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FINAL REPORT
ON THE
EAST AFRICAN CATCHMENT
RESEARCH PROJECT

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THE KIMAKIA AND
ATUMATAK EXPERIMENTS

by

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THE KIMAKIA RESEARCH PROJECT

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INTRODUCTION

In Kenya, Tanzania and Eastern Uganda, perennial streams originate in the high-rainfall, mountainous areas. The indigenous forests clothing these mountains play an important role in maintaining dry season flow by stabilising the soils, maintaining high infiltration rates and reducing surface runoff in the wet seasons. The timber yield of these indigenous forests is low, however, and economic pressures demand that these areas of high potential be more efficiently utilised.

An extreme case of this apparent conflict between maintaining reliable, high quality water supply and obtaining a reasonable economic return occurred in the southern end of the Aberdare Mountains in central Kenya. The numerous perennial streams not only provide domestic supplies for a densely populated smallholder farming area, but also are the source of dry season irrigation for Kenya's major coffee and pineapple plantations. In addition, these streams provide water supplies for the rapidly expanding capital city of Nairobi and help maintain the flow of the two major rivers in Eastern Kenya, the Tana and the Sabaki, on which the people of these drier areas depend.

The dominant forest type over the altitude range from 2000 - 3000 m in these mountains is bamboo *(Arundinaria alpina)*; however, trial plantings of softwoods by the Kenya Forest Department had shown that the bamboo zone had high potential for economic timber production. Other productive forms of land use, such as high-density sheep grazing and dairying, are also possible. To obtain more detailed information on the effects of such changes in land use on total streamflow yield and its seasonal distribution, catchment studies were proposed to compare water yields from indigenous bamboo forest, softwood plantation and sheep pasture.

DESCRIPTION OF THE EXPERIMENTAL CATCHMENTS

The catchments lie at the southern end of the Aberdares 0.5° south of the Equator at a mean altitude of 2440 m. The original three intensively-instrumented catchments are shown in Fig 1 together with a fourth catchment, Makiama, which was added to the project in 1964.

Catchment A is a 36.4 ha valley which lies on the lower edge of the indigenous bamboo forest. In 1956, it was cleared of bamboo, apart from a protective strip on the steep river banks, and planted with pine seedlings *(Pinus patula)* in April 1957. Following the usual Kenya Government practice of plantation development, vegetables were grown among the pine seedlings until 1960, when the closing pine canopy precluded further vegetable growing (Oland, 1962). Catchment B is a 16.2 ha valley under continuous bamboo which was intended to be cleared and planted with Kikuyu grass *(Pennisetum clandestinum)* prior to the introduction of sheep. It was found to leak and was abandoned as an experimental catchment in 1963. Catchment C of 64.9 ha area, is the control catchment under indigenous bamboo with scattered evergreen forest species.

Catchment M (Makiama) is a 36.8 ha valley adjacent to Catchment C. In 1964 it was under *Pinus radiata*, bamboo *(Arundinaria Alpina)* and *Pinus widdringtonia*. Following a severe infestation of needle blight, the *Pinus radiata* area together with part of the bamboo area was cleared and converted to Kikuyu grass *(Pennisetum clandestinum)* with the intention of studying the effects of intensive sheep grazing. Administrative difficulties resulted in only sporadic grazing of this 12.3 ha of grass until 1971 when a controlled, high-density grazing experiment was imposed under the supervision of the Kenya Ministy of Agriculture, Animal Husbandry Research Station, Naivasha. In 1973, some additional clearing of bamboo brought the grass area to 23 ha.

Catchment D extends almost to the altitudinal limit of the bamboo, and following the abandonment of the earlier planting schemes which would have brought Catchment D into a phase of

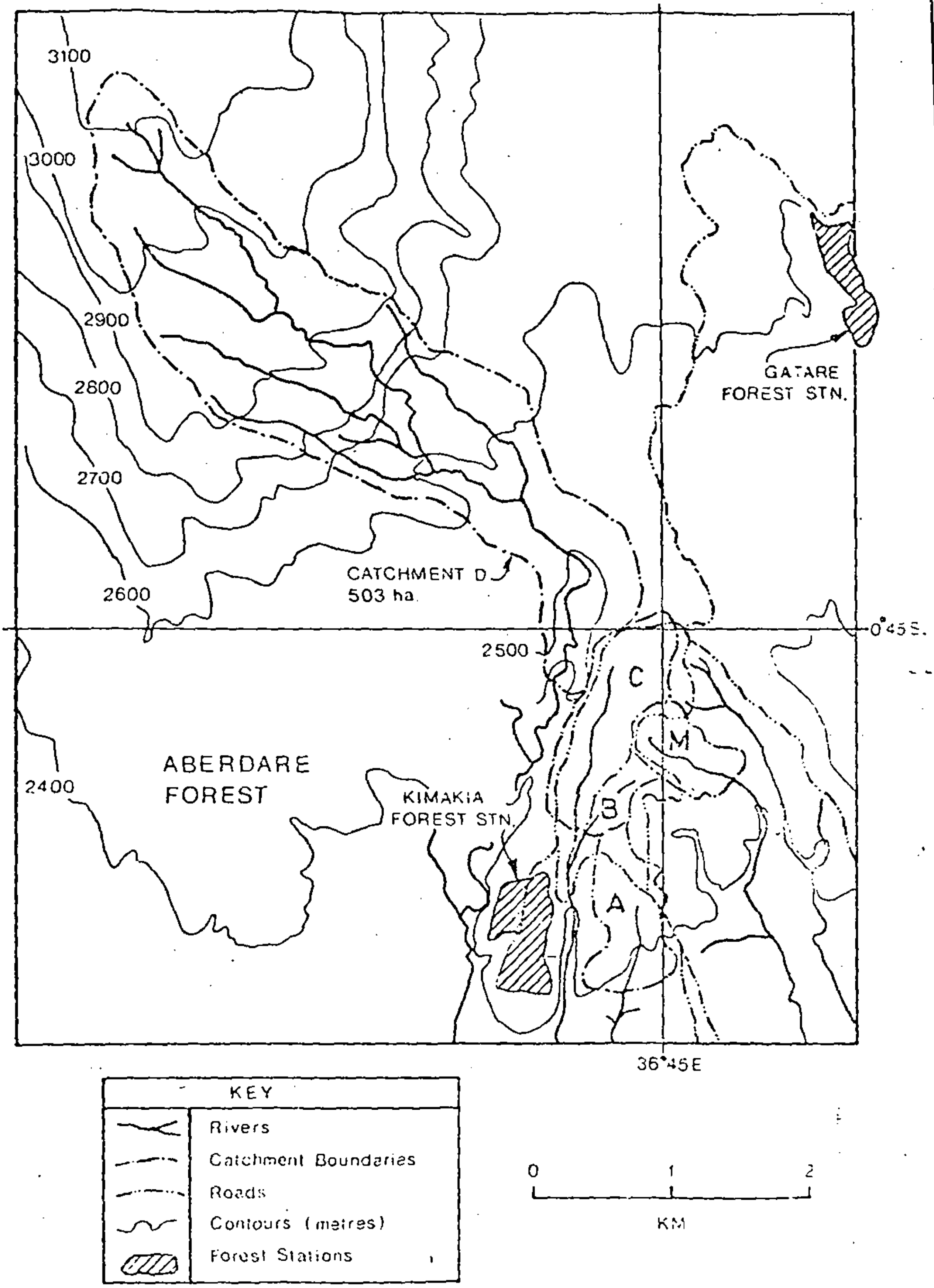

Figure 1 Relative location of the experimental catchments at Kimakia

clearing and planting in 1963, approximately one-sixth of it was cleared in 1972 to provide agricultural land for the forestry workers and their families. It has provided an example of clearing on a large scale and conversion to the third alternative form of land use in the Aberdares, namely smallholder or 'shamba' cultivation.

All the catchments are situated on the Miocene basalts and agglomerates of the Simbara Series and the overlying Pleistocene pyroclasts with intercalated basalt of the Laikipian Group. The pyroclasts and lavas are very variable in composition and distribution, but decompose to a heavy residual clay that appears widespread. The presence of this clay has aided the construction of weirs and, although one stream appeared to be bypassing the gauging structure, water balance checks have shown the other catchments to be water-tight within the accuracy of the other hydrological measurements.

The soils developed on the volcanics are uniform over the catchments (Blackie, 1972). Profiles show a low-bulk density soil with a high organic content for the first metre, and dark-red friable clay below. Both horizons are porous and have high hydraulic conductivities (500 to 1500 mm h^{-1}) Moisture retention in the top 3.2 m at field capacity (1/3 atmosphere) is 1525 mm and at wilting point (15 atmospheres) the profile contains 760 mm.

The climate of the area is summarized in Table I. In an area with a mean annual rainfall in the order of 2400 mm, distributed as shown in Fig 2 of Section 1.2.1. and with over 220 rain days a year, 'dry season' is a relative term only. December to February have less rainfall than the other months and, whilst rainfall in June, July and August is again low, the potential evaporation is also reduced due to the frequent presence of cloud and mist. Wind speeds and temperatures vary little throughout the year. There are no marked seasonal checks on growth and the evergreen vegetation continues to transpire at or very close to the potential rate in the absence of any

TABLE I

Mean Climatological Data (1958-74)

Kimakia Forest Station

Altitude 2438 m, Latitude 0°48'S, Longitude 36°45'E

	Rainfall	Temperature			Humidity	Wind	Radiation	Sunshine
	Monthly Total	Max	Min	Mean	Saturation Deficit	Mean speed at 2 m	Gunn Bellani Radiometer	
	mm	°C	°C	°C	mb	km hr^{-1}	MJ m^{-2}	hr
Jan	90.4	20.1	6.9	13.5	3.7	9.5	26.4	8.3
Feb	118.8	20.7	7.3	14.0	4.5	9.6	26.9	8.5
Mar	195.1	20.4	8.5	14.4	4.5	10.6	26.2	8.2
Apr	435.5	19.0	9.5	14.3	3.1	9.5	22.3	6.9
May	363.9	17.8	9.1	13.4	2.2	7.6	18.5	5.3
Jun	126.9	16.5	7.5	12.0	2.0	6.6	17.2	4.9
Jul	86.5	14.8	7.2	11.0	1.4	5.5	13.2	3.1
Aug	85.3	15.0	7.1	11.1	1.4	5.9	9.6	3.3
Sep	78.0	17.5	6.8	12.2	2.6	7.9	21.3	6.0
Oct	226.0	18.4	8.3	13.4	3.4	9.7	23.3	7.1
Nov	306.9	18.2	8.8	13.5	2.8	10.7	21.6	6.4
Dec	121.5	19.1	7.1	13.1	3.1	8.5	24.6	7.7

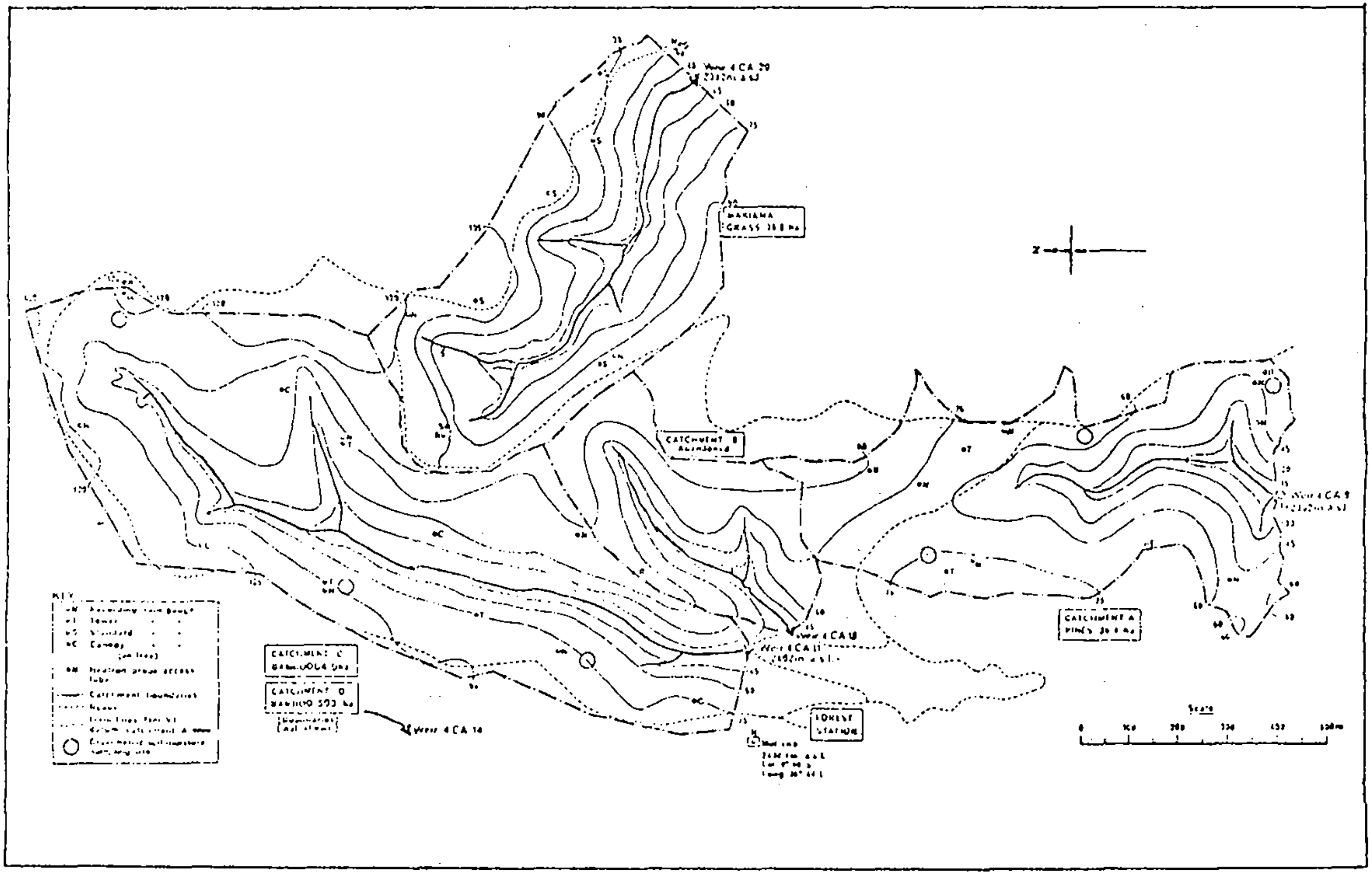

Figure 2 Rainfall networks in the Kimakia catchments

severe soil moisture stress.

INSTRUMENTATION OF THE EXPERIMENTAL CATCHMENTS

Details of the river gauging structures have already been presented in Section 1.2.4. To summarise, there are four operational river gauging structures maintained for the project. Catchment A has a compound 90° v-notch and sharp-crested rectangular weir covering the normal range of flows and a broad-crested section for high flows. Catchment C has an identical weir up to a stage of 1 m, above which the broad-crested weir differs slightly from that in Catchment A. Makiama also has a compound 90° v-notch and rectangular weir covering slightly different ranges in flow. Catchment D has a 90° v-notch weir across which a steel plate bolts to convert it into a sharp-crested rectangular weir for the higher flows. All structures have Lea Rotary Chart Recorders and, since 1970, Leupold and Stevens A35 Recorders have been added as principal instruments.

The rainfall networks are shown in Fig 2. In Catchment A, out of the original network of 10 gauges, a network of 6 were still operating in 1974. Three of these were tower gauges extending to canopy level; one was at standard height (0.3 m) on the weir wall, and two were check gauges associated with recording gauges on platforms in clearings. During the growth of the pines, the raingauges were raised, first by 'Dexion gauges' (see Pereira et al, 1962, p 8) and, later by telescopic towers which extended to the height of the pine canopy. A discussion of the performance of the various gauges making up the catchment networks is given in Section 1.2.1.

Catchment C has a network of nine gauges whose positions have remained virtually unchanged throughout the period of observation. The two Dines tilting siphon recording gauges are installed in a clearing some 10 m in diameter, and in the meteorological site adjacent to the catchment, respectively. One daily gauge is mounted on a post at a height of 1.5 m in a clearing. Originally, the remaining six gauges were mounted on platforms at canopy level, created by lopping *Podocarpus* trees. In 1972, three of these were replaced by tower gauges of the type used in Catchment A.

Catchment M has eight daily gauges and one Dines recorder; all are mounted on posts to avoid interference by sheep.

Catchment D has four 10-day gauges and a Dines recorder. One of the standard gauges is mounted on a tree and the remainder are mounted on posts.

A meteorological site at the Forest Station serves all the catchments. It is equipped with a Gunn-Bellani radiometer and a Lintronic solarimeter in addition to standard instruments and evaporation pans.

Initially, soil moisture was determined by sampling to a depth of three metres in three sites in both catchments A and C at monthly intervals. Gravimetric moisture contents, so determined, were converted to volumetric equivalents using the bulk densities measured at each depth and at each site. From 1968 onwards, neutron soil moisture meters were used on networks of six sites in each of Catchments A and C and at three sites in catchment M. Measurements were made at 10-day intervals in the 'dry' season and at monthly intervals during the remainder of the year. The results from the soil moisture measurements are discussed in Section 3.2.3.

Sediment sampling in Catchments A and C was conducted by taking daily samples of 568 cc (1 pint) from the weirs and bulking these into individual monthly samples, as described in Section 1.2.5. In 1972, an automatic sediment sampler was installed in Catchment D to monitor the storm sediment yield of the larger catchment.

PROGRESS OF THE EXPERIMENTS

Of the original objectives, the comparison of the intensively-instrumented catchments has been achieved. The large-scale studies on less intensively instrumented catchments were abandoned and replaced by two other experiments. The first, involving the introduction of sheep to a highland catchment, had a two-fold aim. First, to determine the feasibility of sheep-rearing at such altitudes and, secondly, to investigate the hydrological effects of replacing bamboo by short grass and to study the associated puddling and biotic influences connected with sheep-rearing. The second experiment has wide application, and covers the effects of converting indigenous forest to 'Shamba' cultivation. There is a ten-year period of records during which the catchment remained under forest. The land-use change took place in 1972 and it is too early yet (1974) to define the hydrological changes that are taking place on the catchment; preliminary results, however, are discussed in Section 3.2.2.

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3.1.2

FOREST POLICY IN RELATION TO LAND USE

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3.1.2

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POLICY REGARDING FOREST CONSERVATION

Policy regarding forest conservation is embedded in the Forest Policy for Kenya as outlined in Sessional Paper No 1 of 1968. The preamble to this Paper reads as follows:-

> "The forest estate of Kenya ranks high as one of the country's most important natural assets in its protective aspect of conservation of climate, water and soil".

This recognition of the importance of forest conservation is the basis of the Kenya Government's forest policy which lays down the basic principles guiding the development and control of forestry in Kenya for the greatest common good. These basic principles have been described under the following main headings:

Reservation of land for forest purposes;
Protection of the forest estate;
Management of the forest estate;
Industry;
Finance;
Employment;
Local Authority forests;
Private forests and other forests not under state ownership;
Public amenity and wildlife; and
Research and Education.

Under Reservation, the policy states that the Government is determined to reserve in perpetuity the existing forests and, wherever possible, add to them so as to provide sufficient land in order to:-

(i) Maintain and improve the climatic and physical conditions of the country;

(ii) Conserve and regulate water supplies by protection of catchments and by any other means necessary for the purpose, including the impounding of water in forest areas;

(iii) Conserve the soil by prevention of desiccation and soil movement caused by water and wind;

(iv) Provide for the needs of the country in timber and other forest products adequate to meet the requirements of the community under a fully-developed national economy, and provide the greatest possible surplus of those products for export markets.

Under Public amenity and wildlife, the policy states that "the Government recognises the value and importance of the forests of Kenya as areas of public amenity, and intends, within the limits set by principles of sound silviculture, to develop and use the forests to fulfil the needs of public amenity and recreation, and to preserve their natural flora and fauna. As far as possible, the principle of multiple land use will be followed so that forests, in addition to fulfilling their protective and productive roles, will be available for recreation purposes by the public. This will include the preservation of areas of special scenic value. Nature Reserves have been and will be declared for the protection of the flora and fauna, either for amenity purposes or for scientific study".

Since 1971, there has been greater emphasis on the establishment of privately owned woodlots and planting on farms. In that year, an extension service was formed, both to advise farmers on tree planting and care of tree crops, and also to make seedlings more easily (or even freely) available to them. The aim was to have at least one extension forester for each district in the country by 1976; in 1974, there were already officers in some 25 districts.

The hydrological research projects based at forest reserves in Kimakia and Kericho, in which the Kenya Forest Department participates, is in keeping with the Forest Department's policy on conservation.

POLICY REGARDING EXTENSION OF SOFTWOOD PLANTATIONS - THEIR AREA AND PROJECTED FIGURES

Land under forest is of three principal types in Kenya: indigenous forest occupying 1,700,000 ha; forest plantations which on 31 December 1973 occupied 135,250 ha (see Table I), and rural afforestation schemes. Except for an estimated 124,000 ha of privately-owned forest land, the forests of Kenya are publicly owned and administered; 53 per cent of the area by Central Government and 47 per cent by County Councils.

Because the commercially valuable species of the indigenous forest are extremely slow growing, the Government has for many years pursued a policy of replacing indigenous forests with plantations of exotic species. The exotic forest plantations are of faster-growing softwood species, and are capable of achieving a growth rate of 17 m^3 ha^{-1} yr^{-1} in areas of high rainfall. This growth potential is significantly higher than the growth rates possible in temperate countries, and for this reason Kenya could become a low cost producer of industrial woods in quantity.

Wooded areas established under the Rural Afforestation Programme serve two purposes. One type of afforestation is intended primarily to increase the production of building poles and fuelwood on private farmland in rural areas, the other aim is chiefly to protect steep slopes from excessive erosion.

In keeping with the Government policy of replacing indigenous forests with plantations of faster growing exotic species, the Kenya Government entered into a loan agreement with the World Bank to finance the softwood plantation programmes in Kenya. This agreement, signed in November 1969, consisted of two parts. One part was the planting of about 19,200 hectares of sawnwood,

TABLE I

Plantation Area (ha) on 31 December 1973

Division	Indigenous Softwoods	Indigenous Hardwoods	Exotic Softwoods		Exotic Hardwoods		Total
			Cypress	Pines	Timber	Fuel	
Kitale	256	55	3526	3270	46	399	7552
Kisumu	15	2065	636	1200	24	312	4252
Eldoret	312	312	8576	9522	60	508	19290
Londiani	629	166	4650	82 3280	111	783	10159
Nyahururu	341	90	4916	4547	146	590	10630
Elburgon	993	40	12937	9628	950	1098	25646
Nyeri	897	767	4337	4739	172	529	11441
Southern	53	40	1348	3997	81	908	6428
Coast	760	71	18	1491	61	86	2487
Embu	94	540	1182	1081	64	291	3252
Turbo	-	-	-	7241	-	22	7263
Nairobi	302	320	5959	6713	453	2936	16683
Baringo	843	161	4948	3942	31	242	10167
Total	5495	4627	53033	61191	2199	8704	135249

and the other part was the planting of about 9,200 hectares of pulpwood plantations between 1969-74. This project represented part of a long term forest industrial programme which aims at the establishment of about 130,000 hectares of pulpwood plantations by 1980. To date, about 104,000 hectares of saw log plantations and 19,000 hectares of pulpwood plantations have been established (Figure 1).

This project is expected to produce 1.3 million m^3yr^{-1} of saw log during the period 2000 to 2005 and about 0.4 million m^3yr^{-1} of pulpwood during the period 1984 to 1993. The saw logs will be used mainly for production of lumber for both domestic and export markets; the pulpwood will be utilized by the new integrated pulp and paper mill at Webuye which has an annual capacity of some 50,000 tons.

THE FOREST DEPARTMENT'S FUTURE GOALS

In spite of the fact that the Forest Department has made remarkable progress in all aspects of forestry since the attainment of Independence, the Department has ambitious proposals in its future plans, as outlined in the Development Plan 1974-1978. Listed below are some of the areas that the Department would like to strengthen and improve.

(i) Rural Afforestation Scheme

As mentioned earlier in this paper, it is the Department's goal to open up an extension forestry programme in every district. It is hoped that before the end of the current Development Plan, all the 41 administrative districts in Kenya will have at least one forest officer in charge of the extension programme. These officers not only provide rural areas with technical advice but also supply seedlings to farmers and local authorities; they also ensure that as many green belts as possible are established in the rural areas, especially where some existing ones are in poor condition. The same officers will assist in species trials in areas where no research has been undertaken in the past. This programme is aimed at making a significant impact in

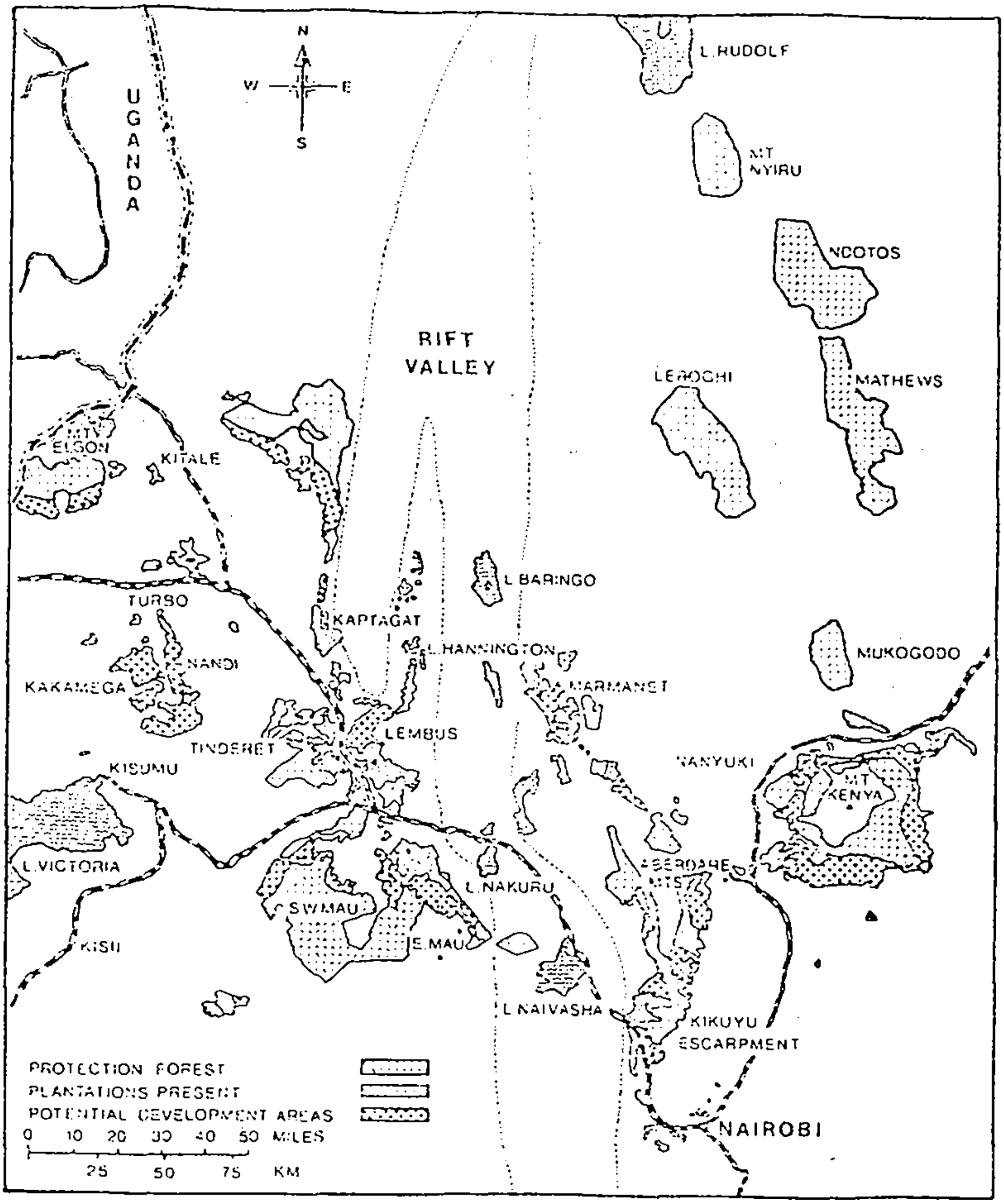

Figure 1 Geographical distribution of protection forest and plantation forest in Kenya

conservation of soil and water catchments in the rural areas.

(ii) Research in Marginal Areas and Coastal Lands

Until now (1974) most of the forestry in Kenya has been confined to highland areas with plentiful rainfall and good soils; forestry in the low-rainfall marginal areas of Kenya has been less well-developed. The Department has now started, and hopes to strengthen, its research programmes in the marginal areas of Kenya. Similar plans for strengthening research programmes will apply in the coastal areas.

(iii) Strengthening of Research Based Sections

The research based sections, eg entomology, pathology, silviculture and utilization, will be strengthened both in staff and equipment to cope with all the proposed expansions in research work.

(iv) Fire Unit

Until now (1974) the Department has not had a separate specialised fire unit to deal with fire problems within the Department, as fire fighting in the field has always been in the hands of field officers. The Department has now set up a specialised fire fighting unit to deal with all problems relating to fires within the Department.

(v) Indigenous Species

It is the Department's wish to strengthen research on the establishment and regeneration of our indigenous species, some of which have hitherto been replaced with exotic, faster-growing species. This programme will be carried out along with the plantation programmes. Conservation and better management of exploitation of the mangrove forests in the coast will also be instituted.

3.1.3

REAFFORESTATION POLICY AT KIMAKIA FOREST STATION

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3.1.3

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INTRODUCTION

Kimakia Forest Station was opened in 1956 with the object of replacing 2025 ha of indigenous bamboo forest with uniform plantations of exotic coniferous trees between 1957 and 1968. Gatare Forest Station, 5 km to the north, was open simultaneously with a similar planting programme; the combined 5000 ha of plantations was planned to contribute to the national softwood planting target of 122,000 ha to be established by 1980 (Dyson, 1958).

At about this time, the national target has been revised to increase the annual rate of planting, and this has necessitated the opening of new forest stations (Min For Dev, 1959). The decision to open two new forest stations in the south-east Aberdare Forest Reserve was made on social and economic grounds, rather than for technical forestry reasons. Indeed, until 1954, the south-west Aberdares were considered too steep and inaccessible for commercial afforestation and exploitation had been confined to cautious selective fellings of overmature, scattered, indigenous trees. The work, carried out mainly during the war period 1939-1945, and undertaken by hand sawyers using pit saws, caused little disturbance of the natural forest and was mostly below the lower edge of the bamboo forest zone. Improved access tracks built during the Mau-Mau Emergency (1952-1957) and particularly more readily available aerial photographic cover showed that while the lower, eastern fringe of the forests was extremely steep difficult country, at higher altitude, in the bamboo zone, the ridges were broader and less steeply sloping. These broader ridges appeared suitable for cultivation and reafforestation by the 'shamba' method (Oland, 1962) using large numbers of resident forest labourers. In 1956, the adjacent Kikuyu lands were overcrowded with landless, unemployed families, who had been compulsorily returned to Kikuyu-land from the large settler farms west of the Rift Valley during the Mau-Mau Emergency. Thus, the opportunity to absorb six hundred of these families into paid permanent employment in reafforestation was welcomed by the Provincial Administration as a social measure, besides representing a substantial contribution to the National Softwood Planting Programme. Three hundred labourers with their families were recruited to each new forest station and housing, shops, schools, dispensaries and other social amenities were built during the years 1957-1959.

