	(777)	(760)	272	660		(736)	(715)	(787)	991

(continued)

Boring	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	REPR.
Line	6	6	6	6	6	0	0	0	0	0	0	0	0	0	0	0	0	4	LEVEL
Place	600W	400W	200W	CENTR	400E	900E	600E	400E	280E	200E	150E	CENTR	200W	400W	700W	900W	1100W	700W	(ZTr)*
220584	(777)	551	29	310	(765)	(701)	641	36	428	(773)	(777)	(760)	276	660		(736)	(715)	(787)	993
310584	(777)	411	4	201	(765)	(701)	474	32	315	(773)	(777)	(760)	225	423		(736)	(715)	(787)	855
050684	(777)	426	11	212	(765)	(701)	501	39	324	(773)	(777)	(760)	232	428		(736)	(715)	(787)	868
140684	(777)	298	+10	146	765	(701)	336	34	270	589	677	751	160	268	89	499	(715)	(787)	751
190684	631	318	+10	165	589	(701)	368	14	284	597	689	748	174	299	88	495	(715)	(787)	772
280684	549	270	+16	131	519	(701)	285	27	237	566	626	643	132	250	75	432	(715)	(787)	724
030784	517	221	+16	97	372	(701)	260	19	184	528	556	543	82	192	65	362	(715)	(787)	691
120784	458	262	+11	137	498	(701)	317	26	262	477	472	524	138	282	76	379	(715)	(787)	738
270784	411	241	+13	133	458	(701)	291	17	238	420	409	498	130	288	67	369	(715)	547	726
010884	411	239	+15	131	458	(701)	289	17	236	416	407	495	128	285	67	366	(715)	559	724
100884	420	254	+9	155	478	(701)	347	17	276	481	471	515	148	323	76	318	(715)	542	754
AMPLITUDE:																			
82/83		357	124	210			435	94	174				186		120				
83/84		425	167	318			428	147	364				320	568					

* ZTr is representative groundwater depth, that is average groundwater depth in central area between Eastern and Western creeks at line 0 with soil surface 10 m above creek level; ZTr = 1000-M; M is gravity head (groundwater level above creek level).

( ) dry hole or estimated value

\+ water level above soil surface

? uncertain observation

m muddy

APPENDIX VII: COMPOSITION CREEK, RAIN AND SOIL WATER ANALYSED IN WAGENINGEN (MMOL(C)/M³) *) (CALCULATED VALUES BETWEEN BRACKETS)

