INTERACTIONS BETWEEN

VEGETATION

AND

WATER YIELD

IN

TASMANIAN HIGHLAND CATCHMENTS

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for the degree of Doctor of Philosophy.

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Except as stated therein, this thesis contains no material which has been accepted for the award of any other degree of diploma in any University. To the best of my knowledge and belief, it contains no copy or paraphrase of material previously published or written by another person, except when due reference is made in the test thesis.

J. J. Edwards

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SUMMARY

A hydrological study has been made of the effects of vegetation on water yield in the Central Plateau catchments of Tasmania. The analysis has measured the efficiency of highland vegetation in straining out small diameter water droplets, both liquid and frozen, that prevail in low cloud, mist and fog. Run-off from experimental has been compared with fog deposits in gauges built to quantify the potential importance of small diameter droplets over large areas. Evapotranspiration losses of water have been examined, and the effect of a severe fire on run-off has been analysed.

Gauges built to collect fog droplets, but exclude rain, have indicated that the potential input from foliage straining out fog droplets is negligible below 900 m. (3000'), of doubtful significance from 900 - 1050 m. (3000' - 3500'), and of potentially great importance above 1200 m. (4000'). Deposits were strongly correlated with altitude, season of year, and rainfall.

Run-off plots have been constructed up to 390 sq. m. (4200 sq. ft.) in area, and large tipping bucket gauges have been designed and built to measure run-off. A large plot at Lake Augusta (1100 m., 3700')

has enabled run-off from small diameter droplets to be correlated with deposits in the fog gauges. A tentative conversion ratio from fog gauge to run-off of 1:1 has been established under conditions of equal exposure. It has not been possible to directly extrapolate this data to a complete catchment because of differences in exposure, vegetation type and altitude. If vegetation was 1/10th as efficient over large areas as the fog gauges, then run-off from fog, mist and cloud would average 1" per year at Lake Augusta and 7" per year at Pine Lake (1200m, 4000').

Analysis of streamflow records from catchments burnt by a severe fire in 1960-61, which razed the highest and most exposed vegetation over 312 sq. km. (120 sq. miles), including four separate catchments, has supported the above results. Evidence is presented to show that in the post fire decade, run-off has been reduced in the Ouse, Nive and Fisher catchments by 109 mm. (4.3"), 58 mm. (2.3") and 69 mm. (2.7") per year respectively. In the lower Travellers Rest catchment a slight average increase of 8 mm. (0.3") per year has been recorded after the fire.

Evapotranspiration losses of water from the Central Plateau have been estimated from a number of methods. Estimates based on empirical formulae relating evapotranspiration to temperature, pan evaporation and net radiation have been shown to be misleading because of the complex relationship between air pressure, available energy and evaporation. A crude analysis of the water budget on Central Plateau catchments supports a theoretical expectation of approximately 760 mm. (30") evapotranspiration loss per year.

CHAPTER I

INTRODUCTION TO THE CENTRAL PLATEAU

The Central Plateau of Tasmania comprises the main water catchment in the State for the production of hydro-electricity. The plateau is a fairly clearly defined unit, with sharp boundaries in the north, east and west, where high fault scarps, 600 - 1000 metres in height, have resulted from Tertiary faulting (Carey, 1947). Along the northern and western margins altitudes are generally above 1200 m., with peaks to 1450 m. The plateau declines gradually in height to the southeast and south, where a boundary is more difficult to define. Approximately 600 m. is commonly accepted as a convenient boundary for the lower margin, for here scarps occur, although they are less clear than the high and continuous scarps of the Great Western Tiers marking the northern boundary. The total area of the Central Plateau exceeds 5000 sq. km., which includes 320 sq. km. above 1200 m. in altitude, and 3100 sq. km. above 900 m.

Topographically there is a big difference between the west of the plateau, which was covered by an ice cap during the Pleistocene, and the centre and east. The western part is characterised essentially by a gentle decline in height south-eastwards from a high rim on the northern and western margins. Projecting above the general surface are a number of peaks, and local relief is steeply undulating in the north, south-west and west, compared to the area in between, where drainage is more indeterminate. The western portion of the plateau contains over 500 lakes of one hectare or more in extent, in a general mosaic [illegible] t [illegible] 000 (Davies, 1965).

Glacial History: The pattern of glaciation on the plateau is well documented. (Jennings and Ahmad, 1957; Derbyshire et el, 1965, Banks and Derbyshire, 1970). A large elongated ice cap covered nearly all of the western side of the plateau. There was a major ice divide running roughly southwest-northeast, from approximately Lake Tooreh in the southwest to Forty Lakes Peak in the north. To the west of the divide, ice flowed through the Walls of Jerusalem neighbourhood to the Mersey and Fish Valleys, and over the scarp in the northwest into the Little Fisher and Fisher Valleys. In the north and northeast it toppled over the Great Western Tiers at many points.

On the opposite flank of the ice divide, movement was outwards in a roughly radial plan. It is thought that small areas projected through the ice cap as nunataks (for example, Clumner Bluff, Howells Bluff, Cathedral Mountain, Turrana Bluff and Western Bluff) although other peaks such as the Walls of Jerusalem, were completely overridden. (Jennings and Ahmad, 1958).

The erosional morphology produced by the ice is evident in the dolerite jointing. In many roche mountonnes and hills can be seen smoothed, gradual slopes which show the direction of ice approach and steep, almost vertical, quarried faces which have been produced where the ice moved away from the rock. Some cirque like features can be seen on the plateau, such as near Eagle Lake, and south of Lake Meander.

The western lakes have been formed in a number of different modes associated with the glaciation. Those of simple origin, such as Rocky Lagoon, Lake Botsford and Clarence Lagoon, were formed from deposition of morainal material. Certain of these simple lakes, for example Double Lagoon and the Bar Lakes, are almost divided by ice pushed ramparts of sand and boulders. Other simple lakes have resulted from glacial overdeepening and the majority of these are small and unnamed, being surrounded almost entirely by rock. Lake basins, due to the melting of ice blocks, are uncommon although some small lakes south of Lake Nameless are believed to be caused by ice blocks melting in morainal deposits. (Jennings and Ahmad, 1957). Most of the large lakes have a compound origin, with both erosional overdeepening and depositional, morainal features. Examples include Lake Ada, Lake Augusta, Lake Ina and Travellers Rest Lake.

The ice cap did not extend to the east beyond Liawenee (approximately), and the origin of lakes on the eastern plateau is unclear. Fairbridge (1948) assigned Lake Echo primarily to tectonic subsidence across the fall of drainage. It is not known if the large eastern lakes arose from a previous glaciation, with consequent infilling of small lakes so that if tectonic forces were responsible. Jennings and Ahmad (1957) have discussed the contrast in origin between western and eastern sections of the plateau. Davies (1965) pointed out that the eastern lakes could most easily be explained of by subsidence.

Geology: The Central Plateau is geologically dominated by dolerite, which was intruded, with accompanying faulting, in Jurassic times. The dolerite was intruded into Permian and Triassic sediments, as sheets or sills (Fairbridge, 1948; Prider, 1947; Voisey, 1943).

In the Mesozoic and early Tertiary, the country was peneplained until the dolerite was exposed over most of the plateau. Small areas of Permian and Triassic sandstones, mudstones and shales remain in the south - central localities.

The peneplain was block faulted during the mid Tertiary, when the plateau was uplifted and defined. In the late Tertiary, volcanic activity poured basalt into many of the valleys. The main basalt outcrop at present underlies the Liawenee plains, where the series ranges from columnar basalt to scoriaceous basalt, pumice and tachylyte breccias. (Voisey, 1949).

The dolerite is everywhere shattered by planes of weakness, including joints, shear planes, and faults (Jennings and Ahmad, 1957). Outcrops occur frequently in the western half of the plateau, particularly along ridge tops, and along the northern andwestern edges of the plateau. Evidence of ice abrasion and plucking, can be seen almost everywhere and rouche moutonnees are frequent. Striations, grooves and friction cracks, resulting from ice movement, have not been preserved. This is presumably due to chemical weathering. (Jennings and Ahmad, 1957).

Soils: Soils throughout the plateau are infertile and strongly acidic. No systematic study or classification of the soils has taken place, and in general little is known of the mechanical and chemical composition of the soils.

Nicolls and Dimmock (1965) broadly classified the soils into

Alpine Humus Soils and Moor Peats. The Alpine Humus Soils are associated with pereglacial solifluction deposits, and consist mainly of dolerite fragments and boulders in a matrix of material varying in colour from brown to red, and in texture from sand to clay. Profile development is often limited to the surface incorporation of organic matter, which increases with poor drainage. The amount of stone embedded in the soil, is everywhere considerable, especially near the surface, where it is the result of continued frost action.

Soils overlying the basalt of the Liawenee plains are similarly shallow and infertile. The surface of these soils contains few stone fragments. A hard pan at an average of approximately 30 cm. depth overlies broken basalt bedrock.

In the flat valleys and plains where drainage is impeded, soils are wet throughout the year and peats have developed to an average depth of about 30 cm.

Vegetation: The pattern of vegetation on the Central Plateau complex, with rapid changes in structure caused by microclimatic differences in relief, exposure, and frost severity, as well as fire history and soil drainage. Detailed descriptions are given by Jackson (1972, 1973).

The high western portion of the plateau, with which this study is primarily concerned, is covered with 7 essential vegetation types:

1. Woodland. Eucalyptus coccifera woodland, with scattered E. subcrenulata, occurs extensively on the freely drained slopes west of Great Lake. Tree height varies up to 15 metres, according to exposure. The understory consists of a complex mosaic of shrubs which vary greatly over small distances. In the absence of trees these shrubs form extensive heath formations.

Athrotaxis cupressioides, coniferous forest occurs in restricted localities beside watercourses and in sheltered sites beside lakes and tarns. Several attractive groves occur near Mt. Jerusalem, where trees up to 15 metres high form an open canopy above Poa labillardieri grassland understory.

2. Tall Heath. Extensive areas of tall heath, grading into low heath and microshrubbery, occur over all sites except very poorly drained localities. The main species are Orites acicularis, O revoluta, O pinifolia, Helichrysum hookeri, Olearia algida, Richea scoparia, R. gunnii, Microstrobus niphopholus, Diselma archeri. Height is variable up to 3 metres, and species constitution varies with drainage and fire frequency.

3. Low Heath. Low heath, from 10 cm. to 1 metre in height comprises predominantly Bellendena montana, Grevillea australis, Beackea gunniana, Oxylobium ellipticum, Richea acerosa, Richea sprengelio Occurrence is generally on sites with summer water stress, although a complex pattern is evident.

4. Microshrubbery: This consists of a mat of prostrate vegetation in exposed habitats. On freely drained sites dominant

plants are Monotoca empetrifolia, Exocarpus humifusum, Cyathodes dealbata and Pentachondra pumila. On poorer sites with restricted drainage Pernettya tasmanica becomes common and the association grades into bog and bolster moor vegetation.

5. Bolster Moor. Bolster moor vegetation consists of extremely densely packed aggregations of shrubbery, with a uniform surface, forming a compact cushion a few centimeters above ground level. Many species within the cushions are morphologically very similar, although frequently from different families. The bolster community inhabits the most poorly drained areas of the plateau, and actively grows towards sites of water movement, with the result that it further impedes drainage and constantly changes the direction of movement of small streams.

Species constitution varies widely but is dominated by Abrotanella forsterioides, Pterygopappus lawrencii, Donatia novae-zelandiae and Dracophyllum minimum.

6. Bog. Bog vegetation intergrades with the Bolster moor communities in areas of impeded drainage. Species are dominated by Astelia alpina, Restio australis, Calorophus lateriflorus, Oreobolus pumila, Celmisia longifolia, Helichrysum pumilum and Ewartia spp.

7. Grassland. Grassland occurs in moderately well drained soils, especially in frost hollows. Poa labillardieri is the dominant species, forming tall tussocks in the absence of fire. Poa gunnii, Ranunculus nanus, Celmisia longifolia and a number of other herbs occupy the inter tussock spaces.

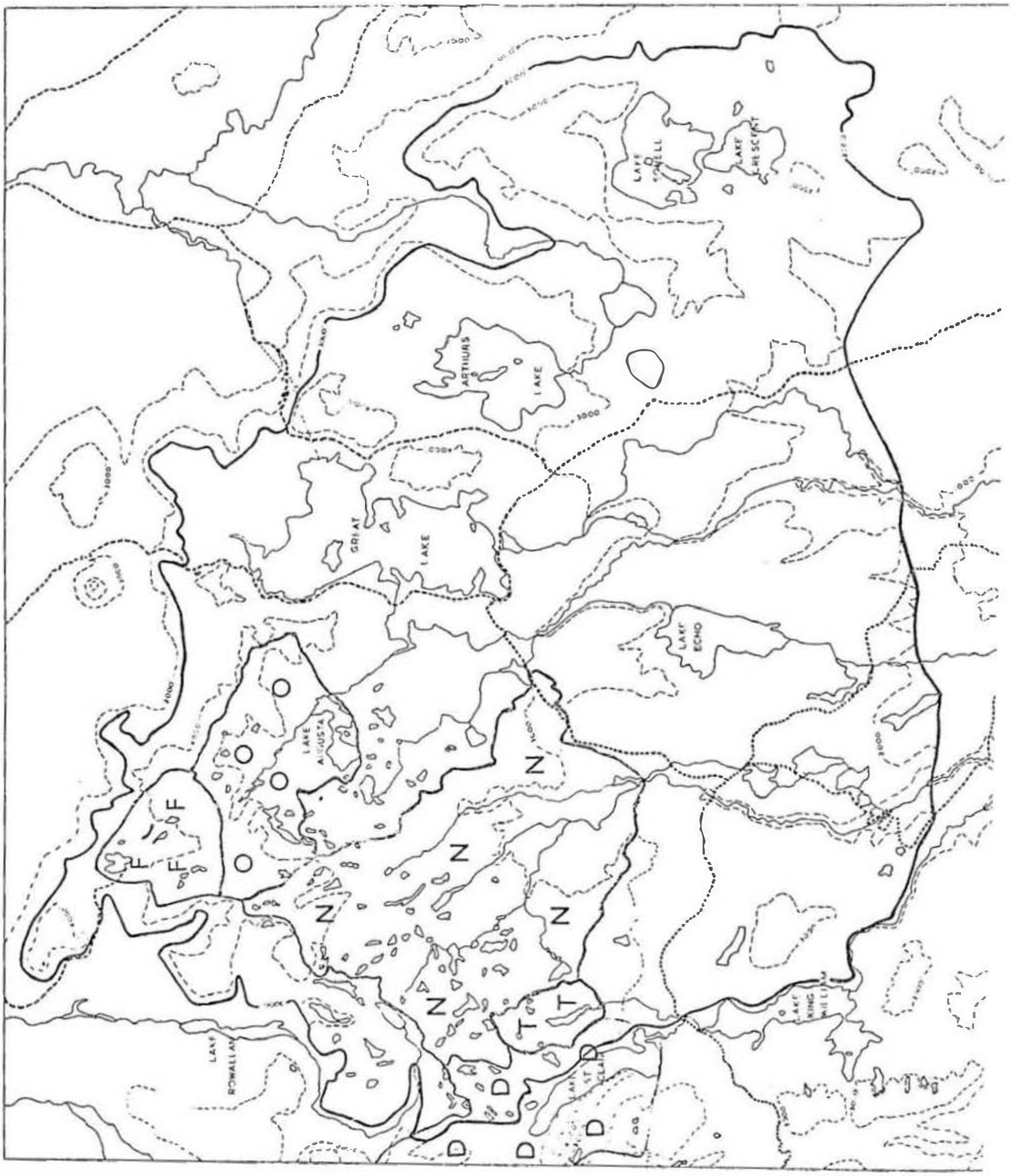

Fig. 1. Central Plateau water catchments.

F = Fisher River at Lake Mackenzie.
O = Ouse River at Lake Augusta.
N = Nive River at Pine Tier Lagoon.
D = Derwent River at Lake St. Clair.

<u>Water Catchments</u>: The Central Plateau lakes comprise the headwaters of four of the State's major river systems - the Derwent, Mersey, Ouse and Nive. For the purpose of this study, distinct catchments are recognised, each being defined by the area sampled by streamflow recorders operated by the Hydro Electric Commission (H.E.C.).

1. <u>Fisher River Catchment</u>. The Fisher River catchment is located in the north western corner of the Plateau. Its essential characteristics are as follows :

Area: 78 sq. km. (30 sq. ml.)

Altitude: 1440 m. - 1080 m. (4700' - 3600').

Cover: Woodland 1%, Moorland 93%, Water 6%.

Area Burnt: 70%

Annual Streamflow: 175 cm (68.9")

Hydrological Records: High accuracy streamflow recorder since 1955.

Long period raingauge at Lake Mackenzie since 1955. Site changed in 1968.

Description: The Fisher River Catchment is the highest on the plateau and experiences the most extreme climate. The highest portions are in the south and east, where a range of hills above the general plateau surface, runs from Mt. Ironstone in the north-east, to Turrana Heights in the south-west corner. Two prominent projections, Blue Peaks and Forty Lakes Peak [illegible] metres and comprise the main breaks in the gradual decline in altitude to the north-west, where the gauging station on the Fisher River is installed below Lake Mackenzie.

2. Ouse River Catchment. The Ouse River gauging station is located at Liawenee, where the Liawenee Canal diverts water from the Ouse River into Great Lake. Essential characteristics:

Area:	236 sq. km. (110 sq. ml.)
Altitude:	1440 m. - 1080 m. (4,700' - 3,600').
Cover:	Woodland 5%, Water 9%, Moorland 86%.
Area Burnt:	34%
Annual Streamflow:	110 cm. (43.2").

