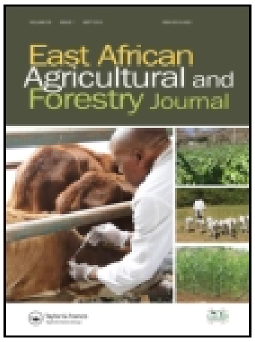

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3.2.1

THE WATER BALANCE OF THE KIMAKIA CATCHMENTS

J. R. Blackie, Institute of Hydrology, Wallingford, U.K.

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 per cent 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 per cent 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 per cent 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 stabilizing 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 per cent 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 per cent 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 per cent. 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 per cent, 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

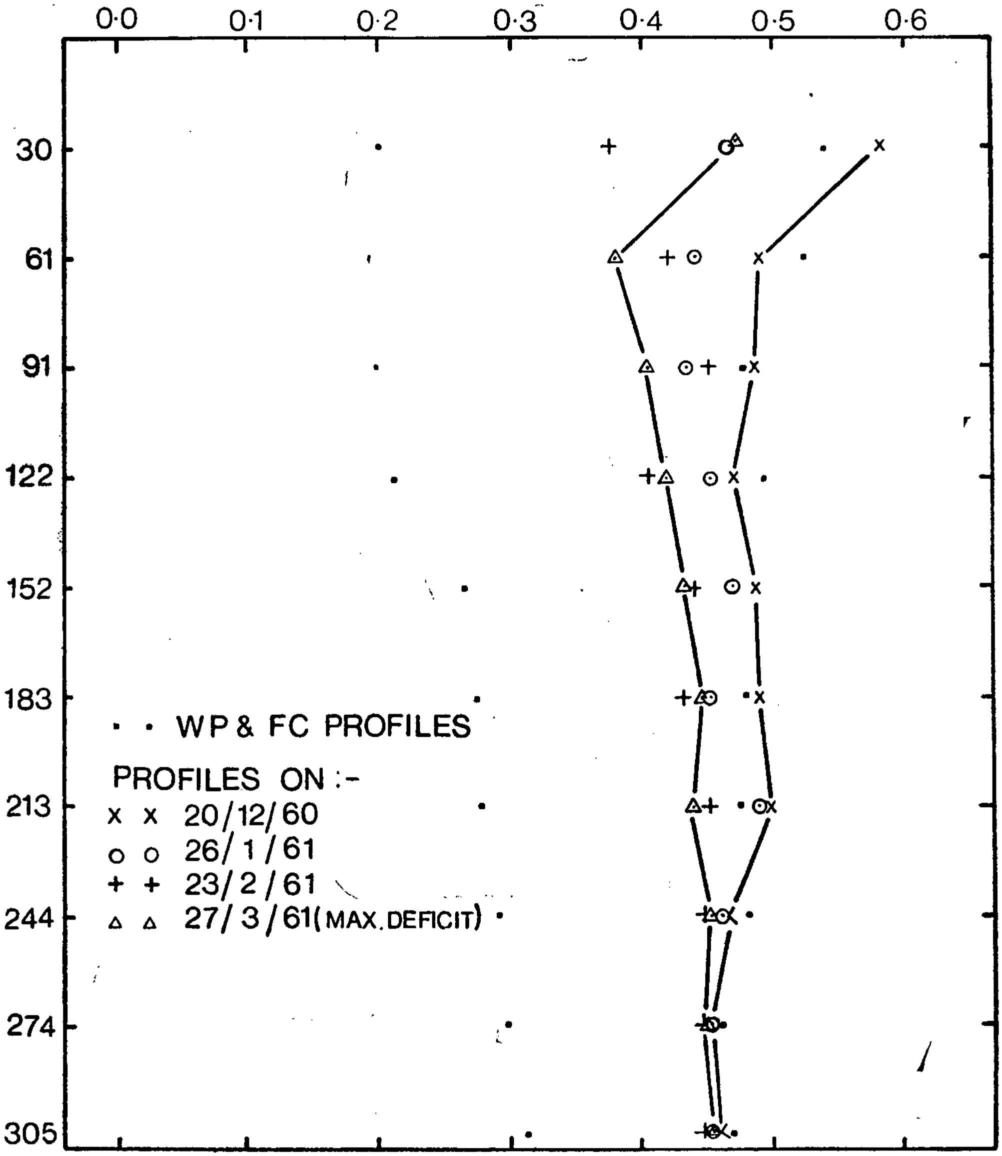

Figure 1.—1961 dry season soil moisture profiles under bamboo in Catchment C

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 Fig. 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 per cent. 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 per cent and − 2.7 per cent in 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 minimized 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 of streamow 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 1,300 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 Fig. 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:

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

Where—

R_o, n are observed; and

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

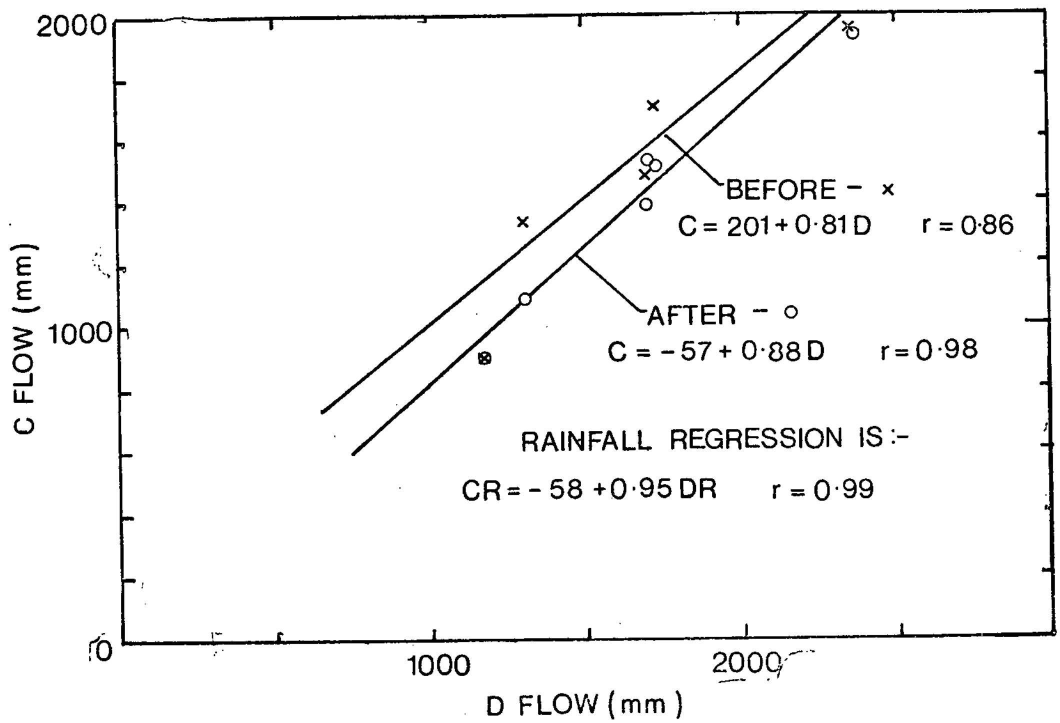

Figure 2.—Comparison of 1960-65 annual flows from Catchments C and D before and after correction of C

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 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 per cent 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, Plate I.)

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 I, experiences very similar 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 Fig. 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 per cent.

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 Fig. 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 summarized 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* Fig. 2 of Section 3.1.1). The close similarity in seasonal distribution is illustrated in Table III. The standard deviations of the monthly means of rainfall and of Penman EO emphasize the conservative nature of the latter.

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).