METHODS OF REAFFORESTATION

Since the prime object of opening Kimakia and Gatare Forest Stations was the re-settlement of landless Kikuyu labourers, the 'shamba' system of establishment was prescribed for as much of the planting programme as possible. Under this system, the bamboo is cut down, cleared, and the residues burnt. The land is then cultivated by hand and planted with food crops by the labourers who maintain the land in cultivation for two to three years. In the second year, tree plants, previously raised in a forest nursery to 30 to 50 cm tall, are planted at regular spacing into the cleared land. Food crops continue to be grown between the small trees until the trees become too large to allow profitable food crops to survive between them. New areas of land are allocated to the labourers from time to time so as to provide continuous agricultural production. The intensive weeding necessary to raise the food crops provides an unrivalled start to the young tree crops, which is only surpassed by raising them in entirely clean-cultivated land. On average, a Kikuyu resident labourer family cultivating easily-cleared bamboo forest provides about 0.6 ha of cleared land for tree planting each year. Thus with 300 families, about 180 ha yr^{-1} could be planted by the 'shamba' system at Kimakia towards the annual target of 200 ha. The balance of 20 ha was achieved by direct planting into cleared and burnt patches of grassland and bush, without benefit of cultivation. The latter method was prescribed for all areas exceeding 30% slope on which it was feared that cultivation might result in excessive soil erosion.

In the event, it was found that the areas of easily accessible ridge tops suitable for cultivation had been over-estimated and also that the 'shamba' planting went ahead faster than had been planned. Similarly, all easily accessible areas of grassland and short bush were converted by direct planting early in the ten-year plan period. By mid-1962, therefore, it was necessary to reduce progressively the labour force (by transfer to other forest stations and by not replacing natural losses) and to reduce the planting programme. At the end of 1968, a total of 1555 ha had been planted and reafforestation now continues at a rate of about 75 ha yr^{-1}.

CHOICE OF TREE SPECIES

The indigenous forests of tropical Africa contain few coniferous tree species capable of yielding the light, pale-coloured, easily-worked, softwood timbers of commerce (the more abundant hardwood species tend to yield timbers suitable for specialist use for which demand is limited). Such conifers as do occur are found mostly in mountain forests at elevations exceeding 2000 m where they comprise rather sparse stands mixed with hardwood species. Kenya, with its mountain forests containing the pencil cedar, *Juniperus procera*, and two species of podo, *Podocarpus milanjianus* and *P gracilior*, was more fortunate than most other African countries in having some general purpose softwood timber available, upon which the early sawmilling industry was based (Gardner, 1932). As early as 1910, however, it was recognised that the indigenous mountain forests, which cover less than two per cent of Kenya's land area, could not supply the timber needs of a developing country for more than a few decades (Hutchins, 1909). A programme of tree species trials was put in hand, therefore, to seek more productive coniferous trees with which to replace the indigenous *Juniperus* and *Podocarpus*. The early trials were successful and after some vacillation, a firm policy of establishing compensatory plantations of exotic conifers was adopted in 1927 (Logie and

Dyson, 1962). Yields of the new plantations frequently exceeded those of the indigenous forest they were established to replace by elevenfold (Dyson, 1965). The plantations have further economic advantages in producing uniform logs of one species and of comparatively even size and quality on a compact, accessible area of land.

The main requirements of a tree species to be used for commercial forestry planting are: mature trees should yield the type of forest produce required (in this case general purpose softwood timber); its seed should be readily available; seedlings can be easily raised in a nursery and transplanted to the field successfully; the young trees should grow rapidly and healthily to form a closed forest crop. Of the many exotic conifers tried for compensatory plantations in Kenya, two species of cypress and two of pine proved outstandingly suitable for highland sites: *Cupressus macrocarpa; C lusitanica; Pinus patula; P radiata.* All four species had been grown successfully in the Kikuyu Escarpment Forest Reserve about 10 km south of Kimakia. Departmental instructions under the Craib 'b' Plan (Min For Dev, op cit), required that they be planted in the proportions 40% cypress, 50% pine and 5% other species, used for firebreaks etc. By 1956, planting of *Cupressus macrocarpa* had been stopped because of disease problems and *Pinus radiata* was suspected of being less suitable on sites receiving prolonged periods of mountain mists, such as occur at Kimakia, and was restricted to an experimental area of 20 ha yr^{-1} for the first five years. This caution was vindicated in 1962 when the greater part of the *P radiata* plantations succumbed to needle blight following three seasons of exceptionally high rainfall. Thus, the main planting programme was completed with *Cupressus lusitanica* and *Pinus patula*. Smaller areas were also planted with *Pinus elliottii, P caribaea, Cryptomeria japonica* and *Araucaria angustifolia*. *Pinus elliottii* and *P caribaea* do not grow well at such high altitude, the *Cryptomeria* has produced a well-formed but slow growing crop and the *Araucaria* has developed into an excellent crop. Unfortunately seed of the latter species is difficult to obtain and a maximum of 20 ha yr^{-1} can be planted with the seed that is available.

A small arboretum comprising about forty coniferous species was established at Kimakia between 1956 and 1959 but none of the other species has done as well as the original choice of *Cupressus lusitanica* and *Pinus patula* (Chapman and Wormald, 1966).

CONCLUSIONS

In conclusion, it may be said that replacement of bamboo forest by plantations of exotic conifers has been successful. Two-thirds of the area originally planned for conversion was achieved in the plan period 1957-1968, and the remaining area is gradually being converted by the small residual labour force required to protect and maintain the established plantations. Thinnings from the older plantations (1974) already contribute a substantial volume of logs to a small sawmill 2 km south east of Kimakia. Clear fellings of the less productive *Pinus elliottii* plantations have commenced, and will build up to yield large quantities of timber in the early nineteen eighties, when the main plantation areas reach rotation age. The forest villages, originally established to settle landless people, have now developed into thriving permanent communities, and land which in 1956 was uninhabited has been converted into a valuable productive area.

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3.2.1

THE WATER BALANCE OF THE KIMAKIA CATCHMENTS

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3.2.1

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INTRODUCTION

As described in Section 3.1.1, the original objective of this study was to determine the effects on the hydrology of this area of the South East Aberdare Mountains of a change in land use from the indigenous bamboo forest to pine plantation. The central part of the experimental programme comprised the instrumentation of two catchments and a meteorological site to measure rainfall, streamflow, soil moisture change and the meteorological variables necessary to estimate Penman's potential evaporation. Those parts of the 36.4 ha Catchment A conforming to the Forest Department criteria regarding slope and distance from the stream discussed in Section 3.1.2, amounting to 27.5 ha or 75% of area, were cleared and planted to *Pinus patula*. The second catchment, designated Catchment C, was of area 64.9 ha and remained under bamboo. Hydrological measurements were recorded on these two catchments from 1958 onwards. A preliminary analysis of these data was presented by Pereira et al in 1962. This showed that water use by the experimental catchment was some 40% lower than the control catchment immediately after clear felling, but increased rapidly as the pines developed. The very high infiltration rates of these forest soils of volcanic origin resulted in no appreciable increase in surface runoff from the overall 1.5% of rainfall recorded in the control Catchment C during the period in which Catchment A was cleared and planted. Further analyses, presented by Dagg and Blackie in 1965, indicated that water use by the experimental catchment appeared to be stabilising by 1964, when the pines were some 12 m tall. However, indications of a departure trend between the two catchments required further investigation.

In the period 1964-66 a third catchment, M, of 36.8 ha was instrumented with the intention of studying the effects of high density grazing. Problems arose in implementing this study, but some 33% of the catchment was planted to grass *(Penisetum clandestinum)* in 1964-65, and grazed sporadically until 1971 when a controlled grazing exercise was imposed. This study was developed further by increasing the area under pasture to 63% in 1973-74.

The latter exercise, together with the need to investigate the apparent trends in water use in Catchments A and C, justified continuing the data collection beyond 1966. Co-operation with the Institute of Hydrology from 1968 and a catchment research project sponsored by the United Kingdom Overseas Development Ministry from 1972 made it possible to upgrade the catchment instrumentation, mount the accumulated data on computer tape and carry out much more detailed quality control.

In this paper, the significant errors detected in the data and the corrections applied are described; the subsequent accuracy of the data is assessed and water balance analyses are presented. Interpretation of the results in terms of the hydrological processes governing catchment response is discussed and finally consideration is given to methods whereby the results can be extrapolated temporally and spatially.

ACCURACY OF THE DATA

The networks introduced to measure rainfall and soil moisture, together with the structures used for streamflow measurement and the meteorological site are described in Sections 1.2.1, 1.2.4 and 3.1.1.

Rainfall

The precision of the network estimates of rainfall is discussed in detail in Section 1.2.1. Almost without exception, the standard error of the annual means for each catchment is less than 2%. Possible systematic errors could arise from mist interception during the cloudy June to August period each year, and from the exposure of the gauges at canopy level over the bamboo and pines. No satisfactory method of estimating the former is available, but a study by Pereira et al (op cit) indicated that canopy exposure can be expected to have minimal effect.

Soil Moisture

Soil moisture estimation by the gravimetric method described in Section 1.2.3 did not produce results of precision comparable with that obtained at Kericho (Section 2.2.1). In general, the standard errors of the catchment mean moisture content were of the order of 50 mm or 3.5%, but they ranged from under 10 mm to greater than 150 mm. Two main reasons for this scatter were overuse of restricted sampling areas and the variability in the depth of transition from the black, high organic content surface soils to the underlying red volcanics. With the introduction of the neutron probe equipment in 1968, these sources of error were eliminated and the precision of the estimates improved. In 1970, for example, the average standard error in the Catchment C (control) means was some 20 mm.

The rainfall distribution at Kimakia is such that prolonged periods of moisture stress are rare. The deficits developed under bamboo in one such period in 1961 are illustrated in Figure 1; this shows no evidence of moisture abstraction from beyond the sampling depth.

Streamflow

As indicated in Section 1.2.4, the uncertainty attached to the ratings of the streamflow structures was in the region of 2%. Errors arising from the method of water-level recording and interpretation were essentially random, and were not considered to increase significantly this uncertainty in cumulative flow over a year or more. A detailed check of the catchment areas revealed errors of + 0.5% and - 2.7 % in

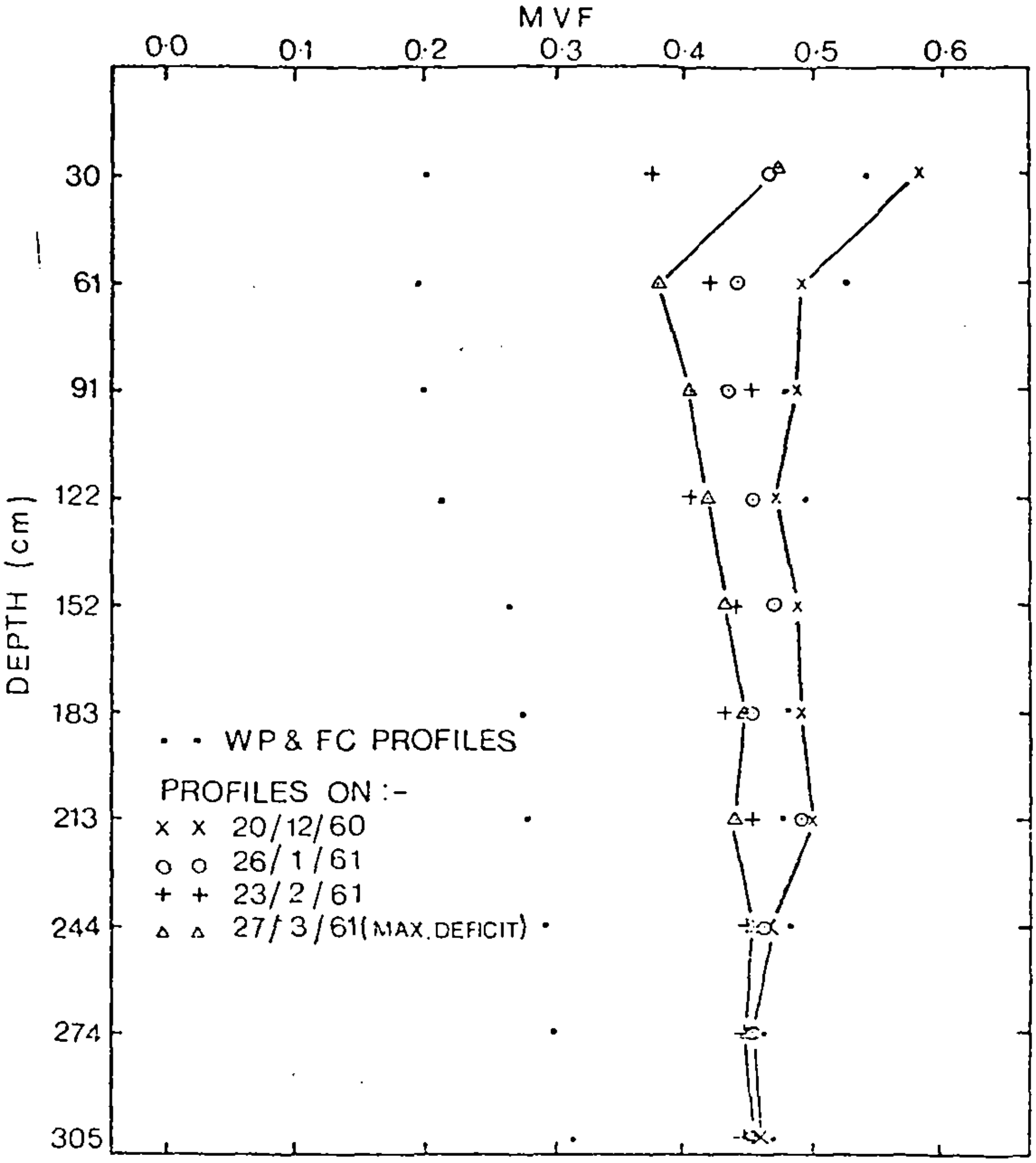

Figure 1 1961 dry season soil moisture profiles under bamboo in Catchment C

Catchments C and A respectively, for which the appropriate corrections were made.

One possible source of systematic error affecting Catchment A (pines) was a slow movement of bedload into the weir stilling pool from 1964 onwards. This could result in a partial blockage of the pipe to the recorder well; in general, errors from this source were minimised by regular cleaning of the stilling pool and correction of the levels against staff gauge readings. It is possible, however, that this source of error may have contributed to the anomalously high 1964 flows (see Tables II and IV). This point is discussed in the paragraphs given below on modelling.

A systematic error in streamflow from Catchment C (bamboo) was eventually identified as the source of the apparent downward trend in water use in this catchment referred to by Dagg and Blackie (op cit). This error arose from the sinking of the concrete base of the reference level, against which the recorder was set, relative to the weir by some 20 mm. Detailed inspection of the records suggested that this had not happened instantaneously. The following tests: (a) double mass plotting of streamflow against rainfall; (b) regression of streamflow on rainfall; (c) regression against streamflow from Catchment M; and (d) regression against flow from the adjacent bamboo covered Catchment D, all indicated that the movement had occurred between late 1961 and 1966. In the absence of any other means of identifying the time interval and sink-rate more precisely, a variety of possible durations and rates were postulated, and the resulting computed flow tested using the methods (a) to (d) mentioned above. These tests were not particularly sensitive, and each involved assumptions which could not be fully justified; nevertheless, the correction finally applied assumed that the movement started during the extremely heavy short rains of 1961, when 1300 mm fell in October and November, and continued at a uniform vertical rate reaching 20 mm displacement in June 1964. The 'corrected' flow so computed is compared with the uncorrected flow and with flow from Catchment D in Figure 2. Whilst this correction was considered reasonable on the evidence available, a residual uncertainty remains over the 1961-66 flow data from Catchment C.

Penman Estimate of Evaporation

Rigorous examination of the meteorological data collected at the Kimakia site revealed, in addition to the expected intermittent random observational errors, two important sources of systematic error in the initial Penman estimates. These were in the radiation measurements over the periods March 1961 to August 1961 and from February 1969 to May 1969, and in the windrun measurements from mid 1966 onwards.

The radiation measurements were derived from Gunn Bellani radiation integrators as described in Section 1.2.2. Five of these instruments were used successively between 1958 and 1974. To check for systematic error due to these changes in instrument, monthly mean daily radiation was regressed on sunshine hours for the period covered by each, using the expression

$$R_c/R_a = a + b\,(n/N)$$

where R_c, n are observed and

R_a, N are maximum possible values of radiation and sunshine hours respectively.

Correlation coefficients were greater than 0.99 for the first (January 1958 to February 1961), third (September 1961 to April 1965) and fifth (July 1970 to June 1974) periods and also for the fourth (May 1965 to June 1970) when data for February 1969 to May 1969 were excluded. Investigation suggested possible temporary alteration to the instrument mounting during the latter period. The scatter in the relationship suggested that the second instrument had never worked satisfactorily during its brief period (March 1961 to

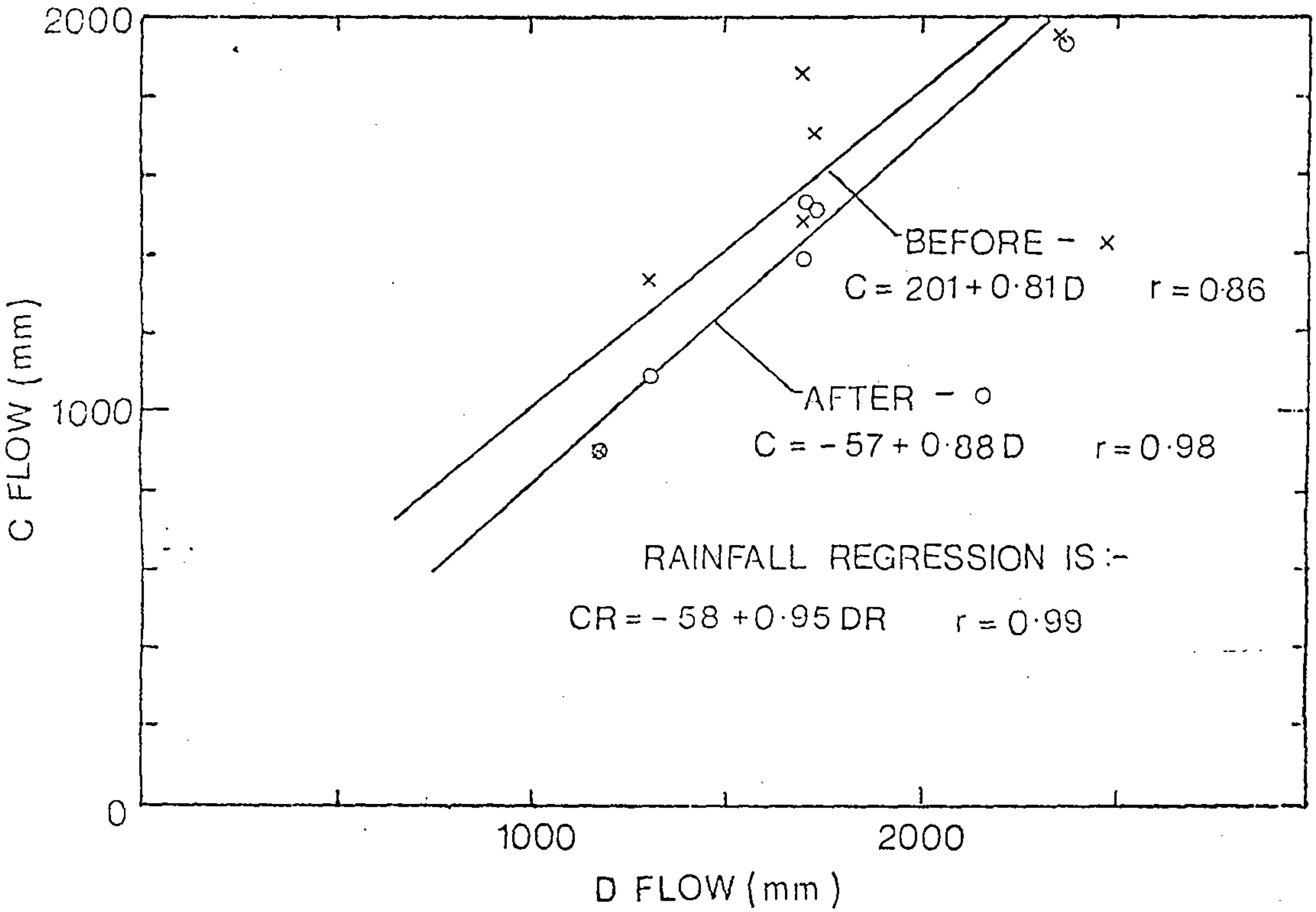

Figure 2 Comparison of 1960-65 annual flows from Catchments C and D before and after correction of C

August 1961) on site. Analysis of variance indicated that the slopes, b, and intercepts, a, did not differ from those in the expression obtained from the entire data run when the above problem periods were excluded. This expression,

$$R_c/R_a = 0.201 + 0.635\ n/N$$

based on 187 data points and with r = 0.999, was used to infill radiation from measured sunshine hours in the periods March 1961 to August 1961 and February 1969 to May 1969. With these corrections, the radiation data were considered to be internally consistent throughout the period of data. Comparisons with a Lintronic solarimeter over periods of several weeks at intervals from 1969 onwards, and with the Kipp solarimeter on an automatic weather station for three months in 1974, produced no evidence of bias in the Gunn Bellani results.

The windrun data from Kimakia had a pronounced downward trend inconsistent with the other meteorological variables. Monthly mean values from 1968 onwards were in the region of 60% of those recorded prior to 1963. That this difference was not due to instrumental error was apparent from the record of instrument changes and intercomparisons. The meteorological site is situated on a shallow saddle on a north/south oriented ridge; the only change in exposure to the prevailing easterly winds was the growth of an open line of *Hagenia abyssinica* trees some 30 to 50 m to the east of the anemometer. (These are visible in Section 3.1.1).

To quantify the shelter effect presumed to have arisen from the trees, and correct the data, it was necessary to compare with a similar site elsewhere. The meteorological site at EAAFRO (latitude 1°13'S, longitude 36°38'E) some 80 km to the south and 300 m lower in altitude has a very similar topographic exposure and, as shown in Table 1, experiences very similar

TABLE I

Comparison of 1960-73 Mean Climatic Variables from Kimakia and EAAFRO Meteorological Sites

Site	J	F	M	A	M	J	J	A	S	O	N	D
Radiation (MJm^{-2})												
Kimakia*	23.6	24.1	23.5	19.9	16.6	15.2	11.8	12.7	18.9	20.9	19.1	21.9
EAAFRO	23.7	23.9	23.1	19.8	16.3	16.1	13.7	15.4	20.1	21.6	20.7	22.2
Mean Temperature (°C)												
Kimakia	13.5	14.0	14.4	14.3	13.4	12.0	11.0	11.0	12.2	13.4	13.5	13.1
EAAFRO	16.7	17.3	17.6	16.9	15.7	14.3	13.5	13.8	15.2	16.5	16.2	15.3
Rainfall (mm)												
Kimakia	99	120	175	442	367	125	66	84	81	252	317	125
EAAFRO	75	43	79	216	165	34	15	23	23	61	139	93
Windrun (km/day), 1960-65												
Kimakia	207	219	232	204	179	155	130	132	170	213	212	198
EAAFRO	270	282	307	257	209	190	183	205	244	301	290	270

* Incorporating the corrected values (see text)

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F (not F)	0.763	0.760.
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Section 3.2.1

ACCURACY OF THE DATA

Penman estimate of evaporation ✓

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Section 3.1.1.

INSTRUMENTATION OF ...

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Section 3.2.1.

Table I ✓

Radiation * (MJm^{-2})

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CATCHMENT DATA ✓

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seasonal trends in climate. The EAAFRO windrun record was known to be consistently good from 1960-72, the only significant change in exposure to the prevailing wind occurring in 1973. Regression of monthly mean daily windrun for Kimakia on that from EAAFRO produced the results shown in Figure 3. A remarkably stable relationship up to the end of 1965 was followed by an abrupt downward trend through the first six months of 1966; a stable period ensued until mid 1967, to be followed by another to mid 1968. From this point no further trends could be distinguished, and the relationship over the period July 1968 to June 1974 (excluding 1973) exhibits a precision only marginally lower than that of the first six years. The data were corrected, therefore, on the basis of the transformation necessary to bring each regression into line with that determined for the first period. On average, the effect of this correction was to increase the Penman EO estimates over the period 1968-74 by some 5%.

Groundwater

In the absence of any systematic measurement of groundwater in the catchments, the change in storage, ΔG, over water years was estimated from empirically-constructed recession curves (Blackie, 1972). That for Catchment C (control) is illustrated in Figure 4. The accuracy of these estimates of storage change is not high, but by ensuring that they are made only between low flow conditions, the error should not exceed 20 mm.

CATCHMENT DATA

The data obtained from the Kimakia catchments, with the above mentioned corrections incorporated, have been made available in the form of daily rainfall, streamflow, Penman EO and ET, and monthly means of the meteorological variables (Edwards, Blackie et al, 1976). In Table II they are summarised in the form of annual totals of rainfall, streamflow and raindays ($R \geq 0.1$ mm). The similarity between C, A, and M in rainfall trend is evident, as is the increase in totals in rainfall with mean catchment altitude (see Figure 1 of Section 3.1.1). The close

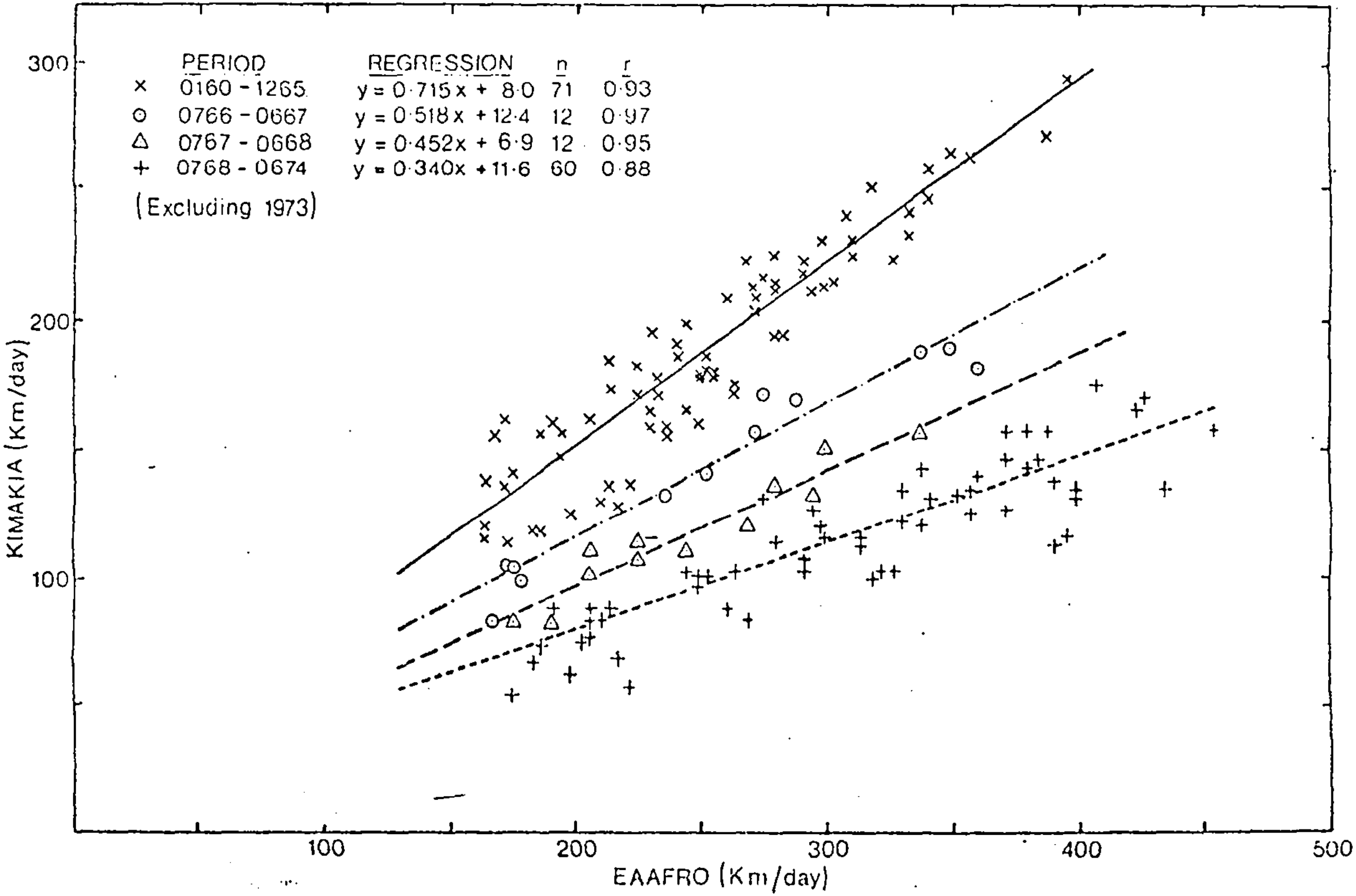

Figure 3 Comparison of monthly mean windrun at Kimakia and EAAFRO

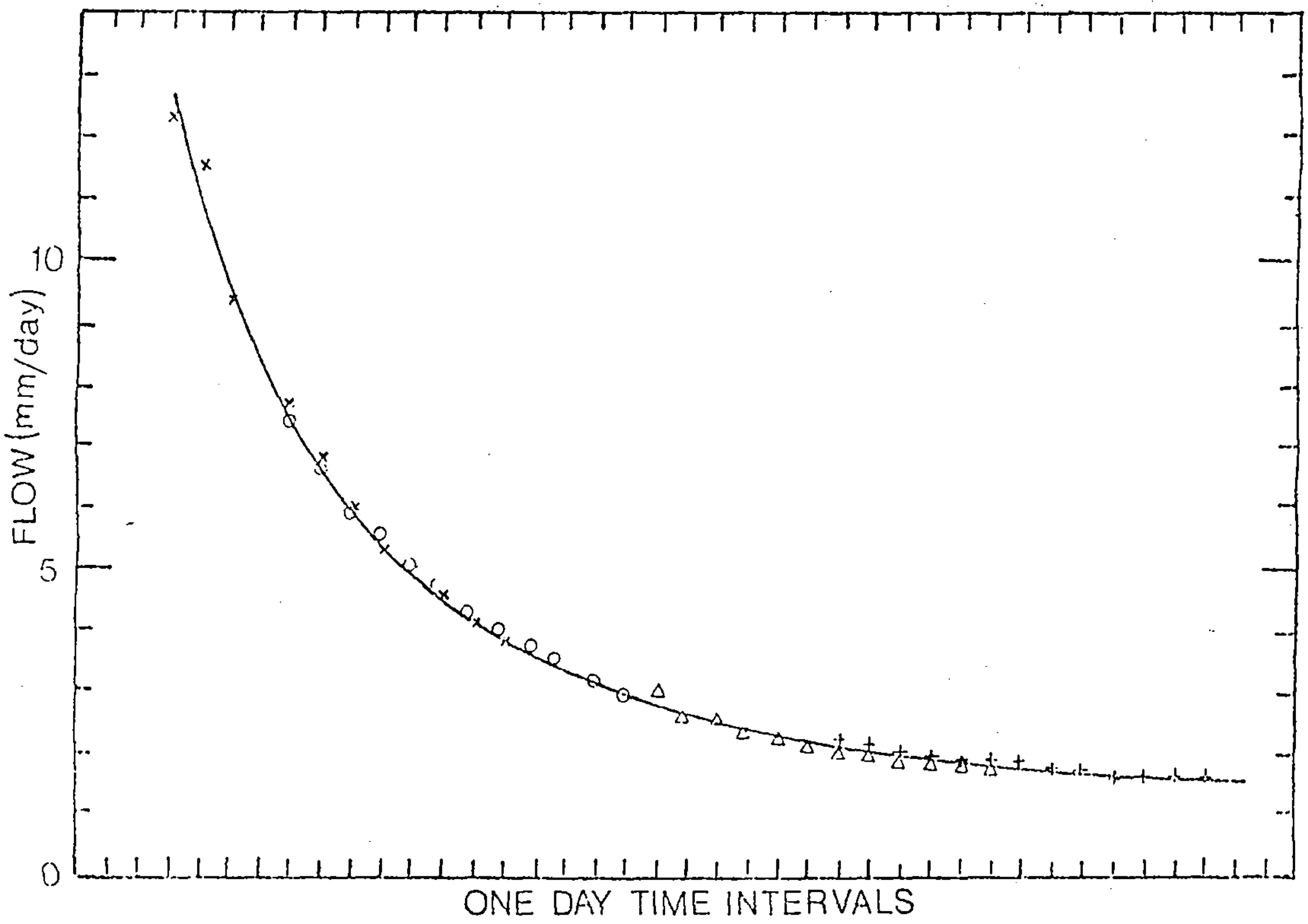

Figure 4 Composite baseflow recession curve for Catchment C

TABLE II

Calendar Year Totals of Rainfall, Streamflow and Raindays

Year	Rainfall (mm) C	Rainfall (mm) A	Rainfall (mm) M	Streamflow (mm) C	Streamflow (mm) A	Streamflow (mm) M	Raindays C	Raindays A	Raindays M
1958	2528	2367	-	1385	1480	-	254	221	-
1959	1905	1818	-	833	919	-	252	214	-
1960	1992	1849	-	908	953	-	249	229	-
1961	3294	3221	-	1953	1858	-	259	239	-
1962	2453	2358	-	1392	1329	-	243	227	-
1963	2754	2713	-	1516	1497	-	241	221	-
1964	2599	2476	-	1531	1611	-	246	233	-
1965	2341	2181	-	1085	1063	-	225	225	-
1966	2350	2238	-	1240	1174	-	218	212	-
1967	2191	2024	2158	953	834	1040	217	212	205
1968	2637	2521	2559	1488	1389	1560	246	245	240
1969	1583	1499	1506	511	454	543	211	200	193
1970	2221	2085	2142	1027	833	1029	234	231	222
1971	1988	1746	1861	790	630	789	222	207	205
1972	2484	2291	2396	1268	1015	1235	228	222	227
1973	1874	1788	1815	786	658	863	210	206	199
1958-73									
TOTAL	37193	35175	-	18666	17696	-	3755	3544	-
MEAN	2325	2198	-	1167	1106	-	235	221	-
SD	±413	±426	-	±370	±393	-	±16	±12	-
1967-73									
TOTAL	14978	13954	14437	6823	5813	7059	1568	1523	1491
MEAN	2140	1993	2062	975	830	1008	224	218	213
SD	±360	±347	±361	±326	±305	±327	±13	±16	±17

C is the control, bamboo catchment
A is the catchment under pines
M is the partially grassed catchment

similarity in seasonal distribution is illustrated in Table III. The standard deviations of the monthly means of rainfall and of Penman EO emphasise the conservative nature of the latter.