Sample No.	Date	Object	pH	EC	EC' (calc)	C total	C an-organic	SiO_2	K	Na	Ca	Mg	Al	Fe	Mn	N (NH_4)	Cl	N (NO_3)	S (SO_4)	H_2PO_4	HCO_3	SOA *	SUM+ *	SUM- *
1	820512	DAM	6.55	33	30	(1100)	(207)	212	20	159	83	66	0	0	1	0	108	15	26	0	120	62	329	331
2	820929	DAM	6.93	42	39	(800)	(346)	340	18	210	103	97	0	0	0	0	113	0	21	0	265	32	428	431
3	830831	DAM	6.85	43	41	(1200)	(348)	342	22	228	109	97	0	10	0	0	115	11	23	0	255	60	466	463
4	830907	DAM	6.38	48	36	830	382	336	18	219	95	93	6	9	4	0	117	0	13	3	185	31	444	348
5	830915	DAM	7.05	47	40	884	333	336	18	223	99	94	4	7	1	0	124	0	13	2	270	40	446	449
6	830921	DAM	6.99	49	41	951	348	358	22	244	99	99	3	10	1	0	129	0	13	4	275	42	478	464
7	820929	EAST	6.80	35	32	(800)	(268)	268	12	179	77	81	0	0	0	0	105	0	21	0	190	37	349	353
8	830303	EAST	6.50	48	44	(2000)	(327)	175	29	224	131	110	0	3	0	0	150	0	56	0	180	115	497	501
9	830309	EAST	6.84	53	49	(2200)	(357)	262	30	252	153	136	0	18	0	0	164	0	34	0	260	129	589	587
10	830331	EAST	6.81	43	41	(1300)	(266)	291	20	230	105	100	0	4	0	0	144	0	53	0	190	72	459	459
11	830406	EAST	6.75	42	39	(1500)	(270)	235	20	223	99	94	0	9	0	0	145	0	32	0	185	86	445	448
12	830413	EAST	6.71	44	38	(1900)	(210)	233	21	208	109	100	0	7	0	0	143	0	43	0	140	118	445	444
13	830420	EAST	6.67	40	36	(1500)	(217)	203	19	193	104	93	0	4	0	0	135	0	45	0	140	89	413	409
14	830525	EAST	6.66	35	33	(600)	(188)	215	12	179	76	75	0	3	0	0	136	30	32	0	120	29	345	347
15	830601	EAST	6.81	36	30	772	221	208	9	177	69	72	2	7	1	0	117	0	13	1	158	39	337	327
16	830608	EAST	6.70	38	32	1220	307	93	14	158	75	71	2	9	1	8	117	0	14	1	203	64	338	398
17	830622	EAST	6.91	36	31	772	246	209	10	176	71	72	0	9	1	0	120	0	11	1	187	37	339	356
18	830706	EAST	6.75	37	30	744	223	162	10	183	73	72	0	8	1	0	116	0	7	1	153	36	347	313
19	830714	EAST	6.91	36	30	856	208	241	12	188	71	71	0	12	1	0	118	0	7	3	158	46	355	331
20	830720	EAST	6.96	37	33	716	276	250	11	188	70	72	0	12	1	0	122	0	7	2	214	31	354	377
21	830727	EAST	7.04	37	34	605	223	261	9	192	70	73	0	12	1	4	152	1	18	4	180	28	361	383
22	830803	EAST	7.06	40	39	772	291	266	10	198	95	75	0	10	1	0	117	0	9	2	237	35	389	400
23	830810	EAST	6.98	39	33	828	247	247	13	202	71	77	0	11	1	0	120	0	11	2	194	41	375	368
24	830817	EAST	7.07	39	34	772	270	273	11	206	75	77	0	12	1	0	118	0	12	2	221	36	382	389
25	830831	EAST	6.69	40	33	828	262	271	19	209	71	75	1	12	1	0	122	0	22	2	172	39	388	357
26	830907	EAST	6.38	43	36	934	482	296	14	220	88	90	0	13	1	0	116	0	11	3	233	31	426	393
27	830915	EAST	7.02	41	35	939	270	297	14	220	83	84	1	12	1	0	107	1	12	2	216	48	415	387
28	821222	WEST	6.90	54	51	(800)	(451)	396	29	284	131	108	0	0	0	0	144	0	45	0	340	24	552	554
29	821229	WEST	7.04	55	51	(1800)	(340)	222	35	282	143	105	0	6	0	11	162	0	45	0	275	105	582	587
30	830105	WEST	7.05	59	55	(1300)	(480)	384	28	258	141	107	0	4	0	74	132	0	32	0	390	59	612	613

(continued)