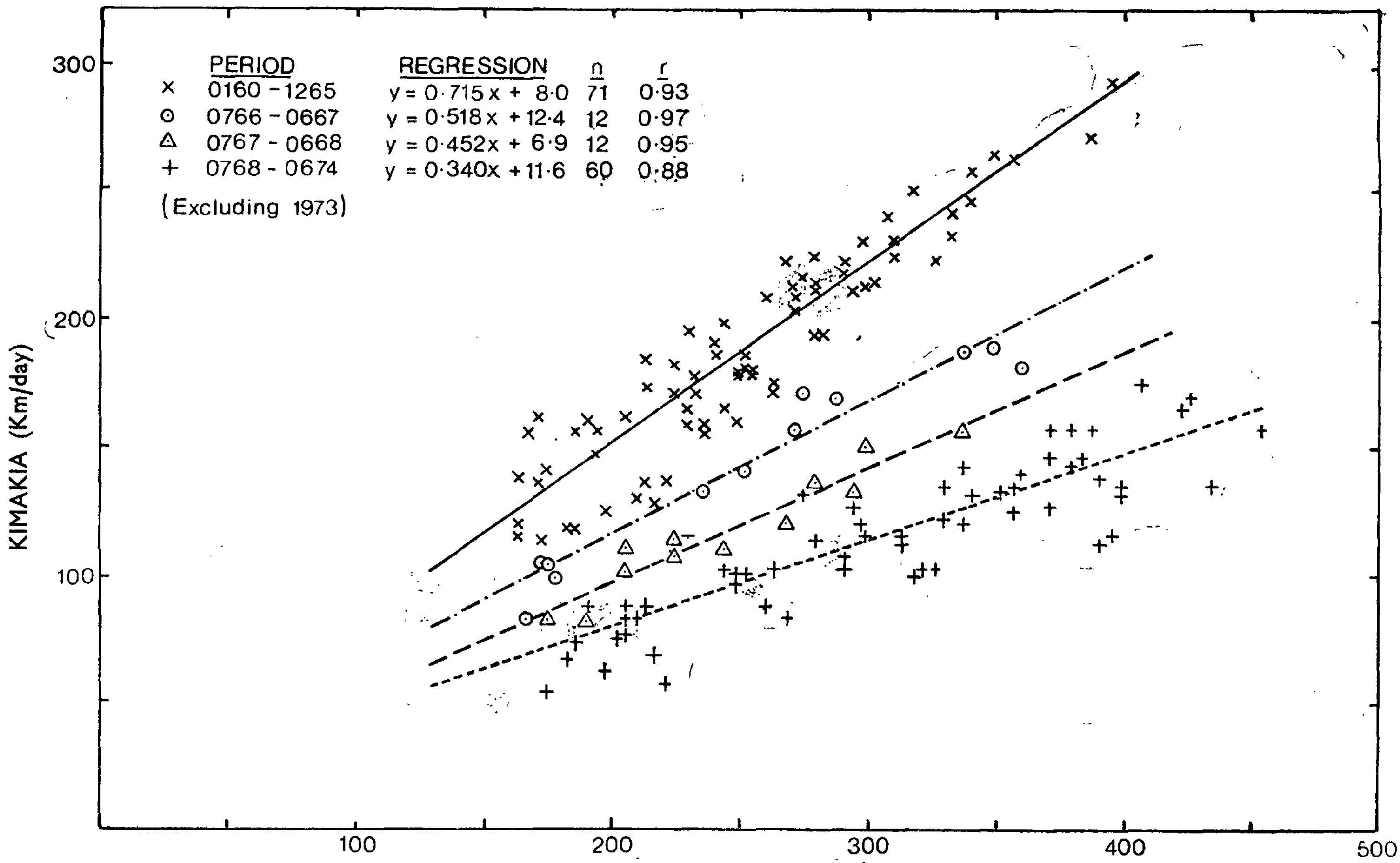

Figure 3.—Comparison of monthly mean windrun at Kimakia and EAAFRO

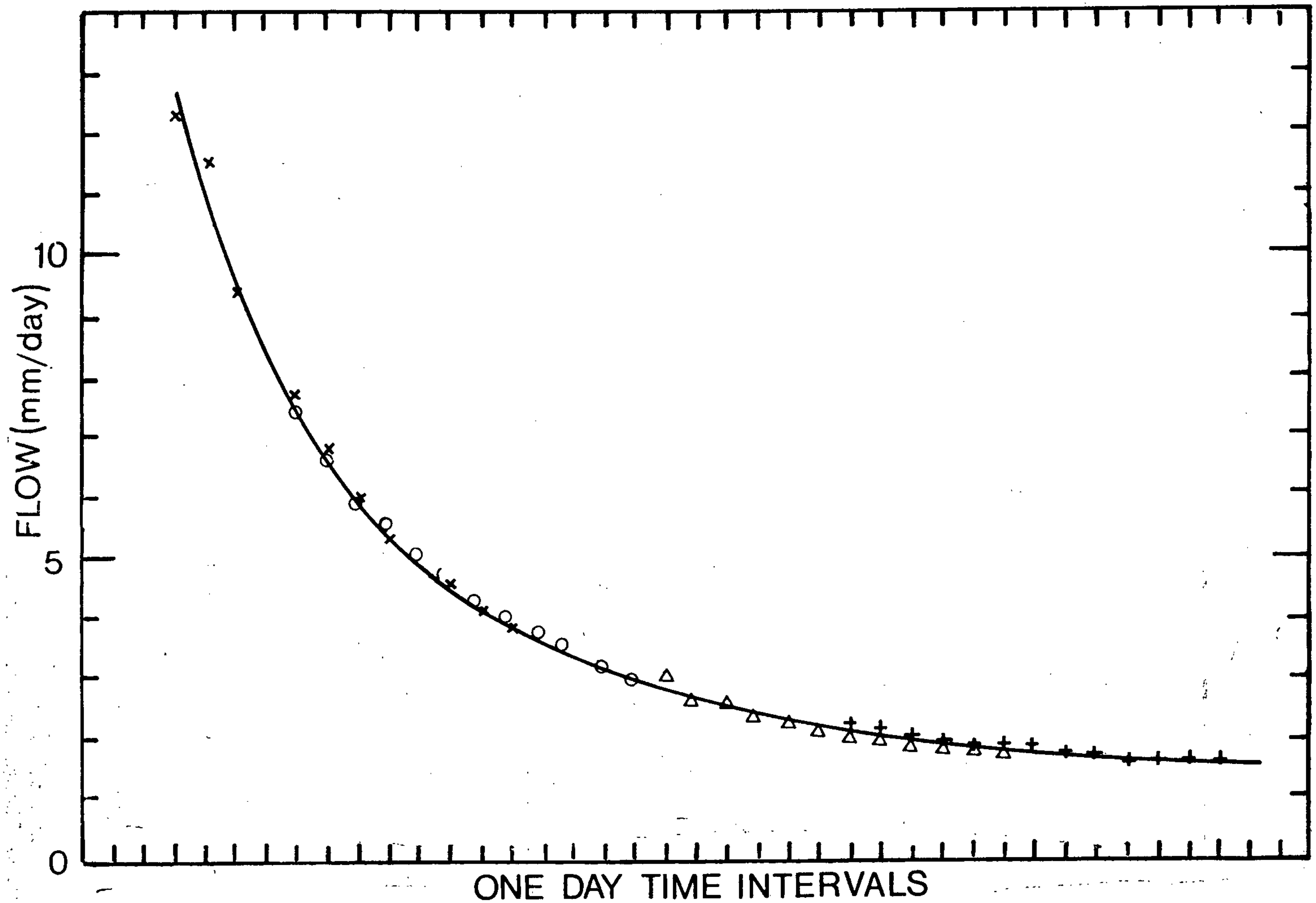

Figure 4.—Composite baseflow recession curve for Catchment C

TABLE II—CALENDAR YEAR TOTALS OF RAINFALL, STREAMFLOW AND RAINDAYS

Year	Rainfall (mm)			Streamflow (mm)			Raindays		
	C	A	M	C	A	M	C	A	M
1958 ..	2,528	2,367	—	1,385	1,480	—	254	221	—
1959 ..	1,905	1,818	—	833	919	—	252	214	—
1960 ..	1,992	1,849	—	908	953	—	249	229	—
1961 ..	3,294	3,221	—	1,953	1,858	—	259	239	—
1962 ..	2,453	2,358	—	1,392	1,329	—	243	227	—
1963 ..	2,754	2,713	—	1,516	1,497	—	241	221	—
1964 ..	2,599	2,476	—	1,531	1,611	—	246	233	—
1965 ..	2,341	2,181	—	1,085	1,063	—	225	225	—
1966 ..	2,350	2,238	—	1,240	1,174	—	218	212	—
1967 ..	2,191	2,024	2,158	953	834	1,040	217	212	205
1968 ..	2,637	2,521	2,559	1,488	1,389	1,560	246	245	240
1969 ..	1,583	1,499	1,506	511	454	543	211	200	193
1970 ..	2,221	2,085	2,142	1,027	833	1,027	234	231	222
1971 ..	1,988	1,746	1,861	790	630	789	222	207	205
1972 ..	2,484	2,291	2,396	1,268	1,015	1,235	228	222	227
1973 ..	1,874	1,788	1,815	786	658	863	210	206	199
1958–73									
TOTAL	37,193	35,175	—	18,666	17,696	—	3,755	3,544	—
Mean..	2,325	2,198	—	1,167	1,106	—	235	221	—
SD ..	±413	±426	—	±370	±393	—	±16	±12	—
1967–73									
TOTAL	14,978	13,954	14,437	6,823	5,813	7,059	1,568	1,523	1,491
Mean..	2,140	1,993	2,062	975	830	1,008	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.