Hydrological Records: Streamgauge with high accuracy rating since 1922. Lake Augusta dam completed 1953. Liawenee rainfall records intermittent - 1919 - 1929, 1955 - 1971. Rainfall at L. Augusta West from 1966. Rainfall at L. Augusta East since 1966. Evaporation pan (American Class A) installed at Liawenee in 1969.

Description: The southern boundary of the Fisher River catchment limits the northern margin of the Ouse watershed, which continues eastwards along a chain of mountains from Mt. Ironstone to Wild Dog Tier. To the south, drainage is more indeterminate, and the border between the Ouse catchment and the Nive catchment is obscure in places.

Lake Augusta, covering approximately 12 sq. km., is the largest lake within the catchment and consists of two arms, of which the eastern extension is artificial. The L. Augusta dam regulates water into the Ouse which is tapped 6 km. downstream by the Liawenee canal. Lake Augusta has an effective storage equivalent to 7.6 cm (3") run-off from the catchment and the Liawenee canal has a capacity equivalent to 0.6 cm (.25") run-off from the catchment per day.

Pillans Lake of 3 sq. km. and a ramification called Julian Lakes, of approximately 1 sq. km., are the only other large lakes within the catchment, although hundreds of lesser lakes and ponds are present in the western half.

3. Nive River Catchment. The Nive catchment is the most extensive on the Plateau, draining into Pine Tier Lagoon:

Essential characteristics:

Area:	733 sq. km. (283 sq. ml.)
Altitude:	1440 m. - 660 m. (4700' - 2200').
Cover:	Forest 70%, Moorland 28%, Water 2%.
Area Burnt:	28%
Annual Streamflow:	79.2 cm. (31.2").

Hydrological Records: Streamflow records since 1953 - high accuracy recorder. (Streamflow records also available for Nive at Gowan Brae since 1964 and for the Little Pine River below Lake Kay since 1958. Although constituting separate catchments, these stations have insufficient periods of record for the purpose of this study). No raingauge stations exist within the catchment with more than 10 years record.

Description: The Nive catchment ranges from the exposed moorland, north of Mt. Jerusalem where it joins the Ouse headwaters, through open woodland in the intermediate zones, to dense forest near Pine Tier Lagoon. The Nive originates in Lake Malbeena at 1,000 m. but a number of tributaries drain other lakes to the north and south. These include the Pine River from Lake Ball near Mt. Jerusalem; the Little River from Three Arm Lake, and the Little Nive River from Lake Ina.

The catchment contains innumerable small lakes, especially in the highest moorland, as well as 5 lakes with an area exceeding 1 sq. km. - Lake Olive, Lake Malbeena, Lake Lenonne, Lake Norman and Lake Ina.

4. Travellors Rest Catchment: This is a small, mainly forested catchment area in the southwestern corner of the Plateau. Water drains through the Travellors Rest Lake into the Travellors Rest River, which in turn flows into Lake King William.

Essential characteristics:

Area:	46.4 sq. km. (18 sq. ml).
Altitude:	1200 m. - 930 m. (4000' - 3100').
Cover:	Forest 40%, Moorland 54%, Water 6%.
Area Burnt:	32% (80% Forest and 20% Moorland)
Annual Streamflow:	161 cm. (63.5")

Hydrological Records: High accuracy streamgauge recorder since 1949. Long period raingauge, rated on Lake St. Clair rainfall for monthly data since 1949.

Description: The northern section of the Travellors Rest catchment constitutes part of the general upper plateau surface, characterised by numerous lakes and tarns with moorland vegetation. This rapidly changes, as the altitude drops approximately 600 m. to the Travellors Rest Lake, a large kidney shaped lake of 2.5 sq. km. area. Vegetation becomes much taller, and dense eucalypt forest predominates near the lake.

The northern end of the lake has been glacially overdeepened, and a number of moraines and an outwash plain lead to a second small lake at the southern end, which is appropriately called "The Park". The Travellors Rest gauging station is situated immediately below this, where the river begins its turbulent run through an incised river course to Lake King William.

5. Lake St. Clair Catchment: This Catchment is only partly included in a strict definition of the Central Plateau, but drains a section of the Cradle Mt. - Lake St. Clair National Park that is similar in most respects to the Plateau.

Essential characteristics:

Area:	249 sq. Km. (96 sq. miles)
Altitude:	1500 m - 720 m. (5000' - 2400')
Cover:	Forest 61%, Moorland 27%, Water 12%.
Area Burnt:	Nil
Annual Streamflow:	182.6 cm. (71.9")

Hydrological Records: High accuracy streamflow records since 1937. Rainfall records at Lake St. Clair since 1938. Evaporation pan at Lake St. Clair since 1960. Originally an Australian Sunken Pan but changed in 1964 to an American Class A pan. Sunshine hours, maximum and minimum temperatures and humidity are also recorded at Lake St. Clair.

Description: The north-eastern section of this Catchment drains from the Mountains of Jupiter on the Central Plateau. The northern and western extremities are defined by the range of mountains constituting the Du Cane Range - Falling Mt., Mt. Massif, Walled Mt., The Parthenon, The Guardians and Mt. Gould. Mt. Manfred

PLATE 1. Ouse River Catchment. View from Wild Dog Tier looking south-west.

PLATE 2. Ouse River Catchment. Dead Pencil Pine west of Pillans Lake.

PLATE 3. Ouse River Catchment. Second Bar Lake from Wild Dog Tier.

PLATE 4. Nive River Catchment. Dead Eucalypts west of Lake Fanny.

PLATE 5. Nive River Catchment. Lake Ball near Mt. Jerusalem.

PLATE 6. Nive River Catchment. View from Layatinna Hill looking west.

PLATE 7. Nive River Catchment. Unnamed lake west of Lake Fanny.

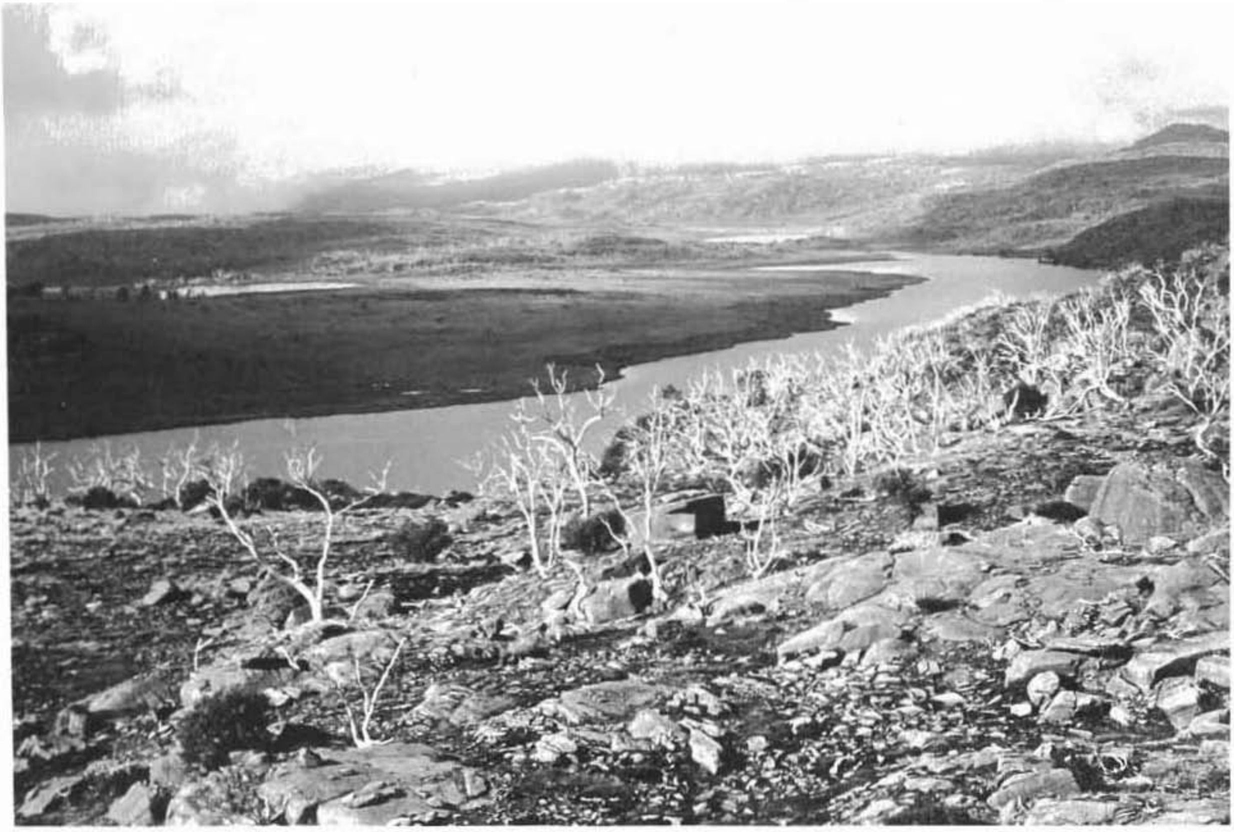

PLATE 8. Fisher River Catchment. Lake Lucy Long looking east toward Mt. Ironstone.

PLATE 9. Fisher River Catchment. Explorer Creek below Lake Explorer.

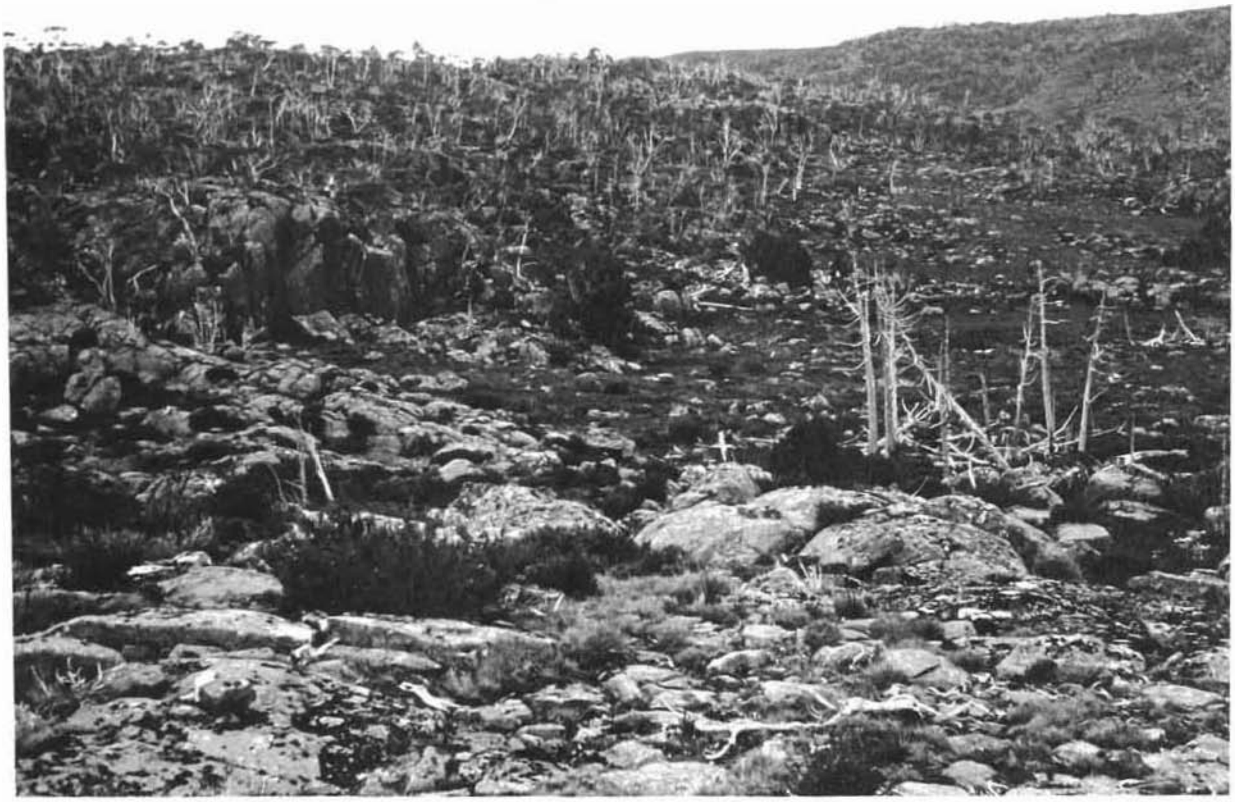

PLATE 10. Fisher River Catchment. Burnt Pencil Pine near Explorer Creek.

PLATE 11. Travellors Rest Catchment. Travellors Rest Lake from the northern end.

PLATE 12. Travellors Rest Catchment. Unburnt Eucalypts beside Travellors Rest Lake.

Mt. Cuvier and Mt. Olympus are also included in this catchment, which is steeply dissected in the western half. Vegetation changes rapidly from alpine moorland, to dense forest, depending on altitude and exposure.

Drainage via a number of rivers is into Lake St. Clair, the largest glacial lake in Tasmania. Lake St. Clair is a piedmont lake covering approximately 27 sq. km., and is over 200 m. (700') deep. The Derwent River leaves the lake from a basin in the south-eastern corner, where the gauging station is sited. The lake has been raised by an H.E.C. dam at the Derwent River outlet.

Climate: The climate of the western plateau is rigorous, with precipitation in excess of 230 cm. (90") near the rim of the Great Western Tiers in the north, and above the fault scarps in the west. A strong precipitation gradient exists across the plateau, with the lower southern and eastern parts receiving less than 64 cm. (25") per annum. Rainfall is mainly determined by the dominant westerly airstream over the state, resulting in a winter maximum. The northeastern margin of the plateau commonly receives rain in summer and autumn, that is missed by the normally wetter western regions because of sustained wind flow from the northeast (Langford, 1965). Snowfall, in winter and early spring, can account for 20 - 30% of total precipitation, although snow rarely lies long, and only accumulates in the highest, most exposed areas, where drifts may persist for up to 6 months. In the absence of a permanent winter cover, severe frost heaving causes much damage to plant seedlings, that have established over the comparatively mild summer months.

Temperatures throughout the year on the plateau average between 4 - 7°C (40 - 45°F), ranging from a mean maximum of approximately 10 - 13°C (50 - 55°F) in February to 0 - 3°C (32 - 37°F) in July, the coldest month. Frosts may occur in any month.

Hours of sunshine on the plateau are recorded only at Lake St. Clair at 740 m., where rainfall averages 150 cm (59"). The average throughout the year for 9 years of record is 1749.4 hours, ranging from 2.3 hours per day in June, to 7.8 hours per day in January. This compares with 2104.6 hours per year at Hobart and 2374.4 at Launceston.

No wind speed records are available for the Central Plateau, although it is probable that average wind speed is in excess of 16 km/hr. (10 m/hr) (Cf. 11.7 km/hr. or 7.3 miles/hr. at Hobart).

Evaporation from an American Class A pan is recorded daily at L. St. Clair and Liawenee, but both pans are poorly sited so that advection effects, and loss of water from the gauges due to native birds and marsupials, effectively question their validity.

The region has a general lack of reliable climatological records. All available data is recorded on Tables 1 - 4.

TABLE 1. Mean Rainfall (inches) on Central Plateau Stations.

Station	Years	J	F	M	A	M	J	J	A	S	O	N	D	Yearly
L. Mackenzie	56-70	2.22	4.81	3.62	7.18	7.82	7.12	8.71	9.53	6.20	5.37	4.39	4.15	71.12
L. Aug. West	66-70	1.60	1.45	2.11	2.93	3.50	2.24	3.85	4.93	2.75	2.49	3.17	2.73	33.15
Liawenee	55-70	1.64	2.73	1.95	3.88	4.02	3.22	4.13	5.20	3.21	3.30	3.02	2.69	38.99
Waddamana	25-72	1.75	2.05	2.04	2.88	2.72	2.85	3.05	3.31	2.82	3.05	2.80	2.58	31.90
Shannon	28-72	1.83	2.17	1.94	3.12	2.93	2.97	3.29	3.54	2.95	3.05	2.79	2.67	33.15
L. St. Clair	38-72	2.96	3.27	3.18	4.88	5.26	5.79	6.24	6.39	6.04	5.61	5.03	4.41	59.06
Butlers Gorge	41-72	3.58	3.52	3.88	5.41	6.44	6.66	7.03	7.04	6.33	6.14	5.85	4.77	67.15
Bronte Park	50-70	1.50	1.92	1.85	3.67	3.25	3.13	3.22	3.83	2.49	3.19	3.31	2.57	34.43
Travellors Rest	54-70	2.78	3.05	3.08	5.18	5.88	5.54	5.18	6.23	5.17	5.14	5.43	3.96	56.62
Miena		2.07	1.93	2.12	2.67	2.81	3.16	3.12	3.33	3.00	3.20	2.41	2.49	32.31

Additional records have been collected from a number of localities for short periods during temporary occupation and are listed by Niolls and Aves (1961). A representation of these follows :

				Calc. Av.*
Breona	3400'	1921 - 56	75.0	73
"Allenvale"		17 - 22	51.3	53
"Cider Park"	3400'	23 - 27	51.8	51
Split Rock		17 - 28	45.3	38
Stone Hut		25 - 31	27.9	27
Gowan Brae		34 - 38	40.1	-
Pine Tier	2200'	43 - 50	36.3	46

* Calculated average has been determined by correlation during years of record with nearby stations with long period records.

TABLE 2. Temperature data for Central Plateau Stations.