Sample No.	Date	Object	pH	EC	EC' (calc)	C total	C an-organic	SiO_2	K	Na	Ca	Mg	Al	Fe	Mn	N (NH_4)	Cl	N (NO_3)	S (SO_4)	H_2PO_4	HCO_3	SOA *	SUM+ *	SUM- *
31	830126	WEST	6.99	57	53	(1300)	(468)	471	22	286	154	124	0	9	0	6	141	0	29	0	370	59	601	599
32	830303	WEST	7.06	49	47	(1900)	(355)	384	24	262	159	103	0	3	1	3	129	0	29	0	290	111	555	559
33	830323	WEST	7.19	48	44	(1000)	(327)	351	15	242	133	100	0	2	1	0	139	0	26	0	280	48	493	493
34	830406	WEST	7.10	48	45	(900)	(283)	328	15	235	136	99	0	5	0	0	139	49	23	0	235	44	490	490
35	830427	WEST	6.24	44	35	895	239	217	19	212	100	74	1	7	1	0	139	26	29	1	96	44	415	336
36	830511	WEST	6.85	45	37	1020	223	273	13	244	102	81	1	4	1	0	147	0	18	2	163	56	446	386
37	830518	WEST	6.92	42	39	1050	322	275	13	227	90	76	1	8	1	0	144	0	20	2	245	51	416	463
38	830525	WEST	6.90	44	38	828	291	274	11	234	89	76	0	2	1	0	148	0	18	2	220	38	413	425
39	830601	WEST	6.80	46	40	800	247	31	16	204	105	83	0	6	1	0	149	55	16	0	175	39	415	434
40	830608	WEST	6.79	40	33	884	200	60	21	177	86	67	1	2	1	0	144	0	20	0	141	48	355	353
41	830622	WEST	6.93	43	35	633	286	280	12	198	94	79	0	2	1	0	129	0	7	2	219	24	386	382
42	830629	WEST	6.92	43	35	772	250	70	10	203	91	77	0	4	1	0	133	0	13	1	191	37	386	374
43	830714	WEST	6.83	45	39	828	379	263	13	207	94	81	0	6	1	0	141	0	7	2	274	31	402	456
44	830727	WEST	7.09	47	40	744	348	297	13	215	108	88	1	4	1	0	124	0	13	2	288	29	430	455
45	830810	WEST	7.05	49	40	1020	356	310	17	213	110	88	1	2	0	1	130	0	13	2	289	48	432	482
46	830817	WEST	6.96	50	42	834	387	346	16	221	110	91	1	2	0	1	139	0	14	2	301	31	442	488
47	830831	WEST	6.98	51	41	800	301	316	25	217	118	94	2	1	0	0	135	11	23	2	237	35	457	443
48	830907	WEST	7.24	54	44	744	333	374	18	233	127	106	1	3	0	0	116	38	13	5	289	30	488	491
49	830915	WEST	7.20	52	43	828	372	373	18	227	126	102	0	3	0	0	115	0	13	3	319	33	476	483
50	830921	WEST	7.17	56	39	884	411	427	19	240	135	113	3	4	0	0	119	0	14	3	349	34	514	520
51	820616	RAIN	6.65	15	12	(400)	(142)	14	10	9	28	6	0	2	1	61	7	3	18	2	90	18	117	138
52	830223	RAIN	4.01	77	66	(400)	(50)	10	35	70	43	21	0	6	1	94	75	219	50	18	0	14	368	376
53	830316	RAIN	4.05	51	49	(400)	(50)	9	18	39	34	14	0	1	1	9	36	183	23	7	0	14	205	263
54	830331	RAIN	6.78	24	23	(400)	(179)	6	19	40	41	16	0	16	0	93	34	32	29	4	125	15	225	240
55	830413	RAIN	6.41	13	10	(400)	(140)	1	6	24	30	10	0	6	1	11	25	4	23	1	70	18	88	141
56	830427	RAIN	6.44	11	8	(400)	(97)	2	7	14	33	7	0	1	1	0	13	0	23	0	50	21	63	107
57	830511	RAIN	6.54	11	7	(400)	(78)	0	8	9	31	6	0	4	1	8	9	0	21	0	45	22	67	97
58	830518	RAIN	6.46	15	6	494	83	5	7	11	28	5	0	4	0	0	19	0	7	0	44	28	55	98
59	830601	RAIN	6.45	15	6	616	83	4	9	9	27	5	0	3	0	0	19	0	8	0	43	37	53	107
60	830622	RAIN	5.95	17	9	354	44	16	16	13	33	8	1	2	0	0	19	51	7	0	11	20	74	109
61	830714	RAIN	6.75	22	13	438	167	8	16	15	28	7	1	5	0	41	28	1	11	1	114	19	113	174
62	830831	RAIN	4.19	45	39	298	52	12	26	17	28	9	2	3	0	0	30	195	14	1	0	10	150	250

(continued)