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 per cent of the catchment under grass had no immediate effect on water use. Overall, the water use of the vegetation cover comprising 33 per cent grass, 47 per cent bamboo and 13 per cent softwood plantation (*P. widdringtonia*) and 7 per cent heath is seen to be some 10 per cent 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 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.

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	14-	134	374	384	143	83	77	86	236	289	86	2,140
	±90	±88	±109	±153	±77	±36	±27	±21	±48	±136	±123	±67	±360
A	97	132	126	359	346	128	71	68	77	218	284	87	1,993
	±85	±91	±96	±149	±66	±42	±24	±18	±40	±117	±124	±72	±347
M	100	133	126	367	372	137	79	71	81	231	282	85	2,062
	±91	±84	±106	±150	±73	±37	±28	±21	±46	±136	±124	±68	±361
							Raindays						
C	10	13	16	25	27	21	21	20	14	19	24	12	224
	±7	±5	±8	±4	±4	±2	±4	±2	±4	±5	±4	±4	±13
A	10	13	15	24	27	20	21	20	13	19	24	11	217
	±6	±5	±8	±5	±4	±3	±3	±2	±3	±5	±4	±4	±16
M	10	13	14	24	27	20	20	19	13	19	24	11	213
	±6	±6	±8	±5	±4	±3	±3	±2	±3	±5	±3	±4	±17
							Streamflow (mm)						
C	31	31	30	101	229	128	57	40	31	52	160	85	975
	±12	±22	±18	±113	±108	±48	±17	±15	±11	±53	±146	±77	±326
A	31	24	24	56	168	132	62	40	29	32	134	98	830
	±12	±11	±13	±51	±104	±44	±20	±11	±8	±15	±132	±100	±305
M	35	29	30	101	231	136	60	42	33	49	168	95	1,008
	±11	±15	±15	±103	±99	±49	±18	±14	±11	±34	±150	±87	±327
							Penman EO (mm)						
	160	149	174	138	106	86	71	78	127	144	125	155	1,513
	±25	±20	±30	±31	±8	±7	±11	±15	±7	±13	±16	±12	±71

TABLE IV—CALENDAR YEAR TOTALS OF RAINFALL MINUS STREAMFLOW AND OF EO

Year	R-Q (mm)			EO (mm)
	C	A	M	
1958 ..	1,143	887	—	1,495
1959 ..	1,072	899	—	1,555
1960 ..	1,084	896	—	1,574
1961 ..	1,341	1,363	—	1,564
1962 ..	1,061	1,029	—	1,438
1963 ..	1,238	1,216	—	1,451
1964 ..	1,068	865	—	1,320
1965 ..	1,256	1,118	—	1,433
1966 ..	1,110	1,064	—	1,487
1967 ..	1,238	1,190	1,118	1,576
1968 ..	1,149	1,132	999	1,398
1969 ..	1,072	1,045	963	1,545
1970 ..	1,194	1,252	1,113	1,431
1971 ..	1,198	1,116	1,072	1,509
1972 ..	1,216	1,276	1,161	1,566
1973 ..	1,088	1,130	952	1,565
58–73				
Total ..	18,528	17,478	—	23,906
Mean ..	1,158	1,092	—	1,494
SD ..	±85	±150	—	±76
67–73				
Total ..	8,155	8,141	7,378	10,590
Mean ..	1,165	1,163	1,054	1,513
SD ..	±64	±81	±82	±71

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 ease of comparison, the AE values for comparable water years, expressed in mean mm day^{-1}, are illustrated in Fig. 5 and the ratios AE/EO in Fig. 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

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		Differences	
		A	C	(mm) A-C	%C
1958–60 ..	Pine seedlings with vegetable intercropping	2,682	3,299	−617	−18·7
1961–66 ..	Rapid growth from 5 to 15 m canopy closure	6,655	7,074	−419	−5·9
1967–73 ..	Continuing growth from 15 to 25 m Stabilized canopy	8,141	8,155	−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 ..	4,193	4,653	−460	−9·9
1971–72 ..	Intensive grazing of above grass area ..	2,233	2,414	−181	−7·5
1973	Clear felling additional bamboo to bring grass area to 63%	952	1,088	−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

cannot be related to any noticeable change in vegetation or management. As shown in Fig. 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 to close agreement over the last seven years is indicated.