		J	F	M	A	M	J	J	A	S	O	N	D	Yearly Mean
Miena 15 Years	Max	60.0	61.7	57.2	51.7	49.2	42.1	40.3	42.0	45.7	49.3	53.9	58.4	50.8
	Min	40.6	42.4	39.6	36.3	33.3	30.4	29.0	29.2	31.2	34.0	36.6	39.5	35.2
Lake St. Clair 16 Years	Max	65.3	65.3	60.9	54.5	48.6	45.7	43.5	45.5	49.4	53.8	55.8	60.4	54.0
	Min	45.9	45.1	43.0	39.8	36.7	34.2	32.6	33.0	34.7	37.6	39.7	43.4	38.7
Shannon	Max	64.4	63.0	59.0	52.3	46.6	43.0	41.3	42.6	47.7	51.1	54.6	59.7	52.0
	Min	42.7	42.6	40.9	37.1	33.9	31.3	30.2	30.3	31.9	34.9	37.2	40.5	36.2
Bronte Park	Max	68.7	68.4	64.6	57.1	51.1	47.7	46.1	47.7	53.0	57.0	59.2	64.2	57.1
20 Years	Min	44.1	44.1	41.4	38.5	35.7	33.0	31.7	32.3	34.7	37.5	39.2	42.1	37.9
Butlers Gorge 25 Years	Max	65.9	64.7	61.1	54.9	49.1	45.7	44.3	45.8	50.6	53.5	56.9	62.1	54.6
	Min	43.1	43.0	41.2	37.4	35.0	32.5	31.5	31.7	33.6	36.4	38.7	41.4	37.1
Hobart (For Comparison)	Max	69.8	70.6	67.5	62.2	57.8	52.8	52.7	55.4	59.0	62.5	65.0	6.79	61.9
	Min	52.4	53.7	51.3	48.0	44.6	41.2	40.6	41.7	43.7	46.1	48.2	51.3	46.9

TABLE 3. EVAPORATION (Inches) at Lake St. Clair

	J	F	M	A	M	J	J	A	S	O	N	D	Y
Lake St. Clair 65 - 70	4.83	4.09	3.15	1.93	1.45	.82	.66	.98	1.54	2.88	3.84	3.96	30

TABLE 4. SUNSHINE (Hours) for Representative Tasmanian Stations

Lake St. Clair	243.6	213.1	180.6	112.4	89.5	72.5	78.3	95.2	103.8	175.6	189.5	195.3	1749
Hobart	232.2	189.5	187.8	141.3	131.2	111.7	129.0	148.8	165.5	184.6	204.9	214.7	2041
Maydena	216.6	187.1	154.9	108.4	97.8	58.0	68.7	103.0	100.3	156.5	161.6	184.1	1597
Launceston	273.6	241.5	222.5	164.9	151.3	119.1	124.1	161.9	189.0	232.3	237.2	257.0	2374

Economic Importance of the Central Plateau:

The prime value of the Central Plateau is as a water catchment for hydro electric power generation. The income derived from water on the plateau is proportional to the quantity of electricity that can be generated from it, and the unit value of the electricity produced. For the purpose of this study, water in Great Lake is taken as a standard for the western part of the plateau, since it is at a representative altitude for the plateau (1020 m), and is the largest catchment on the plateau (draining 942 sq.Km., 364 sq. miles), including the Ouse and Arthurs Lake catchments).

The power generated from Great Lake water after passing through the Poatina and Trevallyn turbines is approximately 230 Kw. per cusec (H.E.C., 1965) and the average income from the sale of electricity in Tasmania in 1971 - 1972 was 0.897 c/unit. The average income derived from water in Great Lake in 1971 - 1972, then, was $0.02/meter^3 ($2.05 per acre inch). Although the income to the H.E.C. from water generated electricity is offset by costs incurred as interest on capital invested, transmission costs, distribution costs and miscellaneous charges, the cost structure is such that most expenses are constant from year to year, and do not depend to any significant extent on water yield. It would be a viable economic proposition then, to spend almost $2 per hectare per year on catchment management for every centimeter depth of runoff that could be produced in excess of the present day figure. Alternatively, it would be economical to invest almost $30 per hectare to earn 7% on invested capital if average streamflow could be increase by 1 cm per year. The income from land on the Central Plateau, via hydroelectricity production, varies from over $400 per hectare in the Fisher River catchment, to $100 per hectare in the Arthurs Lakes catchment. The return from water on the plateau is higher than the income from agricultural produce on most farmlands.

Approximately two thirds of the power generated in Tasmania is used by industry. A rough analysis of the profits of the five major electricity consumers in the State has revealed that the company tax paid by the companies is equivalent to about the same value in Great Lake water equivalents, as the income of the H.E.C. In periods of power rationing, the State is very dependant on water from the Central Plateau, and the water value escallates to many times its average value. The value of water is increasing at a compound rate of approximately 5% per year, reflecting the general rise in costs of power generated.

Grazing on the plateau has been conducted on a transhumant basis since the 1820's. Sheep are driven to the highland native pastures for approximately 6 months, from December until May. Stocking rates vary from 1 sheep to 3 acres, to one sheep per 10 - 20 acres on the poorer moorland. Reports by Scott (1956) and Shepherd (1972) indicate that returns vary from a few cents per hectare to a maximum of approximately $4 per hectare per year. In 1971 - 72, 88,000 sheep and 2,500 cattle were moved to the plateau. Shepherd (1972) showed return on capital to vary widely between graziers, from 3 - 20% for wool prices of 79c/Kilo (36c/lb.).

Dramatic increases in wool prices have taken place since this survey was conducted, so that summer grazing is almost certainly a profitable proposition for graziers, taking into account present day minimal lease rentals and minimal control of stock straying onto Crown Land.

Other forms of land use on the Central Plateau include rabbit trapping, wallaby and rabbit shooting, fishing and bushwalking. Economic returns from these uses are small compared to water yield and grazing. Forestry is important in lower sections of the plateau but no tree harvesting takes place in the high western plateau.

Management Policies: At the present time there is no clearly defined management policy toward the Central Plateau - and no single authority in charge of the area. Responsibility for the area is shared between freeholders, the Lands Department, the Hydro Electric Commission, and the Forestry Commission. The management policies adopted by each of these custodians is listed below. It is noted that no firm management policy exists, but rather guidelines are adhered to loosely.

1. Lands Department: The Lands Department controls most of the leasehold land and Crown Land in the State. On the Central Plateau, west of Great Lake, most of the land is in this category. The Lands Department has recently decided to renew 14 year grazing leases on an annual basis only, as an interim measure. Temporary leases carry no guarantee that the lessee will receive compensation for improvements in the manner of fencing, buildings and pasture improvement, as did 14 year leases. The present policy then, discourages the holder of a temporary lease from improving his land, and encourages overgrazing and burning for an immediate financial gain.

Although Crown Land is controlled by the Lands Department, there is no active management by this Governmental body, or any other body using it. The sale of timber from Crown Land is controlled by the Forestry Commission, and the control of fire is under the authority of the Forestry Commission and the Rural Fires Board. The H.E.C. is also involved in the use of Crown Land.

2. Hydro Electric Commission: The H.E.C. has control of

approximately 14,000 hectares west of Great Lake, most of which is in the Lake Mackenzie area. It also has no policy of active management of land vested in it, apart from the banning of fires from 1st December to 31st March, which it also applies to Crown Land and leasehold land controlled by the Lands Department.

The H.E.C. has 2 permanent men stationed at Liawenee and at Lake Mackenzie, whose duties include a careful watch of illegal uncontrolled burning operations during summer months. The Commission sub-leases small areas near Great Lake and Penstock Lagoon to graziers.

Since the H.E.C. has the only real financial interest in the area, it is the only body with the resources to control an active management policy in the area. Apart from a policy on fire lighting in summer months however, it does nothing toward managing its land. It has no revegetation team to recolonise areas disturbed by its works and has a poor reputation for interest in conservation of the area. Despite the fact that it receives the equivalent of over $200 per hectare per year from water off the land, it has no research team conducting experiments with the aim of managing water yield.

3. Forestry Commission: The Forestry Commission has no interest in the most extreme climatic zones of the plateau although sections of the plateau are included in "Timber Reserve" areas vested in the Forestry Commission. This appears to be the result of drawing a straight line on a map between two points which accidentally includes part of the plateau.

The Forestry Commission also sub-leases portions of its land to graziers in the lower, eastern parts of the plateau.

4. National Parks and Wildlife Board: Part of the Cradle Mt. - Lake St. Clair National Park extends into the western portion of the plateau, near Travellers Rest Lake.

Although a small section of this was burnt in the 1960 - 61 fire, there is little pressure on the land from grazing or burning normally, because the area is isolated and rarely visited.

A number of proposals have been made to include further areas in the Cradle Mt. - Lake St. Clair National Park, especially an attractive area near the Walls of Jerusalem. Although such a proposal has merit, the highland areas of Tasmania are comparatively well endowed with National Parks, and it is felt that a number of lower sites should have priority as new National Parks.

Management policies in Tasmanian National Parks to date have aimed at maximum usage (mainly by walkers) for minimum expense. Grazing is banned in National Parks, although fishing is permitted. Since most of Tasmania's reserves do not have heavy populations of wallabies or rabbits, there has been little need for management of grazing in the past. If the western section of the Central Plateau was declared a park, however, it would probably require active means to control wallaby numbers.

5. Freehold Land: Most of the land near Great Lake is freehold. Owners bring sheep and cattle to their land for approximately

6 months over summer when feed is scarce on lower properties. Some pasture improvement is taking place on lower sites east of Great Lake. In general, graziers regard this land as a form of insurance (Shepherd 1972) and it is only in the milder climatic zones near Interlaken and Lagoon of Islands, that sheep are grazed year round.

Many freehold blocks contain inadequate fences for control of stock so that straying stock may graze extensive areas of Crown land.

The effect of stock on vegetation cover has been extensively studied on the mainland (Bryant 1969, 1971, 1973; Taylor 1956; Costin 1957, 1958; Costin et al 1959), but not in Tasmania. In general it is accepted that sheep contribute to bare ground and erosion because they graze palatable herbs that grow between grass tussocks and shrubs, and because they graze Eucalypts regenerating from lignotubers after fire.

The effect of sheep on vegetation cover is confused by the presence, since the 1920's, of rabbits. Rabbit populations are extremely high in the Central Plateau up to approximately 1140 m. (3,800'), and it is probable that they are more detrimental to vegetation regeneration than are sheep. Although rabbit control is the responsibility of the State Department of Agriculture, no active measures are undertaken to reduce rabbit populations on the Central Plateau. The rabbit flea, infected with myxomatosis, has however, been released with limited success.

CHAPTER II

THE EFFECT OF VEGETATION ON WATER REACHING THE GROUND

Summary: The effect of vegetation in intercepting small diameter water droplets that drift with air currents, rather than fall more or less vertically, as does rain, has been studied. Two approaches have been used:

(1) Gauges to collect fog particles but exclude rain, have been distributed throughout the Plateau. Results have indicated that the potential input from vegetation straining out the fog droplets, is negligible below 900 m. (3000'), of doubtful significance from 900 - 1050 m. (3000' - 3500'), and of potentially great importance above 1200 m. (4000'). The volume of water collected in a cylindrical wire gauze, 17.8 cm. (7") high x 18.4 cm. (7.25") diameter has been measured on a monthly basis for two years. Monthly deposits averaged approximately 10 ml. at 900 m., 600 ml. at 1110 m., and 6000 ml. at 1200 m. Deposits were strongly correlated with season of year and with rainfall.

(2) Run-off plots have been constructed up to 390 sq. metres in area. Small plots 20 sq. metres in area have not produced conclusive results, but a large plot at Lake Augusta has established a tentative conversion ratio from fog gauge to run-off which can be attributed to small diameter fog droplets of 1 : 1 under conditions of equal exposure. It has not been possible to directly extrapolate this data to a complete catchment because of differences in exposure, vegetation type and altitude, but even if vegetation was 1/10 as efficient over

large areas as the fog gauges, then the run-off attributable to fog, mist and cloud at 1100 m (Lake Augusta) would average 2.5 cm per year, and at 1200 m (Pine Lake) 18 cm per year.

Introduction: Precipitation may reach the ground in a variety of forms, each of which is influenced to a marked degree by the vegetation it has to pass through. The nett effect of projecting foliage, may be an increase, or a decrease, in water reaching the ground, depending mainly on altitude, vegetation type, and precipitation form, all of which are inter-related. In high altitudes, including much of the Central Plateau of Tasmania, the precipitation is mostly in forms that are strongly influenced by projecting foliage. This is not so at lower altitudes.

Following is a brief literature review, giving a general understanding, of the role of alpine vegetation, in intercepting water.

1. The effect of vegetation on rainfall reaching the ground:

Since some falling rainfall is retained in any vegetation canopy, the balance between evaporation from wet foliage (both during and after rain storms) and the saving in transpiration loss (which is at least reduced during the period when leaves are wet) is critical to an understanding of the nett interception.

The amount of water intercepted is generally expressed as a percentage of the incident rainfall, although this is clearly only a rough approximation, since the percentage varies with differing rainfall totals. Methods of measuring interception are discussed by

Reynolds & Leyton (1961), Wilm (1963), Law (1957), Delfs (1955), Brookes (1950) and Penman (1963). In most situations rainfall is measured from standard raingauges in clearings, or above the canopy, and throughfall is measured from stationary or roving raingauges, or from trays of various shapes. Stemflow is commonly measured separately. Data collected by various workers demonstrating the magnitude of intercepted water is given by Kittredge (1948), Eidman (1958), Delfs et al (1958), Pereira (1952), Stahfelt (1944), Willett (1944), Anon (1949). The percentage intercepted varies widely, even within a single species, from less than 5% to greater than 50%.

The fate of intercepted water was discussed by Stone et al (1954, 1956), Slatyer (1956b), Penman (1963) and Hewlett (1967). In general, it is accepted that evaporation of intercepted water constitutes a substantial loss, to total water yield, although transpiration is somewhat reduced. Where soil is normally depleted of available water during dry periods, interception will produce no nett loss, since evapotranspiration will deplete stored water in any case.

2. The effect of vegetation on snow reaching the ground.

Snow interception by vegetation is quantitatively much the same as for rain, (Rowe & Hendrix, 1951; Luschev & Petrovskii, 1939), but the effect of wind is much more pronounced for snow than for rain interception. Wind both alters the pattern of snowfall and alters the distribution of snow, after it has settled on the ground and on vegetation. The presence of vegetation generally results in greater depths of snow, in the vicinity of the plants, than in clearings nearby. It is not clear however, if increases in snow depth in small clearings and woodland, compared to open plains, represent a nett gain to a catchment, or whether the increase in one locality is compensated for by a decrease in an adjacent site. Projecting foliage near a catchment boundary however, certainly increases run-off by collecting snow that would otherwise leave the catchment.

Snow melt under trees and near snow fences is slower than more open areas, because of the increased snow depth, and because of the sheltered position of the snow. This has desirable effects on rate and timing of run-off (Costin et al 1961, Martinelli 1967, Moliconov 1953).

3. The effect of vegetation on interception of liquid coated droplets of diameter 20 - 50 microns.

Small diameter droplets of size 20 - 50 μ predominate in fog, mist and cloud (Houghton & Radford 1938, Eldridge 1966). The movement of those droplets, is almost completely determined by air currents, since they fall extremely slowly, even in a horizontal laminar air stream of low speed (Nagel, 1956). The presence of vegetation projecting into the atmosphere can cause these droplets to coalesce under foggy conditions until the large drops resulting reach sufficient weight to overcome the surface tension of leaves and twigs, and they fall to the ground.

<u>Historical Description</u>: Marloth (1904) was probably the first to report the potential importance of small diameter water droplets. He obtained an increase in catch when some grass was inserted in a raingauge during cloudy conditions when a nearby standard rain-gauge recorded nothing. Dieckmann (1931) attached gauge cylinder

on top of a raingauge and collected appreciable quantities of fog. Grunow (1952) standardised a fog gauge after the principle of a dust collector. The height (20cm) was twice the diameter and the vertical cross - sectional area (200 sq.cm) was equal to the catching area of the raingauge to which it was attached. The wires had a diameter of 0.25 mm and mesh width was 1.5 mm. It thereby became convenient for Grunow to measure fog as the difference in catch between a standard raingauge, and one with a gauze attached, with area in any direction equal to that of the raingauge.

In Australia, fog has been measured with gauze with similar dimensions to that of Grunow, by Twomey (1957) and Ellis (1968) and Jackson (Unpublished).

Standard meteorological methods of determining small diameter droplets include impaction of droplets on slides impregnated with oil, magnesium or carbon (Houghton and Radford, 1938), Spectral transmission through fog with the oil of Mie transmission theory (Eldridge 1966), and passage of fog through a series of screens.

<u>Gauge Efficiency:</u> The efficiency of the Grunow type gauge was examined by Nagel (1956). He showed that 29% of the surface was covered with wires and 71% free for passage of air when flat and normal to the wind. Because of the circular design less particles could pass through near the periphery. The calculated average showed that approximately 16% of cloud particles could pass through the gauze. Efficiency was reduced by eddies at the gauze

when wind speed exceeded approximately 10 m/h, and by water drops forming on the gauze, mainly on the windward side, by coalescence with newly arriving droplets. Nagel estimated that less than 10% of the cloud droplets that were blown against the fog-catcher could pass through it. Larger gauze enabled more particles to pass through, and smaller mesh size resulted in more deflection off the sides of the cylinder. The effective collecting area then was less than the rain-gauge, and Nagel expected that about 25% deficiency would occur in a wind speed of 4 m/h increasing for higher speeds.

For the Grunow type gauge, water would enter at an angle of up to 8° from vertical before altering the catch (from geometrical theoretical considerations). For rain entering at a greater angle though, and for some other gauge types where the gauze is more the periphery of the raingauge beneath it, rain should increase the catch. Nagel's 1956 paper included a graph representing the angle of fall of water droplets in a horizontal laminar air flow. This indicated that in a 30 m/hr wind, common in highland areas, raindrops of 1 mm diameter would fall at an angle from the vertical of 70°, and drops of lesser diameter at a greater angle. For a gauze projecting into an air stream flowing at high velocity when rain was falling, then, the catch should be significantly increased. Grunow (1952) however, found that in the absence of fog, the raingauge with the gauze collected about the same amount of rain as the standard raingauge over a period of approximately one year, though single comparisons showed appreciable differences. Nagel considered it necessary to eliminate catches from measuring periods when rain was present, since the conditions for Grunow's experiment could not universally exist.