Sample No.	Date	Object	pH	EC	EC′ (calc)	C total	C an-organic	SiO_2	K	Na	Ca	Mg	Al	Fe	Mn	N (NH_4)	Cl	N (NO_3)	S (SO_4)	H_2 PO_4	HCO_3	SOA *	SUM+ *	SUM- *
63	831006	RAIN	4.05	60	52	393	28	10	30	20	31	11	2	9	0	20	30	242	14	3	0	14	212	303
64	831109	RAIN	6.95	30	11	577	262	12	25	15	30	11	1	6	0	70	20	1	11	2	203	22	158	259
65	830601	6/600 W	6.61	43	32	382	130	0	13	222	17	29	1	3	0	8	198	41	4	0	80	17	293	340
66	830601	6/400 W	4.84	45	39	59	64	54	8	176	31	108	14	4	2	0	62	231	12	0	2	0	357	306
67	830601	6/200 W	7.76	145	125	1760	1430	843	45	543	526	345	5	4	2	0	120	50	24	5	1364	24	1470	1587
68	830601	6/CENTR	6.88	30	25	198	197	153	0	127	43	58	2	2	1	0	117	0	12	0	147	0	233	276
69	830601	6/400 O	6.27	25	17	163	94	22	18	90	31	28	1	3	1	4	125	9	4	0	39	5	177	182
70	830601	0/600 O	6.27	35	31	892	124	52	11	204	30	21	0	3	2	1	194	25	29	0	52	52	273	352
71	830601	0/400 O	5.95	24	17	337	80	89	4	87	12	16	0	3	3	0	103	5	45	0	21	17	126	190
72	830601	0/280 O	6.38	24	19	163	138	8	0	141	15	16	0	4	2	0	124	0	8	0	67	2	178	200
73	830601	0/200 O	6.26	24	19	129	109	11	0	120	23	31	0	3	2	0	121	0	17	0	45	1	180	184
74	830601	0/150 O	3.84	89	75	961	62	26	29	28	12	27	0	114	2	55	40	299	17	0	0	32	412	388
75	830601	0/200 W	6.00	16	13	337	80	1	9	37	33	24	0	13	2	15	32	21	29	0	22	17	134	121
76	830601	0/400 W	5.25	57	49	59	56	74	0	350	6	53	0	5	2	0	465	0	0	0	4	0	422	469
77	830601	0/700 W	5.93	24	18	163	65	42	0	112	16	37	0	4	2	0	90	44	19	0	16	6	172	176
78	830601	0/900 W	6.07	63	52	226	94	60	18	357	37	39	0	4	2	0	421	24	41	0	29	9	458	524
79	830601	4/670 W	6.52	33	27	219	132	0	30	98	43	43	0	4	2	16	98	89	8	0	74	6	236	275
80	830817	6/600 W	6.03	41	29	80	80	67	17	219	44	22	0	5	2	0	210	23	0	0	24	0	310	257
81	830817	6/400 W	6.47	36	27	358	159	53	5	172	32	57	0	5	2	7	153	18	0	0	85	14	280	270
82	830817	6/CENTR	6.91	39	31	406	197	151	1	160	67	88	0	6	4	0	126	0	39	0	149	15	326	329
83	830817	6/400 O	6.13	31	23	358	65	51	29	77	61	36	0	6	3	0	118	21	37	0	22	20	213	218
84	830817	0/600 O	6.35	24	18	163	110	15	3	97	51	14	0	6	3	2	98	0	21	0	51	4	176	174
85	830817	0/400 O	5.35	27	22	496	44	113	9	123	24	34	0	8	3	2	130	15	30	0	4	27	207	206
86	830817	0/280 O	6.13	26	18	39	40	0	2	133	20	23	0	6	3	0	149	0	20	0	14	0	188	183
87	830817	0/200 O	6.23	61	52	247	80	46	48	107	192	129	0	7	3	0	77	357	0	0	32	11	487	477
88	830817	0/200 W	5.84	25	15	177	36	53	0	114	21	26	0	6	3	0	133	0	0	0	8	9	171	150
89	830817	0/400 W	4.63	55	43	39	40	99	1	232	30	41	0	7	4	0	338	23	0	0	1	0	338	362
90	830817	0/700 W	6.52	34	25	163	138	206	6	189	30	24	0	10	3	0	122	22	20	1	78	2	262	244
91	830817	0/900 W	5.94	37	26	20	18	50	3	207	20	16	0	8	4	0	250	0	0	0	5	0	259	255
92	830817	4/670 W	6.53	30	20	198	138	32	1	109	44	25	0	7	3	15	117	0	0	0	78	4	204	199
93	810604	4/670 W	7.51	108	69	2870	827	175	16	371	95	94	0	8	4	151	150	0	10	1	766	147	739	1074
94	810604	4SM70cm	8.87	1400	86	31000	0	1100	0	0	0	0	33	0	0	0	725	31	844	0	0	2232	33	3832