LONG TERM WATER USE

The annual values of rainfall minus flow (R-Q) and of Penman EO are shown in Table IV. The long-term means of R-Q present an immediate comparison of water use between catchments and with Penman EO. Whilst the annual values must be treated with caution because of possible storage changes, the overall indication is of a close similarity in water use between the bamboo control and the pine catchment after the first few years. In Table V the R-Q estimates of water use over each phase of development in Catchment A (pines) are compared. Whilst the 1961-66 figures may still incorporate some systematic errors as described above, the similarity in water use over the 'mature' 1967-73 period suggests that, over this phase of growth, no deleterious effects on water supply arise from this change in land use.

Table VI presents a similar comparison for the development stages of Catchment M (pasture). Though the short duration of the intensive grazing period increases the uncertainty in the water use estimated from R-Q alone, the figures suggest the transition from sporadic to intensive grazing on the 33% of the catchment under grass had no immediate effect on water use. Overall, the water use of the vegetation cover comprising 33% grass, 47% bamboo and 13% softwood plantation *(P widdringtonia)* and 7% heath is seen to be some 10% lower than that of the control Catchment C. The extent to which the increase in grass cover in 1973 and long term intensive grazing will change this remains to be seen.

The water use figures presented in Tables V and VI are compared with Penman EO in Table VII. The magnitudes of the ratios show little variation with time except in the early growth

TABLE III

Mean and Standard Deviations of Monthly Rainfall, Streamflow, Raindays and Penman EO for the Kimakia Catchments, 1967-73

Catchment	J	F	M	A	M	J	J	A	S	O	N	D	Annual
						Rainfall (mm)							
C	102 ±90	145 ±88	134 ±109	374 ±153	384 ±77	143 ±36	83 ±27	77 ±21	86 ±48	236 ±136	289 ±123	86 ±67	2140 ±360
A	97 ±85	132 ±91	126 ±96	359 ±149	346 ±66	128 ±42	71 ±24	68 ±18	77 ±40	218 ±117	284 ±124	87 ±72	1993 ±347
M	100 ±91	133 ±84	126 ±106	367 ±150	372 ±73	137 ±37	79 ±28	71 ±21	81 ±46	231 ±136	282 ±124	85 ±68	2062 ±361
							Raindays						
C	10 ±7	13 ±5	16 ±8	25 ±4	27 ±4	21 ±2	21 ±4	20 ±2	14 ±4	19 ±5	24 ±4	12 ±4	224 ±13
A	10 ±6	13 ±5	15 ±8	24 ±5	27 ±4	20 ±3	21 ±3	20 ±2	13 ±3	19 ±5	24 ±4	11 ±4	217 ±16
M	10 ±6	13 ±6	14 ±8	24 ±5	27 ±4	20 ±3	20 ±3	19 ±2	13 ±3	19 ±5	24 ±3	11 ±4	213 ±17
						Streamflow (mm)							
C	31 ±12	31 ±22	30 ±18	101 ±113	229 ±108	128 ±48	57 ±17	40 ±15	31 ±11	52 ±53	160 ±146	85 ±77	975 ±326
A	31 ±12	24 ±11	24 ±13	56 ±51	168 ±104	132 ±44	62 ±20	40 ±11	29 ±8	32 ±15	134 ±132	98 ±100	830 ±305
M	35 ±11	29 ±15	30 ±15	101 ±103	231 ±99	136 ±49	60 ±18	42 ±14	33 ±11	49 ±34	168 ±150	95 ±87	1008 ±327
						Penman EO (mm)							
	160 ±25	149 ±20	174 ±30	138 ±21	106 ±8	86 ±7	71 ±11	78 ±15	127 ±7	144 ±13	125 ±16	155 ±12	1513 ±71

TABLE IV

Calendar Year Totals of Rainfall Minus Streamflow and of EO

Year	R-Q (mm)			EO (mm)
	C	A	M	
1958	1143	887	-	1495
1959	1072	899	-	1555
1960	1084	896	-	1574
1961	1341	1363	-	1564
1962	1061	1029	-	1438
1963	1238	1216	-	1451
1964	1068	865	-	1320
1965	1256	1118	-	1433
1966	1110	1064	-	1487
1967	1238	1190	1118	1576
1968	1149	1132	999	1398
1969	1072	1045	963	1545
1970	1194	1252	1113	1431
1971	1198	1116	1072	1509
1972	1216	1276	1161	1566
1973	1088	1130	952	1565
58-73				
TOTAL	18528	17478	-	23906
MEAN	1158	1092	-	1494
SD	±85	±150	-	±76
67-73				
TOTAL	8155	8141	7378	10590
MEAN	1165	1163	1054	1513
SD	±64	±81	±82	±71

TABLE V

Comparison of Long-Term Water Use, Estimated from R-Q, Between the Control Bamboo Catchment C and the Pine Catchment A

Period	Catchment A Status	R-Q A	R-Q C	Differences (mm) A-C	Differences %C
1958-60	Pine seedlings with vegetable intercropping	2682	3299	-617	-18.7
1961-66	Rapid growth from 5 to 15 m canopy closure	6655	7074	-419	- 5.9
1967-73	Continuing growth from 15 to 25 m. Stabilised canopy	8141	8155	- 14	- 0.2

TABLE VI

Comparison of Long-Term Water Use, Estimated from R-Q, Between the Control Bamboo Catchment C and the Part Grazed Catchment M

Period	Catchment M Status	R-Q		Differences	
		M	C	(mm) M-C	%C
1967-70	Sporadic grazing of 33% under grass	4193	4653	-460	- 9.9
1971-72	Intensive grazing of above grass area	2233	2414	-181	- 7.5
1973	Clear felling additional bamboo to bring grass area to 63%	952	1088	-136	-12.5

TABLE VII

Comparison of R-Q with Penman EO for the Periods Described in Tables V and VI

Period	(R-Q)/EO A	 M	 C
1958-60	0.58	-	0.71
1961-66	0.77	-	0.81
1967-73	0.77	0.70	0.77
1967-70	0.78	0.70	0.78
1971-72	0.78	0.73	0.78
1973	0.72	0.61	0.70

phase in Catchment A. The extent to which this is a possible basis for extrapolation of the results is investigated further in the following paragraphs.

COMPARISON OF WATER YEAR DATA

To obtain precise estimates of water use over short time intervals, it is necessary to evaluate the storage terms ΔS and ΔG in the general water balance expression (Section 1.1). In these catchments, it is possible to quantify them with reasonable precision, relative to R-Q, only between times when the catchment is experiencing a deficit and the streamflow level is on the lower range of the recession: this means, effectively, intervals of approximately one year between dry seasons.

Applying the criteria for the choice of water years described in Section 2.2.1, estimates of water use, AE, have been computed for Catchments C (control) and A (pines) and are listed in detail in Tables VIII and IX. For case of comparison, the AE values for comparable water years, expressed in mean mm day^{-1}, are illustrated in Figure 5 and the ratios AE/EO in Figure 6.

These water year figures confirm the low water use of Catchment A (pines) relative to Catchment C (bamboo) in the early seedling stage of pine growth and the very close similarity from 1967 onwards. The low values of AE for Catchment A in the 1964 water year cannot be related to any noticeable change in vegetation or management. As shown in Figure 7, it coincides with the largest departure in water year rainfall between the catchments. The water year also covers the period discussed earlier in which streamflow from Catchment A may have been affected by bedload movement. The adequacy of the correction to streamflow from Catchment C restricts the conclusions that can be drawn from comparison of the data over the middle periods from 1961-66; nevertheless, a transition from the distinct difference in water use initially

TABLE VIII

Water Use Estimates, AE, for the Control Catchment C

Water Year Ref No	Starting Date	Rain mm	Flow mm	ΔS mm	ΔG mm	AE mm	EO mm	AE/EO
58	26.02.58	2322	1381	- 97	-52	1090	1497	0.73
59	24.02.59	1858	792	+ 49	+24	993	1404	0.71
60	28.01.60	1966	895	- 21	-16	1108	1583	0.70
61	26.01.61	3456	2160	- 57	+20	1333	1707	0.78
62	28.02.62	2431	1246	+159	+47	979	1260	0.78
63	29.01.63	2656	1533	- 28	-28	1179	1483	0.80
64	30.01.64	2758	1516	- 83	-36	1361	1496	0.91
65	10.03.65	2219	1043	+ 66	+19	1091	1256	0.87
66	27.01.66	2253	1208	-130	-26	1202	1430	0.84
67	16.01.67	2192	956	+ 70	+30	1136	1540	0.74
68	10.01.68	2645	1502	- 51	- 7	1202	1467	0.82
69	21.01.69	1875	534	+ 62	-10	1289	1690	0.76
70	28.02.70	2020	1008	- 55	-13	1080	1361	0.79
71	11.02.71	2036	803	+111	+43	1079	1441	0.75
72	26.01.72	2705	1332	+ 18	+38	1317	1722	0.76
73	27.02.73	1527	706	-162	-77	1060	1477	0.72
	02.02.74							
Totals 58-73		36919	18615	-149	-44	18497	23814	0.78
Totals 67-73		15000	6841	- 7	+ 4	8162	10698	0.763

TABLE IX

Water Use Estimates, AE, for the Experimental Catchment A

Water Year Ref No	Starting Date	Rain mm	Flow mm	ΔS mm	ΔG mm	AE mm	EO mm	AE/EO
58	04.02.58	2416	1519	- 35	+ 4	928	1496	0.62
59	06.02.59	1813	874	+ 29	- 6	916	1548	0.59
60	05.02.60	1842	936	- 34	-26	966	1619	0.60
61	08.02.61	3319	2096	- 59	+ 6	1276	1706	0.75
62	14.03.62	2536	1219	+117	+20	1180	1414	0.83
63	14.03.63	2716	1505	+ 8	+12	1191	1439	0.83
64	11.03.64	2297	1551	-122	-39	907	1362	0.67
65	20.03.65	2255	1027	+ 86	+ 4	1138	1356	0.84
66	24.02.66	1989	1116	-109	-14	996	1368	0.73
67	31.01.67	2029	844	+ 98	+23	1064	1539	0.69
68	24.01.68	2524	1390	- 32	+10	1156	1379	0.84
69	21.01.69	1763	454	+ 47	-50	1312	1690	0.78
70	28.02.70	1882	829	- 60	+11	1102	1361	0.81
71	11.02.71	1816	619	+145	+14	1038	1441	0.72
72	26.01.72	2520	1084	+ 22	+62	1352	1722	0.79
73	27.02.73	1443	604	-192	-64	1095	1477	0.74
	02.02.74							
Totals 58-73		35160	17667	- 91	-33	17617	23917	0.74
Totals 67-73		13977	5824	+ 4	+ 6	8119	10609	0.765

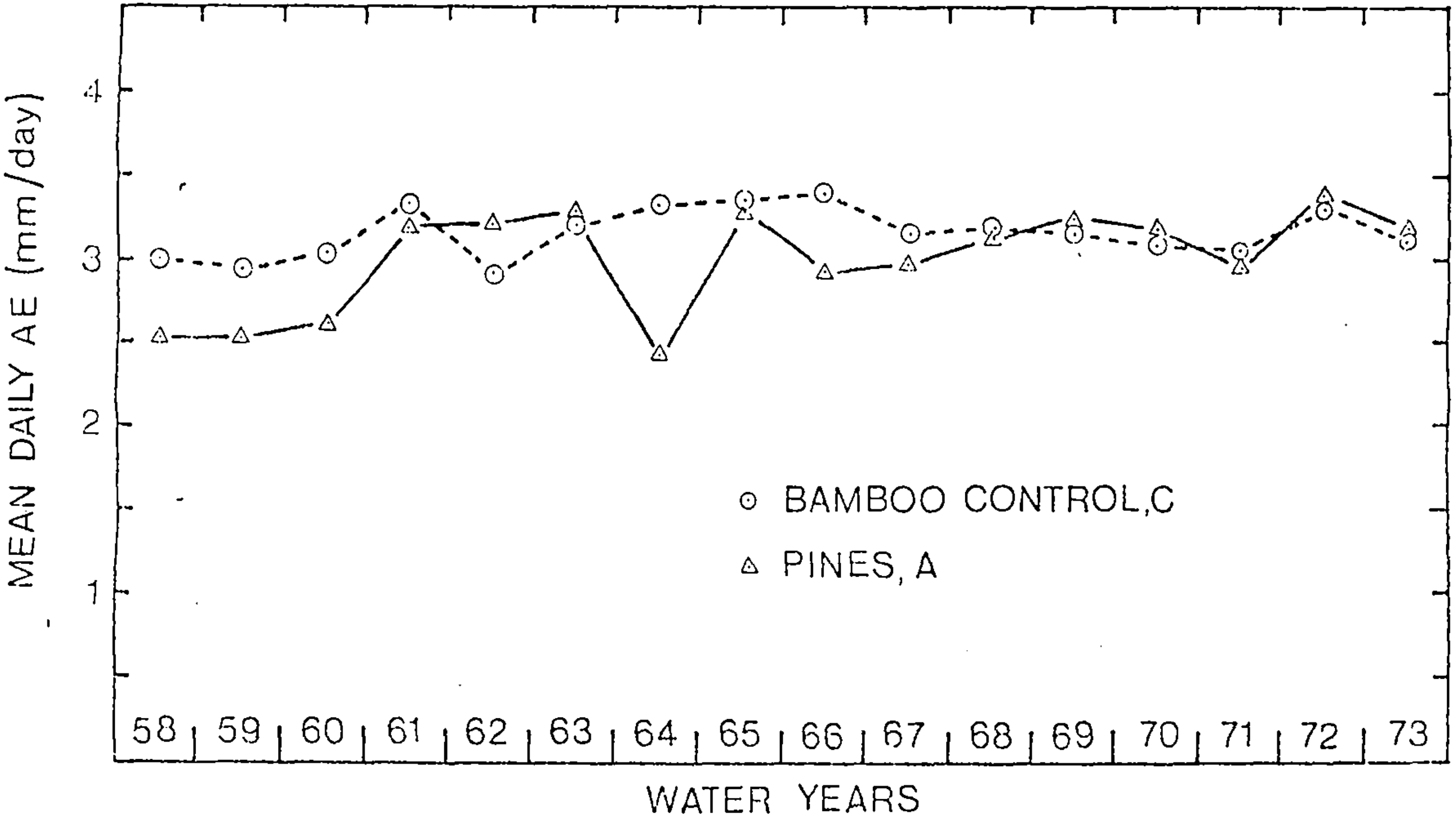

Figure 5 Mean daily water use, AE, by Catchments C and A

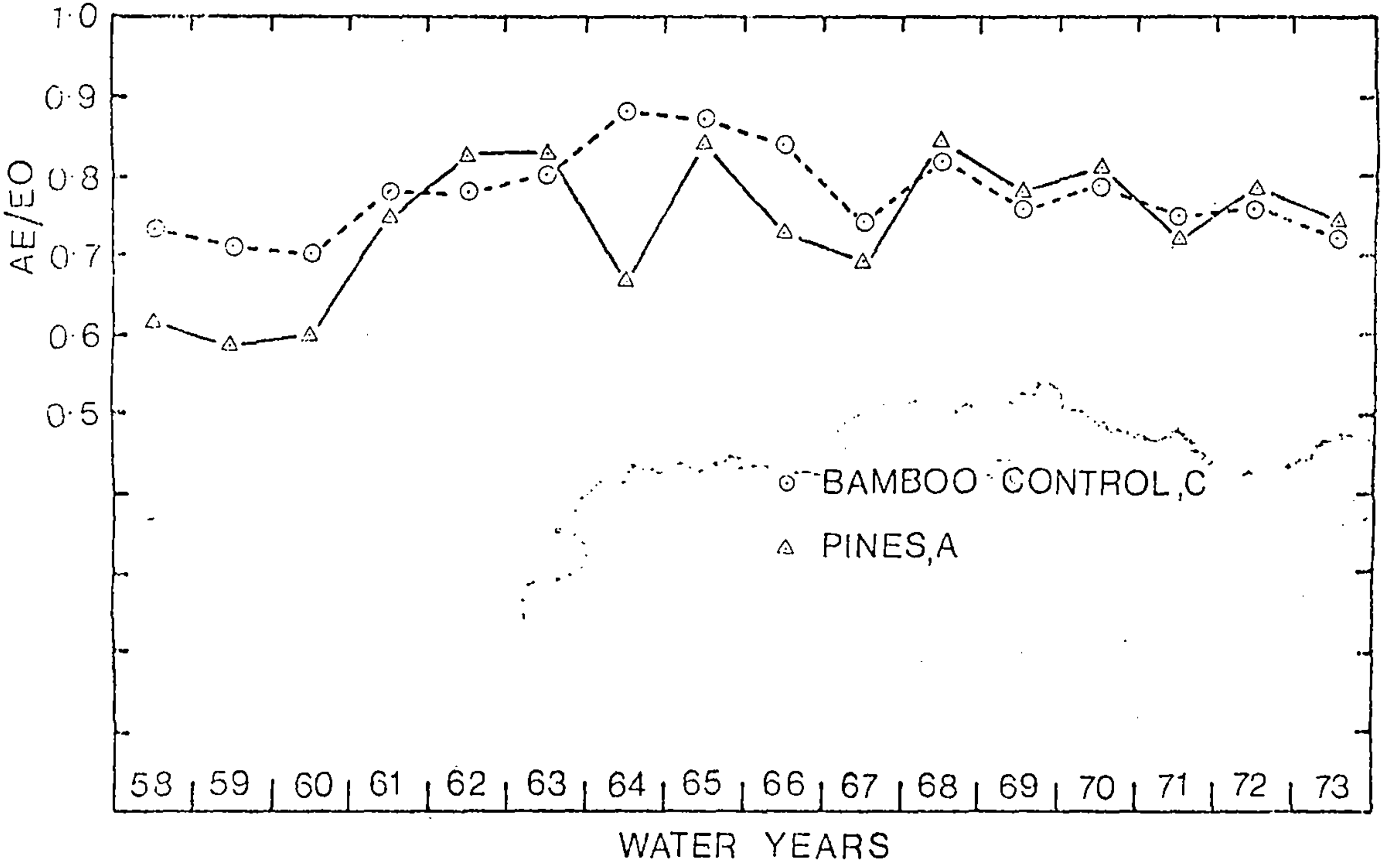

Figure 6 Water year AE/EO ratios for Catchments C and A

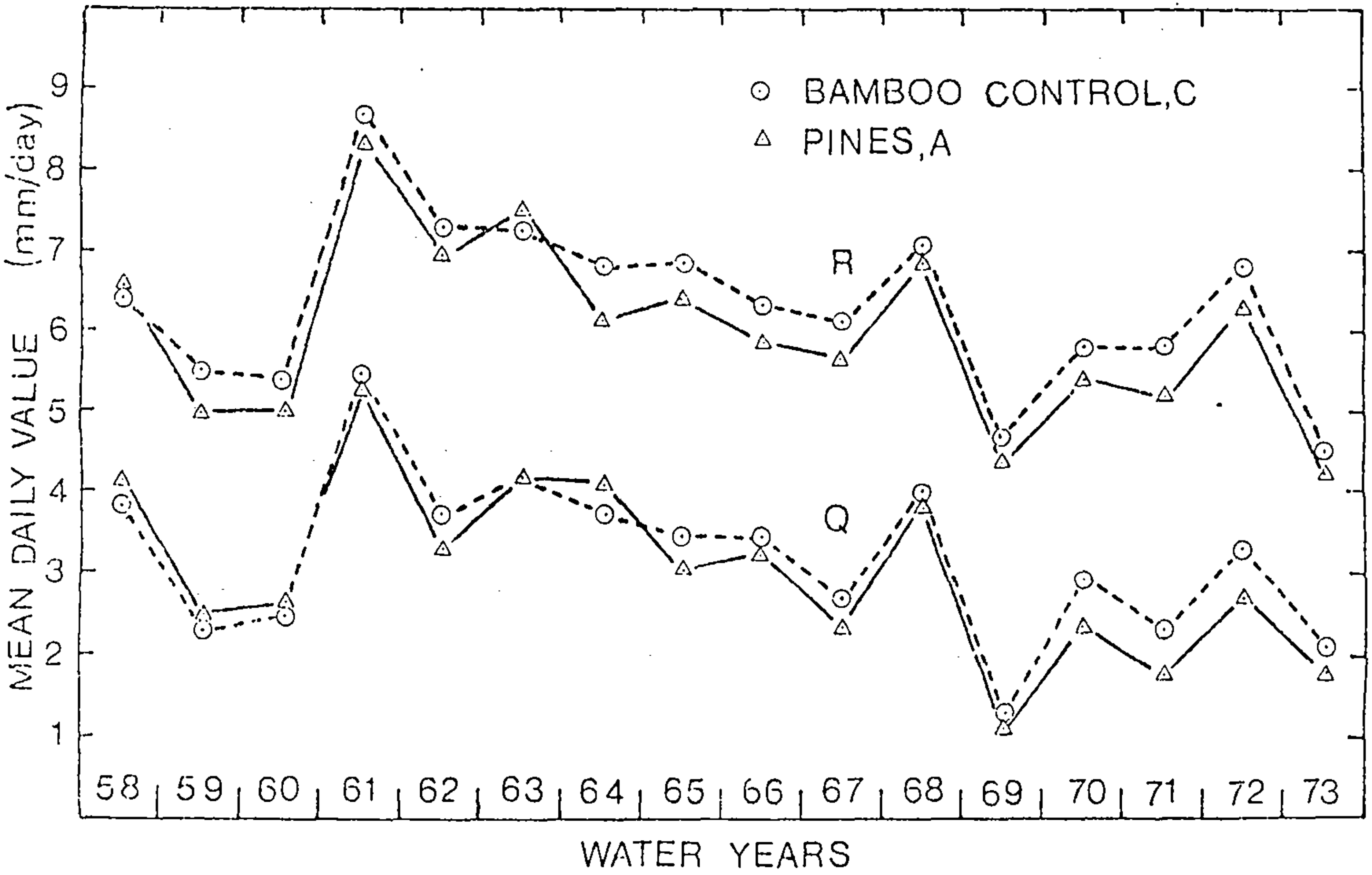

Figure 7 Water year mean daily values of rainfall, R, and streamflow, Q, for Catchments C and A

to close agreement over the least seven years is indicated.

No water year analysis has been performed on Catchment M. In anticipation of full conversion to grazing, the soil moisture sites were all on the areas first planted to grass. Since this represented only 33% of the catchment for most of the period of record, the figures would provide only biased estimates of AE. On the basis of the similarity in rainfall distribution, annual R-Q can be expected to give a reasonable indication of any departure trends in water use when compared with Catchments C and A. As can be seen in Table IV, the difference R-Q for Catchment M was consistently lower than that for Catchments A and C by some 10-12%.

INTERPRETATION OF RESULTS THROUGH MODELLING

The quantification of the water use of the Kimakia catchments described above is relevant to the land use change effected there. To be of wider practical value, some means of extrapolating the results is necessary; ideally, this should be built on a detailed understanding of the physical and plant-physiological processes controlling water use and the time distribution of the streamflow. No detailed studies of these processes were possible at Kimakia with the resources available, but some indication of those exercising the greatest control can be obtained from the data.

From an analysis of individual storms, Pereira et al (op cit) showed that surface runoff from these highly porous volcanic forest soils was essentially dependent on rainfall intensity. No significant difference in the very low levels of surface runoff was detected between the bamboo and pine catchments. Differences in soil type, intensity distribution or catchment topography could result in differences in the magnitude of this component of flow in other areas.

Regarding water use by vegetation, the water year estimates of water use show considerable year-to-year variation. In

Catchment A, it is reasonable to assume that the reduction in the period 1958-60 was due to the reduced ground cover associated with the early stages of afforestation and there is some indirect evidence that the reduction in 1964 may be due in part to an overestimate of flow. In Catchment C, part of the variation during 1961-66 may be due to inadequacies in the empirical correction applied to the water level measurements. Having made allowance for these periods, the question as to whether the residual variation is explained by random error, or by the processes controlling evapotranspiration, remains. Comparison of Figures 6 and 7 indicates that there is no obvious relationship between the magnitudes of water year rainfall and water use; nevertheless, it is noteworthy that the sign of the differences, in successive years, is the same for AE/EO and rainfall on 14 out of 15 occasions in Catchment A and 10 out of 15 in Catchment C.

To investigate further, the Institute of Hydrology model described in Section 1.3.2 was fitted to the catchment data to determine whether the functions simulating the interception and deficit control of transpiration processes could account for a significant part of the variation. Some exploratory work by Blackie (1972) had shown that an earlier version of this model could be fitted satisfactorily to the data from Catchment C, and was sufficiently sensitive to require radically different parameter values for the periods 1958-60 and 1961-63 on Catchment A. In the application described here, the parameters in the above functions have been optimised independently of those controlling percolation and flow, using as observed data the water year values of AE for the period 1967-73 for each catchment. Following this, water use over the entire period of record was predicted and compared with the AE values.

Using the notation and symbols defined in Section 2.2.1, the water use simulation functions applied were:-

(a) The factor model,

$$\hat{AE} = f \cdot EO$$

where f was determined from the sum of AE and EO over periods 1967-73.

(b) The water use model,

$$\hat{AE} = \sum_i \left| FC \cdot EVAP_i + CS_i \cdot (1 - FC/FS) \right|$$

where FC, FS and the interception capacity, SS, were the parameters to be optimised.

(c) The full model, comprising the above expression with the value of FC controlled by deficit above a threshold, DCS, by the function,

$$FC' = 0.5 \left| \cos \left(\frac{DC - DCS}{DCR} \right) + 1 \right| \cdot FC$$

where SS, FC, DCS and DCR are the parameters to be optimised.

The objective function used was

$$F = \frac{\sum_i (AE_i - \hat{AE}_i)^2}{N}$$

The optimum parameter values obtained for each catchment for (a) and (b) are listed in Table X, and details of the predictions in Table XI and XII for Catchments C and A respectively. As can be seen from the reduction in the variance F, the water use model predicted water year evaporation AE with significantly greater precision than the simple factor model in Catchment C, providing strong evidence that the interception process plays a major role in determining the total water use of bamboo; it must therefore be taken into account in any attempt to estimate this water use accurately. Whilst this model reduced the magnitude of the residuals compared to the factor model, it did not fully

TABLE X

Optimum Parameter Values Attained Using
(a) The Factor Model
(b) The Water Use Model

Parameters	C (bamboo)	A (pines)
	(a)	
F	0.763	0.765
	(b)	
SS	2.24	3.30
FS	4.63	1.21
FC	0.53	0.57

TABLE XI

Catchment C Water Use Modelling Using
(a) The Factor Model and
(b) The Water Use Model

Water Year		AE	(a) $\hat{AE}$	(a) δ	(b) $\hat{AE}$	(b) δ
58		1090	1142	+ 52	1148	+ 58
59		993	1071	+ 78	1080	+ 87
60		1108	1208	+100	1176	+ 68
61		1333	1302	- 30	1362	+ 29
62		979	961	- 18	1028	+ 49
63		1179	1131	- 48	1162	- 17
64		1361	1141	-220	1228	-133
65		1091	958	-133	1005	- 86
66		1202	1091	-111	1098	-104
67		1136	1175	+ 39	1179	+ 43
68		1202	1119	- 83	1196	- 6
69		1289	1289	0	1276	- 13
70		1080	1038	- 42	1083	+ 3
71		1079	1099	+ 20	1126	+ 47
72		1317	1314	- 3	1312	- 5
73		1060	1127	+ 67	1072	+ 12
67-73	$\sum$	8162	8162		8244	
	F		41.7		12.5	
58-73	$\sum$	18497	18169		18531	
	F		312.6		164.1	

TABLE XII

Catchment A Water Use Modelling Using
(a) The Factor Model and
(b) the Water Use Model

Water Year	AE	(a)		(b)	
		$\hat{AE}$	δ	$\hat{AE}$	δ
58	928	1145	+217	1136	+208
59	916	1185	+269	1141	+225
60	966	1239	+273	1186	+220
61	1276	1306	+ 30	1331	+ 55
62	1180	1082	- 98	1108	- 72
63	1191	1101	- 90	1122	- 69
64	907	1042	+135	1094	+187
65	1138	1038	-100	1055	- 83
66	996	1047	+ 51	1020	+ 24
67	1064	1178	+114	1169	+105
68	1156	1055	-101	1122	- 34
69	1312	1293	- 19	1250	- 62
70	1102	1042	- 60	1047	- 55
71	1038	1103	+ 65	1095	+ 57
72	1352	1318	- 34	1293	- 59
73	1095	1130	+ 35	1062	- 33
67-73 $\sum$	8119	8119		8038	
F		94.1		73.5	
58-73 $\sum$	17617	18303		18231	
F		759.2		610.7	

account for the negative sequence of residuals from 1963-66; this could be further evidence for the inadequacy of the flow correction in this period.