The effect of snow on the Grunow type gauge was considerable. Grunow (1958) found experimentally that in the absence of fog, a gauge filled with a gauze caught 30% more snow than an ordinary raingauge. He subtracted this amount when snow was falling, to arrive at an estimate of the fog deposits. The efficiency of any gauge in collecting snow, however, must be expected to vary with the condition of the snow and with wind speed, so that Australian conditions may vary widely from this amount. Snow on the gauze closes the mesh and alters the aerodynamical behaviour of the air stream around the mesh. Climatic conditions under which snow is deposited are also frequently associated with undercooled cloud droplets which are deposited as rime when they strike any projecting object. Rime is a granular deposit which builds into the wind, varying in compactness from soft to hard and ranging in density from 0.2 - 0.6 g/cm^3 (Gary 1972). Grunow suggested that rime deposits be removed for uniformities sake at the time of the daily rainfall observations, although this is clearly impossible where isolated recording stations occur, so that rime and snow accumulations are often measured as fog.

Magnitude of Deposits: Spectacular quantities of water have frequently been reported as due to small diameter water droplets. Grunow (1958) undertook extensive fog drip measurements at different places and heights in Germany. He found catch dependance upon height, proximity to sea, inclination of surface, and season. Input varied from nothing to 70% above raingauge catch.

Nagel (1956) on Table Mt., South Africa, performed experiments on the "table-cloth" cloud enveloping the area for over half the year. He calculated that a theoretical maximum of 47 mm per hour could be expected at 1 g/m^3 fog density and 13 m/s wind speed. After eliminating rain periods, he caught 3.75 mm/hr, equivalent to over 10 m per year.

Kohler (1923, 1937) installed fog gauges on mountains in Norway and found that a 100% increase over raingauge precipitation was common.

The above examples are representative of many other experiments conducted with cylindrical gauze similar to the Grunow gauge.

The role of vegetation in intercepting fog has been investigated by a number of workers, and a variety of terminology has sprung up to describe the water collected from mist, rime and fog. The most common terms are occult precipitation, impingement precipitation, and horizontal precipitation. The following table is a summary of available data documenting the increase in water reaching the ground compared to rainfall.

Author	Increase at Edge of Forest	Increase Inside Forest	Location
Linke (1921)	50	25	
Aubreville (1948)	12		Belgian Congo
Isaac (1946)	25		
Ceballos & Ortuno (1946)		200	Canary Islands
Grunow (1955)	50	20	Germany
Brookes (1950)		16	Victoria

Hori (1953) measured 1 mm/hr at the edge of a forest exposed to a Japanese sea fog in the absence of rain, which compared with 0.3 mm/hr some distance inside the forest.

Overlander (1956) in the Oregon fog belt, recorded between 2" and 59" during one measuring period, although his sampling technique was inadequate to determine a valid estimate.

Kittredge (1954) measured fog drip of 0.1 mm per day at Berkeley, California.

In general it is not possible to extrapolate from overseas work to local conditions, nor from a small plot to a complete catchment. The amount of variability even within a single catchment, and the difficulties in interpreting edge effects, mean that extreme care must be taken in extrapolating results.

Rime: When air temperatures are below zero, and suitable initiation nuclei are absent, fog droplets do not freeze and may reach up to -40°C before ice is formed. Under these conditions, the particles immediately freeze upon striking any projecting object. Rime deposits result which grow on the windward side of tree foliage, fence wires and buildings.

Measuring devices for rime are difficult to standardise because as the surface area of the measuring device increases, the deposit per unit area decreases. Measuring devices usually record less then, as the deposits increase in thickness (Albrecht 1931, Gary 1972). Rime deposits also depend on the material on which the ice is deposited.

Meteorological instruments used to measure rime are usually based on a vertical plate mounting. (Tolskii, 1926; Rink, 1933). Kohler

(1923) used copper spheres of 10 and 20 mm diameter.

The magnitude of deposits on mountain tops may be measured by weighing plant material after formation of rime and again following melting, or by measuring throughfall after the deposits have melted. Since rime is commonly associated with snow the latter method is frequently impractical. Large deposits on mountain tops have been observed by Rink (1933), Kohler (1937), Pagleuca (1937, 38) and Gary (1972).

Large Cloud Particles: When clouds are deep, water droplets exist in sizes ranging from less than 20 microns in diameter to over 500 microns diameter. A 200 micron diameter droplet will fall at approximately 70° from vertical in a 10 mph wind and 80° in a 30 mph wind, whereas a 50 micron diameter droplet falls at approximately 85 - 90° in all winds with laminar air flow (Nagle 1956).

The efficiency of collection of water droplets intermediate in size between fog and rain, in gauges primarily designed to measure fog droplets, is unknown. It is probable that much of the water collected in so called fog gauges is attributable to these particles.

Methodology: In order to determine the gain over a complete catchment in precipitation from a combination of cloud, rime and snow there are two obvious alternative procedures. The first is to measure the physical magnitude of each precipitation form with scientific instruments and relate this to the input from projecting foliage, and the second is to measure the effect of vegetation directly by collecting water that drips through the foliage to the ground. The former method offers the potential advantages of precision in measuring each of the component precipitation forms, assuming reliable instruments are available, whereas the extrapolation to water collected by vegetation will be difficult to substantiate. The latter method requires runoff plots over a representative sample of the catchment cover. The difficulties inherent in each method are briefly presented below:

As mentioned earlier, scientific instruments for measuring each of the specific components of water reaching the ground are unsatisfactory. At best the instruments sample the form of water that actually reaches them so that the interpretation of what is collected is not simple as with rainfall, but assumes meaning only when qualified for exposure, wind speed and other microclimatic factors. For example, rime deposits are determined to a spectacular degree by the nature and size of the collecting device (Gary, 1972). The total quantity of water in the air can only be qualified by a product of concentration of droplets and travel distance in a given time, but even this depends largely on exposure, as expressed through wind speed. Further, since movement is predominantly horizontal, any intercepting surface depletes the air downwind from the surface of potential deposits until that space is replenished by turbulent air movement. This edge effect is so important in interpreting the magnitude of deposits that it is surprising that the traditional philosophy of comparing raingauge recordings with those in a raingauge with a gauze cylinder mounted above it, still persists. Even though the gauze may have a surface area, facing any horizontal direction, equal to the collecting area (facing vertically) of a raingauge, the gauze does not indicate anything at all about the magnitude of wind dependant water droplets that could be expected to fall over an equivalent horizontal area of ground. When rain falls during strong winds, the raingauge with gauze cylinder above it may give an increase or a decrease in measured input compared with a nearby standard raingauge, depending on the angle of fall of the raindrops and the quantity of water drops that are blown off the gauze before falling into the underlying container. This will happen even in the absence of fog or mist, and is primarily a function of wind speed, which again depends on altitude and exposure. Thus it is meaningless to assume that in an altitudinal survey of fog, the errors associated with rain falling at an angle will be constant in all sites.

By the same argument, the catch below a solitary bush cannot be expected to give much indication of the magnitude over a large area. When rain is falling at the same time as cloud is being intercepted, or when snow is falling at the same time as rime is being intercepted, then the measurement beneath individual bushes is especially misleading because of the increase in rain (snow) collected by the foliage for purely geometrical reasons.

When measuring input from vegetation projecting into the environment, the obvious method is to collect throughfall with some type of contair as is practiced to determine the interception from rain drops. If this is to be conducted during periods when rain or snow are also falling (probably most of the time) then a suitable distance away from the bushes also needs to be sampled to determine the edge effect of incoming rain falling non vertically, and to allow for changing wind directions.

Alternatively, a homogeneous vegetation cover needs to be present both inside and outside the sampled area, so that a decrease in water collected by foliage on the downwind side will compensate an increase on the windward side during rain storms associated with strong winds.

Experimental Procedure: The procedure adopted in an attempt to determine both the potential input from small diameter water droplets, and the actual input from projecting foliage, was based on a compromise between the two basic methods.

Instruments to sample fog, mist and rime:

In order to measure differences in potential for deposition of these particles on the Central Plateau over large areas, gauges were constructed as follows: (See Plates 13–15).

Roof: Flat, Galvanised iron, 16 gauge with turned edges, 46.5" diameter (118 cm)., 65" (165 cm) above ground level. Secured to support arms by welded bush and to gauze framework by lead washers and nuts.

Gauze: Cylindrical, Brass, mesh separation .07" (1.8 mm) wide diameter .007" (.02 cm). Supported by copper framework and funnel. Cylinder dimensions 7" (17.8 cm) diameter x 7.2" (18.3 cm) high (i.e. area = 50.7 sq. ", the same area as a standard 8" rain gauge). 0.5" at top and base of cylinder closed due to framework for attachment of mesh.

Funnel: Copper, 8.2" (20.8 cm) diameter, attached to mesh

PLATE 13. Gauge used to determine the potential input from small diameter water droplets over the Central Plateau.

PLATE 14. Water droplets on wire gauze of fog-gauge.

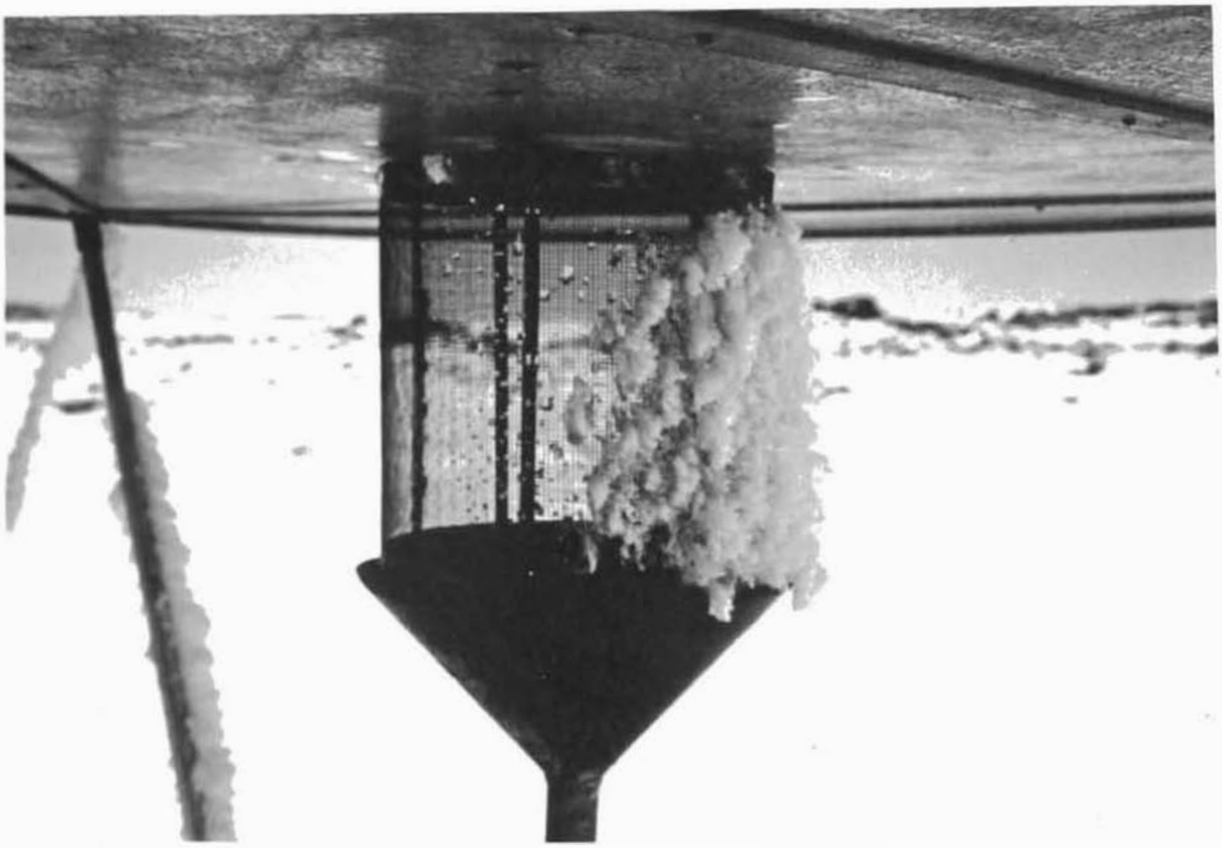

PLATE 15. Rime deposits on wire gauze of fog-gauge.

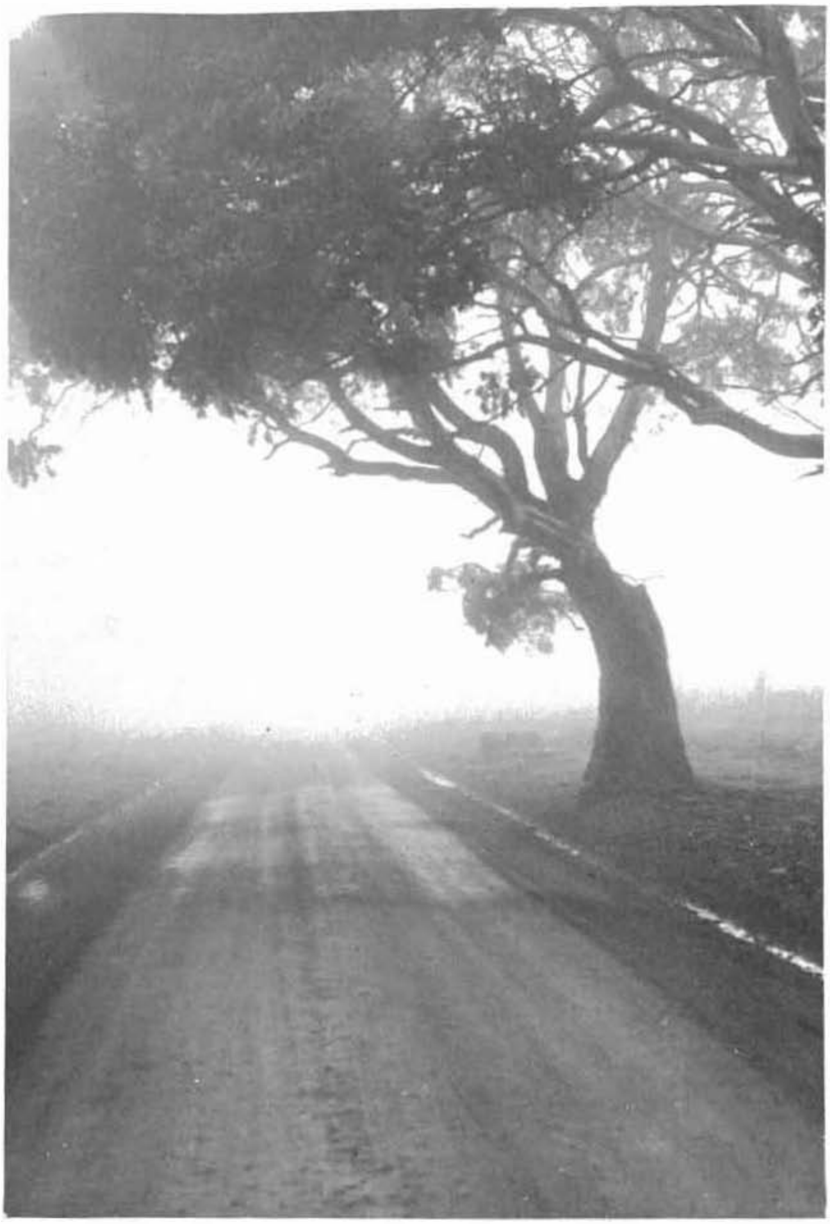

PLATE 16. Wet road beneath tree in heavy mist. Lake Highway south of Miena.

framework by adjustable thread so that top of funnel is level with base of mesh.

Support Arms: 0.6" diameter galvanised tubing, with flange at base, length 84 cm (33"). Attached to roof by screw thread and to 44 gallon container by sliding over 0.4" diameter steel rod welded to drum.

Water Collection: Plastic tubing leading from funnel, through steel tubing to either 22 l (5 gallon) or 9 l (2 gallon) plastic containers inside protective 200 l (44 gallon) drum.

Protective container: 200 l (44 gallon) steel cylinder, 58 cm (23") diameter x 86 cm (34") high. Hinged door with lock welded on one side.

Support: Galvanised wire stays, 13 gauge, attached from the top and base of support arms to steel rods driven into ground.

Gauge Rationale: In order to measure deposits and safely attribute them to small diameter water droplets that are dependent on wind movements, it is necessary to exclude rain altogether, since, as pointed out previously, its presence can lead to an increase or a decrease in water dropping off a gauze cylinder, depending on wind speed. A horizontal roof was chosen so that interference with air flow through and around the gauge would be minimal, and so that water falling on the roof during strong winds would blow off the leeward edge, away from the gauze.

The gauze cylinder used was installed with the top 6 mm. from the roof, so that only a 6 mm. air gap was present. It is apparent that the roof must interfere with the air flow near the top of the gauze more than near the base. Turbulent flow of air is produced from the legs, the roof, and the 200 l. steel container which houses the collected water, as well as from the gauze itself. Near the centre of the gauze, where the mesh is normal to the wind, the area occupied by mesh wire facing the direction of wind movement, is less than near the perimeter. The gauze is then, for the purpose of measuring input of small diameter water droplets, non uniform both horizontally and vertically. It is not an instrument designed to measure the absolute maximum potential from wind dependant precipitation, but rather to indicate relative changes from site differences.