(continued)

Sample No.	Date	Object	pH	EC	EC' (calc)	C total	C an-organic	SiO_2	K	Na	Ca	Mg	Al	Fe	Mn	N (NH_4)	Cl	N (NO_3)	S (SO_4)	H_2PO_4	HCO_3	SOA *	SUM+ *	SUM- *
95	830525	36SM100	8.17	700	649	16000	3240	511	624	638	5130	264	13	171	4	366	342	219	3100	9	3160	919	7210	7749
96	830831	35/SUFL	5.27	153	91	3180	56	71	281	219	126	97	3	15	5	174	138	335	178	8	4	184	925	847
97	830831	35/LAFL	3.78	160	133	1550	79	21	203	177	36	23	66	55	5	136	239	351	182	12	0	51	867	835
98	831006	LAKE	6.86	50	38	1240	308	346	20	228	92	91	8	46	5	0	122	21	0	4	227	65	490	439
99	831006	Leakage	6.75	51	40	718	262	310	18	215	103	84	2	18	4	0	130	73	0	3	180	32	444	417
100	831104	35/LAFL	4.00	144	108	1240	65	22	218	197	54	51	2	11	5	104	194	403	91	7	0	45	742	740

*) – SOA is the sum of the organic anions; SUM+ is the total sum of cations and SUM- of anions.

– H^+ is not given, but included in SUM+; it can be calculated from pH; it is less than 2 mmol/m^3 for pH > 5.7.

– samples no. 65-93 are from groundwater; 94 and 95 are soil moisture samples, 96 is from surface flow and 97 and 100 are from lateral flow, taken at Profile 35.

– composition 0 means less than 1 mmol(c)/m^3.

– sample no. 94 was only partly analysed, because of limited sample amount.

– for other explanation: see text (Section 4.4).

APPENDIX VIII: CORRECTION OF WATER ANALYSIS DATA

Difficulties were encountered in interpretating some of the water analysis data from both the laboratory of the Centre of Agricultural Research (CELOS) in Paramaribo, Suriname and the laboratory of the Department of Soil Science and Geology of the Wageningen Agricultural University, the Netherlands.

VIII.1 Rain-water samples

Some rain-water samples had relatively high conductivities, probably as a result of contamination in the field (see Section 4.2.2). Conductivities and concentrations of rain-water samples were generally higher for the dry season than for the wet season. As it was difficult to separate the contaminated samples from samples of natural higher conductivity, all water samples having a conductivity of more than 50 μS/cm were considered to be contaminated, and were not included in calculating the mean rain-water concentrations per month. They were also not used to establish the nutrient balance.

Another problem was the large variation in composition of the rain-water samples. Analyses from some periods appeared to deviate from what was expected for the time of the year. Laboratory errors were probably the cause of this. It was decided therefore to calculate mean monthly values for use in the water balance instead of using individual data.

The calculation of the mean rain-water composition per month proceeded in stages. The average conductivity values per month were taken after contaminated samples of conductivities higher than 50 μS/cm had been eliminated. The cation concentrations determined in Paramaribo had to be corrected for several samples. Provisional means for Paramaribo were computed and periods of reliable and unreliable data were selected. Zero values in the Paramaribo data were given a provisional value using other, more reliable samples and the Wageningen data. The Paramaribo data from the period November 1981 to January 1983 are consistent for all cations except K, and have not been changed. For K, the consistent period is between February 1982 and July 1983. In the data for other periods, the following adaptations have been made:

- Ca values for the period 15-4-1981 to 13-10-1981, and 23-2-1983 to 1-6-1983 have been multiplied by 1.5;
- Ca values in the period, 22-6-1983 to 14-7-1983, have been multiplied by 2;
- Mg values in the period, 4-12-1980 to 22-4-1981, have been multiplied by 1.5;
- K values in the period, 4-12-1980 to 24-2-1982, have been multiplied by 1.5;
- Na values in the period, 29-4-1981 to 13-10-1981, have been multiplied by 2;
- Na values in the period, 3-3-1983 to 14-7-1983, have been multiplied by 1.25.