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
	26.02.58							
58 ..		2,322	1,381	−97	−52	1,090	1,497	0·73
	24.02.59							
59 ..		1,858	792	+49	+24	993	1,404	0·71
	28.01.60							
60 ..		1,966	895	−21	−16	1,108	1,583	0·70
	26.01.61							
61 ..		3,456	2,160	−57	+20	1,333	1,707	0·78
	28.02.62							
62 ..		2,431	1,246	+159	+47	979	1,260	0·78
	29.01.63							
63 ..		2,656	1,533	−28	−28	1,179	1,483	0·80
	30.01.64							
64 ..		2,758	1,516	−83	−36	1,361	1,496	0·91
	10.03.65							
65 ..		2,219	1,043	+66	+19	1,091	1,256	0·87
	27.01.66							
66 ..		2,253	1,208	−130	−26	1,202	1,430	0·84
	16.01.67							
67 ..		2,192	956	+70	+30	1,136	1,540	0·74
	10.01.68							
68 ..		2,645	1,502	−51	−7	1,202	1,467	0·82
	21.01.69							
69 ..		1,875	534	+62	−10	1,289	1,690	0·76
	28.02.70							
70 ..		2,020	1,008	−55	−13	1,080	1,361	0·79
	11.02.71							
71 ..		2,036	803	+111	+43	1,079	1,441	0·75
	26.01.72							
72 ..		2,705	1,332	+18	+38	1,317	1,722	0·76
	27.02.73							
73 ..		1,527	706	−162	−77	1,060	1,477	0·72
	02.02.74							
Totals 58–73		36,919	18,615	−149	−44	18,497	23,814	0·78
Totals 67–73		15,000	6,841	−7	+4	8,162	10,698	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
	04.02.58							
58 ..	06.02.59	2,416	1,519	−35	+4	928	1,496	0·62
59 ..	05.02.60	1,813	874	+29	−6	916	1,548	0·59
60 ..	08.02.61	1,842	936	−34	−26	966	1,619	0·60
61 ..	14.03.62	3,319	2,096	−59	+6	1,276	1,706	0·75
62 ..	14.03.63	2,536	1,219	+117	+20	1,180	1,414	0·83
63 ..	11.03.64	2,716	1,505	+8	+12	1,191	1,439	0·83
64 ..	20.03.65	2,297	1,551	−122	−39	907	1,362	0·67
65 ..	24.02.66	2,255	1,027	+86	+4	1,138	1,356	0·84
66 ..	31.01.67	1,989	1,116	−109	−14	996	1,368	0·73
67 ..	24.01.68	2,029	844	+98	+23	1,064	1,539	0·69
68 ..	21.01.69	2,524	1,390	−32	+10	1,156	1,379	0·84
69 ..	28.02.70	1,763	454	+47	−50	1,312	1,690	0·78
70 ..	11.02.71	1,882	829	−60	+11	1,102	1,361	0·81
71 ..	26.01.72	1,816	619	+145	+14	1,038	1,441	0·72
72 ..	27.02.73	2,520	1,084	+22	+62	1,352	1,722	0·79
73 ..	02.02.74	1,443	604	−192	−64	1,095	1,477	0·74
Totals 58–73		35,160	17,667	−91	−33	17,617	23,917	0·74
Totals 67–73		13,977	5,824	+4	+6	8,119	10,609	0·765

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 per cent 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 per cent.

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.