The efficiency of the gauge is expected to differ according to the size and nature of the precipitation forms. For instance, rime quickly closes the mesh so that all air is deflected around the edge and efficiency of collection is less than it would be if the meshes were more widely separated. Small cloud droplets coalesce on the gauze, forming large drops that close the mesh at that position until the weight of water in a droplet is sufficient to overcome surface tension of the mesh, and the drop runs down the gauze to the funnel, collecting other drops as it falls. During cloudy conditions then, part of the gauze is closed with drops (See Plate 14) and part is closed because of wires. The proportion that is closed with drops varies with the surface tension of mesh material, with the size of the water droplets comprising the fog, and with the wind speed. Strong winds blow drops from the gauze which are largely collected by the funnel when blown from the leading edge, but are lost when blown from the trailing side. Efficiency of collection of liquid droplets would presumably be increased by reducing the mesh separation during strong winds and by increasing it during still conditions and when the particle size in the cloud was large. The efficiency of catch of liquid droplets, then, depends on the wind speed and particle size, so that it varies from day to day, and the gauges constructed represent a compromise for average conditions. It is important to bear in mind that the water collected by the gauges should be looked at in a relative sense only, and that the relationship with water caught by projecting vegetation may vary widely.

The assumptions inherent in comparisons between gauge readings at different sites are that:

(a) The efficiency of collection of all forms of wind dependant precipitation - fog, rime and all droplet sizes between approximately 20 and 200 μ diameter - are of the same order of magnitude, or else the proportion of all precipitation forms at different sites is the same.

(b) Efficiency of collection is in the same order of magnitude over a wide range of wind speeds or else wind speeds are the same at all sites.

Although these assumptions have not been quantitatively verified, a number of subjective observations have shown them to be broadly justified for a difference of an order of magnitude.

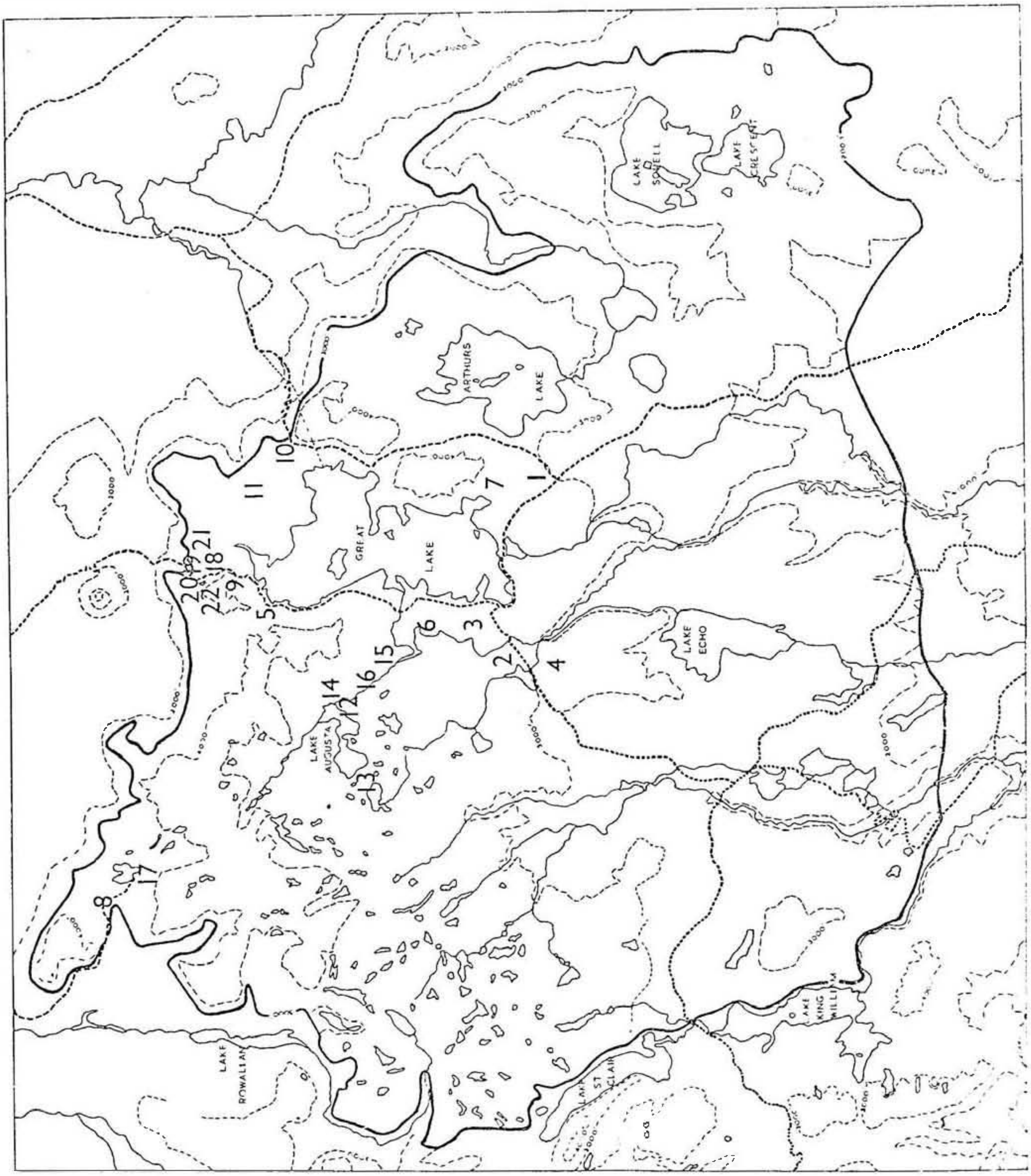

Fig. 2. Fog Gauge installation sites numbered according to altitude (See Page 51).

Sites of Gauge Installation: Gauges have been installed at the sites indicated in Fig. 2. Altitude varied from 900m - 1200m. At Pine Lake (1200m), five gauges were set up within 1000m of each other to demonstrate differences due to microclimate (primarily exposure). One gauge had the gauze removed to act as a control to determine the input from rain and snow that was independent of the gauze cylinder.

Measurement: The volume of water collected by each gauge was measured each month for most gauges. In isolated localities such as Lake Mackenzie and Westons Creek, measurement was less frequent, varying from 1 month to 6 months, according to convenience. Readings not taken at the end of each month were converted to a monthly estimate by assuming a constant daily catch between readings. Individual monthly totals given in the results may therefore not be strictly correct, although they will be when averaged over a number of months. In all cases, gauges have been read within three days of each other for any single month and for any block of gauges being measured for that month. Readings are at all times comparable, therefore. No evaporation retardant for water within containers was used since space between the container opening and the inlet tube was small and little potential existed for evaporation, even in the warmest months. Measurement during days when water within containers was frozen was determined by depth of ice which was removed at a later date after thawing. Slight inaccuracies of measurement due to inaccurate depth calibration with volume may have occurred in these instances. Usually, however, measurement periods were selected when water would be in the liquid form.

Run-off Plots to Measure Input from Fog, Rime and Cloud:

In order to examine water collected by foliage from wind dependent precipitation forms, and its comparability with the physical gauges installed, a number of run-off plots were installed as follows:

1. 56 sq. metre run-off plots:

Location: Lake Augusta (1125m) and Pine Lake (1200m).

Dimensions: 7.5m x 7.5m (25' x 25').

Recording Mechanism: Tipping Bucket Gauge (See Appendix I) with bucket volume 1.2 litres. Counting via Hengstler 500 Electronic, battery operated, 6 digit counter.

Control: Bare plot of equal dimensions.

Construction: Plots were covered with block polyethylene sheeting, .006" gauge attached to 7.6 x 2.5cm (3" x 1") timber around the edge. Sites were selected so that water would drain to one corner where the recorder inlet was positioned. Three bushes of Orites acicularis were uprooted and stacked to the centre of one plot at each site as shown in plate 17.

Measurement: Measurement was undetaken approximately each month.

PLATE 17. Small run-off plot at Lake Augusta.

PLATE 18. Large run-off plot at Pine Lake.

PLATE 19.   Large run-off plot at Lake Augusta.

2. 490 sq. metre run-off plot:

Location:	Pine Lake
Dimensions:	29.7m x 16.5m (90' x 50').
Recording Mechanism:	Tipping Bucket gauge with bucket volume 12 litr (See Appendix I), equivalent to .025 mm (.001") depth over the plot. Recording via pen recorde and 2 week chart.
Control:	Pluviograph and Roofed small diameter precipita gauge with identical pen recorders.
Construction:	Plot covered with block polyethylene sheeting consisting of 2, 9. m.(30') sheets welded together by heat sealing and attached to timber round the edge as with the smaller 56 sq.m. plots. Site selected for absence of projecting rocks and slope draining to one corner. Site prepared for plastic by removing sticks, stones and protuding bushes, and by digging drainage channels where fall was considered insufficient. 10 gauge wire framework constructed in a grid for attachment of bushes as shown in plate 18 Artificial forest of <u>Eucalyptus coccifera</u> branch cut down and 4 thicknesses of household carpet nailed to the base to prevent tearing of plastic. Branches stood on plastic and tied to framework, leaving 6 metres round the perimeter of the plot bare.
Operation:	This experiment failed due to a combination of factors after approximately one month of recordi

3. 392 sq. metre run-off plot:

Location: Lake Augusta

Dimensions: 19.8 metres square (60' x 60').

Recording Mechanism: Tipping-bucket gauge with tipping volume 12 l, equivalent to .031 mm depth (.0012") over the plot. Recording via pen recorder and 2 week time chart.

Control: Pluviograph, 5 raingauges and Roofed fog gauge with similar recorder to pluviograph.

Construction: Plot was selected in an area of continuous dolerite rock covering several hectares that had been exposed during H.E.C. operations on the Lake Augusta dam. Walls of concrete, 8 cm. in height, were constructed to define the plot and drainage was via 13 metres of 7.6 cm. diameter (3") plastic pipe, to the recording tipping bucket gauge. Holes in the dolerite were drilled with a pneumatic rock drill, on a grid of 2 metres x 2 metres, approximately 10 cm. deep. Steel posts with 1" reinforcing steel welded to the end were inserted in the holes to act as support for the artificial forest of Eucalyptus coccifera branches which was tied to the posts. (See plate 19). Polystyrene foam insulation, 2 cm. thick was glued to the recording gauge and a kerosene heater installed beneath the gauge to prevent

Construction: (Contd.) freezing of water within the buckets.

Operation: Construction was completed in April 1973 and operation continued under October 1973.

Rationale Behind Run-Off Plots:

Most Tasmanian alpine species are multistemmed, with branches arising near or below ground level. It is not possible to measure throughfall by using numbers of containers similar to those used in throughfall studies of trees because of this multiple branching and the many drip points that concentrate throughfall near the centre of the bushes, so that very large containers would be necessary even to cope with drip from a single rainstorm. Since it was necessary to leave plots unattended for weeks at a time, it was also necessary to eliminate edge effects from rain, which meant that large areas had to be sampled with consequent large volumes of water.

After some trial and error, large tipping bucket gauges were designed and built to measure discharge from plots described above. This enabled large areas to be sampled without the necessity of using large numbers of individual containers. The theory, construction and operation of these gauges is discussed in Appendix II.

A preliminary attempt to seal the base of a bush of Orites acicularis (the main shrub at most alpine sites) with concrete did not prove successful, primarily because of the difficulty of sealing all the stems arising from beneath the ground. It was consequently decided to uproot bushes used in the trials, and to set them on top of the plastic used as an impervious ground cover. *Orites acicularis* leaves are needle shaped and extremely xeromorphic, with the result that leaves change colour and shape very little even after long periods of detachment from a root system, especially in winter months when rains are an almost daily occurance. The same is true to a lesser extent with the eucalypts, which retain their leaf shape and colour right through the winter when branches are cut from a tree. Although considered undesirat the practice of detachment of branches from their roots enabled simulate natural conditions for as long as 6 months without undue loss of leaves, and without the complication of transpirational loss that would have resulted from using living bushes in pots. Direct uptake of water by leaves was considered negligible for all trials.

Polythene sheeting used to ensure complete impermeability of the ground was of .006 gauge and 9 m. (30') wide. This proved satisfactory in the smaller 56 sq. metre plots, but was plagued by troubles in the large plot (490 sq. metres) at Pine Lake. This was partly caused by the lateness of installation of the plot (October 1972) and dry weather in spring dried up several pools of water holding down the polythene and wind was able to move the plastic up and down with a flapping motion. A second difficulty was caused by tearing of the plastic in a few strategic positions where water drained to the recording gauge. Repairing tape recommended by the manufacturers of the polythene proved unsatisfactory in the extreme conditions of the site and makeshift measures were only beginning to work when vandals tore the plastic into an irreparable state. The result of this important trial at Pine Lake was only approximately 1 month's record during which time nothing of any significance could be detected from the charts comparing run-off, rainfall, and small diameter particles in the roofed gauge.

In early 1973 it was decided to transfer this trial to Lake Augusta where a large slab of dolerite rock had been exposed by H.E.C. operation This rock was at a convenient slope of approximately 3% and covered over 2 hectares in area. Although the mist gauges had revealed that this site had much less potential for collecting wind dependant precipitation forms than Pine Lake, the site was so ideal from other points of view, notably the completely impervious surface and location off the main road away from most potential vandals, that the advantages were considered to outweigh the disadvantages.

Results: Monthly fog deposits are presented in Tables 5 to 9. Gauges in isolated sites that were measured less frequently than every two months have been calibrated against a reference station in order to obtain an estimate of the time distribution of collected water. Such cases have the monthly estimate marked with an E. The reference stations are as follows:

Gauge Station	Reference Station
Westons Creek	Above Brcona
Microwave Station	Liawenee Plains
Todds Corner	Liawenee Plains
Lake Mackenzie East	Lake Augusta East
Lake Mackenzie West	Lake Augusta East

An E is also marked against estimates for individual records for short periods when either a gauge was damaged or the container had been stolen. In these cases the estimate is based on the nearest intact gauge.

The gauge at Lake Augusta West was irreparably damaged by vandals in March 1972 and was not replaced. The Dud Bay gauge was removed in July 1972 for a different experiment. Gauges at Lake Mackenzie have not been read since September 1972.

Figs. 3 - 9 present a summary of fog deposits, with graphs of the effect of altidude, time, and rainfall. Fig.3 depicts the variation in fog deposits with time for a representative selection of stations (Pine Lake East, Pine Lake south, Liawenee Plains, Poatina turnoff).

TABLE 5. Monthly Fog Deposits, 1971 (ml).

Gauge Station	Alt.(ft)	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Poatina Turnoff	3000		30	25	0	0	0	0
Skittleball Plains	3300				265	265	450	20
Dud Bay	3500		126	50	10	0	160	0
Monpeelyata Canal	3500				385	390	387	16
Pine Creek	3500						700	244
Liawenee Plains	3550	435	662	130	490	500	260	80
Todds Corner	3550			25	10^E	10^E	10^E	0^E
L. Mackenzie, West	3700		2000^E	300^E	1000^E	1000^E	1000^E	400^E
Above Breona	740			880	790	840	1200	769
Microwave Aerial	3740			60	140	145	60	40
Westons Creek	3740			730	780	890	1275	971
L. Augusta, East	3750	700	1900	310	1030	1110	920	330
L. Augusta, West	3750	1205	2221	530	950	980	1750	493
" " Sheltered	3750				100	100	155	30
Above Liawenee (1)	3750	940	2100	390	1150	1200	1100	150
" " (2)	3750				635	648	780	264
L. Mackenzie, East	3800		1600^E	240^E	800^E	800^E	800^E	320^E
Pine Lake South							1770	1548
Pine Lake, Sheltered	4000			1500	1710	1820	1390	1530
" " Canal	4,000			5550	5700	6010	4600	4946
" " East	4025	10100	9810	5790	5600	6030	7770	7665
" " West	4050	4520	9000^E	4200	7400	6100	3700	6800

E = Estimated Value - See P. 50

TABLE 6. Monthly Fog Deposit - 1972 (January - June).

Gauge Station	Jan.	Feb.	Mar.	Apr.	May	June
Poatina Turnoff	0	0	0	0	5	15
Skittleball Plains	0	0	0	20	40	390
Dud Bay	0	0	0	10	30	50
Monpeelyata Canal	24	5	29	28	29	310
Pine Creek	30	30	90	97	100	6[illegible]9
Liawenee Plains	0	0	22	21	22	585
Todds Corner	50[E]	12[E]	20[E]	19[E]	20[E]	400[E]
L. Mackenzie West	160[E]	200[E]	200[E]	200[E]	200[E]	500[E]
Above Breona	219	178	166	436	450	1913
Microwave Aerial	55	12	28	27	28	550[E]
Westons Creek	1276	741	585	314	325	520
L. Augusta, East	176	171	170	219	226	547
" " West	517	350				
" " Sheltered	0	0	10	20	21	70
Above Liawenee (1)	0	0	45	43	45	1094
" " (2)	151	86	66	162	168	1094
L. Mackenzie, East	90[E]	120[E]	120[E]	180[E]	180[E]	450[E]
Pine Lake South	504	519	533	760	786	2187
Pine Lake, Sheltered	500[E]	553	554	892	921	1913
" " Canal	2261	2196	2177	2818	2911	4921
" " East	4042	3558	3417	4379	4524	5468
" " West	1854	1579	1498	2007	2074	4374

TABLE 7. Monthly fog deposit July - December, 1972.