In Catchment A, also, the water use model reduced the variance when compared to the factor model, implying that the interception process also plays an important role with pines. In the prediction of actual evaporation, AE, the sequence of large positive residuals from 1958-60 is an indication of the inadequacy of both models or parameter values during the seedling/cultivation period.

The parameters DCS and DCR optimised to values resulting in virtually no control of FC by deficit in either catchment. Consequently, the predictions and F values were effectively unchanged from those obtained using model (b). This result is in agreement with the soil moisture observations discussed in Section 3.2.3, which show that significant moisture stress is not a feature of the Kimakia environment. The finding contrasts with that described in Section 2.2.1 for bamboo at Kericho where, with greater deficits developing over a longer dry season, deficit control of transpiration was found to be of some importance in predicting water use.

Following the optimisation of the parameters in the water use functions, those in the functions controlling movement of the remaining water through and over the catchment to form streamflow were progressively optimised, using first monthly and then daily flow as the observed values; the variance,

$$F_Q = \sum_i (Q_i - \hat{Q}_i)^2$$

was taken as the objective function. The efficiency of fit, RE, of the model was characterised by

$$RE = \frac{FQ - FO}{FO}$$

where

$$FO = \sum_i (Q_i - \bar{Q})^2$$

This statistic, RE, is analagous to the explained variance in regression analysis.

RE values of 94% and 87% were achieved in prediction of the complete 1958-1974 runs of streamflow in Catchments C and A respectively, with cumulative errors in the volumes of + 0.2% and - 0.5%. The departure trends in the residuals followed broadly an inverse pattern to those of the water use models. The cumulative departures at monthly intervals for the model fitted to Catchment C are illustrated in Figure 8.

EXTRAPOLATION OF RESULTS

The importance of the interception process in determining total water use by bamboo and forest has been demonstrated in the preceding paragraphs. The simple factor approach to prediction of water use by a vegetation type is seen, therefore, to be an approximation valid only when rainfall amount and frequency are similar to that pertaining over the period when the factor was derived. The function used to simulate the interception process in the model may be used to predict water use within the catchment from which it was derived, with reasonable precision. It would overestimate water use in prolonged drought conditions unless the deficit control function, optimised over such a period, was incorporated.

These functions could doubtless be optimised on other catchments to give comparable precision of prediction within those catchments. The parameter values obtained in any one catchment should be used only with care in predicting water use by the same vegetation elsewhere; three main reasons for this statement are (a) the possible inadequacy of the functional representation of the processes, (b) the presence of interdependence between the parameter values and (c) the

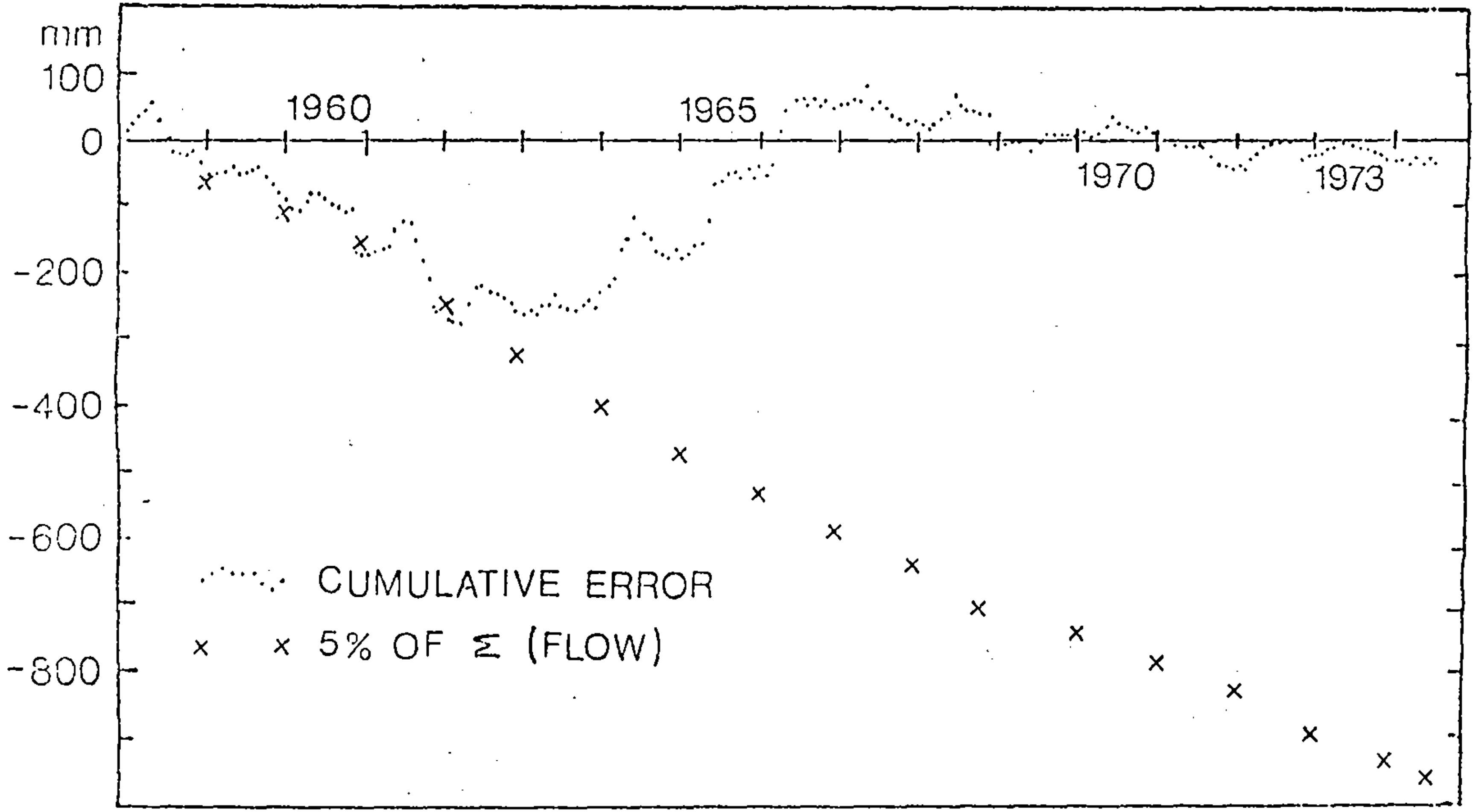

Figure 8 Cumulative error in flow prediction for Kimakia C using the IH model as optimised on 1967-73

inherent characteristic of all optimisation processes whereby any bias present in the data used to fit the model is transferred to the parameter values. Provided the model is used only on data from the same source, with the bias remaining constant, its presence is irrelevant; where the parameters are applied to other data with different bias, however, large systematic errors can be expected. Model adequacy is of considerable importance where spatial extrapolation is contemplated; as already discussed, the water use model applied reasonably successfully at Kimakia would be inadequate in a catchment experiencing severe moisture stress. It would also be inadequate in a situation experiencing prolonged low intensity rainfall because of the implicit assumption of a maximum daily interception amount.

An example of the errors arising from the transfer of optimised parameter sets for the water use model is given in Table XIII. In this case, bias in the data is considered to be minimal but the volume errors are large and the model fit, quantified by F, is very much poorer.

Thus, there are severe restrictions of the use of optimised conceptual models to extrapolate in space, although they are useful tools for prediction within their catchment of origin if vegetation type remains stable. To extrapolate accurately from one environment to another requires that the functions used are accurate representations of the processes, and that the main parameters have been determined by process studies. In terms of water use estimation, the Monteith-Penman expression described in Section 1.2.2 comes close to meeting these requirements but requires data at frequency intervals possible only with the use of automatic weather stations.

TABLE XIII

Effects of Interchanging Water Use Model Parameter Sets Between the Bamboo Catchments Kericho 16 and Kimakia C

Catchment	Period	AE (mm)	Optimum Parameters $\hat{AE}$ (mm)	Optimum Parameters F	Other Parameters $\hat{AE}$ (mm)	Other Parameters F	Error (%AE)
16	02-12	13633	13769	62.3	12781	237.6	- 6.2%
C	67-73	8162	8244	12.5	8993	274.4	+10.2%

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3.2.2

CATCHMENT SEDIMENT YIELDS AT KIMAKIA

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3.2.2

CATCHMENT SEDIMENT YIELDS AT KIMAKIA

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INTRODUCTION

Continuous monitoring of suspended sediment by means of daily samples, as described in Section 1.2.5, was carried out on catchments A (pines), C (bamboo) and D (large bamboo catchment) at Kimakia from 1960 to 1962. By then, the steady flow sediment yield had been shown to be so low, even from the experimental catchment A, that the sampling was discontinued. With the manpower and funds available at that time, it was not possible to sample stormflow sediment load through the clearing and planting period on catchment A; in 1972, however, catchment D, a 503 ha catchment under bamboo was allocated to the forestry workers for smallholdings. Since the clearing and cultivation techniques employed were similar to those used in the initial stages on catchment A, this presented an opportunity to make good the deficiency in the earlier work and automatic stormflow sediment samplers were installed.

No quantitative measurements of bedload were made in this study though some indication of the relative quantities can be obtained from the frequency of clearing of the weir stilling pools on each catchment.

MEASUREMENTS OF SUSPENDED SEDIMENT 1960 and 1961

Table I shows the measured suspended sediment (ppm) obtained from the monthly samples in catchments A (pines), C (bamboo), and D (large bamboo catchment).

The rains in 1960 came from March to May and in October-November; Table I, therefore, shows that the post short-rains sediment yield was lower than post long-rains sediment yield, and remained low from the end of 1960 onwards. Although the reduction coincided with the cessation of cultivation in catchment A due

TABLE I

Measured Suspended Sediment Concentrations (ppm) for Years 1960-61

	1960			1961		
	Pine Plantation (A)	Bamboo (C)	Bamboo (D)	Pine Plantation (A)	Bamboo (C)	Bamboo (D)
January	-	-	-	13	13	9
February	-	-	-	6	20	17
March	-	-	-	34	60	11
April	-	-	-	15	4	11
May	479	171	188	34	7	4
June	326	156	324	14	8	10
July	92	215	106	18	2	3
August	28	76	33	11	5	7
September	130	108	73	13	2	0
October	625	124	90	30	6	9
November	5	41	19	50	14	8
December	3	1	1	27	7	8
MEAN	141*	47*	70*	22	13	7

* 8 months only

to the closing of the pine canopy, this was not the case for the uncultivated catchments C and D. A more probable explanation is that the high yields in all the catchments during 1960 were due to road construction by the Forestry Department. This would be expected to affect Catchment A more than the other catchments in view of the diversion of storm drainage from the road through Catchment A into the stream (see Figure 2, Section 3.1.1). By 1961, suspended sediment yield in all catchments had fallen to very low values even during the severe 'short rains' of October and November. In terms of erosion in the catchments, the suspended sediment losses (kg ha^{-1}) are shown in Figure 1 for the two small catchments. Assuming that the suspended solids derived originally from surface soil, the peak value for Catchment A (pine plantation) during November (332 kg ha^{-1}) represents an overall soil loss of 0.1 mm depth over the catchment. The total figures for the year 1961 are shown in Table II.

SUSPENDED SEDIMENT YIELDS IN CATCHMENT D (LARGE BAMBOO CATCHMENT)

In 1972, clearing of the bamboo forest in the lower part of Catchment D began. By May 1973, about 10% of the catchment was being cultivated, and this area increased to about 30% in 1974. A variety of crops were grown, chiefly maize with beans, peas, cabbages, kale, lima beans, English potatoes and sweet potatoes. Because of the slow growth of maize at these altitudes (about 2500 m), it is planted at the end of the long rains, usually from May to July, and harvested in February to April of the following year. Considerable disturbance of the soil occurs, therefore, and an increase in sediment yield is to be expected.

Suspended sediment samples were taken by means of an automatic sampler (North Hants Engineering Co Ltd) during 1974. The steady-flow sediment samples obtained has a mean concentration of solids of 7.4 ppm; comparison of this value with the value given in Table I for 1961 shows that there is no difference

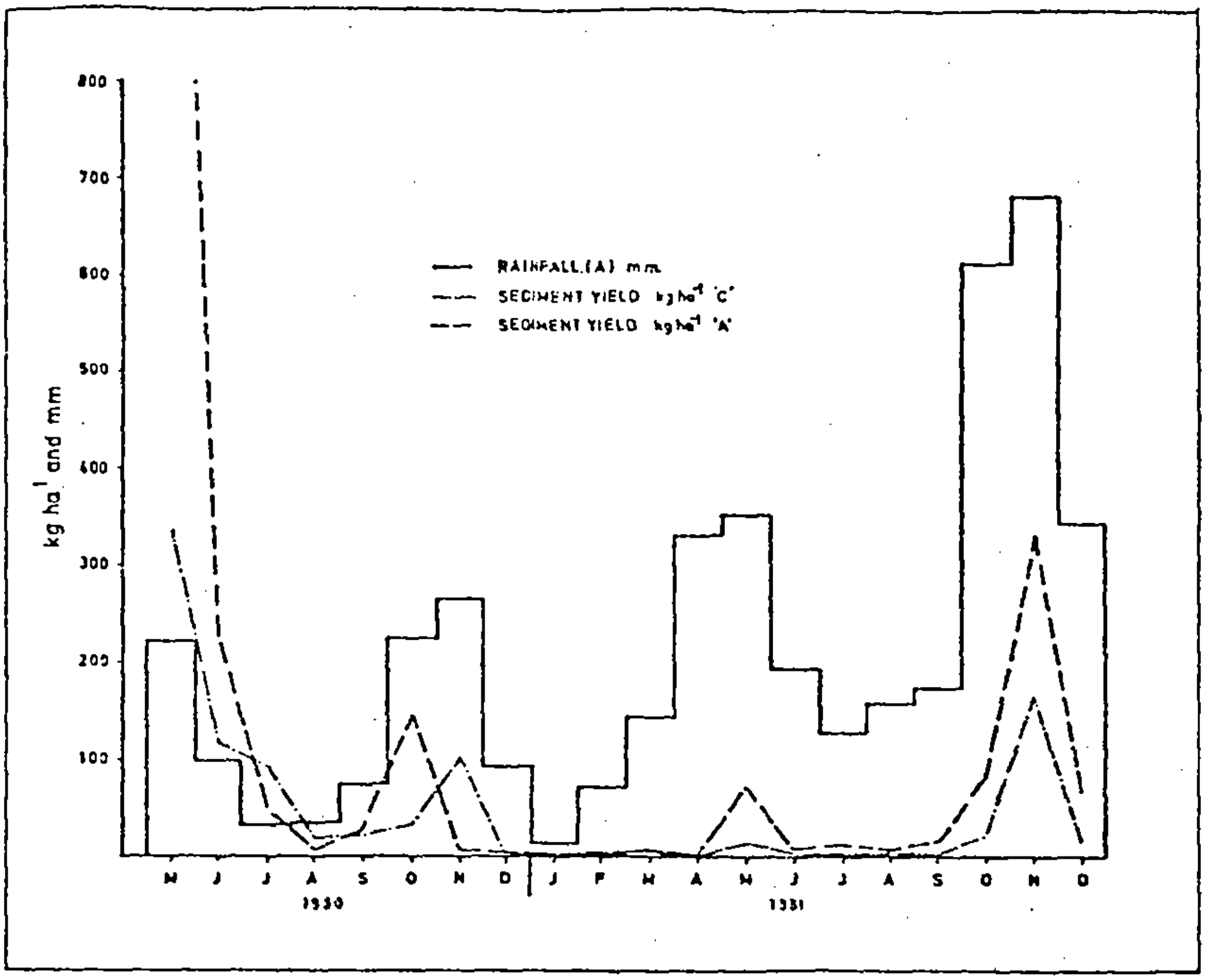

Figure 1 Monthly rainfall and suspended sediment in two small catchments at Kimakia

TABLE II

Sediment Yields and Depths of Erosion in the Kimakia Catchments A (Pines), B (Bamboo), C (Bamboo)

	A	B	C
% Organic Matter	10.5	7.9	25.5
Mean Concentration of solids (ppm)	22	13	7
Suspended Sediment (kg ha^{-1})	452	249	172
Bulk Density of Soil at Depth 15 cm (g ml^{-1})	0.33	0.33	0.33
Equivalent Depth of Erosion (mm)	0.14	0.07	0.05

between mean concentration of solids in 1961 and 1974. The average concentration of the stormflow samples was 14.8 ppm, although not all the large storms were sampled.

From these preliminary results, it is clear that no large scale soil transport to the stream is detectable so far. Observations suggest that the soil is still stabilised by the bamboo roots which are only slowly being removed and that the protective strips of bamboo forest along the steep stream banks are effective barriers to sheet erosion. It is too early to comment on the long term effects of cultivation and the Ministry of Water Development have plans to continue this study.

BEDLOAD

As a qualitative indication of the bedload transported in each catchment, frequencies of silt removal from the stilling pools are given in Table III. This table shows that the frequency of clearance was much higher for Catchment A than for any of the others. The quantity of silt removed in each clearing on Catchment A was also much greater, averaging 9 m^3. Whilst some part of this quantity may have resulted from the clearing, cultivating and planting operations in 1958-1960, the composition of the material suggested that the bulk of it was derived from the road in the upper part of the catchment.

Clearing in the control catchment (C) consisted only of infrequent removal of small quantities of silt composed mainly of organic matter from the area surrounding the inlet to the recorder stilling well. Despite the greater slope of the streambed, similar comments apply to Catchment D (large bamboo catchment) although in this case the source of the material was considered to be streambank erosion immediately above the stilling pool during high flows. So far, there is no evidence of any increase in bedload resulting from the post-1972 clearing and cultivation.

Whilst appreciable quantities of silt arrived in Makiama stilling

TABLE III

Frequency of Clearing of Silt from the Weirs

Catchment	Year 1965	1966	1967	1968	1969	1970	1971	1972	1973	1974	Total
A (pines)	1	2	1	4	4	1	5	2	2	3	25
C (bamboo)	0	0	0	0	0	0	1	0	2	1	4
M (grasses)	0	2	2	1	0	1	0	0	0	0	6
D (bamboo)	0	0	0	0	1*	1*	1*	1*	1*	0	5*

* Pool not completely filled

pool following the clearing of bamboo from some additional areas of the catchment, the total volume removed was considerably less than in Catchment A.

CONCLUSIONS

The suspended sediment yields from all the experimental catchments are low. Although the pine catchment yields twice as much sediment as the bamboo control catchment, the total soil loss is negligible following the cessation of cultivation and stabilisation of the soils under the softwood plantation.

Indications are that the sediment losses increase more as a result of peripheral forest activity (eg road building and road maintenance) than from the planting activity. It is recommended, therefore, that silt measurements be re-started when the cutting and logging operations begin.

On the cultivated catchment, there are no signs yet of increased sediment yield. Observations should continue, therefore, to obtain the important comparison of undisturbed indigenous forest with a partially cleared and cultivated catchment. An attempt should also be made to monitor the long term effects of intensive grazing on sediment yield in the Makiama catchment as soon as the pasture in the recently cleared areas has become established.

3.2.3

SOIL MOISTURE DEFICITS UNDER BAMBOO FOREST, PINE PLANTATIONS AND GRASS

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3.2.3

SOIL MOISTURE DEFICITS UNDER BAMBOO FOREST, PINE PLANTATIONS AND GRASS

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INTRODUCTION

The catchments which form the basis of this study are the original Kimakia intensive experimental catchments: the bamboo control catchment (C), and the changed land use catchment (A) which was cleared and planted with pines using the 'shamba' system. The group is completed by the Makiama catchment (M) which was brought into use after the discovery that not all the streamflow from the catchment originally intended for clearing and planting with grass passed through the gauging structure. Soil moisture assessment on these catchments is important for at least two reasons: first, because soil moisture includes that component of the water cycle available for plant growth and transpiration and, second, because it influences the partition, between infiltration and rapid runoff, of rain reaching the soil surface.

SOILS OF THE KIMAKIA CATCHMENTS

The catchments are on volcanic ash and tuff associated with the Rift Valley formation and soils are of polygenetic origin with developed soil surfaces that were subsequently buried by volcanic ash (Scott and Friend, 1962). The dark red friable clay at the bottom of the profiles represents the soil of the original land surface; this occurs on the bamboo and pine catchments at about 1.2 m depth but can be as close to the surface as 0.3 m. On these catchments, the top humic layer is 0.15 to 0.3 m thick but can extend to a metre on the area of impeded drainage at the upper end of the catchment under pines. The Makiama catchment was not included in the original soil survey and appears from the neutron moisture meter calibration sampling of the soils to be less uniform in soil type than the other two. It has a larger transition layer varying in thickness from 0.3 m to 1.5 m at depths which, in the other catchments, correspond to the original land surface and dry bulk densities (DBD) similar to those of the original soil occur at depths from 1.3 to 2.9 m. This layer probably developed from the different exposure of this catchment, affecting the layers of ash deposited by the wind.

The surface soil of the grass area has been considerably disturbed by the initial clearing, planting and reclearing when the young pine trees developed needle blight and were uprooted.

PROGRAMME OF SOIL MOISTURE SAMPLING

Gravimetric soil moisture samples to a depth of 3.2 m were taken at monthly intervals from 1958 to 1971 in the two original catchments, in which three sites were selected to represent the upper, middle and downstream areas of the catchments. Tables showing the physical properties of the soils at these sites are given by Pereira, Dagg and Hosegood (1962). In the pine catchment, the lower site was near the recording raingauge; the middle site was close to the fork in the forest track; and the upper site near the westward one of the two top tower gauges as shown in Figure 2 of Section 3.1.1. In the bamboo catchment, two of the three sites were near the two lower neutron access tubes that were closest to the meteorological site, and the third near the recording gauge at the head of the catchment. Gypsum block sites were selected close to these sampling areas and readings were taken at weekly intervals.

From 1968 onwards, soil moisture was measured by the neutron moisture meter in all three catchments (including Makiama, which had not previously been sampled gravimetrically); the networks of access tubes used on the three catchments are shown in Figure 2 of Section 3.1.1. These tubes allowed observations to be taken to a depth of 2.7 m, giving a better areal representation of soil moisture than the three gravimetric sites in each catchment. Readings were taken at ten-day intervals from the beginning of the year in the dry season until the profiles reached field capacity during the long rains; they were taken thereafter at monthly intervals until the end of the year, when the annual cycle was repeated. These intensive dry season observations continued until 1973 when readings were taken at monthly intervals only until June 1974, when this phase of the experiment finished.

METHODS OF ANALYSIS OF SOIL MOISTURE DEFICIT DATA

The problem of comparing the results of soil moisture sampling on different days in the catchments was again resolved by using the method discussed in Section 1.2.3. As explained in that section, the method consisted of representing soil moisture deficit (SMD), calculated as the difference between measured soil moisture and field capacity soil moisture, as the dependent variable in a multiple regression equation

$$\mathrm{SMD} = \beta_o + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_4 X_4$$

where the independent variables X_1 to X_4 are harmonic functions of time with period 365 days. The regression was calculated using the SMD measurement recorded at each site; a significance test then compared the values, from site to site, of the coefficients β_1 to β_4; significant differences would suggest that the amplitude and phase of the annual fluctuations in SMD varied significantly over the catchment. If the data demonstrated the reality of such differences, a further test determined whether there was evidence that the coefficients β_o varied from site to site; a positive result would suggest that SMD was consistently higher at some sites than at others, although the amplitude and phase of the annual cycle did not differ.

WITHIN-CATCHMENT COMPARISONS OF SMD

In the bamboo control catchment (C) the gravimetric data were reliable at the three sites until 1967 but during this year a sharp decrease in mean SMD was very noticeable, and only occasionally did core samples approach values obtained using the neutron moisture probes. The probable explanation is that the cumulative effects of dense gravimetric sampling had altered the soil moisture characteristics at the gravimetric sampling sites.

Over the period 1958-1966, there was no significant difference in the amplitude and phase of SMD fluctuations at the different sites in the bamboo, but there was a significant difference in mean SMD ($P < 0.01$). In the period 1968-71, none of the regressions was significant, suggesting the absence of any annual trend in SMD at any site and the absence of differences in mean SMD between sites; however, SMD estimates in this period were highly variable, possibly because of the cumulative effects of gravimetric sampling as described above.

A similar picture is evident in the data from the pine catchment (A), but here the three sites yielded reliable data to the end of 1968; thereafter, the extreme variability in gravimetric measurements ruled out any valid comparison between the pattern of SMD variation emerging from gravimetric and neutron moisture meter measurements. In the initial clearing and planting phase, 1958-60, there was no significant difference in amplitude and phase of SMD fluctuations between sites, although mean SMD differed significantly. This pattern of significance was repeated during the following period 1961-68.

Over the period 1968-74 when the neutron moisture meter was in use, there was no significant difference shown by the six sites in the bamboo. For the same period, the six sites in the pines showed no significant difference in amplitude or phase of annual SMD fluctuations but mean SMD varied significantly from site to site, possibly because of the impeded drainage area at the head of the catchment. There were no gravimetric samples taken from the grass catchment (M) and the neutron moisture meter data for 1968-74 showed no significant differences between the three sites.

BETWEEN-CATCHMENT COMPARISONS OF SMD

On the basis of the harmonic regression model fitted to the catchment data over the period 1968-74, there was no significant difference between the bamboo control catchment and the pine or grass catchments in terms of the amplitude and phase of annual SMD fluctuation; however, the annual mean SMD was significantly greater for bamboo than for the pine and grass catchments, the most significant difference being between bamboo and grass, 62 mm, compared with the bamboo and pine catchment, 19 mm. The mean deficit for bamboo over the period 1968-74 was 49 mm. The extent to which such differences are real is uncertain, however, in view of the significant site-to-site differences in mean SMD found within the pine catchment.

FIELD CAPACITY LEVELS

Comparison of SMD annual fluctuations obtained by neutron meter and the gravimetric method is of doubtful validity because of the unreliable readings for the latter during the 1968-71 period of overlap. However, it is possible to compare the two methods by means of the field capacity levels determined in the field by neutron moisture meter (see Section 1.2.3) and from 'undisturbed' cores at one-third atmospheric tension in the laboratory. The only comparable sites from each catchment are shown in Table I; the difference between soil water content and field capacity down to a depth of 2.7 m below the surface is less than 1.7% for two sites on catchment 11 and 0.7% for catchment 10. There is therefore good agreement between the two methods of obtaining estimates of this important reference level for SMD.

THE 1971 DROUGHT

The most significant drought during the period of neutron moisture meter observations occurred at the beginning of 1971, and the deficits in moisture volume fraction (MVF) at 30 cm intervals to a depth of 2.7 m are shown for bamboo, pines and two sites under Kikuyu grass in Figures 1 to 4. These figures

TABLE I

Comparison of Field Capacities Established by Neutron Moisture Meter (NSM) and Laboratory Gravimetric Methods (GSM)

Depth m	Catchment C Site 3 (Gravimetric Site 1)		Catchment A Site 3 (Gravimetric Site 2)		Catchment A Site 5 (Gravimetric Site 1)	
	NSM	GSM	NSM	GSM	NSM	GSM
0.3	260 ± 2.8	256	221 ± 5.2	236	222 ± 2.7	253
0.6	164 ± 2.7	169	161 ± 1.3	162	150 ± 2.1	151
0.9	177 ± 2.5	155	159 ± 1.6	150	146 ± 2.9	142
1.2	151 ± 1.1	151	158 ± 1.5	177	146 ± 0.7	160
1.5	147 ± 1.1	148	142 ± 1.4	142	146 ± 1.7	127
1.8	148 ± 1.3	144	149 ± 0.8	134	155 ± 1.0	142
2.1	149 ± 3.9	152	143 ± 1.6	136	157 ± 1.9	144
2.4	145 ± 1.6	150	152 ± 1.4	139	156 ± 3.7	144
2.7	65 ± 0.9	70	78 ± 0.6	67	79 ± 1.0	69
Total	1406 ± 4.9	1395	1363 ± 9.6	1343	1357 ± 7.9	1332
Laboratory Wilting Point Determination		677		735		685

All data in mm of water for each layer. The surface layer is 45 cm thick, each deeper layer 30 cm thick and the bottom layer 15 cm thick.