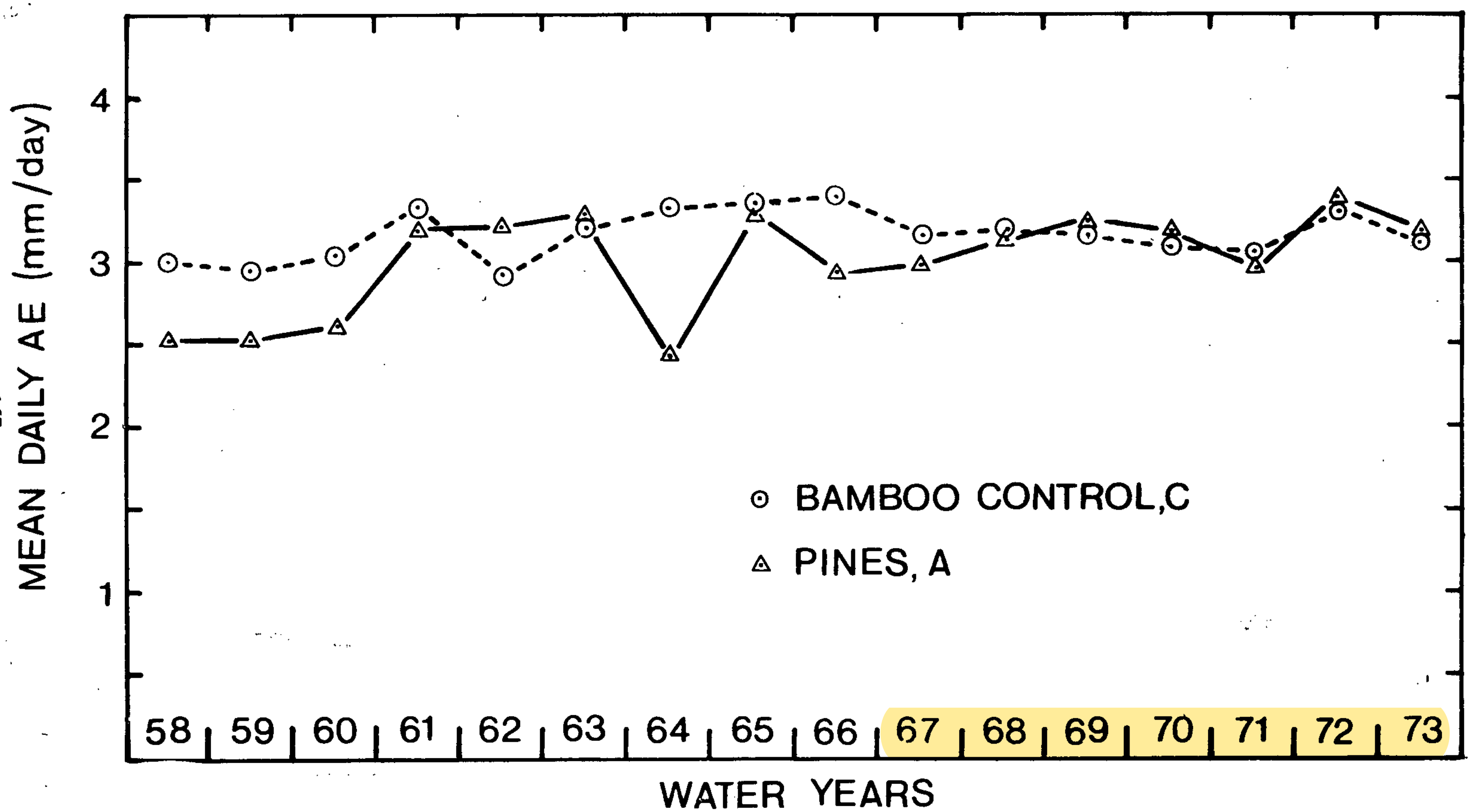

Figure 5.—Mean daily water use, AE, by Catchments C and A

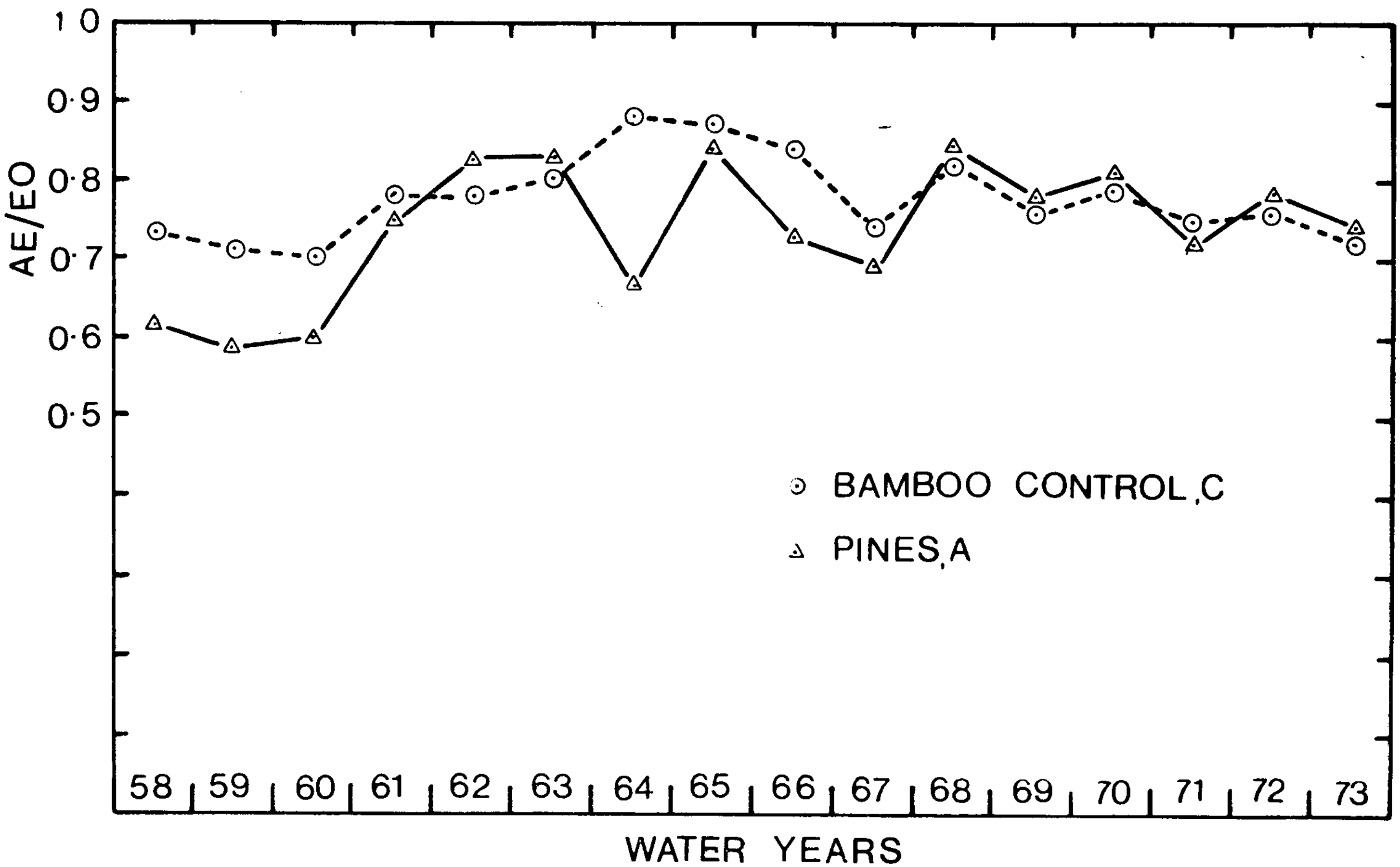

Figure 6.—Water year AE/EO ratios for Catchments C and A

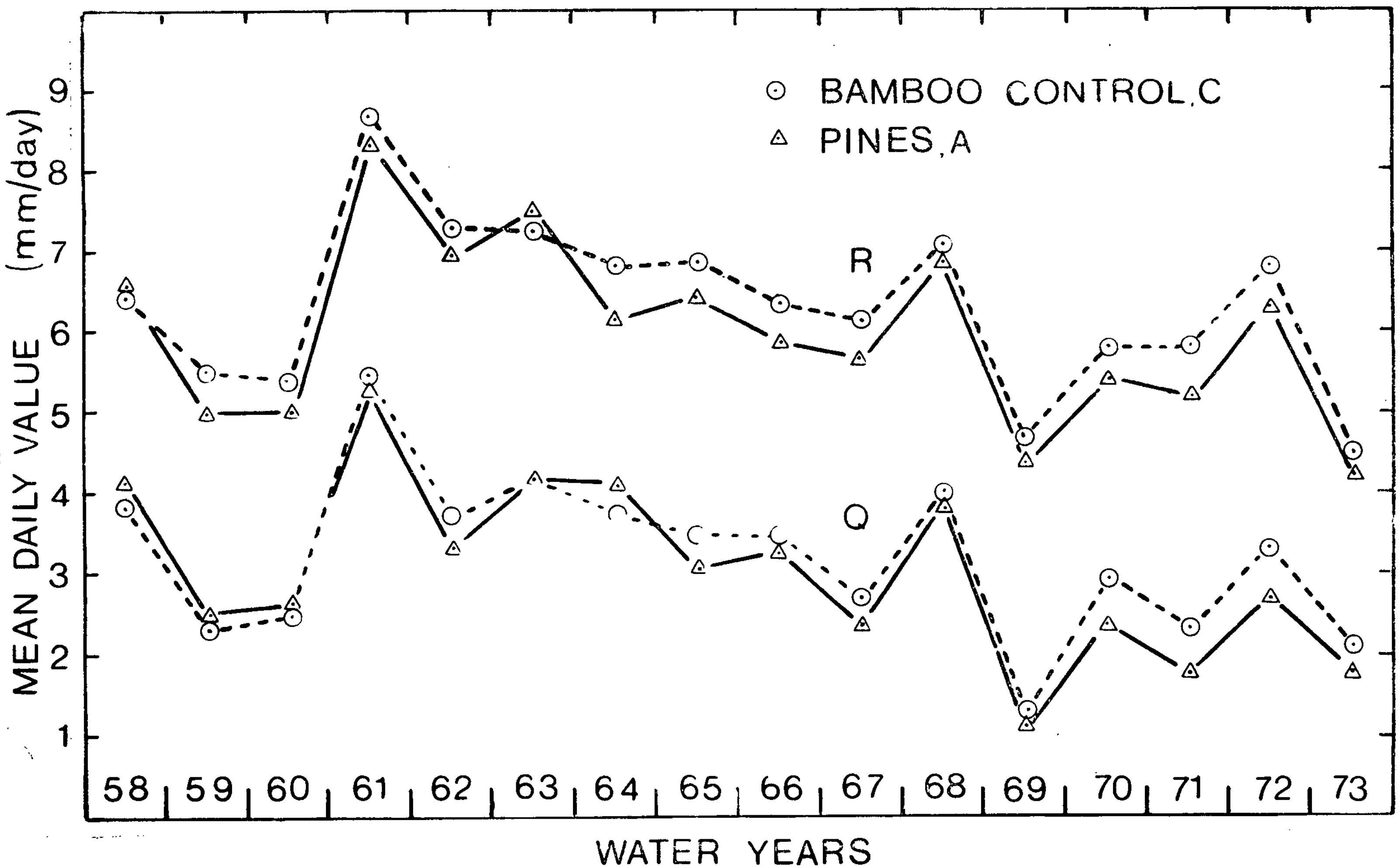

Figure 7.—Water year mean daily values of rainfall, R, and streamflow, Q, for Catchments C and A

From an analysis of individual storms, Pereira *et al.* (op. cit.) showed that surface run-off 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 Figs. 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 optimized 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—

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

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

(*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 optimized.

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 Tables XI and XII for Catchments C and A respectively. As can be seen from the reduction in the variance F, the water use model

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	1·80
FS	4·63	4·41
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	.. ..	1,090	1,142	+52	1,148	+58
59	.. ..	993	1,071	+78	1,080	+87
60	.. ..	1,108	1,208	+100	1,176	+68
61	.. ..	1,333	1,302	−30	1,362	+29