Gauge Station	July	Aug.	Sept.	Oct.	Nov.	Dec.
Poatina Turnoff	40	30	10	10	0	0
Skittleball Plains	642	793	200	0	120	90
Dud Bay						
Monneelyata Canal	650	650	230	0	80	70
Pine Creek	1051	1260	330	10	200	415
Liawenee Plains	894	960	420	20	150	180
Todds Corner	850	900	390	20	150	170
L. Mackenzie West	1300^{E}	1500^{E}	800^{E}	300^{E}		
Above Breona	936	2300	890	150	320	650
Microwave Aerial	600^{E}	1000^{E}	400^{E}	20^{E}	160^{E}	190^{E}
Westons Creek	900^{E}	2000^{E}	900^{E}	150^{E}	300^{E}	600^{E}
L. Augusta, East	1291	1450	770	340	390	235
" " West						
" " Sheltered	290	400	30	30	40	50
Above Liawenee (1)	742	1400	820	40	150	185
" " (2)	991	1475	700	50	200	310
L. Mackenzie, East	1200^{E}	1300^{E}	700^{E}	260^{E}		
Pine Lake South	2933	2675	1050	300	590	800
Pine Lake, Sheltered	4036	3800	1100	470	610	725
" " Canal	9223	10000	3400	800	2400	2170
" " East	10266	11100	3700	1100	3490	3300
" " West	8029	9000				
Pine Lake West With Gauze Removed			260	80	250	275

TABLE 8. Monthly Fog Deposit January – June, 1973.

Gauge Station	Jan.	Feb.	Mar.	Apr.	May	June
Poatina turnoff	0	0^E	0^E	0^E	10^E	20^E
Skittleball Plains	20	40	20	97	208	154
Dud Bay						
Monpeelyata Canal	40	30	20	80	140	168
Pine Creek	415	205	305	950	1127	1279
Liawenee Plains	80	75	30	20	440	568
Todds Corner	0^E	0^E	0^E	20^E	20^E	40^E
L. Mackenzie West						
Above Breona	1650	563	606	690	930^E	730^E
Microwave Aerial	90^E	80^E	35^E	25^E	470^E	580^E
Westons Creek	1600^E	560^E	600^E	700^E	800^E	900^E
L. Augusta, East	235	75	70	120	230	365
" " West						
" " Sheltered	10	20	20	40	128	146
Above Liawenee (1)	185	14	90	105	208	348
" " (2)	300	211	90	114	101	229
L. Mackenzie, East						
Pine Lake South	1600	785	644	1038	932	732
Pine Lake, Sheltered	725	1093	644	2747	3182	3522
" " Canal	2170	3825	2470	9300	10198	9548
" " East	3300	5395	3185	9700	10000^E	9500^E
" " West (No Gauze)	270	608	537	1535	1630	1033

TABLE 9. Monthly Fog Deposit July - August, 1973.

Station	July	Aug.	Mean Monthly June 71 - Aug 73.	Mean Rainfall (Approx.)
Poatina turnoff	30	20	10	33
Skittleball Plains	710	350	204	35
Dud Bay			32	35
Monpeelyata Canal	800	250	202	35
Pine Creek	1475	880	547	50
Liawenee Plains	621	690	297	36
Todds Corner	40	40	133	36
L. Mackenzie West			1150	100
Above Breona	1230	1550	840	75
Microwave Aerial	621[E]	700[E]	252	45
Westons Creek	1200[E]	1600[E]	856	50
L. Augusta East	1638	1088	595	50
" " West			973	50
" " Sheltered	350	200	94	50
Above Liawenee (1)	2840	1630	755	45
" " (2)	2780	1325	537	47
L. Mackenzie East			891	100
Pine Lake South	1600	1150	1139	80
Pine Lake Sheltered	4100	3350	1746	90
" " Canal	11350	8230	5150	90
" " East	15250	12200	7287	90
" " West			4618	90
" " West (no Gauze)	2200	2000		

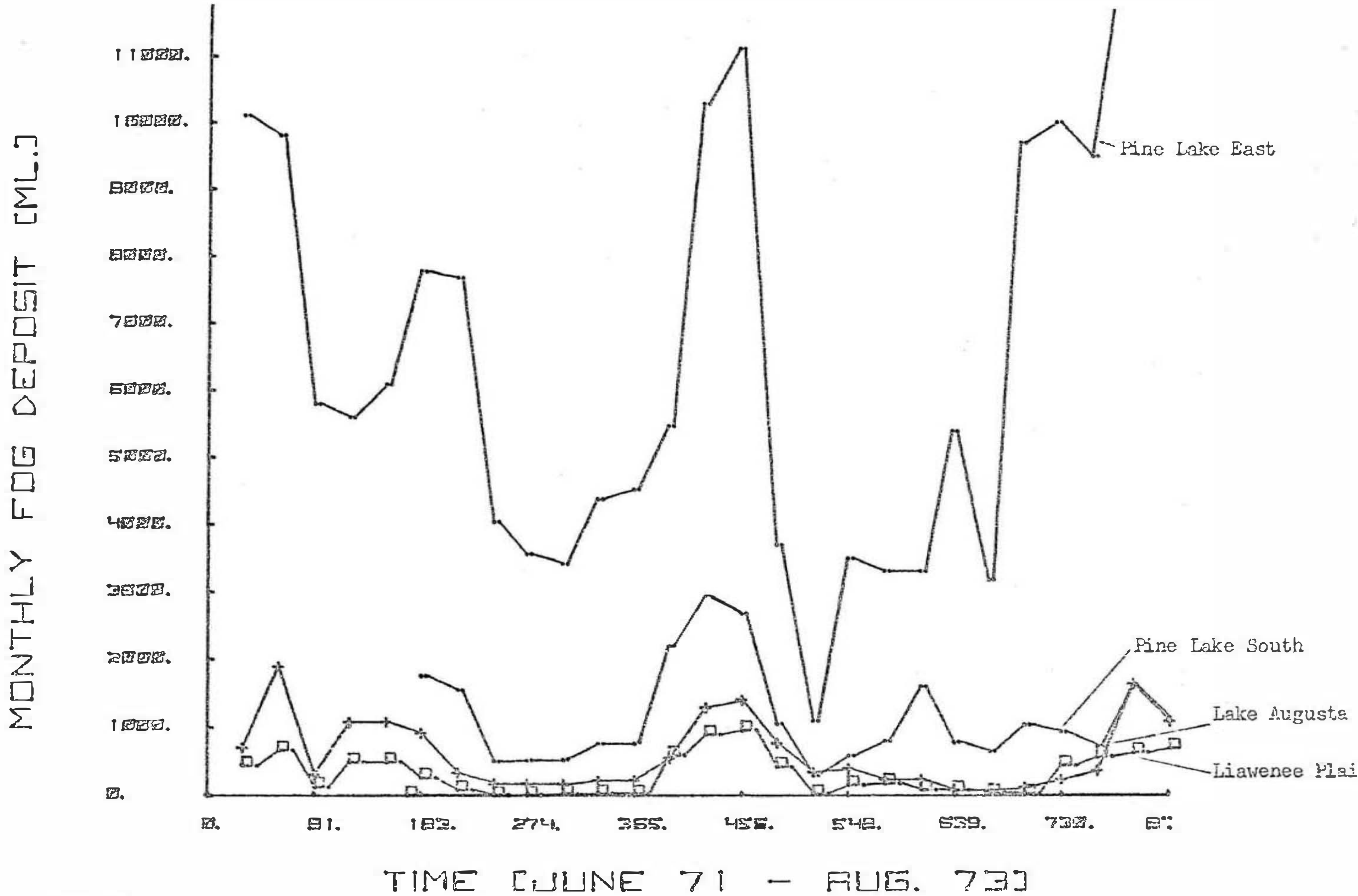

FIG. 3. Monthly fog deposits for representative Central Plateau Stations (June 71 - August 73).

FIG. 4. Mean monthly fog deposits for all gauges compared with rainfall.

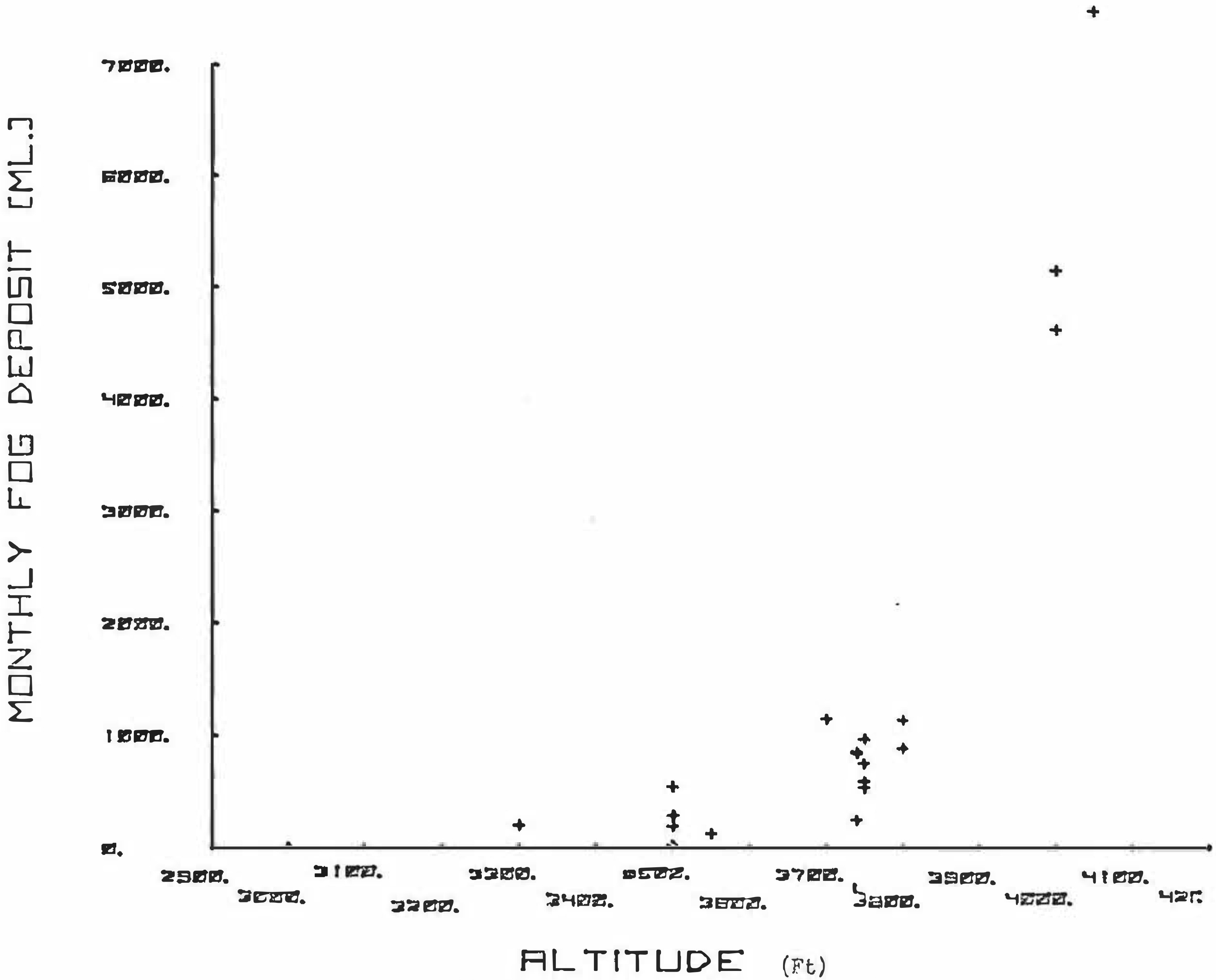

FIG.5. Mean monthly fog deposits compared with altitude.

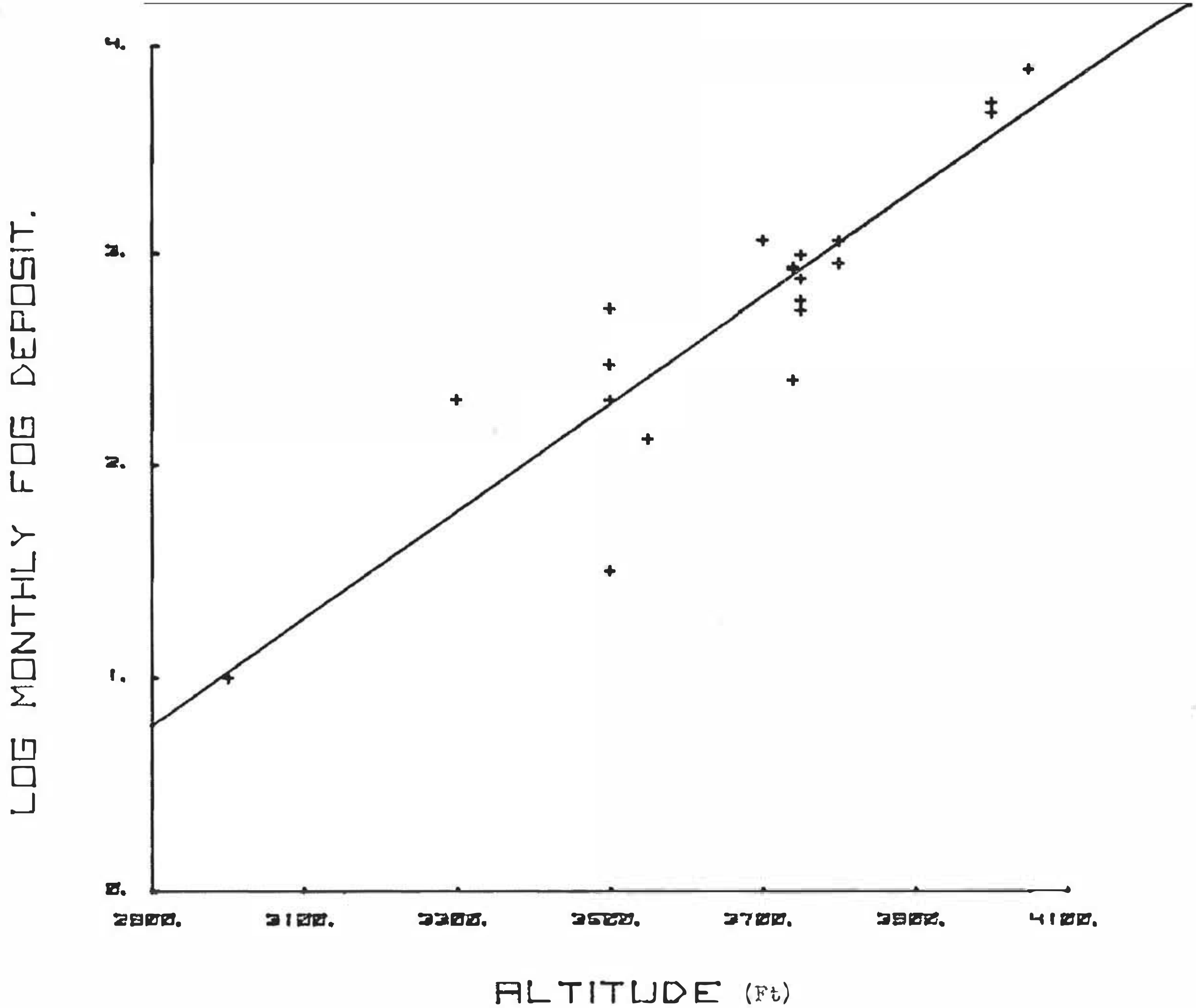

FIG. 6. Regression of log mean monthly fog deposits on altitude.

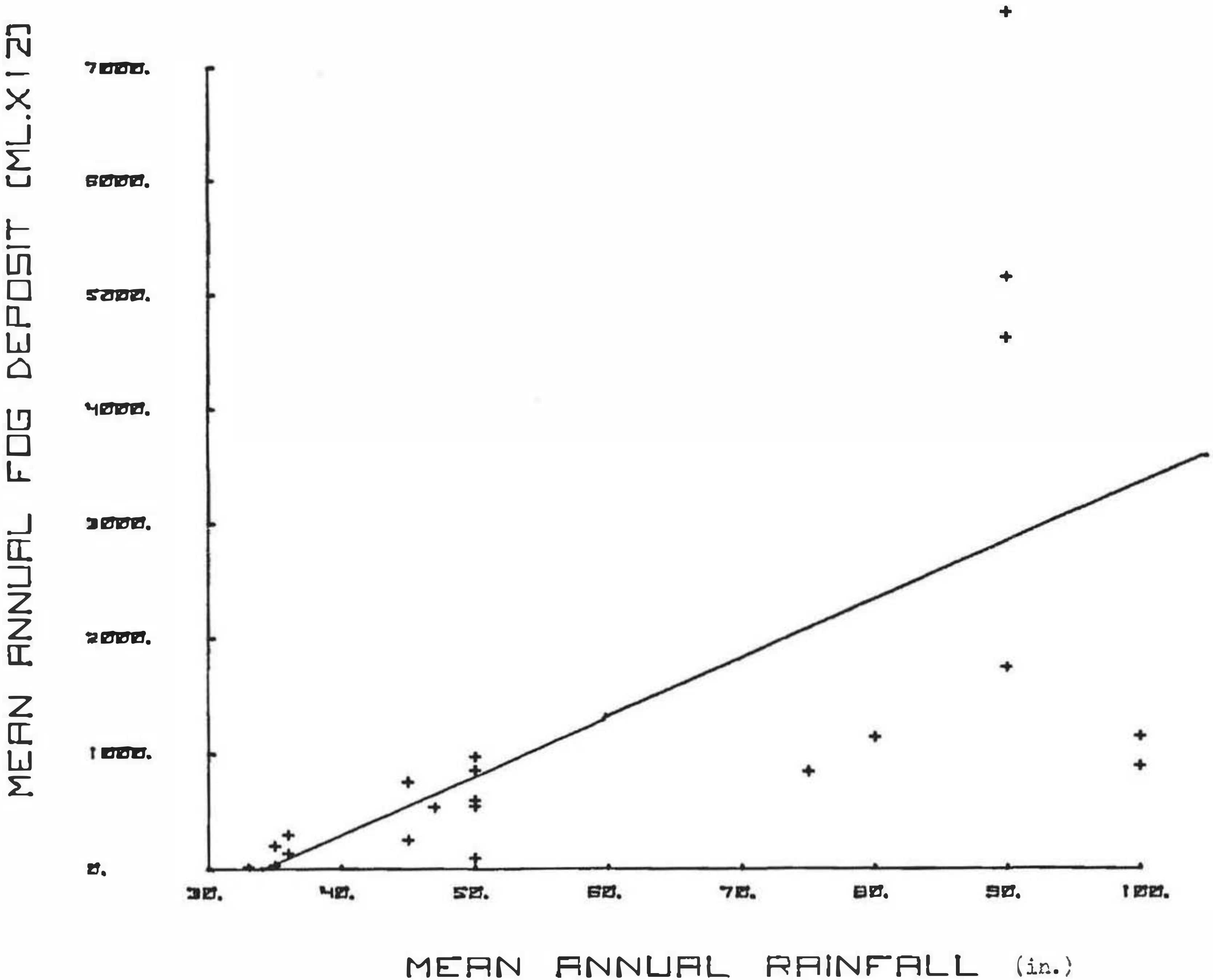

FIG. 7. Regression of mean annual fog deposits on rainfall at gauge site.