These adaptations bring the values of the cations in line with each other, and with the corresponding EC values, the time of the year, and the Wageningen results. The original Wageningen values and adapted Paramaribo values are given in Table VIII.1

Comparison of the mean values of the Paramaribo and Wageningen data give good agreement for Mg, K and Na, and somewhat less satisfactory relationships for EC. Values for Ca and P differ considerably, the Wageningen values being about twice as high for Ca and one-third as high for P than those from Paramaribo. The Wageningen mean values for the period April to July have been taken to set the level and the Paramaribo values to calculate the seasonal trends. These calculated values are given in Table 4.14 and are the best estimates for rain-water composition. The values have been multiplied by the actual rainfall amounts in order to calculate the weekly, monthly and yearly inputs of cations and P.

VIII.2 Creek water samples

Results of the analysis of creek water samples done in Wageningen and Suriname differed in some aspects, especially for Ca. For some periods, data from the Suriname laboratory were considered to be incorrect, and the following method was used to correct them.

Graphs of the cation concentrations of both laboratories were constructed to etablish the effect of the season on the composition of creek water and to show

TABLE VIII.1 Corrected mean monthly values of EC, Ca, Mg, K, Na and P in rain-water samples

Month	Number of samples		EC (µS/cm)		Ca (mg/l)		Mg (mg/l)		K (mg/l)		Na (mg/l)		P (mg/l)	
	A	B	A	B	A	B	A	B	A	B	A	B	A	B
Jan	3	0	24	–	0.61	–	0.14	–	1.14	–	1.06	–	–	–
Feb	5	0	17	–	0.77	–	0.16	–	1.07	–	0.95	–	–	–
Mar	5	1	17	24	0.69	0.82	0.12	0.19	0.47	0.74	0.70	0.92	–	0.124
Apr	11	2	9	12	0.38	0.63	0.11	0.10	0.48	0.25	0.45	0.44	0.050	0.031
May	9	2	10	13	0.29	0.59	0.09	0.06	0.38	0.29	0.34	0.23	0.138	–
Jun	8	3	11	16	0.38	0.59	0.09	0.08	0.42	0.46	0.23	0.24	0.125	0.062
Jul	6	1	10	22	0.33	0.56	0.11	0.09	0.51	0.63	0.23	0.34	0.125	0.031
Aug	5	1	12	45	0.36	0.56	0.09	0.11	0.56	1.02	0.28	0.39	0.150	0.031
Sep	4	0	17	–	0.45	–	0.09	–	0.66	–	0.34	–	0.175	–
Oct	1	0	8	–	0.60	–	0.10	–	0.30	–	0.40	–	0.100	–
Nov	1	1	14	30	0.32	0.60	0.06	0.13	1.83	0.98	0.31	0.34	–	0.062
Dec	6	0	20	–	0.78	–	0.12	–	1.24	–	0.73	–	–	–

A Analysis carried out at the Centre for Agricultural Research (CELOS), Paramaribo, Suriname.

B Analysis carried out at the Department of Soil Science and Geology, Agricultural University, Wageningen, the Netherlands.

periods of deviating results. Concentrations were higher in dry periods of low creek discharge and lower in wet periods of high discharges. The Wageningen data were slightly higher for Mg, K and Na, considerably higher for Ca and considerably lower for P. The Wageningen data were only available for a limited period, 1983 and a few samples from 1982. The Suriname data had to be used therefore for the period 1980 – 1982.