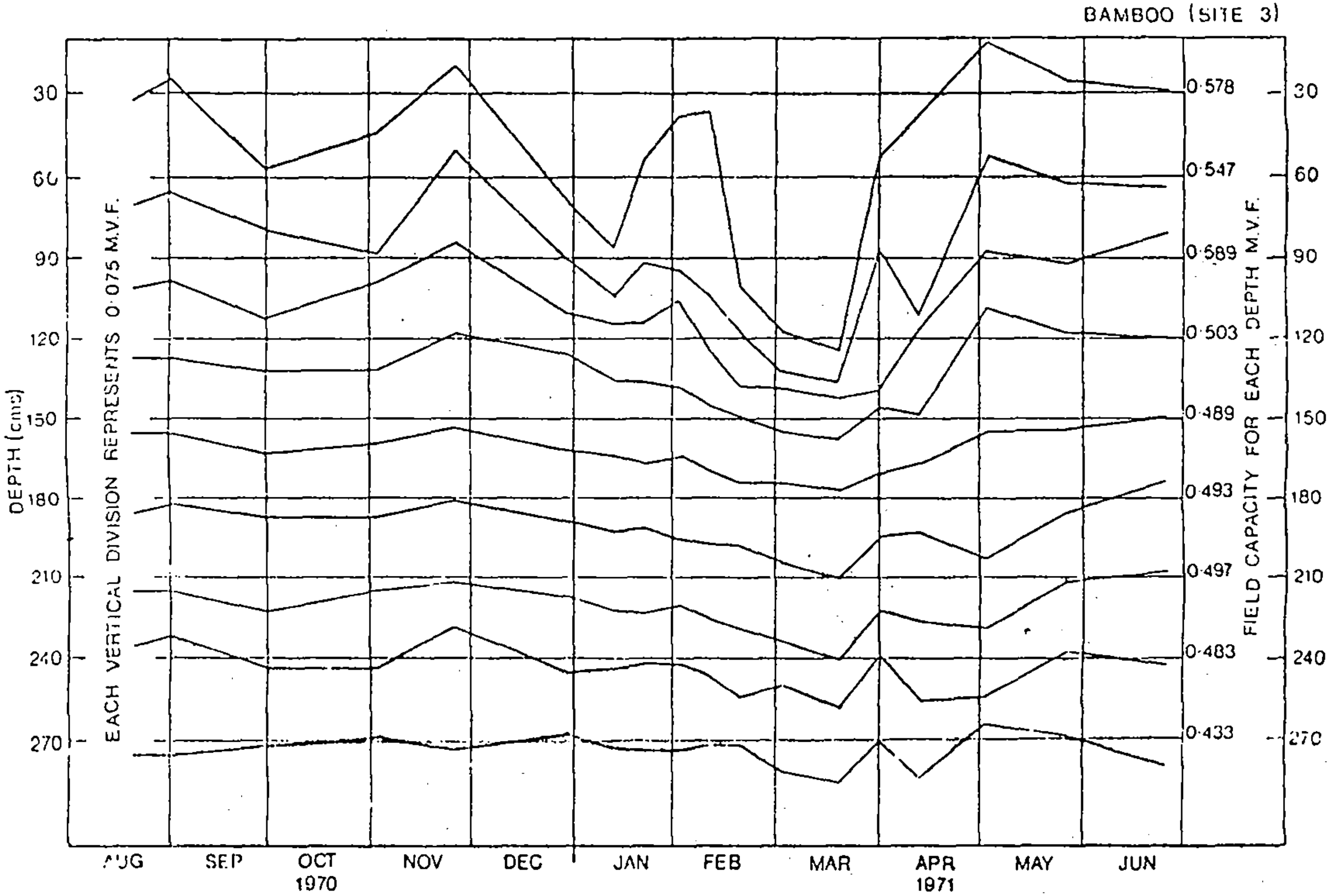

Figure 1 Soil moisture deficits under bamboo during 1970-71 drought

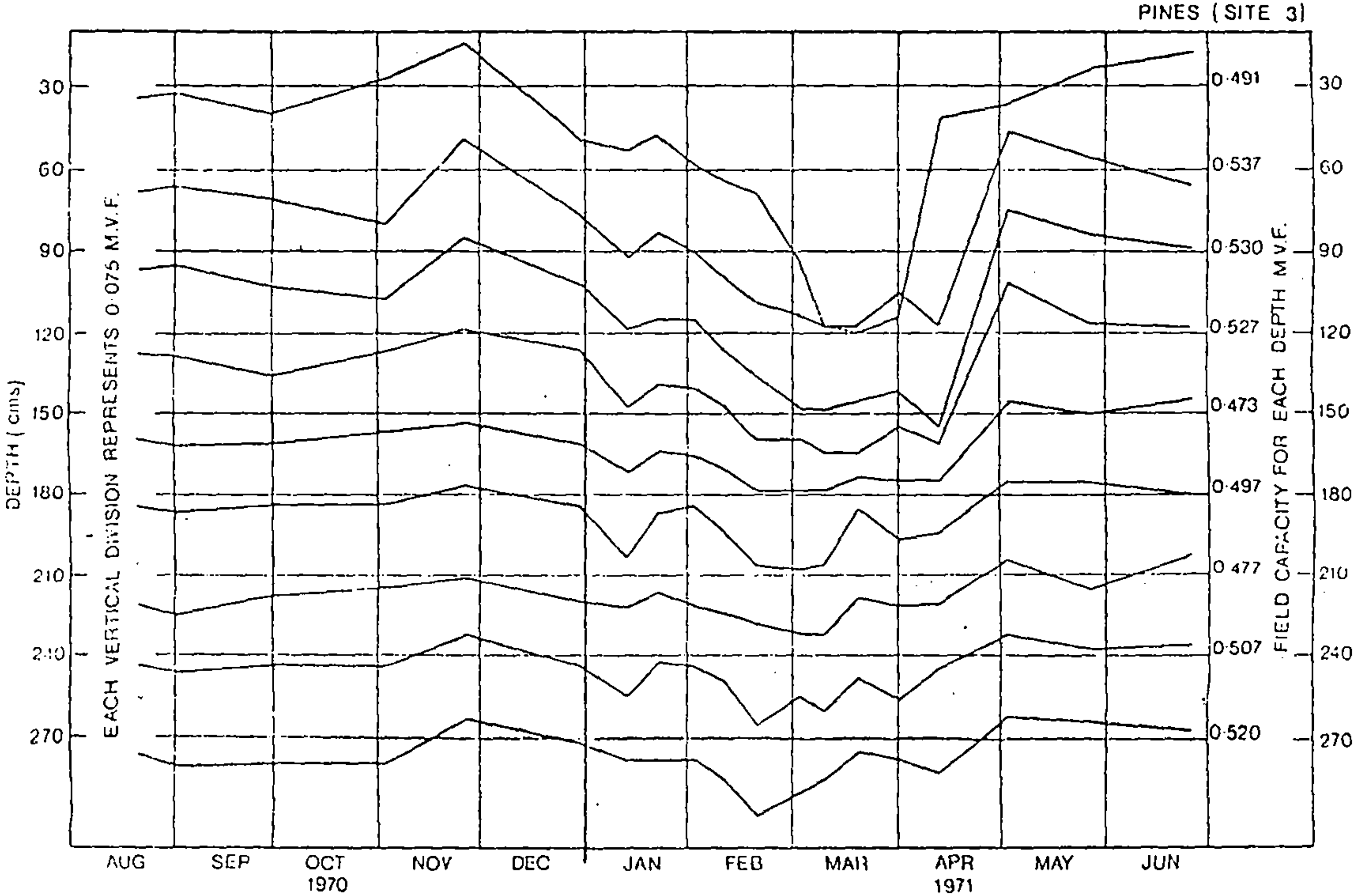

Figure 2 Soil moisture deficits under pines during 1970-71 drought

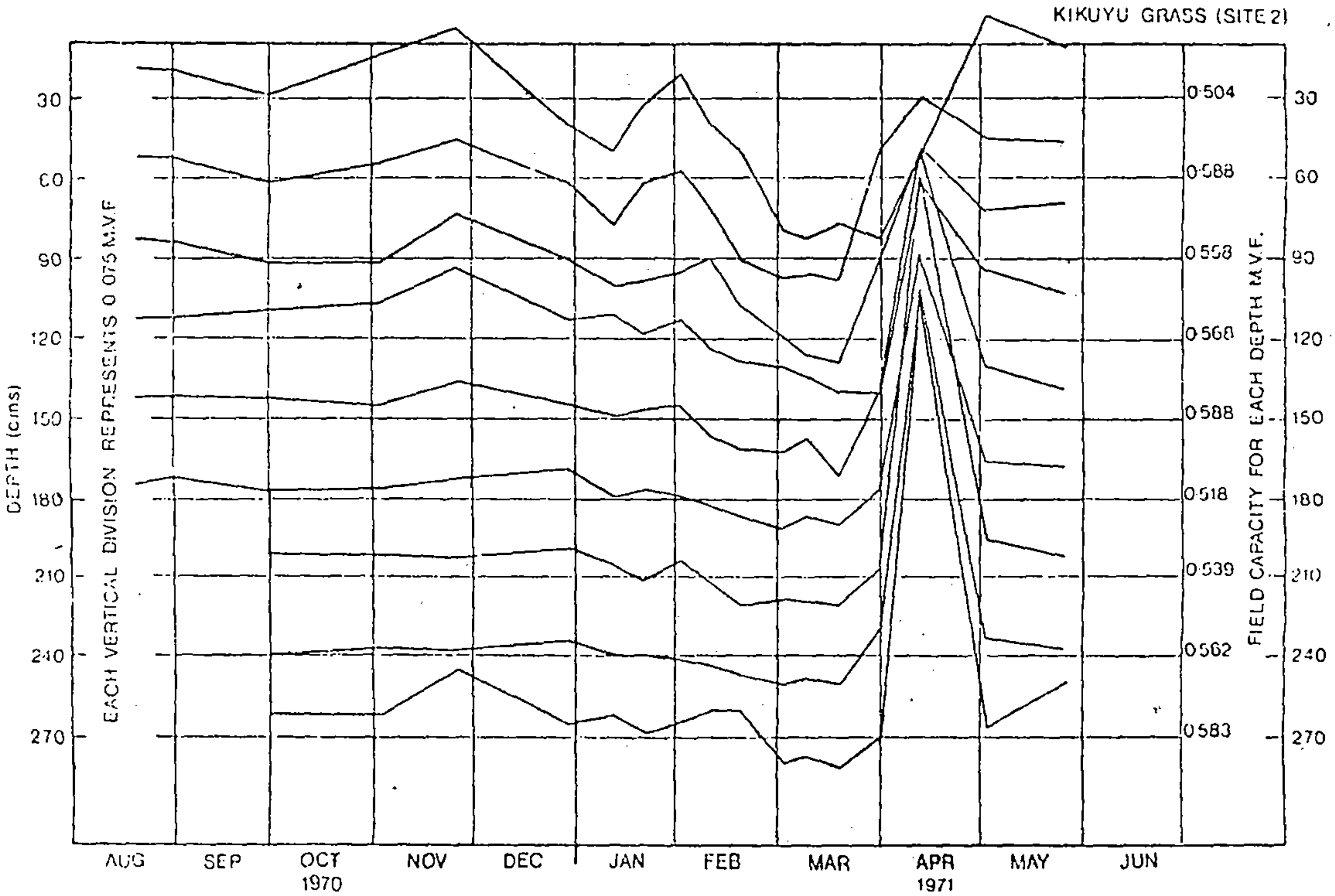

Figure 3   Soil moisture deficits under grass (Site 2) during 1970-71 drought

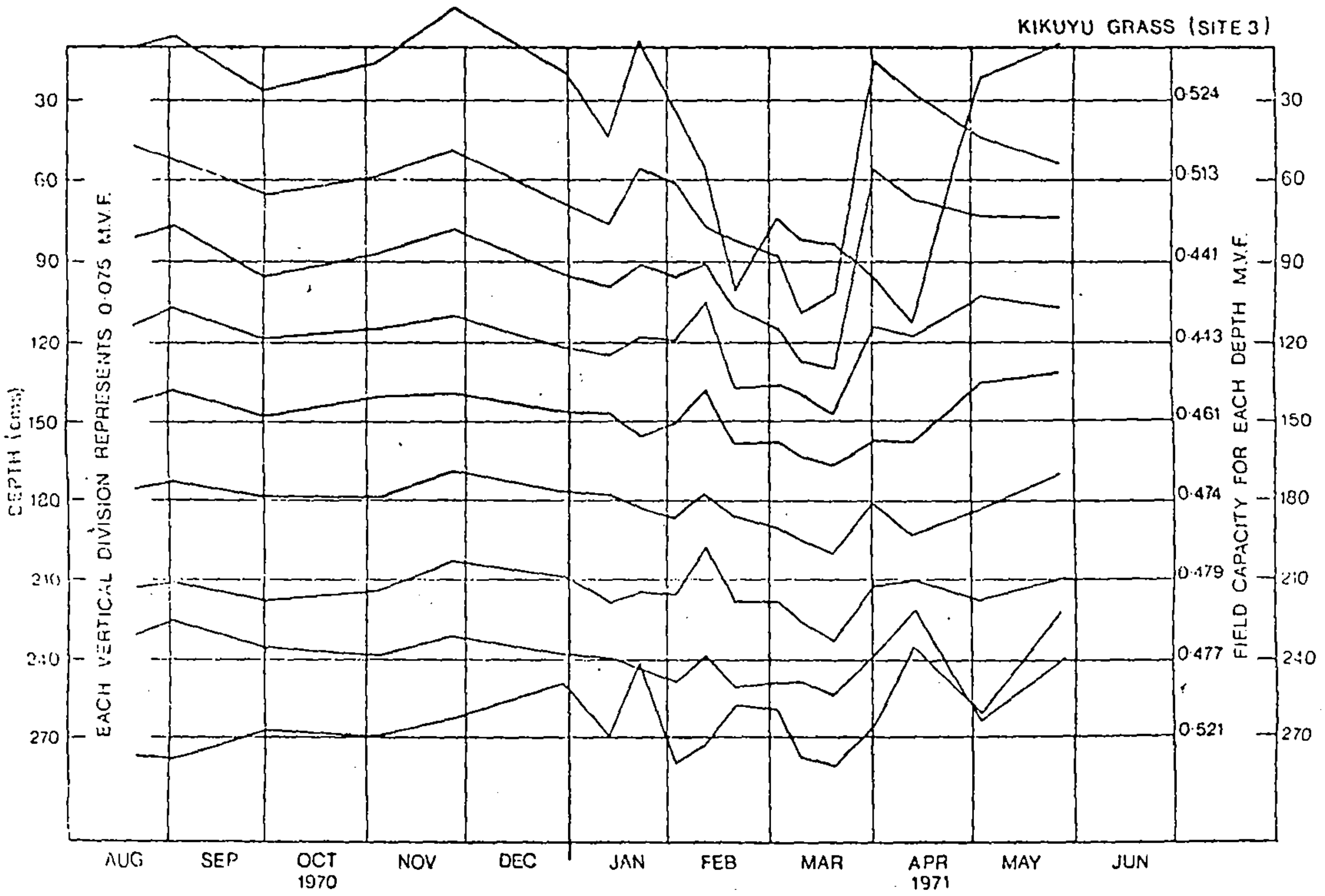

Figure 4 Soil moisture deficits under grass (Site 3) during 1970-71 drought

show that sampling to 2.7 m depth adequately covered the changes in moisture content except when the drought was most severe. On the upper grass site, there is some evidence of a perched aquifer which is supported by its recharge to saturation level up to the 60 cm depth by mid April.

The average depletion rates in mm day^{-1} at depths from 30 cm to 2.7 m, together with DBD classes recorded at the time that the neutron moisture meter was calibrated, are shown in Table II. The changes in DBD correspond to the different soil layers. The root activity shown by the Figures 1 and 2 and depletion rates of Table II can be compared with the root distributions found by Pereira and Hosegood (1962); root activity matches the distribution of roots given by these authors except for differences at greater depths resulting possibly from the shallower soil of the Kimakia catchments.

When the drought was most severe, the top 45 cm of the profile under pine was at wilting point and the similar layer under bamboo was close to this deficit. The sites under grass were not so affected by the drought.

PERCOLATION RATES IN KIMAKIA SOILS

Over the drought period, an estimate of percolation rates can be made from an analysis of the profile response to those small rainfall inputs that occur but which are insufficient to recharge the profile. The depth of rainfall is ignored and the distance through the profile travelled by the wetting front gives the water movement per day. The results of this analysis are shown in Table III.

VEGETATION WATER USE

By considering periods when soil profiles could be taken to be free from water draining through the profile, an estimate was made of vegetation water use by taking a simple water balance

TABLE II

Average Depletion Rates in mm day^{-1} and DBD on Kimakia Catchments for 30-270 cm Depths in the 1971 Drought

Depth cm	Bamboo Site 3 (12.1.71-20.3.71)		Pines Site 3 (12.1.71-10.3.71)		Grass Site 2 (12.1.71-20.3.71)		Grass Site 3 (12.1.71-20.3.71)	
	mm day^{-1}	gm cm^{-3}	mm day^{-1}	gm cm^{-3}	mm day^{-1}	gm cm^{-3}	mm day^{-1}	gm cm^{-3}
30	0.64	0.60	1.27	0.57	0.46	0.61	0.65	0.61
60	0.35		0.33		0.23		0.29	
90	0.30		0.39		0.33		0.34	0.78
120	0.24	0.84	0.22		0.21		0.25	
150	0.15		0.09	0.91	0.23		0.18	
180	0.19		0.04		0.12	0.78	0.22	
210	0.20		0.15		0.12		0.16	
240	0.15		0.07		0.12		0.15	1.00
270	0.15		0.09		0.12		0.12	
Total depletion rate to 2.7 m	2.30		2.60					

TABLE III

Percolation Rates in Kimakia Soils

(For explanation of derivation, see text)

Catchment	Catchment Vegetation	Profile MVF	cm day^{-1}
C	Bamboo	0.506 ± 0.009	26.9 ± 2.9
A	Pines	0.449 ± 0.013	31.9 ± 2.9
M	Grass - Site 2	0.565 ± 0.007	30.2 ± 4.7
M	Grass - Site 3	0.492 ± 0.014	29.8 ± 3.9

of the profile. Results are shown in Table IV as the mean soil moisture depletion rate in mm day^{-1} for the different types of vegetation. The total depletion expressed as a ratio to Penman's EO is also shown as a mean value and by 100 mm SMD classes. The depth of profile used was only 2.7 m and these means are only a very approximate guide to deficit totals. The data for the grass catchment are too few to show any trend with increasing SMD with acceptable precision as there were no values above a mean deficit of 190 mm.

SUMMARY AND CONCLUSIONS

The most important point to emerge from the analysis of variance of the SMD data was that the amplitude and phase of annual fluctuations in SMD did not differ for the three catchments under bamboo, pines and Kikuyu grass; however, the mean annual SMD under bamboo was significantly greater than under either grass or pines. However, the reality of this difference is somewhat suspect, in view of the significant differences in mean annual SMD found when comparing sites within each catchment. Such differences in mean SMD could be explained by impeded drainage, slope position or perched groundwater. The differences between sites on the catchment under pines were more marked during the early clearing and planting stage than later when the trees were more mature. The two methods of soil moisture sampling (gravimetric, neutron moisture meter) could not be compared directly, but estimates for field capacity obtained from gravimetric laboratory determinations and neutron field observations showed good agreement.

TABLE IV

Soil Moisture Depletion Rates to 2.7 m

	Mean SMDR* (mm day^{-1})	Soil Moisture Depletion as a Ratio to Penman EO			
		Mean	0 - 100 mm SMD	100 - 200 mm SMD	200 - 300 mm SMD
Bamboo	4.30 ± 0.31	0.79 ± 0.05	0.83 ± 0.06	0.79 ± 0.08	0.62 ± 0.10
Mean SMD		94 ± 13	55 ± 11	160 ± 17	239 ± 25
Pines	3.76 ± 0.22	0.80 ± 0.04	0.90 ± 0.04	0.64 ± 0.07	0.58 ± 0.23
Mean SMD		86 ± 9	58 ± 7	142 ± 10	214 ± 24
Kikuyu Grass	3.63 ± 0.41	0.66 ± 0.07	0.71 ± 0.08	0.60 ± 0.12	-
Mean SMD		81 ± 19	33 ± 10	158 ± 16	

* Soil moisture depletion rate

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3.3

SUMMARY OF RESULTS OF THE KIMAKIA EXPERIMENTS

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3.3

SUMMARY OF RESULTS OF THE KIMAKIA EXPERIMENTS

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The main objective of the study at Kimakia was to determine the effects of a land-use change from indigenous bamboo forest to pine plantations by monitoring and comparing the hydrological responses to similar rainfall inputs of two adjacent catchments, one under bamboo and the other converted to *Pinus patula* plantation. A later, secondary objective was to conduct a similar study on intensive sheep grazing. The results obtained from the main exercise, up to the point where the pines had reached a height of some 25 m are summarised below; the second study suffered a number of delays, and results from the preliminary stages only have been presented. It is currently being continued by Kenya Government.

No initial calibration period, with the catchments under the same land-use, was possible in either study. Whilst this did not complicate the assessment of annual water use, it meant that inherent differences in seasonal streamflow distribution between catchments could not be quantified and any effects on this distribution of the land-use changes have had to be inferred indirectly.

The 16 years of rainfall, streamflow, soil moisture and meteorological data from the two main catchments and a shorter sequence of data from the grass catchment, have been processed and quality-controlled. A number of systematic errors was detected, notably in the streamflow from the control catchment in the period 1961-66 and in the windrun from 1967 onwards, and corrections have been applied. Long-term mean water use has been estimated for each phase of development of the pines, together with its variability. During the initial stages of pine growth, when vegetables were cultivated between the seedlings, the water use was depressed by some 19% compared to the bamboo. As cultivation ceased and canopy closure progressed, the water use difference decreased. From 1967 to 1973, when the fully established pines grew from 15 m to 25 m mean height, the mean water use by both pines and bamboo was found to be 76% of Penman EO.

Grass was fully established on 33% of the third catchment by 1967. This was grazed sporadically until 1970 when an intensive grazing scheme was initiated to be followed in 1973-74 by clearing and planting to grass of a further 30% of the catchment. Mean water use from 1967 onwards was some 10% lower than that of the bamboo, with no significant differences detected between grazing periods.

Model simulation of the interception and transpiration processes in pines and bamboo indicated that, for both vegetation types, the evaporation rate of intercepted water was considerably higher than the transpiration rate. The contributions to total water use from each process were similar for both vegetation types. These processes were shown to account for most of the variability in annual water use in both catchments from 1967 onwards.

These results, together with (i) the analysis of soil moisture data which showed no significant differences in amplitude and phase of moisture content changes between catchments and (ii) surface runoff studies showing no difference in response on these soils, imply that neither annual total water yield nor its seasonal distribution are significantly affected by the land-use change to pines, after the establishment period.

Short-term dry season water use estimates were made from the routine soil moisture readings. These show a general similarity in magnitude of water use by established pines and bamboo, albeit with some relative reduction for pines at high soil moisture deficits. Whilst this also implies no major change in seasonal water yield, the water use rates determined by this method for both vegetation types may be biassed through the inclusion of a variable proportion of interception loss and an unknown element of percolation loss.

This study has established that a significant difference in water use between bamboo and seedling pines exists. During the middle period of growth of the pines, however, water use is virtually identical to that of bamboo. Since the interception and transpiration components of water use are similar for both vegetation types, it would appear that a similar response could be expected in environments differing from that encountered at Kimakia, provided the soils have similar stability and infiltration rates.

Whilst the clearing and planting of the pine catchment was shown to have a negligible effect on sediment yield, except for the effects of road works, it is important that further checks on sediment are carried out during the logging phase when greater soil disturbance will occur. Initial effects of grazing on sediment yield were encouraging but monitoring should continue to establish long-term trends.

4.1.1

THE ATUMATAK RESEARCH PROJECT

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INTRODUCTION

Large areas of potentially productive rangeland in East Africa (Ecological Zone IV, Pratt, Greenway and Gwynne, 1966) have deteriorated as a result of overgrazing into bushland and dry thicket (Langdale-Brown, Osmaston and Wilson, 1964; Hornby, 1936; Staples, 1942; Pratt, 1963; McCulloch, 1965). Increases in human and animal populations, reduction in the extent of traditional grazing lands and advances in veterinary medicine, have all contributed to greater pressure on grasslands which are particularly sensitive to over-grazing. As a result, there is a replacement of the perennial grass species by sparse annuals, biennials and herbs with a concomitant spread of woody species. The grasslands degrade into bushland and, with sheet erosion accelerating the process, the bushlands into dry thicket.

At the same time, the removal of vegetative cover and truncation of the soil profiles leads to a lowering of the infiltration rate, flash flooding and a drastic modification of the soil moisture regime. In these regions of erratic but intense rainfall, the cycle is self propagating and may eventually result in the complete removal of the soil by sheet and gully erosion. Examples of this impoverishment of the land can be cited from Karamoja in Uganda, Baringo in Kenya and the Kondoa-Irangi Region of Tanzania. Both from an ecological and hydrological point of view, the land use practices which give rise to this loss of productivity are disastrous on a local and national level. On occasions, attempts to provide alternative water supplies to support increasing numbers of cattle have accentuated the problem by encouraging grazing far beyond the carrying capacity of the land.

These problems have long been recognised and remedial measures proposed (Thomas, 1943; Heady, 1960; and Thornton, 1968). Apart from the cost of bush clearing and development of range management schemes, there is a considerable human problem of persuading local people that drastic destocking and controlled grazing are for their own long-term future benefit. Under these circumstances, a single demonstration of land improvement may be a more powerful tool than a plethora of scientific rationalisation. Accordingly, development schemes have been a favoured method of educating people to use improved systems of range management and one such scheme, the Karamoja Development Scheme, provided the background to the Atumatak Catchment Experiment.

A co-operative experiment between EAAFRO and the Government of Uganda was proposed in 1956 to determine the extent to which the deterioration of these grasslands could be halted or reversed by inexpensive treatment and good management. The nature of the experiment and the treatments tested are in the following sections.

DESCRIPTION OF THE EXPERIMENTAL CATCHMENTS

The catchments chosen lie at the head of the Atumatak valley midway between the Moroto and Kadam Mountains adjacent to the Moroto-Mbale road (Fig 1). Together they form a well defined 811 ha basin draining north into the Omanimani River. The altitude of the basin ranges from 1345 to 1460 m with an average slope of two per cent. The intermittent streams (Lodoketeminit River, East and West) are dry channels with sandy beds characterised by brief flash-floods of violent intensity. The vegetation has affinities with the Turkana region of northern Kenya and with parts of the southern Sudan. The prevalence of desert species is anomalous in view of the mean annual rainfall of 750 mm (1959-74) and is attributed to the trampling and over-grazing of the domestic stock (Kerfoot, 1962).

The soils are derived from the Basement Complex peneplain and are in an advanced state of accelerated erosion, with the

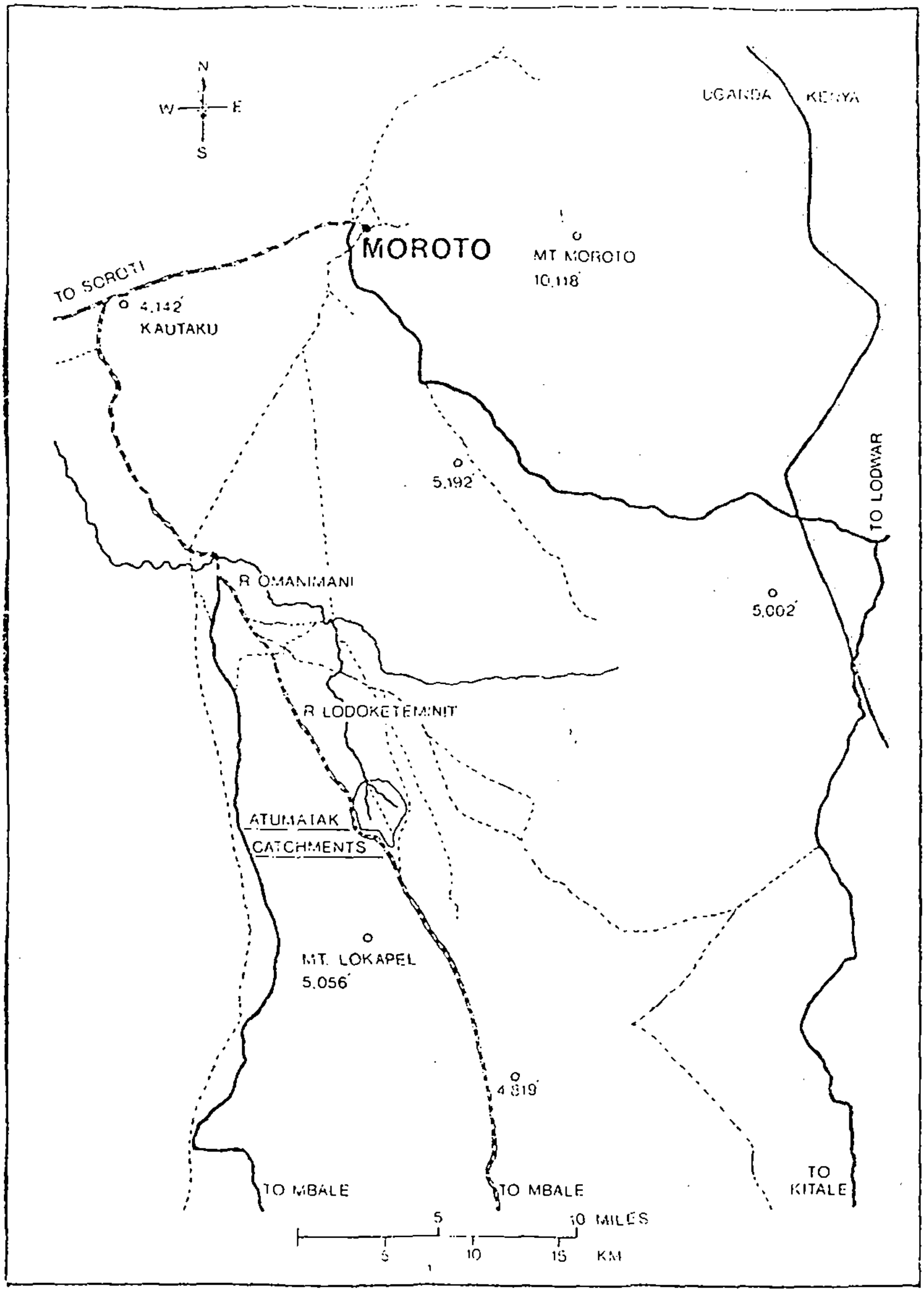

Figure 1 Location of the Atumatak experimental catchments

original top soil present only in isolated thickets where the thorn-scrub and sansevieria have been too thick for goat grazing. The soil types are described by Wilson (1962) and show an unexpected degree of complexity for such a small area. An analysis of the physical properties, however, reveals that, in spite of the differences in the appearance of the soil types and the vegetation they support, they are remarkably uniform in moisture retention and infiltration characteristics (Dagg, 1962). All the profiles are truncated, particularly on the ridge tops where the soil depth may be only 15 to 45 cm. Erosion pavements or stone mantles are extensive and the overall rainfall acceptance was found to be considerably lower than that of many agricultural soils in East Africa (Pereira, 1956).

The climate of the area is summarised in Table 1. It can be seen that the rainfall of 400 to 1000 mm per annum is highly variable but in more temperate latitudes would be considered as adequate for many forms of agriculture. With potential evaporation in the region of 2000 mm yr^{-1} and much less variable, it is clear that, even if the soils were able to retain a higher proportion of the rainfall as soil moisture, some months and years would experience a severe deficit of available water. As it is, with some 10% of the rainfall being lost as stormflow and the remainder rarely penetrating below a depth of 50 cm, water is only available for plant growth in four to six months of the year. The high evaporation pan readings in relation to the Penman estimates in the dry season are indicative of considerable heat advection from the dry non-transpiring surroundings (Appendix 7.1.3).

EXPERIMENTAL PROGRAMME

The establishment of the experiments, the surveys, calibrations and the work on bush clearing techniques in the Intensive Reclamation Area during the period 1957-1961 have been described in detail in Pereira et al (1962).