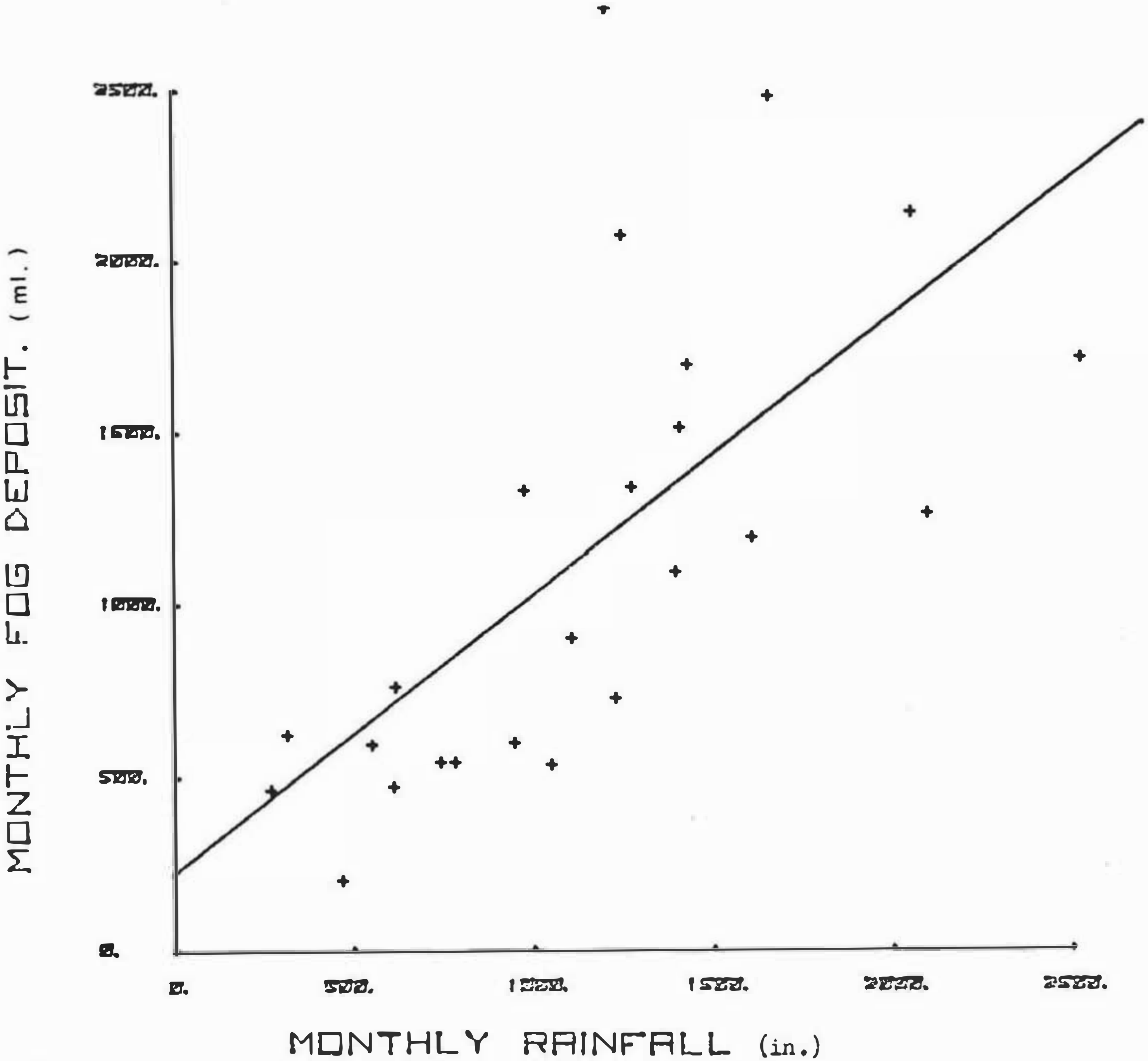

FIG. 8. Regression of mean monthly fog deposits for all gauges, on estimated mean monthly Central Plateau rainfall.

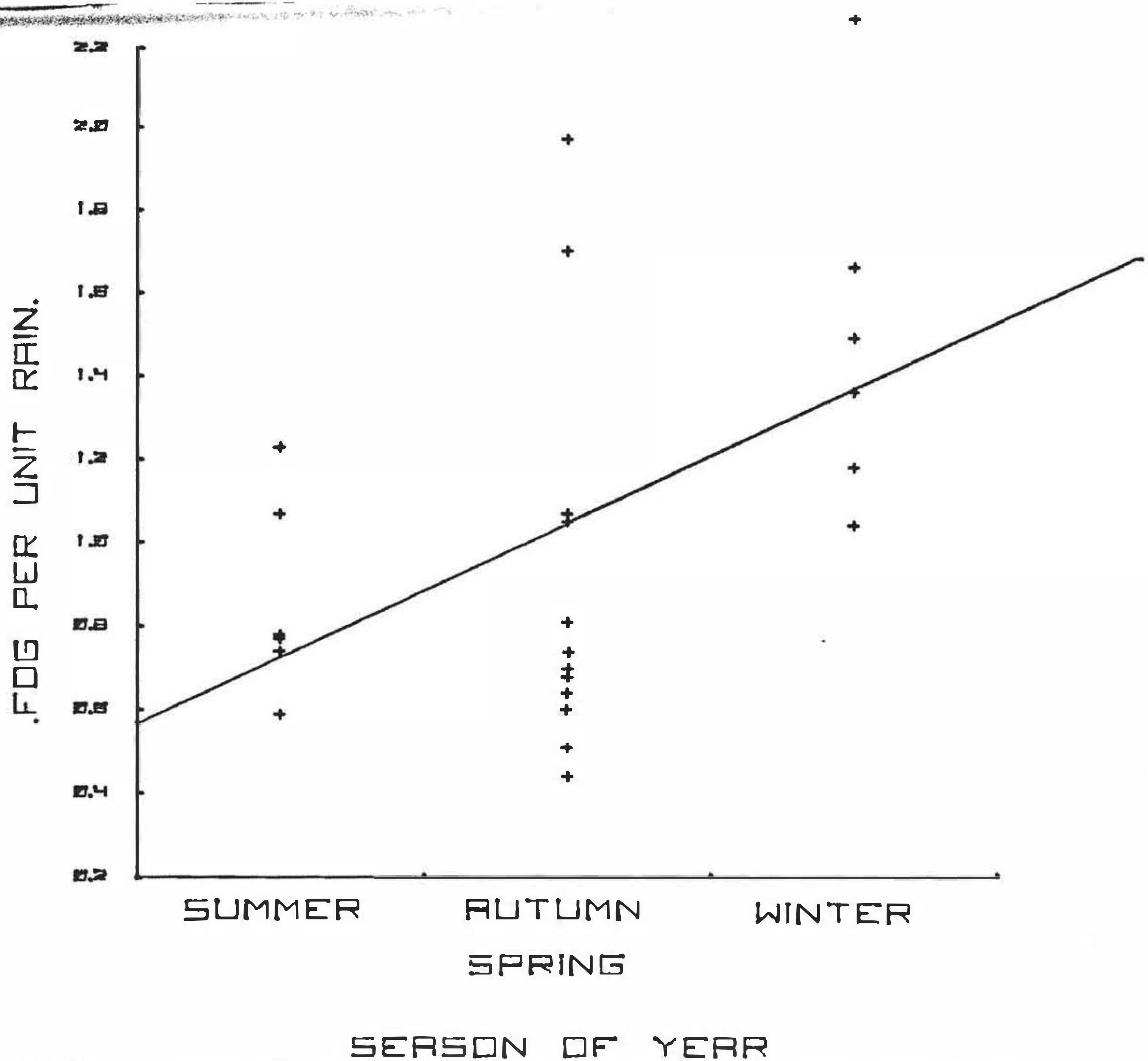

FIG. 9. Regression of the proportion of fog and rain deposits on season of year.

Table 10 presents data at Lake Augusta for comparison between run-off from a bare plot, 56 sq. m. (625 sq. ft.) in area and an identical plot with three <u>Orites acicularis</u> bushes in the centre of the plot (Plate 17).

These plots were plagued with break-downs when first installed, primarily due to failure of the tipping-bucket gauges used to measure run-off. During the course of the trial other comparisons were lost because of either battery failure, blockage of the outlet with sediment, tearing of plastic or further tipping bucket trouble. Since it was only necessary for failure in one component of one plot to invalidate a comparison between bare and forested plot, the resulting valid comparisons are not as numerous as was initially hoped for.

Table 11 presents data for similar plots at Pine Lake. The same comments apply here as for Lake Augusta.

TABLE 10. Run-off from Lake Augusta experimental plots, one bare and the other with three *Orites acicularis* bushes attached above a plastic ground cover.

Date	Run-off (inches) Bare	Run-off (inches) Bushes	% increase (of artificially vegetated plot over bare plot)
Oct. 1971	7.35	6.14	-20
Dec. 1971	0.43	0.31	-30
Dec. 1971	2.62	1.97	-20
Aug. 1972	2.26	2.15	- 5
Aug. 1972	2.89	3.27	13
Nov. 1972	1.23	1.52	24
Dec. 1972	2.12	2.12	0
Mar. 1973	1.76	1.96	11
Apr. 1973	1.70	1.40	-18
May 1973	3.28	4.02	23
June 1973	2.23	2.32	4
Total	27.87	27.18	-2

<u>TABLE 11.</u> Run-off from Pine Lake experimental plots, one bare and the other with three *Orites acicularis* bushes attached above a plastic ground cover.

Date	Run-off (inches)		% increase due to bushes
	Bare	Bushes	
Oct. 1971	1.15	.90	-22
Dec. 1971	5.54	6.96	26
Feb. 1972	6.02	6.02	0
Mar. 1972	1.03	0.99	-4
Mar. 1972	3.60	4.70	31
June 1972	4.14	4.26	3
July 1972	2.27	3.64	60
Aug. 1972	8.70	11.40	31
Total	32.45	38.87	20

TABLE 12. Hydrological data for Lake Augusta run-off plot from July - September, 1973.

Date	Plot run-off (RO). inches	Rain (R) (inches)	Fog (inches)	RO-R.	Fog / RO-R.
July 10,11,12	0.88	0.52	0.20	0.36	0.6
14,15	0.84	0.83	0.40	0.01	40.0
15,16	2.30	2.20	0.32	0.10	3.2
17	0.31	0.26	0.09	0.05	1.8
19,20,21,22	0.90	0.46 S	0.25	0.44	0.6
25,26	0.55	0.51	0.20	0.04	5.0
31	0.09	0.04	0.14	0.05	2.8
Aug. 1	0.85	0.76	0.10	0.09	0.9
1,2	0.13	0.14	0	- 0.01	0
3	0.26	0.27 S	0.13	- 0.01	0
4	0.07	0.07	0.01	0	-
5,6	2.21	1.92	0.88	0.29	- 3.0
7,8	0.24	0.26	0.08	- 0.02	- 4.0
9,10	0.04	0.04	0	0	-
11,12	0.40	0.31	0.08	0.09	0.9
18	0.09	0.05	0	0.04	0
19	0.11	0.05	0.02	0.06	0.3
20	0.04	0.04	0	0	-
Sept.19,20,21	1.35	0.79 S	0.08	0.56	0.1
26,27	0.89	0.55 S	0.14	0.34	0.4
Total A	9.15	8.00	2.52	1.15	2.19
Total B	12.55	10.07	3.12	2.48	1.26

Total A is total for periods during which snow was absent.

Total B is total for all periods, including days with snowfall.

S - signifies period which includes some snowfall.

TABLE 13. Hydrological data for 2 week periods at Lake Augusta run-off plot, July - September 1973.

Time Period	Plot run-off (RO) (inches)	Rain (R) (inches)	(RO)/(R)	Fog	RO-R	Fog/RO-R
4 - 15 July	1.72	1.35	1.27	0.80	0.37	2.16
15 - 17 July	2.30	2.20	1.05	0.32	0.10	3.20
17 - 30 July	1.77	1.02 (S)	1.74	0.60	0.75	0.80
30 July-1 Aug.	0.94	0.80	1.18	0.25	0.14	1.79
1 - 14 Aug.	3.25	2.84	1.14	1.10	0.41	2.68
15 - 27 Sept.	2.24	1.34 (S)	1.67	0.22	0.90	0.24
Total A	8.21	7.19	1.14	2.47	1.02	2.44
Total B	12.22	9.55	1.28	3.29	2.67	1.23

Total A is total for all periods during which snow was absent.

Total B is total for all periods, including periods with snowfall.

S - signifies period which included some snowfall.

Discussion:

1. Mist Gauges: Although these gauges have obvious drawbacks as precise instruments for measuring all small diameter droplets, they have provided a useful guide to the potential input of fog, mist and rime to high altitude sites by virtue of projecting foliage.

Units of Measurement: Traditional methods of measuring water collected beneath fog gauges have used units of depth, as with rainfall. The mesh area facing any horizontal direction has commonly been constructed the same as the area of a raingauge facing vertically, and comparisons between fog and rain have been made on the resulting depth measurements. As pointed out on page 37, this is considered invalid by the author and quite misleading since the water collected by a wire gauze, even in the absence of rainfall, is unlikely to represent anything like the depth of water that would reach the ground over an equivalent area of horizontal ground surface.

In this thesis, although the area of mesh facing any horizontal distance is the same as the area of an 8" diameter raingauge, water is presented as a volume, not a depth. Since rain is excluded from the fog gauges by a flat, horizontal roof, the volume of water measured is considered quite independent of rain, and cannot be compared with rain until a conversion factor can be established.

(a) The effect of the gauze. A control experiment at Pine Lake to determine the effect of the gauges on water deposition in the absence of the cylinder of wire mesh was begun in September 1972. An initial calibration of this gauge with a nearby gauge beside the Liffey River diversion canal established a conversion factor of 1.11 from the Pine Lake Canal gauge to the Pine Lake West gauge. After removing the gauze from the latter gauge the average conversion factor dropped to 0.16 for an 11 month period. The effect of removing the wire mesh then, was to reduce water collected by 81.7%. Since the projecting remains of the framework after removal of the gauze still constituted a suitable surface for deposition of snow and rime, there is little doubt that the gauges almost exclusively measured wind dependent precipitation.

Since gauges at altitudes below 3500 feet recorded very little precipitation, even in months of high summer rainfall, it is apparent that rain was almost totally excluded.

(b) The effect of Altitude. Tables 5 to 9 and figs. 3, 5 and 6 show spectacular increases in deposits above 3800'. Fig. 6 a regression of log fog deposits on altitude, indicates that this increase is exponential within the range of sites tested. Since the locations of gauges installed on the Central Plateau cover an extensive range of rainfall regimes and altitudes, the uniformity of fog deposits within one altitude zone is striking. For example, in the altitude zone from 1100 m. - 1140 m. (3700' to 3800'), gauges are separated by up to 30 miles, yet, average between 600 ml and 900 ml per month.

At sites below 1050 m. (3,500'), the gauges record very little water and it must be concluded that there is no potential for plants to gain water from small diameter droplets of precipitation below 900 m. (3000'). The presence of fog at these sites is commonly the result of radiative cooling at night and the resulting fogs are slow moving and composed of very small diameter particles. The potential for deposition of water by foliage in these conditions is much less than in the fast moving low cloud formations moving over the higher sites.

Although water deposited in the gauges is labelled fog, it is important to bear in mind that water deposited is in most cases the result of low cloud formations with a range of droplet sizes from less than 20 microns diameter to over 200 microns. The terms fog, mist and cloud are used interchangeably in these pages as general terms to describe the conditions under which small diameter wind dependent particles are present.

(c) The effect of Exposure. Most of the gauge installations have been on exposed sites in order that deposits will not depend on wind direction. In some cases then, the sites are not representative of large areas, (for example, the gauge at Pine Lake East, and the first gauge above Liawenee). In general, however, these gauges have recorded very little difference from less exposed gauges.

The effect of wind speed on water deposited in the containers is complex. Although the potential deposits are clearly proportional to cloud density and wind speed, the actual relationship depends on the turbulence and surface tension of water drops on the gauze. In wind speeds above approximately 20-30 km $hr.^{-1}$, drops are blown from the gauze and may miss the collecting funnel. At high wind speeds then, the deposits are generally higher than at low wind speeds, but the efficiency of collection is less.

In situations where gauges are located in very sheltered sites amongst bushes, the input falls dramatically. For example, a gauge at Lake Augusta within a dense stand of _Orites acicularis_ shrubland, recorded an average of only 16% of that of a more exposed gauge approximately 30m away. A gauge at Pine Lake in a similar situation, recorded an average of 23% of that of an exposed gauge 70m. away.