62	.. ..	979	961	−18	1,028	+49
63	.. ..	1,179	1,131	−48	1,162	−17
64	.. ..	1,361	1,141	−220	1,228	−133
65	.. ..	1,091	958	−133	1,005	−86
66	.. ..	1,202	1,091	−111	1,098	−104
67	.. ..	1,136	1,175	+39	1,179	+43
68	.. ..	1,202	1,119	−83	1,196	−6
69	.. ..	1,289	1,289	0	1,276	−13
70	.. ..	1,080	1,038	−42	1,083	+3
71	.. ..	1,079	1,099	+20	1,126	+47
72	.. ..	1,317	1,314	−3	1,312	−5
73	.. ..	1,060	1,127	+67	1,072	+12
67–73	Σ	8,162	8,162		8,244	
	F		41·7		12·5	
58–73	Σ	18,497	18,169		18,531	
	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*) $\hat{AE}$	(*a*) δ	(*b*) $\hat{AE}$	(*b*) δ
58	.. ..	928	1,145	+217	1,146	+218
59	.. ..	916	1,185	+269	1,147	+231
60	.. ..	966	1,239	+273	1,193	+227
61	.. ..	1,276	1,306	+30	1,333	+57
62	.. ..	1,180	1,082	−98	1,109	−71
63	.. ..	1,191	1,101	−90	1,124	−67
64	.. ..	907	1,042	+135	1,097	+190
65	.. ..	1,138	1,038	−100	1,063	−75
66	.. ..	996	1,047	+51	1,028	+32
67	.. ..	1,064	1,178	+114	1,172	+108
68	.. ..	1,156	1,055	−101	1,127	−29
69	.. ..	1,312	1,293	−19	1,267	−45
70	.. ..	1,102	1,042	−60	1,060	−42
71	.. ..	1,038	1,103	+65	1,109	+71
72	.. ..	1,352	1,318	−34	1,301	−51
73	.. ..	1,095	1,130	+35	1,079	−16
67–73	Σ	8,119	8,119		8,115	
	F		94·1		66·8	
58–73	Σ	17,617	18,303		18,355	
	F		759·2		633·1	