During this period, the runoff patterns under typical local grazing intensities were determined and detailed surveys of the

TABLE I

Mean Climatological Data (1959-74)

Atumatak

Altitude 1524 m, Latitude 2°14'N, Longitude 34°39'E

	Rainfall	Temperature			Humidity	Wind	Radiation	Sunshine*
	Monthly Total	Max	Min	Mean	Saturation Deficit	Mean Speed at 2 m	Gunn Bellani Radiometer	
	mm	°C	°C	°C	mb	km hr^{-1}	MJ m^{-2}	hr
Jan	10.4	29.9	15.0	22.5	13.1	8.8	27.0	9.8
Feb	22.2	30.3	15.4	22.8	12.7	8.0	26.6	9.2
Mar	56.7	29.7	15.8	22.8	11.6	8.0	26.2	8.7
Apr	121.7	28.2	16.1	22.2	9.0	6.5	23.5	7.9
May	105.8	27.4	15.1	21.3	6.8	4.1	23.3	8.2
Jun	54.3	27.6	14.2	20.9	7.5	4.0	23.2	8.6
Jul	110.1	26.2	14.6	20.4	6.6	3.8	21.7	7.2
Aug	93.3	26.9	14.4	20.7	7.3	4.4	23.6	8.0
Sep	59.6	28.3	13.9	21.1	8.6	4.8	26.0	8.9
Oct	49.8	28.6	15.8	22.2	10.5	7.3	25.5	8.7
Nov	49.3	28.4	16.0	22.2	10.8	8.7	24.8	8.5
Dec	20.0	28.9	15.0	21.9	11.5	9.0	25.8	9.5

* Sunshine records incomplete (1971-74)

soil and vegetation were made. From the results of the Intensive Reclamation Area experiment undertaken as part of the Karamoja Development Scheme, it was established that chain clearing of the bush with some subsidiary hand clearing was the maximum treatment feasible in terms of the likely economic return from this region. Costs ruled out the use of arboricides, cultivation and re-seeding. Following the bush clearing, periods of complete exclusion of cattle and other stock were shown to be necessary for the establishment of a grass cover.

Accordingly, one catchment (B) was cleared in 1961/62 and fenced to exclude cattle while the other (A) continued to be grazed in the normal manner. By 1964, the grass cover had established itself remarkably quickly and a further vegetation survey was carried out jointly by the District Agricultural Officer and staff of the East African Herbarium. A summary of the vegetation changes during the course of the experiment is given in Section 4.1.2.

Having demonstrated that this minimum treatment led to the re-establishment of a good grass cover, the next stage was planned to be the introduction of controlled grazing to determine the maximum densities which could be imposed on the catchments without causing a reversal of the reclamation process. Discussions on the grazing patterns were completed by mid-1965, when it was decided that a three-block, three-year rotational grazing scheme be adopted at a density of one beast per four hectares. Grazing started in 1965, but because of the many difficulties experienced on site, which included theft of fencing wire, illicit grazing, theft of stock and a particularly violent cattle raid in December 1970 which resulted in the deaths of 23 people and loss of all Government stock, the proposed rotational grazing scheme was never fully implemented.

Since there appeared to be no immediate prospect of the controlled grazing scheme being fully and permanently established, it was decided to analyse the hydrological data collected up to 1971 to determine the effects of the establishment of the grass cover with minimal grazing.

Throughout the period from 1958 to 1971 records of rainfall, runoff, infiltration and the meteorological variables necessary to compute Penman estimates of potential evaporation have been collected. In view of the frequent theft of and damage to equipment, the harrassment of observers and the difficulties of communication and in maintenance of equipment, the gaps in the records are surprisingly small. A description of the instrumentation used in the catchments is given below and analyses of the hydrological data are presented in later sections.

INSTRUMENTATION OF THE CATCHMENTS

Because of the large range of discharge and the silt-laden nature of the flow, it was decided that compound rectangular-throated flumes be used for the measurement of streamflow. These structures were installed under the direction of the Uganda Water Development Department and almost immediately were subject to silting and to erosion of the downstream river banks as a result of the violent flash-floods. Sediment deposition in the approach section not only cast doubts on the validity of the theoretical calibration of the flumes but also prevented the entry of water into the tapping points. Thus the water level recorders were insensitive to changes in stage and could not record the storm hydrographs.

Two measures were taken to solve this problem which in retrospect were ill-advised and led to further difficulties in interpretation of the streamflow records. In the first place, a concrete kerb was constructed in the approach section to stabilise the deposition of sediment in the forecourt. This was an improvement in terms of the cross-sectional profile of deposited sand but it affected the rating of the flumes to an unknown extent. The second measure was the laying of a perforated pipe from the tapping point to the throat of the centre flume which, because of the differential head established in the pipe, affected the water level in the recorder well. After repeated efforts to gauge the flow by current meter were foiled by the sediment problem and the unpredictability of flow events, a scale model of the flumes was built at EAAFRO and calibrated first at the University of Nairobi and later at the Hydraulics Research Station, UK. From these laboratory calibrations and the records from a second water level recorder placed in one of the flumes, it has been possible to obtain a stage-discharge curve for the structures (Appendix 7.1.1) and correct the records retrospectively.

Rainfall is very variable over the catchments and a dense network of 18 daily and five recording gauges has been maintained (Figure 2). The area of the two catchments is 811 ha, giving a density of one gauge per 35 ha; a very dense network in terms of existing national networks in semi-arid regions. The records from these gauges are of intrinsic value to the study of the areal distribution of rainfall in these regions, therefore, and a special study has been made of them (Section 4.2.2).

A meteorological station was installed in the catchments to measure the variables required to estimate potential evaporation. Raised and sunken evaporation tanks were also maintained over the period of the experiment.

Soil moisture content would have been difficult to measure due to the isolated location of the experimental catchments. Soil moisture tension has been recorded, therefore, at 20 profiles in the catchments to study the depth of penetration of water into the soil and the availability of this water during the year. Electrical resistance units have been used for this purpose and an analysis of the records is given in Section 4.2.1.

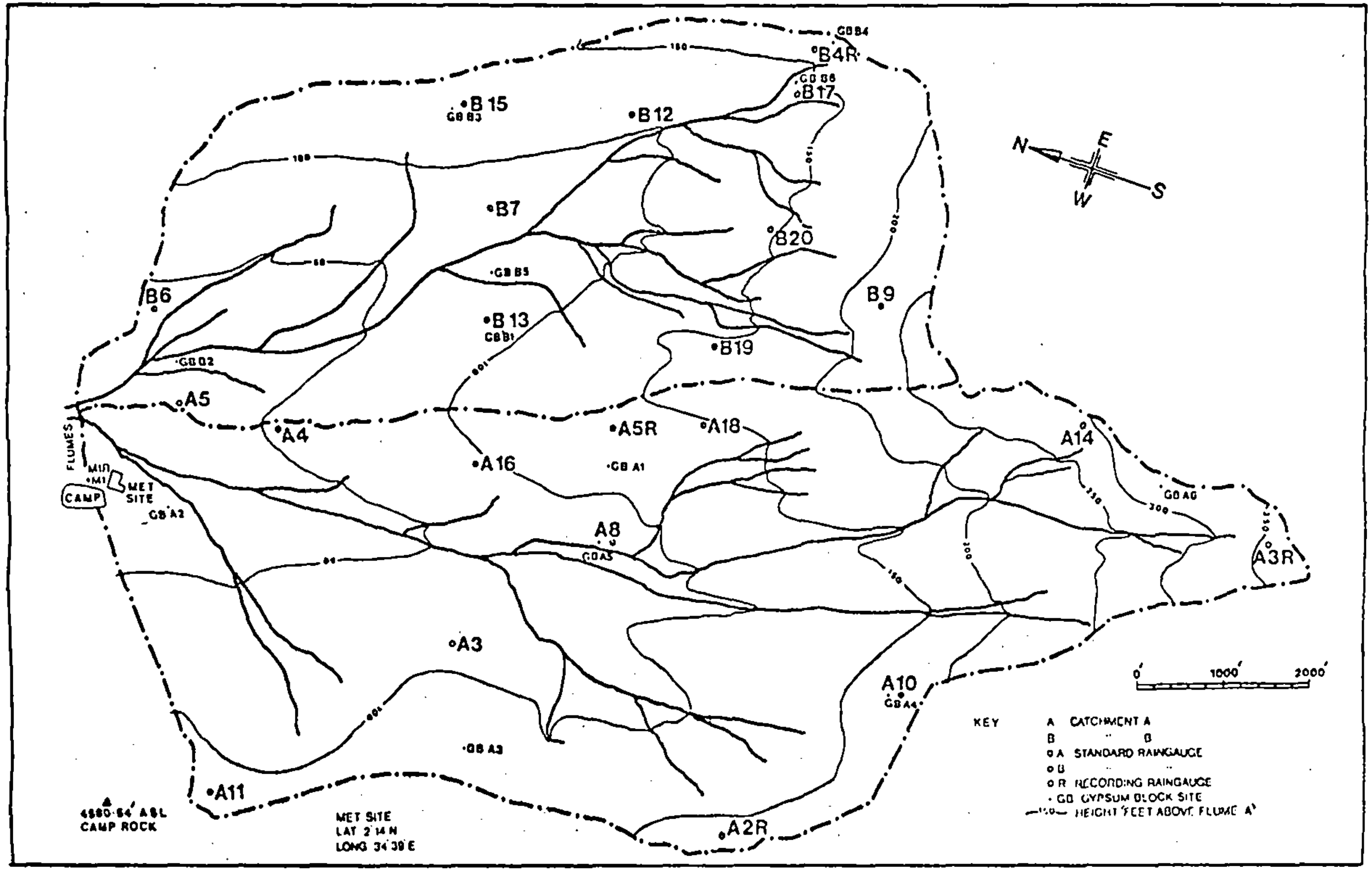

Figure 2 Raingauge networks in the two experimental catchments

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4.1.2

THE ASSESSMENT OF VEGETATION CHANGE ON THE ATUMATAK WATER CATCHMENT EXPERIMENT FROM 1957 TO 1975

J G Wilson* and the late D M Napper**

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INTRODUCTION

When civil administration in Karamoja District began in 1921, parts of the district were being severely overgrazed and the vegetation was changing from savanna to bush. The problem was exacerbated by the administrative policy of allowing Pokot people from Kenya to settle in an area then known as Karasuk, which prior to this time had been Karamojan grazing territory (Brasnett, 1958). Once the Pokot, or Suk as they were then called, were established in the Karasuk area, they kept up a steady westward expansive pressure and, again with administrative favour, were allowed to occupy and graze more Karamojan territory from 1921 until 1940 when a rudimentary boundary was established between the Karamojong and the Pokot along the Kanyangareng River, south of Moroto Mountain and some 16 kilometres east of Atumatak.

The effect of the Pokot incursion and expansion was quickly apparent; in a few years the Karasuk area became severely overgrazed. Furthermore, as the grazing territory of the Karamojong decreased, the concentration of stock in the eastern parts of Karamoja increased, with consequent signs of overgrazing, erosion and vegetation degradation from savanna to bush or thicket. Degenerative changes in the vegetative cover of the east and central parts of the district became more marked in the post-Second World War period as the cattle population grew steadily. This was accelerated by government policy of compulsory inoculation of cattle against rinderpest and other diseases and of the provision of water supplies in the form of dams and boreholes in hitherto waterless country.

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EXPERIMENTAL MEASURES

By 1953, the situation had deteriorated so markedly that 12 bush-clearing trials were conducted over an extensive area, covering a wide range of bushland and thicket communities (Wilson, 1962). By 1955, these trials had demonstrated that simple clearing of a shrub-dominated community, which had succeeded a grass-dominated community as the result of overgrazing, led to the re-establishment of the original cover only where a residuum of perennial grasses survived.

It was to investigate the hydrological effects of re-establishing the perennial grassland under controlled grazing conditions that the catchment experiment described in Section 4.1.1 was begun in 1957. Two adjacent catchments were instrumented at Atumatak some 40 kilometres south of Moroto in an area where the degradation problem was severe.

THE VEGETATIVE COMPOSITION OF THE CATCHMENTS

One of the main factors governing regeneration is the extent to which graminaceous elements have been replaced by bushland and thicket. The Atumatak site was one where the degree of replacement by unpalatable succulent and woody elements was not quite complete, though superficially it appeared to be so. Not only did Atumatak possess this residuum of perennial grasses but it also differed from vast areas of Karamoja both in elevation (and hence in topography) and in the nature of the vegetative change. In short, Atumatak with its rolling topography and higher elevation represented the extreme case which, strictly, was typical only of the type of severe sheet and gully erosion that occurred in upland areas of Karamoja. The vegetative change that was taking place over most of the much more gently undulating plain-land was insidious although less spectacular.

Qualitatively, the original savanna vegetation of Atumatak and surrounding land of similar elevation might be termed Dry Combretum Savanna, with the trees *Combretum guienzii*, *Terminalia* *brownii, Heerea reticulata, Acacia hockii* being salient components, while ground cover included such grasses as *Eragrostis caespitosa, E rigidior, E superba, Heteropogon contortus* and *Sehima nervosum* besides a mixture of *Hyparrhenia spp* and *Themeda triandra*. This contrasts markedly with the vegetation on the plains which was typically a grass savanna with few trees and of a much more even composition reflecting the uniformity in soil type, soil depth and degree of slope. Overgrazing of the grass savannas on the plains led to the replacement of perennial grasses by shrubs and small trees which formed communities of often astonishing uniformity, salient woody components being small trees such as *Lannea humilis, Acacia mellifera, A senegal, A tortilis* and *Dichrostachys cinerea*. Ground cover under persistent grazing was at all times sparse but these communities were essentially bushland and not thicket. Moreover, on these virtually flat plains, there was much less erosion and water loss than at Atumatak. Much of this bushland was relatively stable; there was little indication of further degenerative changes such as the appearance of *Sansevieria ehrenbergii* and the consequent thickening of the shrub layer.

In the Atumatak area the vegetative composition was different and degeneration had proceeded far beyond mere replacement of savanna by bushland. Erosion on the denuded soil, and the concomitant high water loss, induced conditions where only desert-related vegetation, which Kerfoot related correctly to the vegetation of Turkana District, could survive (Kerfoot, 1962). This vegetation forms thickets in which succulent plants are conspicuous, particularly the agave *Sansevieria ehrenbergii*, and reflects not the existing climatic conditions but rather the consequence of accelerated runoff and severe erosion from denuded sloping land surfaces.

At the start of the experiment in 1957, much of the vegetation of the catchment areas had degenerated into dense thicket interspersed with patches of bare eroded soil. On ridge tops, however, and towards the confluence of the two streams where both slope and erosion were less severe, bushland with relict savanna elements was prevalent; in addition, minor elements such as riparian vegetation occurred over small areas.

THE CLEARING PHASE

The local populace was allowed to graze both catchments A and B without hindrance for five years, during which time rainfall and runoff records were collected; thereafter catchment B was closed to grazing and mechanically cleared of all tree and shrubby plants, excepting large isolated trees (Evan Jones, 1962). The cleared vegetation was windrowed and later burned. Thus, in 1962 the second phase of the experiment began; it was to explore the consequence of clearing both in terms of the rate of reversion to a grass-dominated type of vegetation more akin to that of the original savanna, as well as a change in the rate of runoff from both catchments.

DEVELOPMENT OF PERENNIAL GRASS COVER AFTER CLEARING

In the two years immediately after the clearing of all woody species from catchment B, there was an initial rapid colonisation by pioneer annual herbs and grasses followed by a more stable wave of perennial grasses and other herbs which gradually replaced many of the annuals. Colonisation proceeded unhindered by either heavy grazing or prolonged dry periods and though there was no appreciable change in the distribution of the grasses, the more palatable perennial species formed a very much higher percentage of the total herbage and their growth was denser. Regeneration of trees and shrubs was uneven, occurring all over the catchment and not reflecting the distribution pattern of the ecological types previous represented. The most growth was made by *Acacia brevispica*, *Dichrostachys cinerea*, *Ipomoea spathulata*, *Lannea humilis*, *Albizia amara spp sericocephala*, *Fagara chalybea*, *Coleus barbatus* and the various species of *Grewia*.

The marked similarity between soil distribution and the varying types of vegetation on the catchments (Figs 1 and 2) was also reflected in the herbaceous vegetation of catchment B. The sandy loams on the flatter ground of the ridge tops demarcating

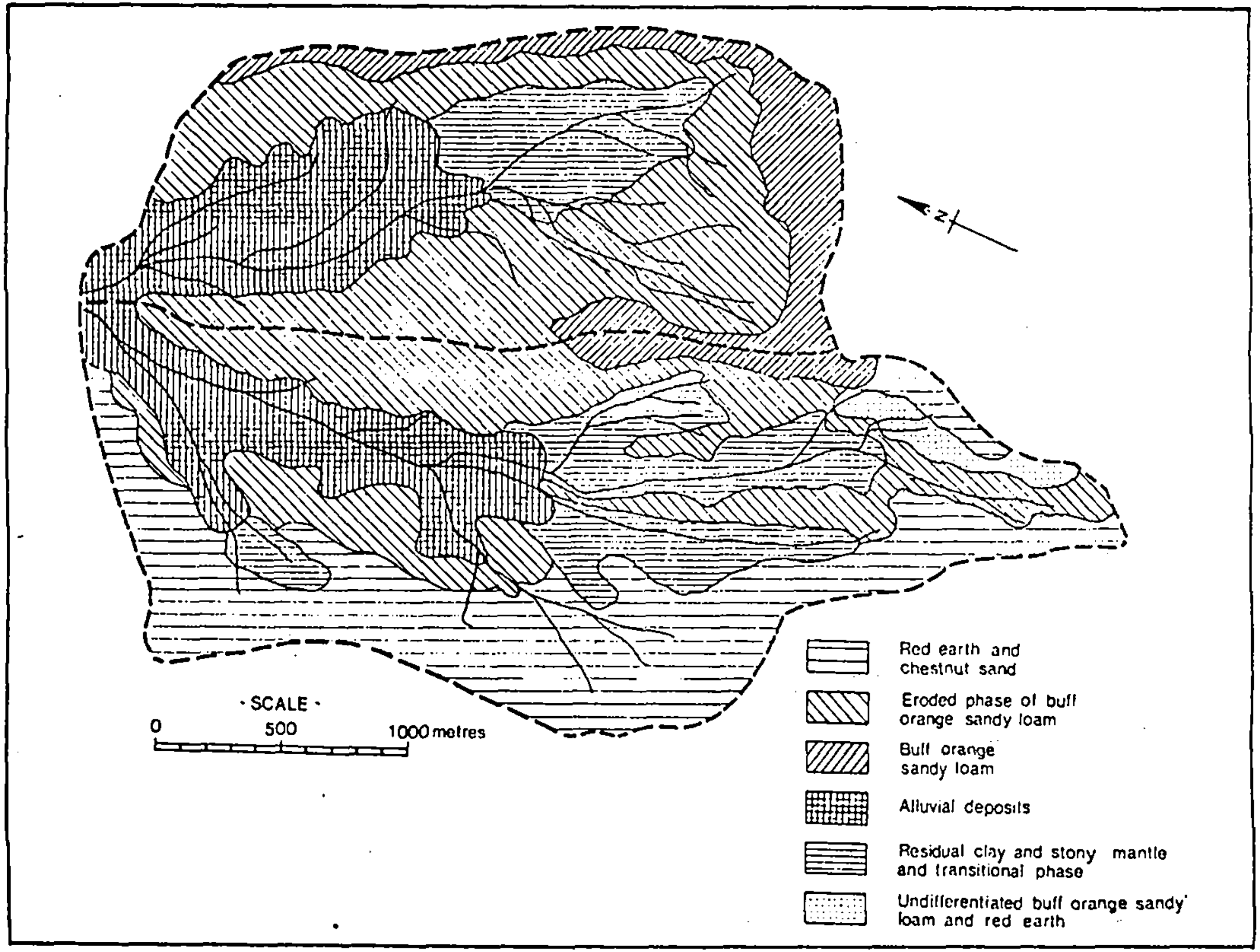

Figure 1 Distribution of generalised soil types in the Atumatak catchments

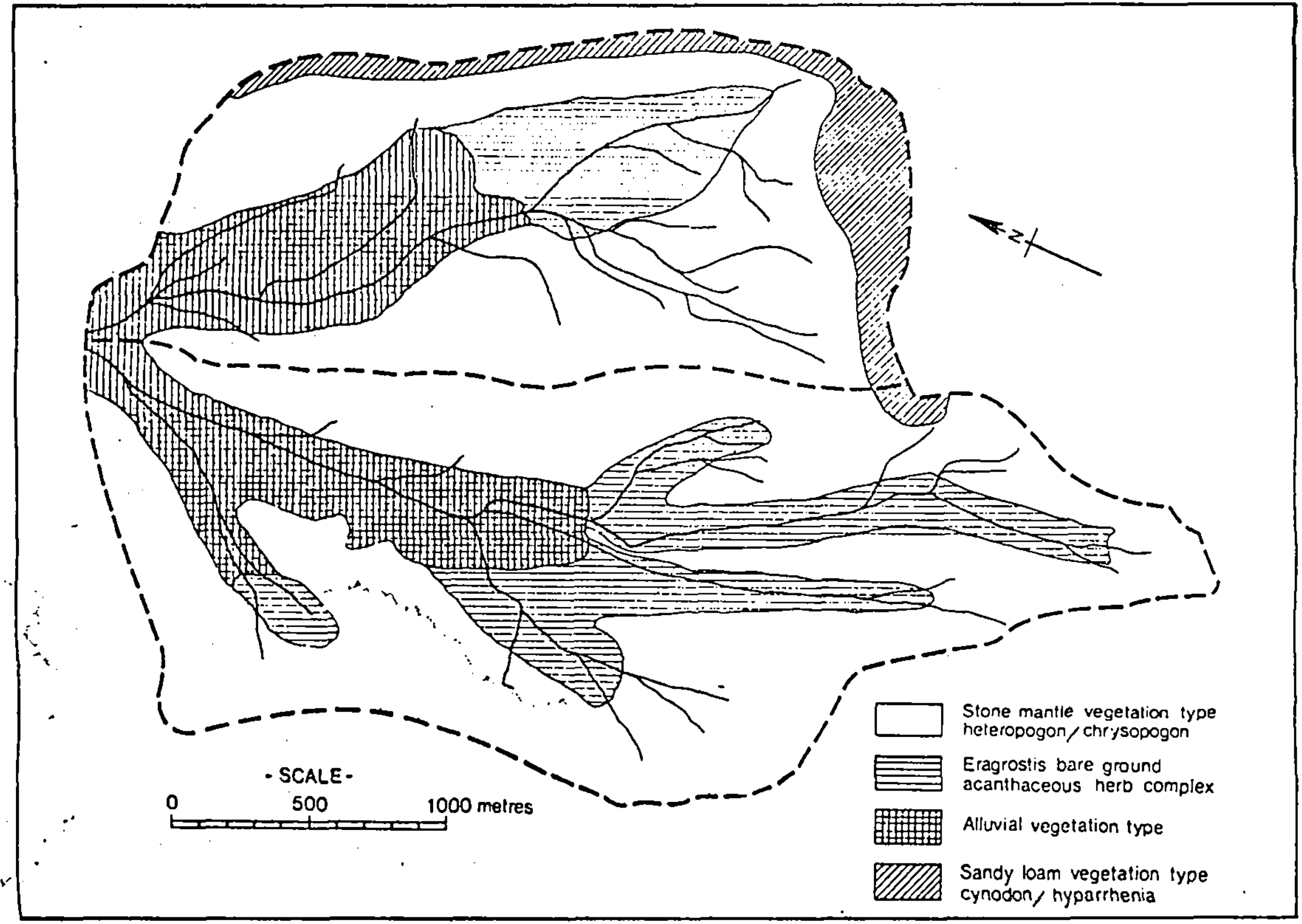

Figure 2 Distribution of vegetation types at Atumatak

catchment B carried a uniform growth of *Cynodon dactylon* largely in almost pure stands, giving a leaf cover of 66%; where the slope was greater, pure stands of *Hyparrhenia dissoluta* with 70% leaf cover occurred. The eroded sloping sides of the valley carried much less of these species though locally they were abundant. The dominant cover was a mixture of the perennials *Eragrostis rigidior* (previously listed as *E gymnorrhachis*), *Digitaria macroblephara, Hyparrhenia dissoluta,* the annuals *Harpachne schimperi* and *Aristida adscensionis* and a considerable proportion of *Blepharis integrifolia* and *Barleria acanthoides* (previously reported as *B longissima*), together with *Eragrostis superba, Sporobolus festivus, Microchloa kunthii* and trace representations of a number of other annual and perennial herbs. In the centre of the catchment, the higher ground which consisted for the most part of stone mantle soils, had a very sparse and characteristic cover of *Heteropogon contortus* and *Chrysopogon aucheri* var *aucheri* which formed dense tufts separated by wide bare areas. The alluvium around the stream, as would be expected, carried the best cover of the palatable perennial species such as *Cynodon dactylon, Chloris gayana* etc.

To obtain relative measurements of cover, a series of transects was made prior to burning off the regenerating bush by the line intercept method on (a) the *Cynodon dactylon* overlying the sandy loams (Tables I and II Transect 1), (b) the mixed *Eragrostis* - bare ground-acanthaceous herb complex on the eroded slopes (Transects 3, 5, 6 and 7), (c) the transition from the *Hyparrhenia dissoluta* occurring on the edge of the loams to the *Eragrostis* complex (Transect 2) and (d) the sparse *Heteropogon-Chrysopogon* cover on the stone mantle soils (Transect 4).

The pure stand *Cynodon dactylon*, although appearing dense, was shown to have a total cover not exceeding 73% of which 90% was *Cynodon*, the remainder being a small quantity of *Panicum maximum*, 6% and traces (each less than 1% of the total sample) of *Microchloa kunthii, Sporobolus festivus, Solanum incanum* and *Commelina* species. The *Microchloa* and *Sporobolus* were obvious remnants from the earlier pioneer stages.

TABLE I

Percentage Composition of Line Transects

	Transect Number						
	1	2	3	4	5	6	7
% leaf cover	73	63	77	37	53	58	48
Perennial Grasses							
Cynodon dactylon	66	2	10				
Eragrostis rigidior		20	28	2	9.5		20
Digitaria macroblephara		4	9.5				
Hyparrhenia dissoluta		13				9	4
Cenchrus ciliaris		2.5					5
Heteropogon contortus				20			
Chrysopogon aucheri				6			
Sporobolus marginatus					13		
Others	4	2	6	6	5	9	
Annual Grasses							
Harpachne schimperi		3	6		1	12	1.5
Michrochloa kunthii						15	
Aristida adscensionis							2
Others					1		
Herbs							
Barleria and Blepharis		6	2.5		13		1.5
Other Perennials		4	2	2	1	3	4.5
Other annuals	3	3.5	7	2	2	4	1
Major vegetation types	a	c	b	d	b	b	b

a	*Cynodon dactylon* overlying the sandy loams
b and c	Transitional *Hyparrhenia* - *Eragrostis* - bare ground
d	*Heteropogon* - *Chrysopogon* on the stone mantle soils

TABLE II

Percentage Composition of Total Cover

	Transect Number						
	1	2	3	4	5	6	7
Perennial Grasses							
Cynodon dactylon	90	3	13				
Eragrostis rigidior		32	36	4	18		41
Digitaria macroblephara		6	12				
Hyparrhenia dissoluta		21				16	7
Cenchrus ciliaris		4					9
Heteropogon contortus				53			
Chrysopogon aucheri				15			
Sporobolus marginatus					24		
Others (i)	6	3	8	15	10	16	
Annual Grasses							
Harpachne schimperi		5	8		2	21	3
Microchloa kunthii						26	
Aristida adscensionis							5
Others (ii)					2		
Herbs							
Barleria and Blepharis		9	3		25		3
Other perennials (iii)		7	3	5	2	5	9
Other annuals (iv)	4	6	9	5	4	7	2

Regenerating shrubs and trees have been disregarded in the above tables except for their contribution to the total leaf cover: few were more than 1½ ft high.

(i) Other perennial grasses. *Bothriochloa pertusa, Chloris roxburghiana, Cymbopogon pospischilii, Eragrostis caespitosa, E superba, Panicum maximum, Sehima nervosa,* and records of the tabulated species comprising less than 1% of the transect.

(ii) Other annual grasses. *Brachiaria leucacrantha, Chloris virgata, Sporobolus festivus,* and records of the tabulated species comprising less than 1% of the transect

(iii) Perennial herbs. *Coleus barbatus, Pentanisia ouranogyne, Solanum incanum, Stylosanthes fruticosa.*

(iv) Annual herbs. *Commelina* spp, *Dischoriste radicans, Endostemon tereticaule, Gutenbergia petersii, Helichrysum glumaceum, Ipomoea* spp, *Oxygonum sinuatum, Polygala liniflora, Ruellia patula.*

The transitional area - *Hyparrhenia-Eragrostis* - bare ground - gave an overall figure of 63% cover, but the initial 20% of this was nearly pure *Hyparrhenia* on the sandy loams and for this part of the transect the percentage cover was 85%, 83% of this being *Hyparrhenia* . Also present here were *Eragrostis rigidior* , 12% and *Stylosanthes fruticosa*, 5%. The remainder of the transect was through more open vegetation with only 41% cover. Here *Eragrostis rigidior*, 39% of the cover, was the most abundant grass, with *Digitaria macroblephara*, 8%, *Harpachne schimperi*, 7% and *Cynodon dactylon*, 4%. *Barleria acanthoides*, 10% and *Stylosanthos fruticosa*, 7%, were the commonest herbs.

On the eroded slopes, very varied figures were obtained for percentage cover; over large areas the soil had been completely washed away so that not even pioneer species had become established. The total cover varied between 41% and 77%. The perennial grass normally dominant was *Eragrostis rigidior* and the incidence of this useful constituent appeared to be increasing rapidly, except in areas still suffering badly from erosion where *Harpachne schimperi* and *Microchloa kunthii* predominated (Transect 6). Certain areas showed a local concentration of *Sporobolus marginatus* (Transect 5), and in others the acanthaceous herbs *Blepharis integrifolia* and *Barleria acanthoides* together constituted a dominant feature representing nearly 20% of the cover with neither of the dominant grasses representing more than two thirds of this. Over most of the slopes, these two herbs were the most abundant constituent of the non-graminaceous part of the cover.

The stone mantle soils have a very sparse, almost exclusively perennial cover totalling only 37%. *Heteropogon contortus* was dominant, 53%, and *Chrysopogon aucheri* var *aucheri* , 15%, while *Sehima nervosa* and other perennial grasses made up a further 15%. Other herbs, although present, formed only 10% of the cover.

Catchment B and the between-thicket cover of catchment A already showed great differences in the density and proportional composition of the ground cover, that of A being everywhere sparse or absent. *Barleria acanthoides* was a major dominant on A and in places formed up to 75% of the total cover. A visual comparison of the graminaceous element of the cover of the two areas, which in the past were extremely similar, showed a very marked increase in the density and amount of the perennial grasses *Hyparrhenia dissoluta, Eragrostis superba* and *Eragrostis rigidior,* and small increases in *Cenchrus ciliaris, Chloris roxburghiana* and *Cynodon dactylon.* Not recorded previously on either catchment, but developing locally into an appreciable element on B, was *Digitaria macroblephara.*

When catchment B was cleared, cattle were excluded to allow unimpeded recovery of grass and by 1964, the overall grass cover had improved to such an extent that a herd of 60 mature animals was introduced, representing a stocking rate of approximately one animal to 4 hectares. The proposal for rotational grazing of the catchment by its division into four paddocks was never effected because of shortage of trained personnel. Nevertheless, grazing continued by the resident herd and surplus fat animals were sold for slaughter in 1965 and replaced. The grazing rate was well within the carrying capacity of the regenerated pasture and annual burning of surplus grass took place every dry season. In the meantime, catchment A continued to be grazed by the local herds whose owners also tried to poach the much superior grazing on catchment B and on a number of occasions cut the fence wire. Eland, on occasions, entered catchment B but they were not a significant grazing element. By 1968, perennial grasses were well-established over most of the catchment, particularly on the upper reaches where the soils were least eroded and stands of grass grew as high as four to six feet.