The Suriname data were corrected for periods of deviating concentrations that had been attributed to laboratory error. These periods of deviating concentrations were indicated on the graphs and a factor was determined to bring these values in line with the other periods as follows:

- Ca values for the periods 9-7-1980 to 7-10-1981 and 23-3-1983 to 1-6-1983, were multiplied by 1.5;
- Ca values for the period 8-6-1983 to 24-8-1983 were multiplied by 2;
- Mg values for the period 9-7-1980 to 22-4-1981 were multiplied by 1.5;
- K values for the period 9-7-1980 to 10-3-1982, were multiplied by 1.5;
- Na values for the periods 29-5-1980 to 25-6-1980 and 29-4-1981 till 7-10-1981 were multiplied by 2;
- Na values for the period 3-3-1983 to 24-8-1983 were multiplied by 2.

TABLE VIII.2 Measured mean monthly concentrations of P in creek water (mg/l), and monthly discharges.

Month	Discharge (cm/month)	Dam site		Eastern and Western creek	
		A*	B*	A	B
Dec 79	<0.1	1.150			
Jan 80	<0.1	0.400			
Apr 80	0.02	1.000			
May 80	1.95	1.050		1.050	
Jun 80	10.58	0.625		0.238	
Jul 80	8.43	0.100		0.100	
Apr 81	5.70	0.050		0.065	
May 81	9.71	0.095		0.094	
Jun 81	12.38	0.205		0.152	
Jul 81	9.21	0.140		0.115	
Aug 81	6.30	0.113		0.107	
Sep 81	3.68	0.100		0.105	
Oct 81	3.69	0.100		0.125	
Apr 83	6.25				0.031
May 83	9.65				0.062
Jun 83	6.81				0.039
Jul 83	3.39				0.070
Aug 83	1.25				0.062
Sep 83	0.42		0.093		0.096

* see footnote Table VIII.1.

The adaptations were made for the treated and untreated catchment, Western and Eastern creek area, and also for the whole catchment (sampling at the dam site). Differences in composition between treatments remained and were even increased by this adaptation, but the increase was small as only extremely low values had to be adapted. As a result of these corrections the pattern of the concentrations for the whole period became more consistent.

From the graphs of the corrected Suriname data, missing values were estimated by interpolation until estimates were available for all weeks with discharge between November 1979 and July 1984. The corrected Suriname data was then brought to the level of the Wageningen data by calculating the mean ratio between the Wageningen data and the corrected Suriname data for all samples analysed in both laboratories. The following ratios were obtained: Ca 1.55; Mg 1.13; K 1.08; and Na 1.09. Finally the corrected data to be used for the nutrient balance were calculated by multiplying the corrected Suriname data by these ratios.

In Suriname, P was measured on a limited number of samples only and the values obtained are considerably higher than those obtained in Wageningen. As the laboratory in Suriname was not well equipped to analyse very low P concentrations, and the Wageningen laboratory specializes in these analyses, the Wageningen values have been used. The Suriname data are used to study the differences between the two creeks and between dam site and the creeks, as well as differences resulting from time of sampling. Measured average monthly P concentrations are given in Table VIII.2. The data of Eastern and Western creeks were combined because essentially they were the same.

Concentrations at the dam site were higher directly after construction of the dam in the dry season of 1979. Decomposition of organic matter from dying trees in the small, newly formed pool above the dam is considered to be the reason for this increase. Concentrations at the dam site remained higher than in the Eastern and Western creek until June 1980, after which somewhat higher concentrations were measured only in June and July 1981. The concentration of P in the creek water rose at very low discharges in 1983 but also at high discharges in 1980, 1981

TABLE VIII.3 Phosphorus concentrations of the Eastern and Western creek waters, estimated from discharge

Discharge (cm/month)	Estimated P concentration (mg/l)
< 1.0	0.09
1.0-5.0	0.06
5.0-9.0	0.04
> 9.0	0.06

Based on data in Table VIII.2.

and 1983 somewhat higher concentrations occurred, possibly caused by the slightly higher turbidity of the water during peak flows.

The data of Table VIII.2 and the considerations given above were combined to reconstruct the P concentrations throughout the period, November 1979 – July 1984. The most important criterion in this reconstruction was the discharge. With increasing discharge, concentrations decreased until at very high discharges concentrations increased slightly. The estimated P concentrations, extracted from Table VIII.2 are given in Table VIII.3. These concentrations were used to estimate the nutrient balance in the two catchment areas.