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 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 optimized 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 optimization 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 optimized, using first monthly and then daily flow as the observed values; the variance—

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

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

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

where—

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

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

RE values of 94 per cent and 87 per cent 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 per cent and − 4.0 per cent. 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 Fig. 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, optimized over such a period, was incorporated.

These functions could doubtless be optimized 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 inherent characteristic of all optimization 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

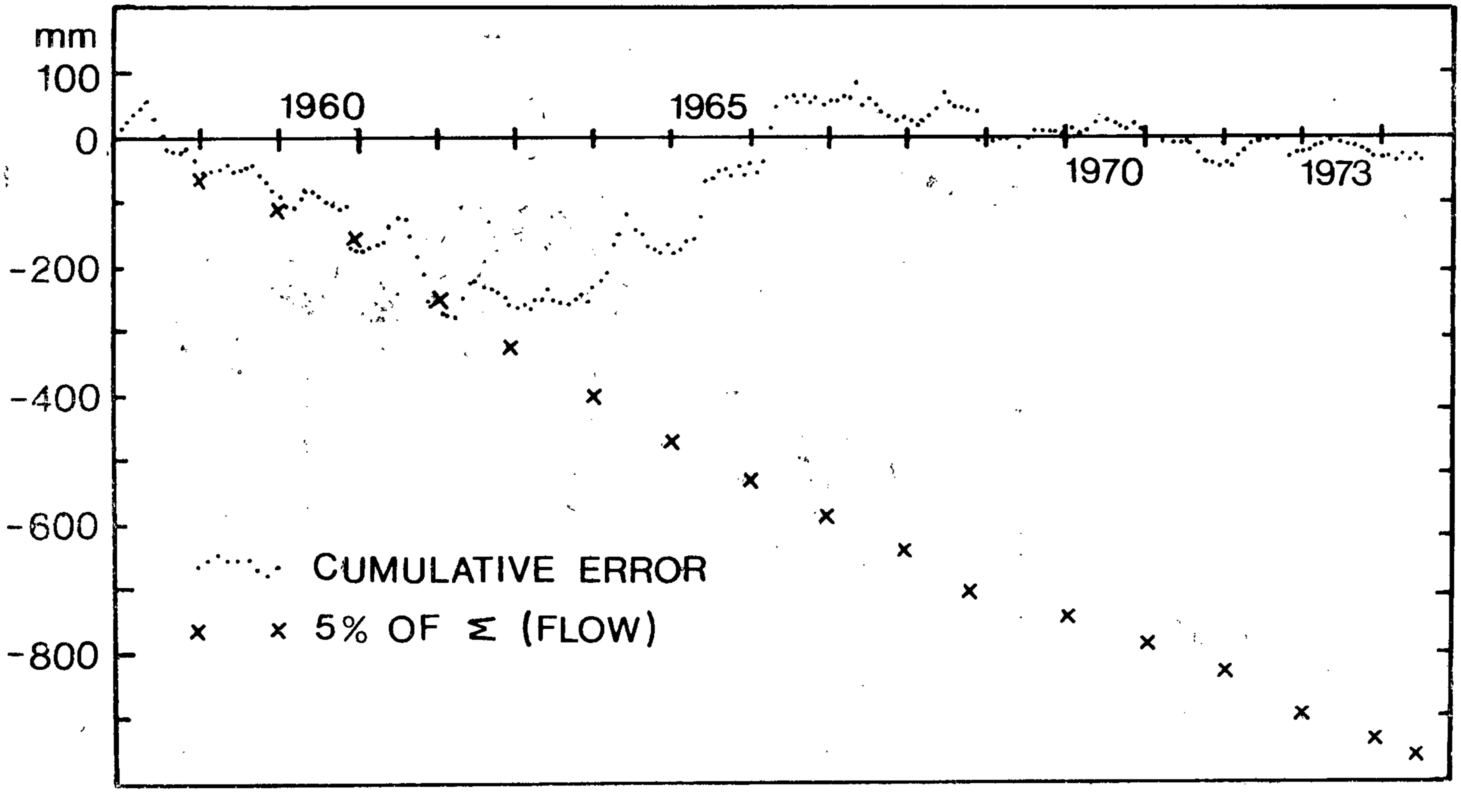

Figure 8.—Cumulative error in flow prediction for Kimakia C using the IH model as optimized in 167-78

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		Other Parameters		Error (% AE)
			$\hat{AE}$(mm)	F	$\hat{AE}$(mm)	F	
16 ..	02–12	13,633	13,769	62·3	12,781	237·6	−6·2%
C ..	67–73	8,162	8,244	12·5	8,993	274·4	+10·2%

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 optimized 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 optimized 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.

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