On the valley flanks, perennials too had recovered but there was a clear difference in the composition and volume of grass there as compared to that on the upper, flatter reaches.

Experimental operation became progressively more and more difficult from 1970 onwards as raingauges were broken or and *Ormocarpum trichocapum*. None of these exceed 2 m in height and many clumps exhibit signs of fire-trimming.

CONCLUSIONS

From an ecological viewpoint, the vegetation surveys which were undertaken during the course of the Atumatak experiment demonstrate conclusively that a perennial grass cover can be established by inexpensive bush clearing and simple grazing control measures.

The least eroded soils on the upper catchment levels became quite rapidly re-colonised by a *Hyparrhenia spp* - dominated grassland. On the valley sides, however, where the degree of slope was greater, the regeneration of grass has been less vigorous. *Hyparrhenia spp* is scattered and the dominant grass is *Eragrostis rigidior* which forms loose clumps with much less ground cover and available herbage. This is significant as it demonstrates the persistence of the consequences of severe sheet erosion which preceded clearing; they affect the composition of the grass succession for at least 12 years after clearing.

The experiment succeeded in re-establishing a perennial grass cover which has withstood a stocking rate on an all the year round basis, of at least one animal to four hectares. Once a recovery of grass was established visual signs of erosion were negligible and the grass communities showed no signs of reversion to a mixed shrub/herb/grass community.

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4.2.1

ASPECTS OF THE HYDROLOGICAL REGIME OF THE ATUMATAK CATCHMENTS

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INTRODUCTION

The background to the Atumatak experiment has been described in Section 4.1.1. At the time of the first Special Issue (Pereira et al, 1962) the land use change in Catchment B had only just been accomplished and, although little analysis of the Atumatak streamflow data had been completed, the indications were that stormflow could be predicted from rainfall with a high degree of accuracy. Subsequently, the difficulties of maintaining and operating instrument networks in this area became overwhelming, and the note of optimism for the successful conclusion of this experiment sounded in the previous Special Issue has been difficult to sustain as the continuity and quality of the catchment data has deteriorated.

At the same time, so little is known about the hydrology of these semi-arid areas that the interpretation of the experimental data is important notwithstanding their low quality compared with similar data from less hostile regions. This section covers the period during which Catchment B was cleared, enclosed and subjected to controlled grazing. The long-term plan to impose a similar controlled grazing programme in Catchment A has been abandoned as indeed has the whole scheme, having been overtaken by the events described in Section 4.1.2, which have resulted in a relaxation of the pressure on the land due to depopulation consequent upon renewed tribal raids and stock theft.

The hydrological analysis is of necessity incomplete due to the poor quality of the data and the only partial monitoring of the complex pattern of streamflow response to rainfall. As recognised at the outset, a water balance approach to the problem of comparing different land uses was not possible and analysis has been confined to the individual events when timing and zero errors are thought to be insignificant. Gypsum block readings have been used to indicate changes in the infiltration characteristics of the catchment as has evidence of vegetative regeneration (Section 4.1.2).

RAINFALL

Atumatak lies in the belt of rangeland which has been described as having medium potential for agriculture (Brown, 1963). It has a mean annual rainfall of the order of 750 mm (1959-69) with three years exceeding 1000 mm in that period, and four years having less than 600 mm (Table 1). The seasonal distribution of rainfall shows two peaks: one in April/May and one in July/August, with a pronounced minimum from November/February during which no significant rainfall may be recorded. The chief feature of the seasonal rainfall, however, is its high variability from year to year. Table II gives the mean monthly rainfall for the eleven years of record, together with monthly standard deviations. The Table shows that even the wetter months have a high year to year variation; November, in particular, has recorded high totals (229 mm in 1961) as well as zero rainfall).

The diurnal rainfall distribution and frequency distribution of hourly rainfall have been discussed in Section 1.2.1. The initial analysis of ten-minute periods for storms greater than 6.4 mm (0.25 in) showed that more than 13% of such intervals recorded intensities greater than 100 mm hr^{-1} (4 in hr^{-1}) (McCulloch, 1962).

The spatial distribution of such storms is irregular, and the indications are that the physical area of the storms is smaller than in other parts of East Africa. Fiddes (1975), in an analysis of areal reduction factors for different networks in East Africa, concluded that the Atumatak catchments had significantly lower areal reduction factors than the other networks and that, generally, storms of smaller areal extent were to be expected in Central and North Uganda, compared with the rest of East Africa. Fiddes' table of areal reduction

TABLE I

Annual Rainfall (mm) for the Atumatak Catchments A (Control, Untreated) and B (Bush-cleared, Fenced) 1959-69

	A (control, untreated)	B (bush-cleared)
1959	557	654
1960	836	925
1961	1082	1118
1962	719	672
1963	1006	1010
1964	636	647
1965	520	566
1966	611*	611*
1967	1002	1037
1968	525	565
1969	578	543
Mean:	734 ± 64	759 ± 65

* Excludes January and March

TABLE II

Mean Monthly Rainfall (mm) and Standard Deviation (σ) of Monthly Rainfall (mm) for Atumatak Catchment A (control, untreated) 1959-69

	Mean	σ
January	11*	±14
February	25	±21
March	47*	±26
April	106	±66
May	115	±83
June	48	±35
July	121	±59
August	84	±26
September	51	±28
October	44	±28
November	55	±72
December	27	±28

* 1966 excluded

factors is reproduced here for reference (Table III).

EVAPORATION

Daily open-water potential evaporation (EO) has been computed from the meteorological records summarised in Edwards, Blackie et al (1976). The seasonal pattern is shown in Table IV together with the standard deviation of monthly totals. In the period 1959-1969, mean monthly rainfall does not exceed mean monthly potential evaporation, and the mean annual rainfall total of 734 mm is only 35% of the mean annual EO (Fig 1). Taken as an indication of the agricultural potential of the region, Fig 1 would place Atumatak in the medium potential zone, ie marginal for cultivation due to the low reliability of rainfall, but suitable for livestock production.

The seasonal variation in EO can be seen from Fig 1 to mirror the monthly rainfall pattern. Evaporation values of the order of 5 mm day^{-1} occur over the April to August 'rainy' period, when there is slightly increased cloud cover and low mean wind speeds (3-4 km hr^{-1}). During the hot, dry October to March period, however, high radiation levels coupled with much higher wind speeds (about 8 km hr^{-1}) give rise to potential evaporation rates of the order 6-8 mm day^{-1}. Evaporation pan losses during this dry season of over 10 mm day^{-1} illustrate the importance of the 'oasis' effect, the influence of advective heat energy brought by the hot, dry easterly winds with their long fetch over Somalia, southern Ethiopia and northern Kenya. Table V shows the monthly mean values of pan evaporation and Penman EO for years when the pan figures are thought to be consistently good.

RAINFALL ACCEPTANCE STUDIES

In the absence of any feasible method for measuring the moisture content of soil profiles in this remote area at the start of the experiment, electrical resistance blocks (gypsum blocks) were installed to give a qualitative guide to the effectiveness of rainfall penetration. The objective was to monitor the effects

TABLE III

Area Reduction Factors for Atumatak

(after Fiddes 1975)

Period (hour)	Area Reduction Factors for Storms of Given Recurrence Interval		
	2 year	5 year	10 year
¼	0.54	0.59	0.61
½	0.63	0.70	0.73
1	0.73	0.76	0.77
2	0.77	0.79	0.80
8	0.81	0.81	0.80
24	0.85	0.87	0.88

TABLE IV

Mean Monthly EO (mm) and Standard Deviation of Monthly EO, for Atumatak, 1959-1970

	Mean	σ
January	202	±25
February	180	±30
March	188	±13
April	161	±24
May	156	±16
June	150	±12
July	142	±14
August	156	±12
September	175	±22
October	186	±23
November	180	±36
December	192	±35
Total	2067	

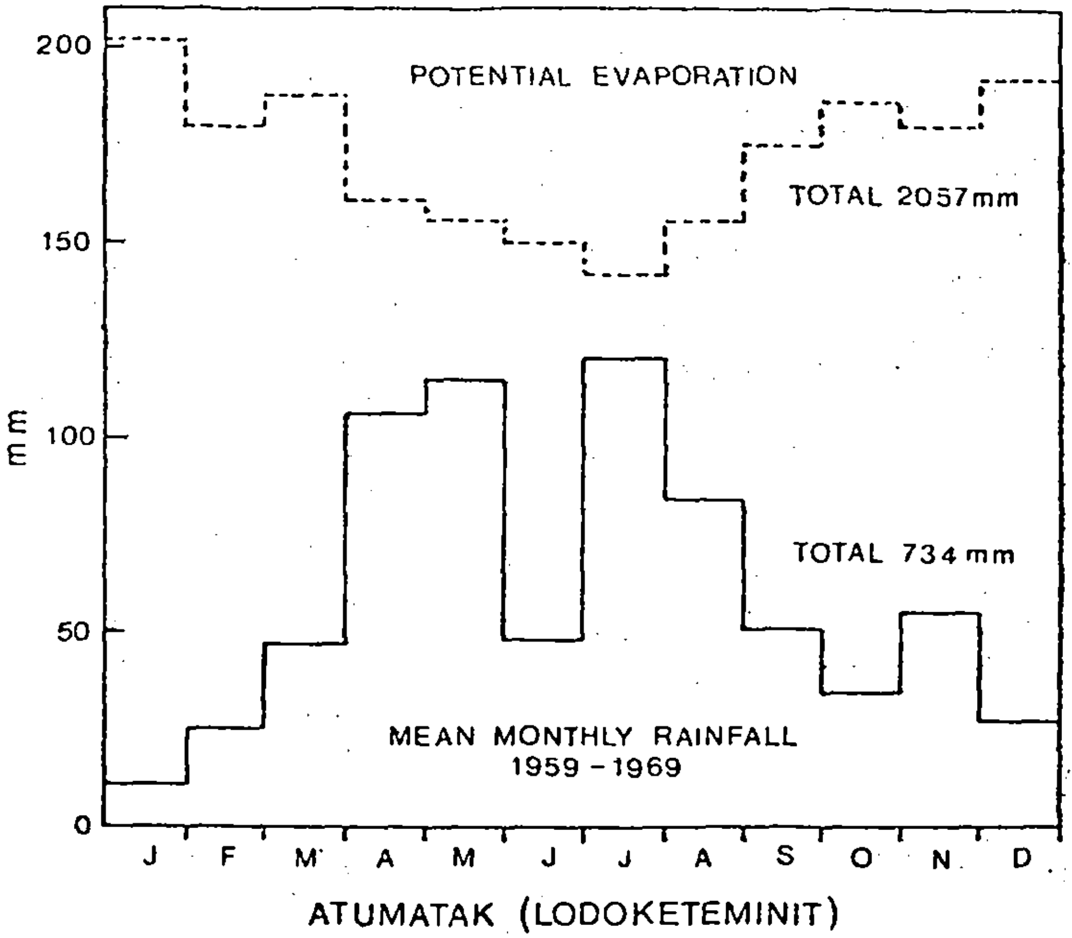

Figure 1 Mean monthly rainfall and potential evaporation at Lodoketeminit meteorological site

TABLE V

Comparison of Mean Monthly Pan Evaporation with Mean Monthly Penman EO (mm) for Selected Years

	Pan Evaporation* (1)	Penman EO (2)	Ratio, (1)/(2)
January	283	209	1.4
February	245	191	1.3
March	263	207	1.3
April	193	168	1.2
May	142	157	0.9
June	141	150	0.9
July	134	148	0.9
August	154	150	1.0
September	180	181	1.0
October	224	200	1.1
November	232	194	1.2
December	262	211	1.2
Total	2453	2166	1.1

* USWB Class A pan with grid cover; records from 1962-73 excluding 1964-65

of bush clearing and grass regeneration in Catchment B on the infiltration of rainfall into different soil types and on different slopes. Resistance blocks were installed, therefore, at six sites in each catchment, chosen to cover a range of soil types and slopes (Dagg, 1962). The Catchment A records were used as a control during the experimental phase of the project.

The resistance blocks were read weekly, and although persistent theft of the block leads and occasional failure of the resistance meter resulted in gaps in the records, sufficient data were obtained for a semi-quantitative interpretation of the moisture content changes over most of the period of the experiment.

The major problem of interpretation arises from the fact that with high evaporation rates and generally low rainfall amounts, shallow soil profiles can be recharged and depleted between weekly readings of the resistance block profiles. Furthermore, the better the grass cover, the greater is the water lost by transpiration, and the greater the removal of stored water by plant roots from the soil; with weekly readings, therefore, profiles under bare soil may sometimes appear to have given higher infiltration rates than profiles under grass.

By analysing the frequency of wetting of blocks at various depths over the whole period, however, a general pattern emerges. A count was made of the number of occasions on which each block at a particular site indicated water was available for plant growth. Table VI shows the frequency of penetration of rainfall to a particular depth, therefore, given that the six sites are representative of the catchment as a whole (Dagg, 1962). In spite of the anomalies, such as the consistently good penetration to 2.44 m (8 feet) in Catchment A, a definite pattern emerges.

During the pre-clearing phase, there is little difference between the catchments. A tendency for Catchment A to be wetter than Catchment B is evident. Immediately following the clearing

TABLE VI

Frequency of Rainfall Penetration at Atumatak

	Year	Mean no. readings	½'	1'	1½'	2'	3'	4'	6'	8'
Pre-clearing	1959	A 31	38	38	10	6	13	0	0	0
		B 31	38	18	4	8	0	0	0	0
	1960	A 48	47	43	19	11	21	14	0	0
		B 50	44	35	7	21	0	0	2	0
	1961	A 48	66	59	52	39	30	12	17	17
		B 49	62	48	32	38	12	12	4	4
Mean for pre-clearing phase 1959-61		A	50	46	27	18	21	9	6	6
		B	48	34	14	22	4	2	2	1
Values for clearing phase 1962-63	1962	A	Very few readings							
		B								
	1963	A 44	48	37	31	36	13	18	52	32
		B 43	50	50	38	45	35	23	14	9
Post-clearing	1964	A 48	22	15	9	13	1	3	6	3
		B 47	32	24	18	12	4	2	0	0
	1965	A 31	19	19	12	9	0	0	0	13
		B 31	27	18	13	17	0	0	0	0
	1966) 1967) 1968)		Very few readings							
	1969	A 46	8	4	4	3	0	0	0	0
		B 43	19	19	11	15	1	0	2	0
	1970	A 50	20	19	16	14	1	2	0	8
		B 53	44	42	37	41	1	0	2	0
Mean for post-clearing phase 1964-70		A	17	14	10	10	0	1	2	6
		B	30	26	19	21	2	1	1	0

B is the cleared catchment and A, the control
Figures indicate the mean percentage frequency with which available moisture was indicated by the resistance blocks

in 1961 and 1962 there are unfortunately very few readings; 1963, however, has a fairly complete record, and it is clear that a striking change has taken place with much more frequent penetration beyond 0.3 m (1 foot) in the cleared catchment (B). This is to be expected; the mechanical clearing operation disturbed the soil and broke the surface. What is significant, however, is that the change continues into the post-clearing phase with an increasingly higher frequency of rainfall penetration in B than in A. The anomaly of more frequent penetration to 2.44 m (8 feet) in A is still present, but this can be traced in fact to a single site (KA2) on alluvial deposits of the Sebei Series (Dagg, 1962) and probably indicates the presence of lateral flow to the deeper layers in the riparian zone.

On the whole, the gypsum block records closely reflect the observations by Napper and Wilson (Section 4.1.2) on the regeneration of the perennial grasses. They indicate that water is freely available in the root zone in Catchment B for about 25% of the year, compared with less than 15% in the control catchment. Rehabilitation of the eroded grasslands is clearly a cumulative process; as the colonizing grasses decrease surface runoff and increase infiltration, so more water becomes available in the soil to sustain plant growth.

STREAMFLOW

Within the climatic environment depicted by Fig 1, it is evident that no surplus of groundwater storage can be built up to sustain perennial streams in the headwater catchments of Atumatak. The optimum conditions of rehabilitated vegetative cover will attenuate flood peaks and delay runoff so that streamflow might at best be prolonged for days instead of hours. The destructive 'torrent-flow', described by Pereira (1962), will be reduced to a level at which recharge of the shallow river bed aquifers will be more effective but, paradoxically, increased infiltration and storage of soil moisture on the revegetated parts of the catchments will lead to greater water use within the catchment and an overall reduction in total streamflow available downstream. The increase in perennial grass cover, however, leads to a reduction of overland flow and soil erosion. In terms of sustaining life in regions of ephemeral streams such as Atumatak, the return to a more stable ecosystem is ample compensation for a reduction in volume of streamflow.

In the experimental catchments, attempts were made to measure the silt-laden streamflow by means of rectangular-throated flumes (Odell and Owen, 1962). Difficulties were experienced with the high silt loads, and after several modifications, the gauging structures were eventually rated by model in hydraulics laboratories (see Appendix 7.1.1). Even then, the rapid response of the catchments to rainfall, coupled with timing inaccuracies on the streamflow charts, has made the interpretation of the runoff records extremely difficult. For this reason, it has not been possible to produce a detailed analysis of the streamflow response to rainfall. All the storms which produced clearly-defined streamflow records in both catchments, in which timing errors are small, have, however, been analysed.

It is evident that, following the clearing and fencing in Catchment B, peak flows initially increased for about two years until the regeneration of grasses was well established. At this point, the pattern changed, with both peak flow rates and total volume of runoff decreasing compared with the control catchment (A). This can be shown best by Table VII which compares runoff as a percentage of rainfall in the three periods: before, during, and after the change in land use.

While ratios of streamflow to rainfall were very similar on both catchments in the pre-clearing phase, they rose sharply during the clearing, and were twice as high in the experimental catchment as in the control. As the vegetation became established during the post-clearing phase, the ratios became much lower and, indeed, the experimental catchment finally recorded less than half the runoff of the control for similar rainfall inputs over the period 1964-68. Over the range of storms sampled the mean ratio Q/R is of the order of 10% of

TABLE VII

Depths of Runoff and Rainfall (mm) for a Sample of Storms (n)

	Catchment A (control, untreated)				Catchment B (bush-cleared)		
	n	Q	R	Q/R%	Q	R	Q/R%
Before clearing 1959-61	59	70.73	678.8	10.4	76.02	785.9	9.7
During clearing 1962-63	53	65.40	838.3	7.8	135.44	868.0	15.~~2~~6
After clearing 1964-68	61	160.09	1109.1	14.4	74.86	1092.8	6.8

rainfall. This is much lower than the 30-50% estimated by Pratt (1962). The frequency distribution of Q/R values (Table VIII) shows that very few storms gave more than 40% runoff; these are due to heavy rainfall on already saturated ground.

The volume of storm runoff clearly depends to a very large extent on the antecedent soil moisture conditions and the intensity of the storm. With the wide range of conditions at Atumatak, no simple relationship could be found between volume and storm runoff or peak runoff and total rainfall or peak intensity. The general shape of the hydrograph is one of very rapid rise to peak discharge within an hour of rainfall occurring and a still rapid but more gradual recession, so that about 75% of the flow occurs in the first hour and a half of flow. Typical hydrographs for the clearing phase and the post-clearing phase are shown in Fig 2. The shape of the hydrographs changes very little; Catchment B shows a much higher total streamflow during the clearing than Catchment A, but after the new vegetation has become established, the reverse pattern is evident. Throughout the period of the experiment, there was no tendency for Catchment B to show a longer recession limb than the control. This confirms that there is insufficient stored moisture to sustain flow and that there is little chance of encouraging significantly longer periods of streamflow.

CONCLUSIONS

The experimental records from the Atumatak catchments are relatively poor in quality for a number of reasons and a full hydrological analysis is not possible. Nevertheless, the data show that simple bush-clearing and exclusion of cattle brought about a significant change in hydrological regime. Once the vegetation had been re-established on the cleared catchment, the level of peak discharge following a rainstorm was reduced as was the total streamflow. Moisture penetration throughout the root zone was significantly increased and this, no doubt, contributed to the rapid increase in ground cover.

TABLE VIII

Number of Occurrences of Q/R% Values Fitting in Percentage Classes

%								
		0-4.9	5.0-9.9	10.0-14.9	15.0-19.9	20.0-29.9	30.0 39.9	40 and over
1959-61	A	32	11	3	8	3	2	5
	B	30	11	9	5	3	3	3
1962-63	A	34	6	3	4	4	1	0
	B	22	9	3	3	7	4	4
1964-68	A	21	8	13	5	8	5	1
	B	40	9	2	5	2	2	1

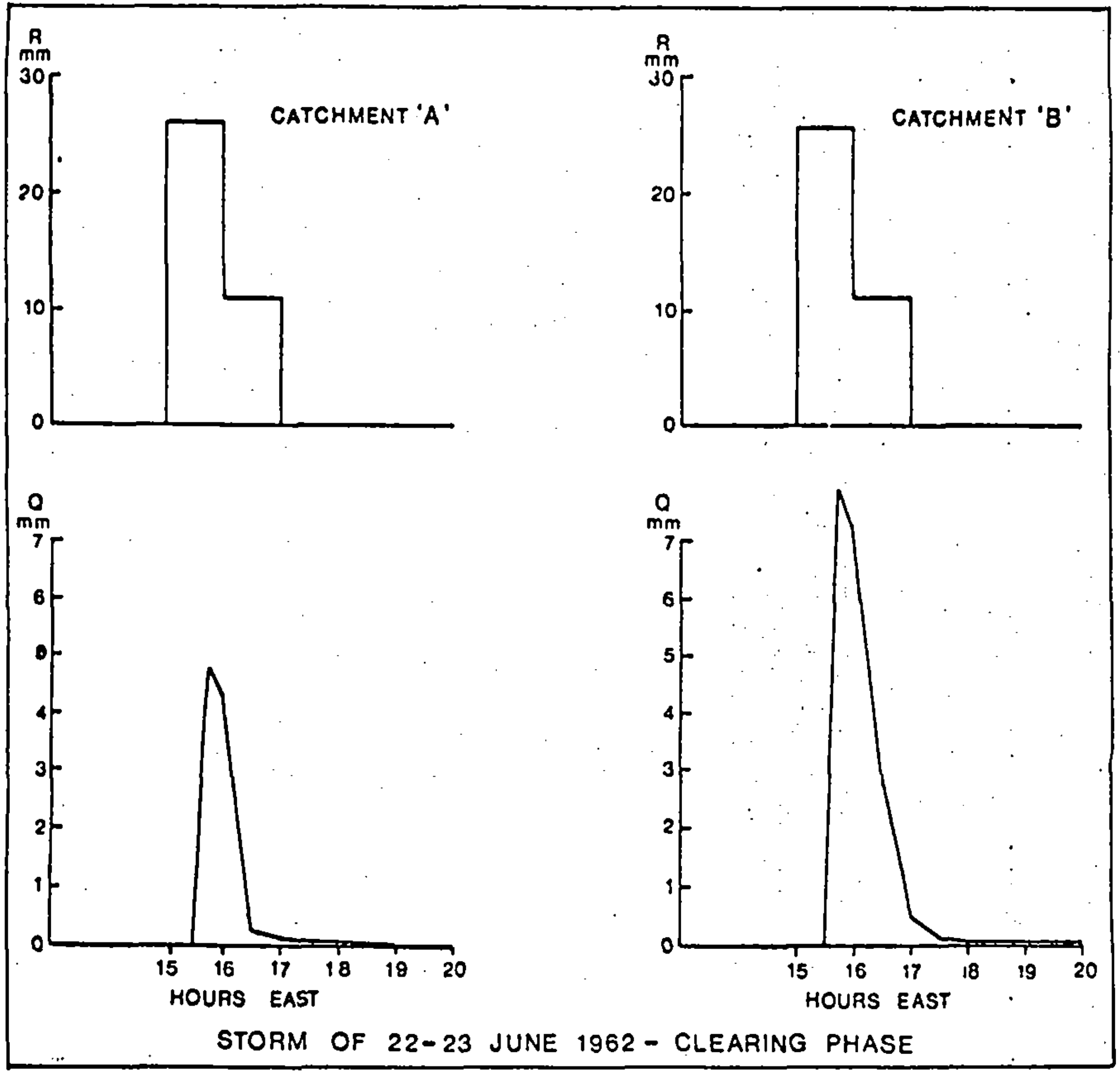

Figure 2(a) Typical hydrographs of the clearing phase

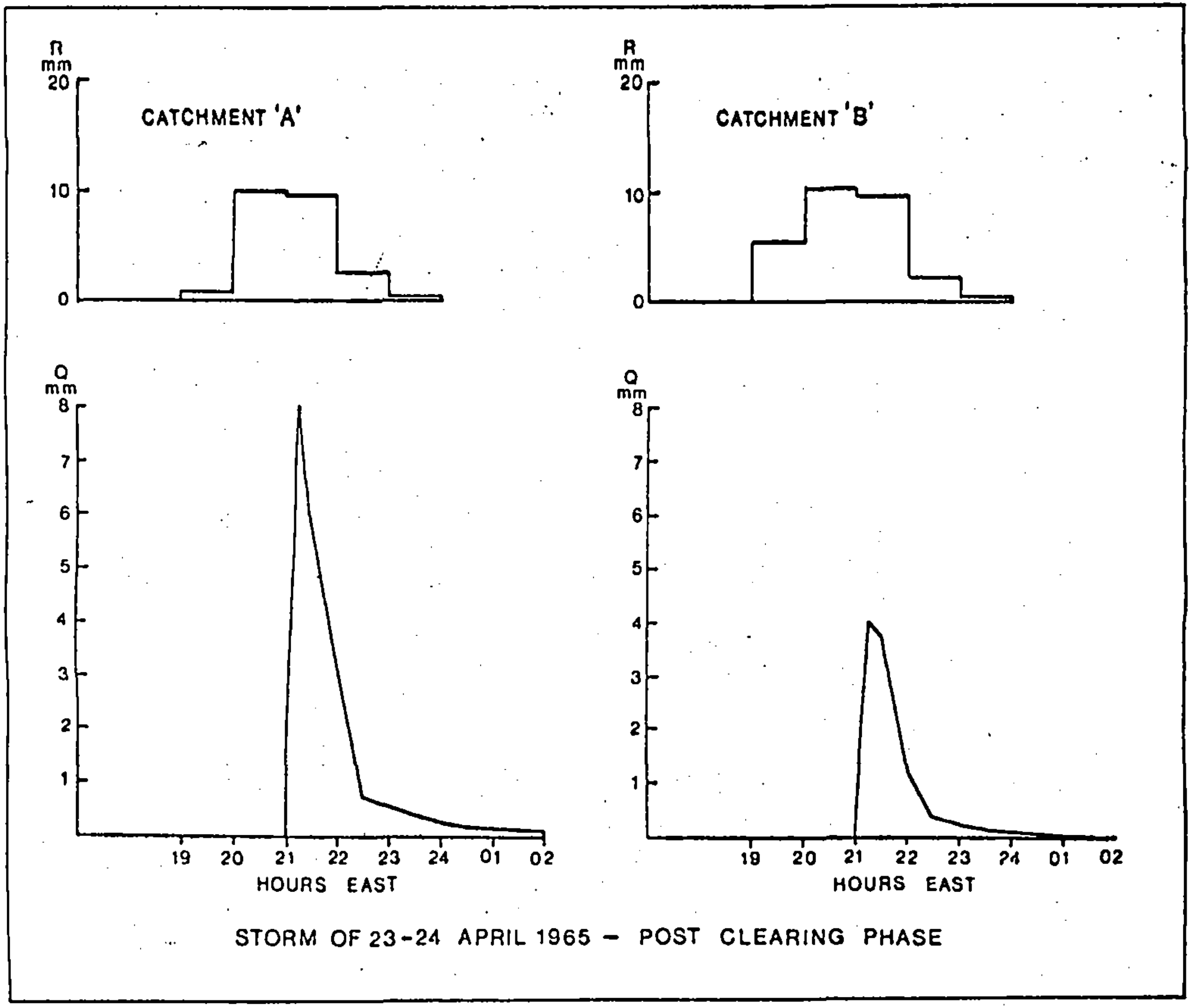

Figure 2(b) Typical hydrographs of the post-clearing phase

In the harsh environment of Atumatak, rainfall is insufficient in quantity and concentration to sustain permanent streamflow. The present experiment suggests that the change in land-use by bush-clearing and controlled grazing will not change this situation, although the increase in infiltration will result in sporadic groundwater recharge and will extend the time during which moisture is available for grass growth.

In spite of the rapid rehabilitation of the cleared catchment, it is not known how long the eroded stone mantle areas will take to develop a soil or vegetation cover, if at all, and these areas will continue to contribute to the flash floods which are characteristic of the area. While the restoration of the grass cover over most of the catchment can do much to reduce the flood peaks, it will still be necessary to supplement the land management measures with flood control structures downstream to protect bridges and vulnerable road sections.

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4.2.2

A COMPARISON OF PROCEDURES FOR COMPUTING MEAN AREAL PRECIPITATION APPLIED TO THE ATUMATAK DATA

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INTRODUCTION

In experimental catchments such as those at Atumatak, an accurate assessment of mean areal rainfall is essential to the hydrological analysis. The convectional origin of rainfall in the semi-arid areas of East Africa (Johnson, 1962), however, gives rise to scattered showers of erratic spatial distribution and often violent intensity and the irregular pattern of rainfall leads to large variations in catch between gauges in the catchment network. Under these circumstances, a dense systematic sampling network will give the best estimate of the areal mean. Clearly this is difficult to achieve in practice and at Atumatak, as in most experimental catchments, raingauges are sited partly for convenience, near tracks or roads, partly for security reasons, in conspicuous positions, and partly at random. The resulting network may not be well-distributed over the catchment and does not necessarily give an unbiased estimate of the mean areal rainfall. The true mean areal rainfall is, of course, never known, so that there can be no fully satisfactory way of selecting which computational procedure for estimating mean areal rainfall from data is 'optimum'. If estimates given by alternative computational procedures differ very markedly, however, then it may be possible to explain the difference in terms of variations in distribution of rainfall over the catchment and this in turn may demonstrate where a raingauge network is defective. It is often useful, therefore, to compare different estimates of mean areal rainfall over any catchment, and the purpose of this paper is to compare arithmetic mean and Thiessen estimates with other possible procedures.

METHODS OF ESTIMATING AREAL RAINFALL

The two most commonly used methods of estimating mean areal rainfall are the arithmetic mean and Thiessen polygon methods.

It is well known, however, that the arithmetic mean can give rise to biased estimates of the catchment mean with variable rainfall over an irregularly spaced gauge network (Thiessen, 1911). In spite of this the arithmetic mean is widely used because of its simplicity. The Thiessen method was introduced as a means of overcoming the above difficulty and has been adopted as a standard method in many parts of the world. It requires the laborious calculation of individual gauge weightings and, although computer programs do exist (Diskin, 1970; Grigg, 1972), automated methods are not widely used in developing countries.

At the same time, the Thiessen method is not without drawbacks and in areas where the spatial variation of rainfall is such that a linear gradation of rainfall between adjacent gauges cannot be assumed, the method can give too much weight to the remote gauges. Thus, if rain falls only in an isolated part of the catchment where a single gauge is situated, the mean is positively biased according to the distance between that gauge and its nearest neighbours, ie the area of the polygon for that gauge.

On the other hand, if the gauges in a network are evenly distributed, the Thiessen area weightings are all equal and the mean calculated from this method is the same as the arithmetic mean. This is rarely the case, however, with hydrological networks.

A subjective method of accounting for variable spatial distribution is to construct isohyets and sum the area enclosed by adjacent pairs. This method is ill-suited to routine use and it is only preferable to the Thiessen method when additional information (such as the variation of rainfall with altitude) is available and can be used to interpret the irregularities in a rainfall pattern. In areas where topography has a minor influence, such as Atumatak, the time-consuming and subjective nature of the method is a severe disadvantage although it is without doubt the best method of reflecting rainfall patterns.

Other techniques have been proposed from time to time (Whitmore et al, 1961; Akin, 1971) most of which suffer from the same disadvantage as the Thiessen method and are no more efficient. More recently, automated methods have been tested with varying success (Unwin, 1969; Mandeville and Rodda, 1970; Edwards, 1972; Shaw and Lynn, 1972) and two of these, which involve the fitting of rainfall surfaces to the data (orthogonal polynomials and multiquadric surfaces) have been chosen to compare with the conventional methods.

It has been shown that low order polynomial surfaces are very useful for representing rainfall which is predominantly frontal (Mandeville and Rodda op cit, Edwards op cit) but it was thought that the complex patterns of rainfall in semi-arid areas might requires surfaces of too high an order to be stable at the catchment boundary. Multiquadric surfaces on the other hand, have considerable potential for representing convectional rainfall and it was desirable to test the method in areas where such rainfall predominates.

DESCRIPTION OF THE AUTOMATED TECHNIQUES

The fitting of rainfall surfaces to rainfall data is an objective method of simulating spatial patterns although the choice of surface to be fitted is subjective to some extent. If the rainfall at each gauge is considered as accumulating as it falls, each data point can be represented by the cartesian co-ordinates (x, y and z) where z is the depth of rainfall. Clarke and Edwards (1972) have shown that the fitting of rainfall surfaces to rainfall data is closely related to formulating linear statistical models. The techniques to be described are an extension, therefore, of the original model described by McCulloch in the first Special Issue (Pereira et al, 1962).

The surfaces to be fitted can be polynomials of different order or multiquadric surfaces constructed from hyperboloids, cones or paraboloids (Lee, Lynn and Shaw, 1974). In practice, it is preferable to use low-order polynomials to avoid instability around the periphery of the network and in the case of the multiquadric surfaces the simple multiple cone surfaces are both objective and efficient (Lee, Lynn and Shaw op cit).

Both these techniques were developed originally for the interpretation of geological well records and although they are admirably suited to analysis of rainfall data it is difficult to test their effectiveness in simulating rainfall patterns in the absence of a knowledge of the 'true' rainfall surface. In catchments with dense networks of raingauges, such as Atumatak, the tests are more meaningful although, inevitably, an element of doubt remains as to how accurate the point rainfall values are in such remote areas.

Orthogonal polynomials can be expressed by:-

$$z_i = \beta_0 P_0(x_i,y_i) + \beta_1 P_1(x_i,y_i) + \beta_2 P_2(x_i,y_i) + \beta_3 P_3(x_i,y_i) + \varepsilon_i$$

where $P_j(x,y)$ is a polynomial of order j in the cartesian co-ordinates (x,y) and the unknown parameters β_j are estimated by least squares; the orthogonality condition on the P_j (x,y) avoids ill-conditioning problems (Richards, 1971).

The error term ε_i may be used to introduce an element of uncertainty about the precise shape of the rainfall surface. If ε_i is regarded as a random variable with an expected value of zero and variance σ_E^2, the residual variance obtained from the analysis of variance table can be used under certain circumstances as an estimate of the precision of the mean areal rainfall and hence the efficiency of the gauge network (Clarke and Edwards, op cit, Herbst and Shaw, 1969). These circumstances are that the fitted rainfall surface is a good representation of the 'true' rainfall surface and that the lack of fit arises from random errors in the rainfall measurement at each gauge site.

The multiquadric technique fits a series of right circular cones of the form:

$$z = C_j \quad |(x_j - x)^2 + (y_j - y)^2|^{\frac{1}{2}}$$

at each of the data points x_j, y_j, $(j = 1, 2, 3 \ldots\ldots n)$.

The value of z at any point is given by the sum of the contributions from all the n quadric surfaces.

$$z = \sum_{j=1}^{n} C_j \, |(x_j - x_i)^2 + (y_j - y_i)^2|^{\frac{1}{2}}$$

There are n such equations with C_j as the unknown. A surface is produced, therefore, which fits all the data points exactly. There is no provision to incorporate uncertainty in the rainfall model and no allowance is made for random errors in the rainfall measurement.

INTEGRATION OVER THE CATCHMENTS

To calculate the mean areal rainfall, the volume under the rainfall surface is integrated over the catchment and divided by the catchment area. With irregularly shaped catchments, analytical integration is complex and to simplify the integration procedure the catchments were represented by a series of rectangles equal in area to the catchments. Fig 1 shows the division of the catchments in this way and the actual catchment boundaries.

A selection of daily storms were analysed using the different methods of estimating mean areal rainfall. In addition, two sets of monthly data were also analysed. April 1975 represented a wet month and February 1974 a dry month.

COMPARISON OF THE MEAN AREAL RAINFALL ESTIMATES

As expected, in view of the dense network of raingauges, there was generally excellent agreement between the four methods,

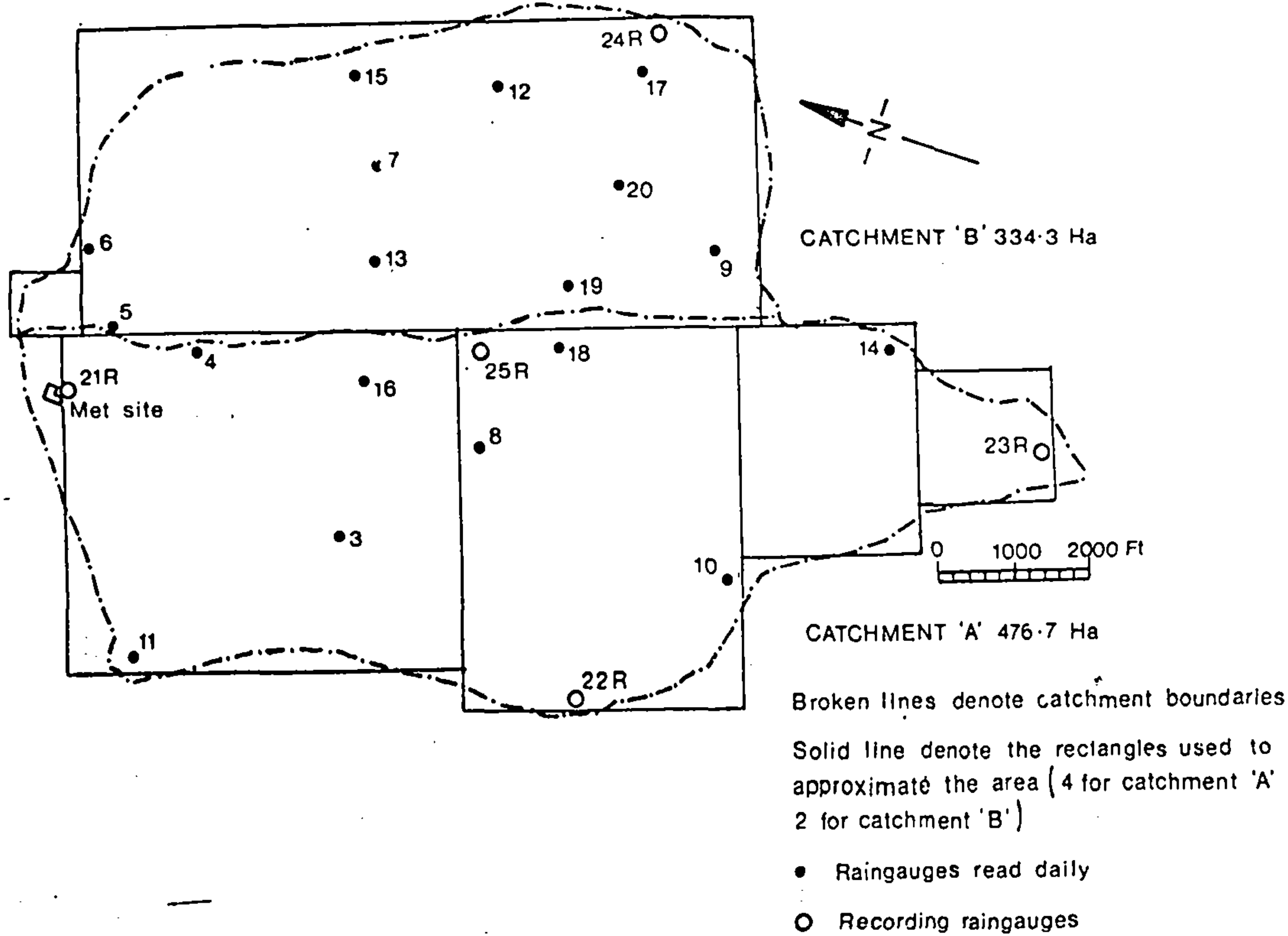


Figure 1 Approximation of catchment boundaries to facilitate integration under rainfall surfaces

ie arithmetic mean, Thiessen polygons, orthogonal polynomials and multiquadric surfaces. Table 1 summarizes the results of the analysis together with other statistics of the data.

The largest variation between the multiquadric technique and the others occurs in the analysis of the storm of 24 July 1967. This particular storm gave rise to a pattern of rainfall in which low values were recorded in the centre of the catchment and high values around the periphery. Under these circumstances, the multiquadric technique by fitting inverted cones to the rainfall data, results in high values on the catchment boundary which inflate the value of the areal mean. Fig 2 shows the contour plot of the multiquadric surface compared with the quadratic polynomial and an appropriate isohyetal map. There is insufficient information to judge which technique gives rise to the more realistic rainfall surface in this particular case, although it is clear that while the multiquadric technique exaggerates the peripheral rainfall, the quadric polynomial accounts for only 59% of the sums of squares in the analysis of variance table (Table II).

In this storm the Thiessen polygon method apparently underestimates the mean areal rainfall by 3.9% compared with multiquadric technique. In the other tests, differences between the Thiessen polygon estimate and the other methods are negligible. It may be concluded that, with a network of this density, no significant errors are introduced by estimating mean areal rainfall by the Thiessen method in spite of the variation in spatial distribution.

COMPARISON OF POLYNOMIAL AND MULTIQUADRIC SURFACES

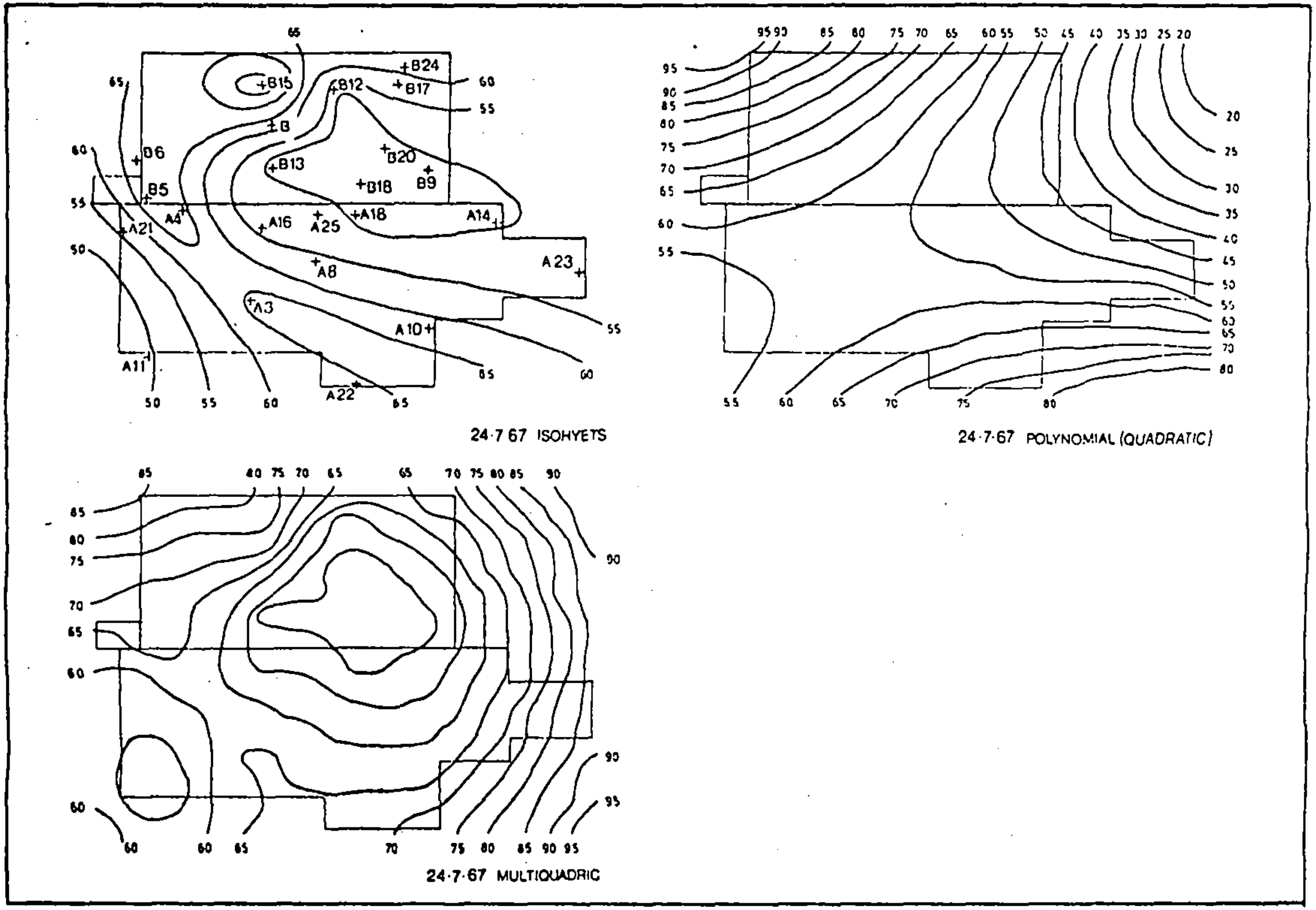
The contour plots of the rainfall surfaces show that there are considerable differences between the polynomial and multiquadric surfaces. Figs 3 and 4 give further plots for the storms of 22.6.62 and 13.4.65 together with isohyetal maps. It can be seen that the low order polynomial surfaces are evidently too

TABLE I

Comparison of Estimated Mean Areal Rainfall on Atumatak Catchments A and B

Date of Rain	No of working gauges	St dev of rain recorded (mm)	Gauge with Max (mm)	Gauge with Min (mm)	Average Rainfall in mm over the Catchment											
					Arithmetic Mean			Thiessen Areas			Polynomial Fitting			Multiquadric		
					A	B	Total	A	B	Total	A	B	Total	A	B	Total
13.4.65	23	6.3	B17 39.4	A21R 20.1	26.5	33.6	29.9 (+2.7)	26.6	32.5	29.4 (+0.7)	25.1 (Cubic)	33.1	28.4 (-2.5)	25.8	34.0	29.2
1.4.64	25	8.1	B6 52.1	A23R 17.5	31.1	39.1	34.4 (-0.4)	31.8	38.5	35.0 (+1.4)	31.3 (Cubic)	40.2	35.0 (+1.3)	30.6	40.1	34.5
22.6.62	19	5.8	A16 46.7	B6 25.4	36.0	37.2	36.6 (+1.1)	35.0	36.9	35.8 (-0.6)	35.1 (Quadratic)	36.6	35.7 (-0.8)	35.3	37.0	36.0
24.7.67	16	8.5	B15 77.5	B9 48.3	58.1	57.8	58.0 (-4.3)	57.7	58.7	58.2 (-3.9)	57.1 (Quadratic)	60.6	58.5 (-3.4)	61.0	59.9	60.6
Feb 1964	22	10.0	B15 52.8	A11 17.0	30.5	41.0	35.3 (+2.3)	29.9	41.3	34.6 (+0.3)	28.9 (Cubic)	42.5	34.5 (+0.1)	29.4	41.8	34.5
April 1965	23	13.1	B13 170.4	A22 105.2	137.9	152.0	144.7 (+1.1)	136.2	151.0	143.1 (+0.0)	136.4 (Cubic)	152.7	143.1 (+0.0)	134.7	155.0	143.1

Figures in brackets denote the percentage difference between the given mean and the value obtained from the multiquadric surface fit



24·7 67 ISOHYETS

24·7·67 POLYNOMIAL (QUADRATIC)

24·7·67 MULTIQUADRIC

Figure 2 Rainfall isopleths for the storm of 24.7.67

TABLE II

Analysis of Variance for the Storm 24.7.67

Source	Degrees of Freedom	Mean Square	Mean Square Ratio
Linear fit	2	90.91	2.17 NS
Addition for: Quadratic fit	3	179.06	4.27 *
Residual	12	41.96	
Total	17		

NS - not significant at the 5% level

* - significant at the 5% level

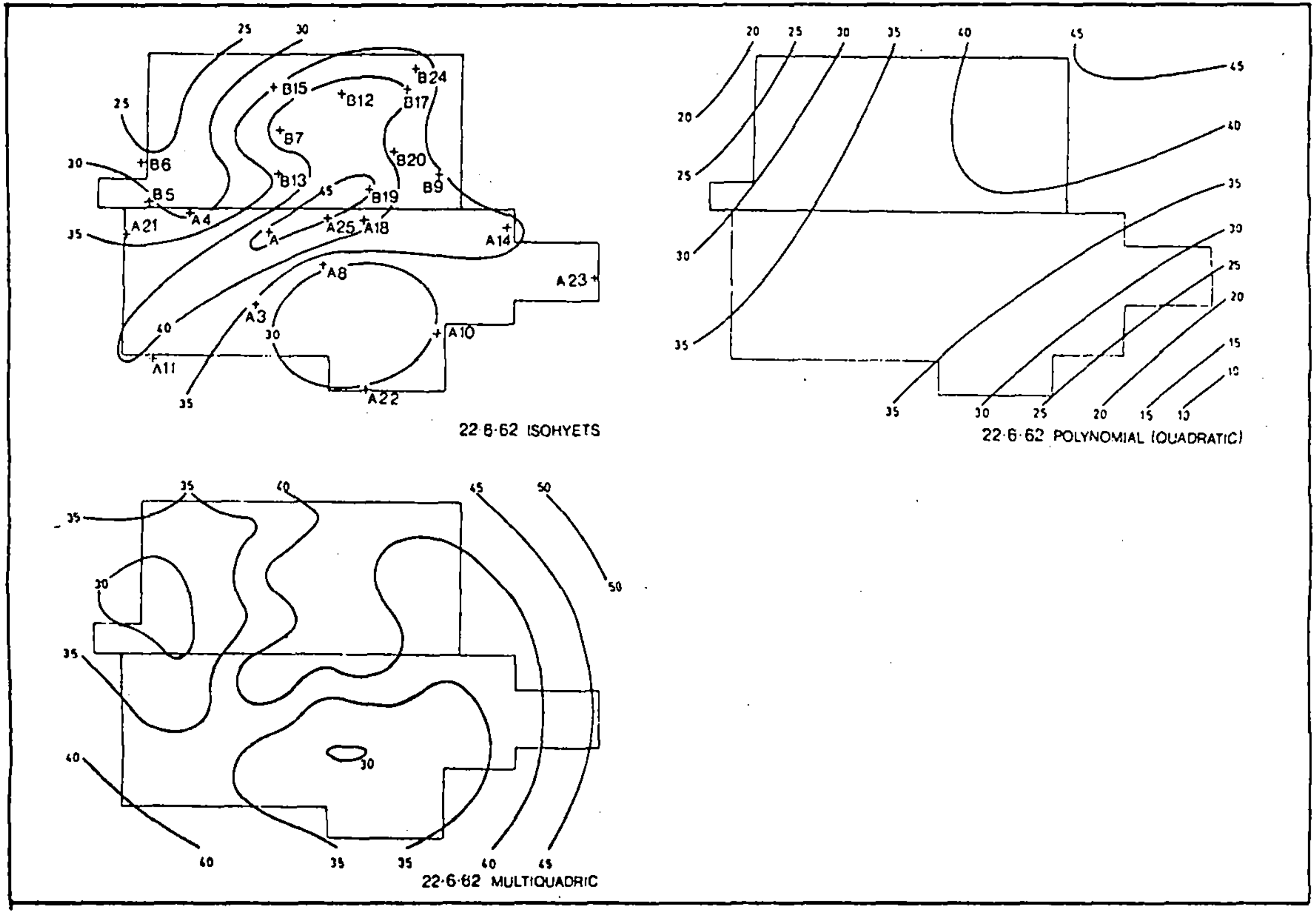


Figure 3 Rainfall isopleths for the storm of 22.6.62

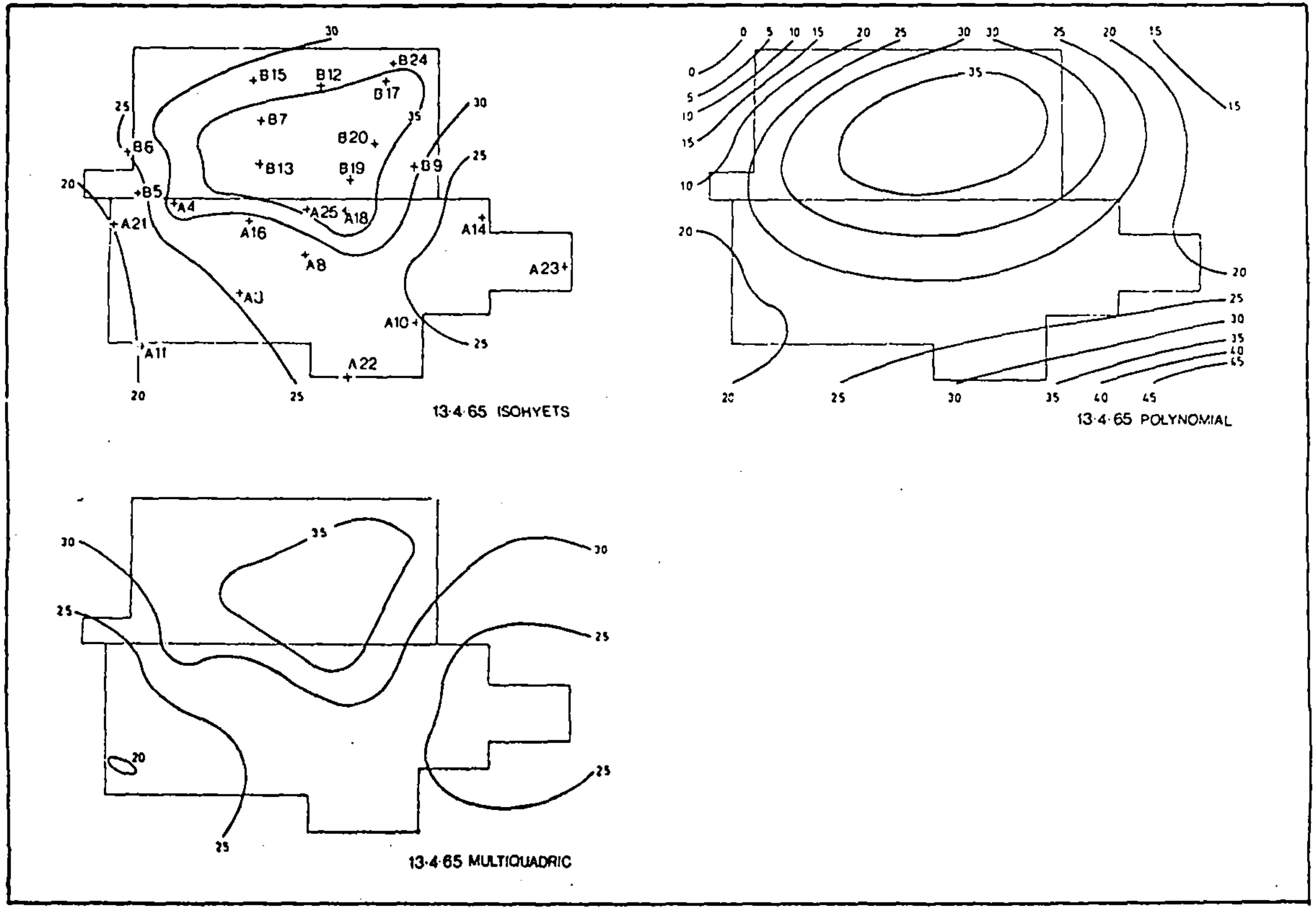


Figure 4 Rainfall isopleths for the storm of 13.4.65

severely restricted and give rise to unduly simplified rainfall patterns. On the other hand, the multiquadric surfaces are in general agreement with the subjective isohyetal plots and in the absence of any evidence to the contrary can be taken as good representations of the actual rainfall distribution.

If surfaces are continued too far from the data points, there is little control over their form. In the case of the cubic polynomial fitted to the test storms this can give rise to negative rainfall on the margins of the catchment. Provided that the gauges are evenly spread and, in particular, cover the catchment margins, the computed mean areal rainfall should not be affected.

The storm of 24 July 1967 demonstrates that the multiquadric technique can also give rise to anomalous effects outside the raingauge network. Once again, this would not result in practical difficulties provided that extrapolation beyond the limits of the raingauge network was not excessive.

CONCLUSIONS

The analysis of several storms at Atumatak has shown that in spite of the spatially variable rainfall both the arithmetic mean and mean areal rainfall calculated by the Thiessen polygon method are in good agreement with the values calculated by more sophisticated methods. This verifies that the raingauge network established at the start of the experiment was sufficiently dense to allow either of the conventional methods to be used in calculating mean catchment rainfall for periods as short as one day.

At the same time, it has been demonstrated that the multiquadric technique of surface fitting gives a good representation of rainfall pattern in this area of erratic rainfall. Although the technique may appear unduly complex, for a fixed network of gauges, when the normal equations have been formed and the matrix inverted once, a set of gauge weights similar to the

Thiessen polygon weights can be obtained. It suffers in the same way as the Thiessen method however in that if the network changes or a gauge is out of operation for a period, the gauge weights all have to be recalculated. As an automated technique where computer facilities are available, the multiquadric technique has much to recommend its use in semi-arid areas.

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4.3

SUMMARY OF RESULTS OF THE ATUMATAK EXPERIMENTS

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The Atumatak catchment experiment in Uganda was frought with difficulty from its inception, largely due to its remote location and the problems of conducting hydrological research in semi-arid areas. The silt-laden streams were almost impossible to gauge accurately and a variety of different approaches were made to solve the problem of silting at the gauging structures. None of the attempted solutions was entirely satisfactory and, consequently, the streamflow records have been unusually difficult to interpret.

After the initial enclosure of the two catchments, a system of controlled grazing was scheduled to be imposed upon one of the catchments. It was some time before the system to be adopted could be agreed. Meanwhile, the catchment from which cattle were excluded experienced a rapid regeneration of both annual and perennial vegetation. Although some areas had little or no soil remaining on the exposed stone mantle and, hence, no potential for rapid recolonization, the general effect was of a startling recovery once the pressure of grazing had been removed.

In regions like Atumatak, where rainfall is considerably less than potential evaporation, erratic and violent rainstorms produce flash floods, the peak flows from which are very largely controlled by the vegetative cover on the catchment. When the experimental catchment recovered from the overgrazing, therefore, there was an immediate reduction in peak discharge and the shape of the hydrograph reflected the greater retaining capacity of the vegetated surface. Although this effect was comparatively easy to demonstrate from the recorded runoff data, further attempts to relate rainfall to runoff in a predictive manner failed as a consequence of the timing and stage errors in the flow records. A statistical approach comparing the volume of runoff from the two catchments without reference to its distribution in time, clearly demonstrated the pattern of reduced runoff in the rehabilitated catchment compared with the eroded control. This was also reflected in the gypsum block records of soil moisture in the catchments. Those from the regenerating catchment indicated much deeper penetration of infiltrated rainfall over the whole catchment in contrast to the limited penetration of the capped and truncated soils in the control. Where comparable soil profiles had become wet in both catchments, it was noticeable that the profile below a well-vegetated surface dried out more quickly as a result of the higher natural transpiration.

After several years of demonstrating the beneficial effects of controlled grazing on these catchments, there was a resurgence of cattle raiding among the Pokot and Karasuk tribesmen from across the border in Kenya. Several murderous attacks and successful cattle raids had the effect of depopulating the region and removing the overgrazing problem. Within a very short space of time (two to three years), there were signs of a general recovery of the vegetative cover. This was mostly annual grasses but, where pockets of perennial vegetation had managed to survive, there were encouraging signs of recolonisation.

Although the Atumatak experiment has not been entirely successful, the principle of rehabilitating eroded grasslands through the complete exclusion of cattle and by limited bush clearing has been adequately demonstrated. In the rehabilitated catchment, the grass cover has withstood a continuous stocking rate of one animal to four hectares without any visible signs of damage. The expected hydrological effects of reduction in peak flows and attenuation of the hydrographs have also been clearly demonstrated. It is doubtful, however, whether streamflow can be prolonged beyond a few hours, even with a complete recovery of the perennial grasses, in climatic environments similar to Atumatak.

damaged and fence-wire was cut. The neighbouring Karamojong were harassed increasingly by the Pokot and began to drift away. As a result, catchment A, which up to that time had been subject to intense grazing, now began to be grazed less frequently. In the dry seasons of 1973, 1974 and 1975, grass fires thinned a significant number of shrubs in the upper part of the catchment, in consequence of which there has been a notable return to savanna in that area.

In December 1970, 78 cattle and 5 calves on catchment B were stolen by Pokot raiders with a considerable loss of human life. It was futile to replace the cattle until a police post was established at Atumatak. Accordingly, the experiment was confined to operating on a care and maintenance basis until February 1975, when a combined Pokot and Turkana raiding party stole all moveable property, grain and livestock from Atumatak. The remaining instruments on the catchments were either stolen or destroyed and, with this final act of vandalism, the Atumatak experiment was brought to a close.

Ironically, the prime reason for the establishment of the experiment has been overtaken by recent events. All around, grazing pressure has been lifted as the Karamojong have moved out. Grass cover has increased, fuelling ever more extensive and intense fires in the dry season, and with the *Hyparrhenia* grassland replacing the Sanseviera thicket, this upland area has been transformed.

In catchment B, the thick ground cover of *Hyparrhenia spp* established on the high ground is healthy with negligible bush regeneration. In the valley bottoms, there is now also a good establishment of *Hyparrhenia spp* but a greater frequency of shrubby regrowth. The valley slopes are still largely uncolonised by *Hyparrhenia* but a moderate cover of smaller loose-clump forming perennials prevails (chiefly *Eragrostis rigidior*). Shrubs are also more frequent though not amounting to more than 5% of the total cover. Common species include *Acacia brevispica*, *Albizia amara*, *Commiphore spp*, *Pilosa spp*, *Dichrostachys cinerea*, *Grewia spp*

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