Since these two sheltered sites were amongst dense shrubland, the recorded reduction may be explained as due to either reduced wind speed within the gauge vicinity, or to reduced fog density (because of the effect of nearby bushes in straining out the fog droplets). It is likely that both these factors are important.

(d) The relationship between Fog Deposits and Rainfall. Figs.4,7,8 and 9 show clearly that there is a correlation between rainfall and fog deposits. The regression of mean monthly fog deposits on mean monthly rainfall is significant with a probability of less than 0.001. The strong correlation is expected because geographical and meteorological conditions conducive to rainfall are also suitable for formation of fog, mist and low cloud.

For individual gauges, however, the relationship between fog deposits and rainfall is more complex. Fig.7 presents the regression of fog deposits for individual gauges over a two year period, on annual rainfall. Rainfall is the mean of records at Liawenee, Lake Augusta and Bronte Park for the same period as the fog gauges. Although it is apparent that there is a wide scattering of points about the regression, the slope is significant with a probability of 0.001. Gauges at Pine Lake (1200m.) record more fog per unit rainfall than lower sites. It is probable then, that at the highest altitudes, ranging from 1200m. - 1350m. (4,000' - 4,500'), the relative importance of fog is greater than at lower sites, despite the higher rainfall at these localities.

The proportion of fog deposits and rainfall at different seasons of the year is presented in Fig. 9 for the average of all gauges over the months of operation. The regression has a probability of approximately 0.02, indicating that fog per unit of rainfall is more important in winter than in summer.

2. Run-Off Plots: Both the small run-off plots (8 m. x 8 m.) installed at Lake Augusta and at Pine Lake were hampered by instrumental failure in the early stages of the experiments. Since measurement was only possible once a month, the resulting number of comparisons between bare and vegetated plots was insufficient for resolving statistical differences. The Lake Augusta trial recorded an overall decrease in run-off in the vegetated plot (compared to an adjacent bare plot) of 2%, and at Pine Lake an overall increase of 20% was measured (Tables 10 and 11). The results were non-significant with a probability (that the results represent no real change) of 0.8 at Lake Augusta and 0.1 at Pine Lake. Individual comparisons were converted to a percentage difference in order to standardise data for the statistical test.

By averaging individual comparisons between bare and vegetated plots over long periods, as in the above trials, it is inherently difficult to measure precipitation due to fog, mist and rime because such increments are swamped by much greater falls of rain and snow.

It is also necessary to have most of the vegetated plot bare in order to exclude edge effects when rain falls at an angle far removed from vertical during strong winds. In the above 8 m. square plots, with bushes 1 m. tall over an area 2 metres square in the centre of the plot, only 17% of the plot is covered with foliage and rain can fall at an angle upto 70° from vertical before increasing run-off in the plot for purely geometrical reasons. This is the angle at which 1 mm diameter droplets fall in 30 Km/hr winds (Nagle, 1956).

The plots also have the drawback that snow deposition in the vicinity of any projecting foliage is greater than in the open. During winter months then, when deposits from fog, mist and rime are expected to be at a maximum, it is probable that much of the increase in vegetated plots is due to local increases in snow deposition.

The large run-off plots at Pine Lake (490 sq.m.) and at Lake Augusta (392 sq.m.) were constructed in an attempt to overcome the difficulties which are inherent in small plots. In order to increase the size of plots to this size it was necessary to devise and construct an instrument for measuring the large volumes of water involved, that could readily be converted to a time chart, and which was within the financial budget allocated to the experiment. The large (12 l) tipping bucket gauge described in the enclosed paper was designed and built for this purpose.

As described previously, the plot at Pine Lake produced no reliable results and the trial was moved to Lake Augusta in 1973 where a large area of dolerite was exposed. Results of this site are presented in Tables 12 and 13.

Rainfall at the site was determined by five 15 cm diameter by 17.5 cm deep cylindrical raingauges, with kerosene added to prevent evaporation and consumption by native animals. These were measured approximately every two weeks. Daily rainfall was measured from a pluviograph and from the H.E.C.'s standard " gauge approximately 40 metres away. Daily fog deposits were recorded on a pluviograph chart beneath a roofed fog gauge.

Data is presented in Tables 12 and 13. Table 12 presents daily information from time charts attached to the run-off plot, the fog gauge, and the pluviograph; and from the H.E.C. daily read raingauge. Rainfall is presented as the mean of the two gauges.

In Table 13, rainfall is calculated from the average of the five 15 cm. diameter gauges, plus the pluviograph and H.E.C. gauge. The accuracy of single raingauges is widely acknowledged to be low, so that the second table is considered most accurate and is believed to adequately sample the area for rainfall totals over a two week period.

The first table, however, has the advantage of recording single run-off events, so that short period run-off during prevailing foggy periods can be separated from the average rainfall plus fog, measured over a two week period. After allowing for up to 20% variation in actual rainfall from the measured amount then, it is apparent that:

1. Run-off from the artificially vegetated plot increases dramatically after snow has fallen. The effect of vegetation in increasing local snow deposition is well known. It is difficult to extrapolate local deposition demonstrated here to large areas.

2. At certain periods the run-off in the plot (compared to rainfall)

in visually documented heavy mist, is far in excess of any possible errors in estimating rainfall. Such a time was 31st July when 0.09" run-off compared with 0.04" rain (average of 5 gauges) and when fog was measured as 0.14". Another such period on the 11th and 12th August produced 0.40" run-off when the two raingauges both recorded 0.31" and the fog gauge 0.08".

3. At other periods the difference between measured run-off and rainfall is consistent with the above results but individual comparisons may be misleading because of possible errors in measuring rainfall.

From the overall analysis, where rainfall is averaged from seven gauges, the increase due to the artificial forest is seen to be relatively consistent with the input to the fog gauge (in the absence of snow). The ratio: $\frac{F}{D}$

where F = Fog Deposit in roofed gauge.

D = Measured difference between run-off and rainfall averaged from 7 gauges,

is seen to vary from 1.8 to 3.2., with an average of 2.5.

In the run-off plot, approximately 33% of the area is covered with foliage, after allowing 4 metres around the edge to prevent errors due to rain falling at an angle from vertical during strong winds. Since height of foliage was approximately 3 metres, it was possible for rain to enter at an angle of 60° from vertical without increasing run-off because of edge effects.

For a rough order of magnitude comparison between average efficiency of collecting small diameter water droplets, for the wire gauze, and the Eucalypt foliage on the run-off plot, the volume of water collected per unit area may be compared. Since the proportion of foliage on the run-off plot is approximately one third, and the run-off plot has run-off attributed to small diameter droplets of $\frac{1}{3}$ that of the fog gauge on a depth basis, it is apparent that the Eucalypt foliage and the wire mesh were approximately equal on a volume per unit area basis.

Although the comparison is somewhat complicated by the difference in exposure between the foliage on the windward edge of the plot and the sheltered side, the results are believed to be realistic when viewed in the light of earlier experiments (Edwards, 1968) in which an artificial mist applied to small areas of different foliage produced similar results over a moderate wind speed range.

Since both the fog gauge and the run-off plot were sited in positions exposed to all wind directions, they were not strictly representative of large areas. When it is appreciated that to sample a complete catchment it would require similar plots over a wide range of altitudes, exposures, and rainfall regimes, the dangers in extrapolating the data obtained to large areas are obvious.

Nevertheless, even if the efficiency of normal vegetation was 1/10 that of the mesh gauges, the input at a site near Lake Augusta would be approximately 2.5 cm per year, and at Pine Lake approximately 17 cm.

It must be concluded that small diameter water droplets that are not normally sampled in raingauges, are of considerable importance above 1100 m. on the Central Plateau. The wire mesh of the fog gauges and vegetation foliage are roughly equal in efficiency in causing droplets to coalesce and fall to the ground, under exposed conditions. It is not possible to extrapolate these results to large areas because of differences in exposure, vegetation type and altitude, but the results have indicated that the highest sites may receive water from this source equivalent to several inches each year.

CHAPTER 3.

EVAPOTRANSPIRATION

Summary : Evapotranspiration losses of water from the Central Plateau have been calculated using a number of methods. Estimates based on empirical formulae relating evapotranspiration to temperature, pan evaporation, and net radiation have been shown to be misleading. The relationship between evapotranspiration and altitude is complex and lack of reliable hydrological and meteorological data prohibits accurate estimates of losses on the Central Plateau. A crude analysis of the water budget on the Central Plateau catchments supports a theoretical expectation of approximately 76 cm (30") mean evapotranspiration loss per year.

Introduction: Water loss through evapotranspiration has an important bearing on the net gain to be expected from low cloud and rime. This is because of the possible direct relationship between water gain from projecting foliage (that is suitable for straining out the small diameter droplets) and transpiration loss. For example, before encouraging tree growth on the plateau to increase run-off from cloud and rime, one would want to be confident that such an increase would not be compensated for by an increase in evapotranspiration over the catchment.

Evapotranspiration can be estimated by a number of methods, none of which are expected to be highly accurate for the Central Plateau because of limiting meteorological data and drying out of soil during the summer months.

The following brief analysis of methods suitable for estimating evapotranspiration on the Central Plateau has been conducted to gain a probable order of magnitude for losses from the plateau. This was done to clarify the effect of vegetation density and type on transpiration, and to aid the analysis of fire and streamflow in the next chapter.

The Effect of Elevation on Evaporation. In general the effect of altitude on evaporation has been wrongly appreciated - it has been assumed that because it gets colder with increasing altitude, evaporation becomes less.

Gale (1972) has presented a paper quantifying the relationship between pressure reduction associated with altitude and evaporation.

He demonstrated that in a Mediterranean climate with a lapse rate of $.0012^{\circ}$ C m^{-1}, a rise of 1000 metres can increase potential transpiration by 7%, compared to sea level, assuming equal solar radiation and wind speeds. This rose to an increase of 18% in transpiration loss under iso-thermal conditions. When the increase in radiation with altitude was also considered, potential transpiration increased dramatically with altitude for the sites considered. Gale compared Jerusalem at 830 metres with Tel Aviv at sea level and calculated that midday rates were 50 - 60% higher in Jerusalem than on the coast.

In Tasmania the average lapse rate is approximately 0.0018° C m^{-1} which would correspond to approximately 6% increase in potential transpiration per 1000 metres for equal radiation (assuming 50% sea level humidity, wind speed 500 cm sec^{-1} and 1.2 cal. cm $^{-2}$ leaf absorbed radiation). (Extrapolated from date by Gale, 1972).

Although no radiation data is available for Tasmanian highlands, it must be assumed that under cloudless conditions, evapotranspiration losses are greatly in excess of those at lower altitudes because of the general increase in radiation with altitude. Pan evaporation data from Lake St. Clair and Liawenee support this, although, as previously pointed out, their reliability and validity is suspect.

Methods of Analysis of Evapotranspiration:

1. Temperature and Evaporation. Fig. 10 presents the relationship between temperature and evaporation from an American Class A Pan for all the months of the year at Hobart, Lake St. Clair, Lake Eucumbene in N.S.W. and Nursery Hill in New Zealand. It is immediately apparent that

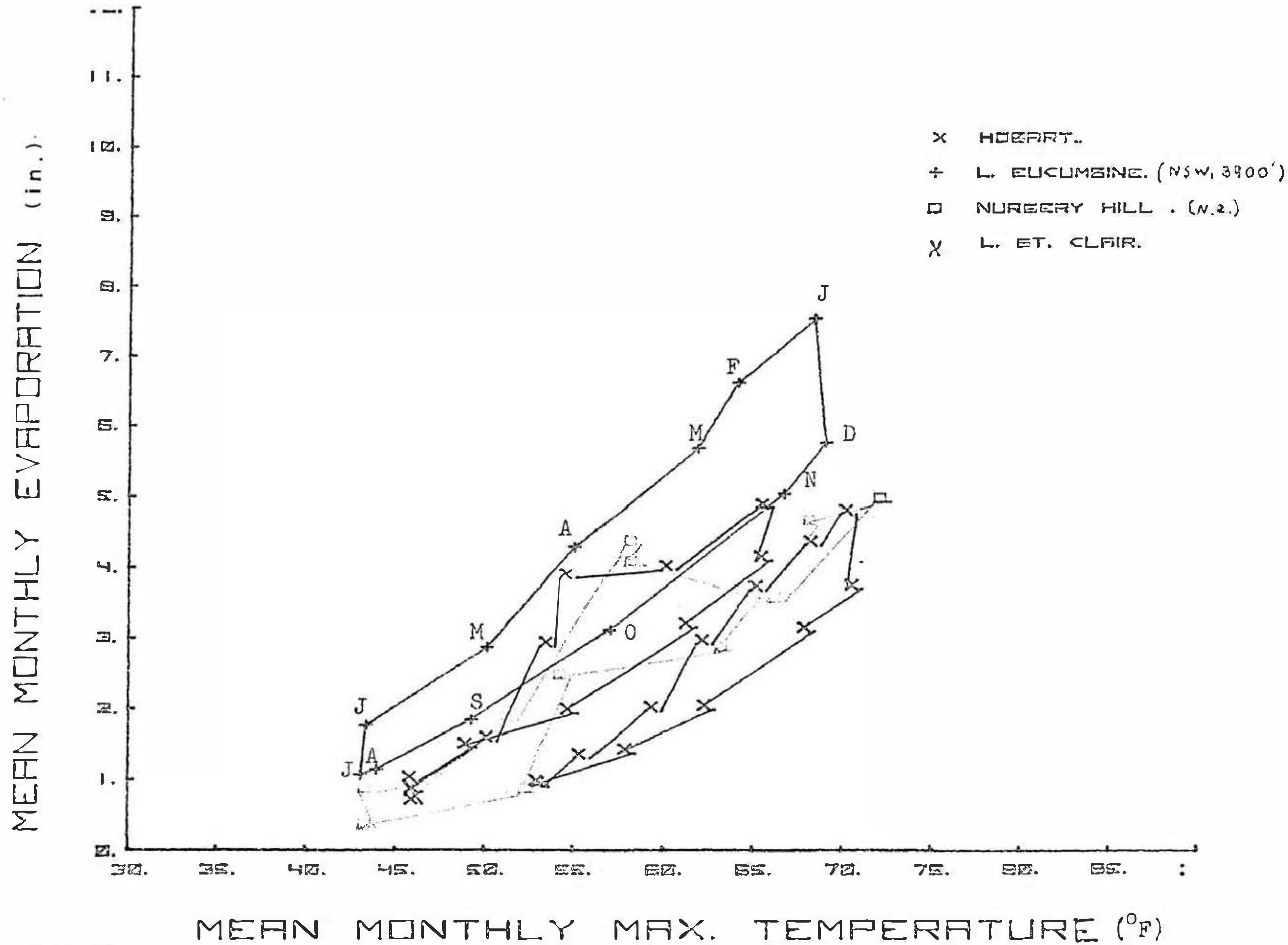

FIG. 10. The relationship between pan evaporation and mean monthly maximum temperature at different localities.

evaporation becomes more efficient (at a given temperature) as altitude increases, and that the relationship changes with season because of radiation variations. Pelton et al (1960) explained the lag in mean temperatures behind solar radiation as a result of heat stored in the soil. They concluded that mean temperature methods of estimating evapotranspiration, such as that of Thornthwaite (1948) had very limited use for estimates of potential evapotranspiration. Ward (1971) pointed out that Thornthwaite's formula works quite effectively under conditions in which air temperature and net radiation availability are closely related, but that in other conditions it is unsatisfactory. Thornthwaite's formula continues to be used because of its minimal input data requirements.

Table 14 presents results from the formulae of Thornthwaite (1946 and 1948) and Blaney and Criddle (1950) for Hobart, Lake St. Clair and Miena.

TABLE 14. Mean monthly evapotranspiration calculated from empirical formulae based essentially on temperature and daylength (inches).

	BLANEY & CRIDDLE			THORNTHWAITE		
	Miena	L. St. Clair	Hobart	L. St. Clair	Miena	Hobart
J	2.31	2.55	2.82	3.7	3.2	3.4
F	1.99	2.11	2.37	3.1	2.9	3.0
M	1.66	1.77	2.05	2.5	2.5	2.8
A	1.20	1.30	1.50	1.7	1.7	1.9
M	1.02	1.08	1.29	1.2	1.2	1.4
J	0.73	0.80	0.95	0.8	0.6	0.9
J	0.72	0.79	0.97	0.8	0.4	0.9
A	0.86	0.95	1.16	0.8	0.6	1.2
S	1.39	1.20	1.45	1.2	1.1	1.6
O	1.65	1.50	2.13	1.9	1.7	2.2
N	1.82	1.93	2.23	2.2	2.4	2.4
D	1.77	2.11	2.42	3.0	3.1	3.7
Y	17.02	18.39	21.39	22.9	21.4	25.6

The formula of Blaney & Criddle is -

$$u = Kt\, p\, (114 - h)$$

where u is monthly consumptive use (inches)

K is a crop constant (K = 0.7 has been assumed)

t is mean monthly air temperature ($^\circ$F)

p is monthly percentage of daytime hours in the year.

h is the mean monthly relative humidity (%).

The formula of Thornthwaite is -

$$PE = PE^* \cdot \frac{h}{12} \cdot \frac{N}{30}$$

where $PE^* = 1.6 \left[\frac{10T}{I}\right]^a$

where T is mean monthly air temperature ($^\circ$C)

h is mean number of daytime hours per month.

N is number of days per month.

I is a heat index, which is the sum of 12 monthly indices,

i, given by

$$i = \left[\frac{T}{5}\right]^{1.514}$$

a is a function of I.

Both a and I can be found from tables (Thornthwaite and Mather, 1955), of PE* can be obtained from a log - log plot of PE* v's T where a straight line passes through (PE* = 1.6, T= $^I/10$) and (PE* = 13.5, T = 26.5).

PE* is an adjusted value of potential evapotranspiration based on a 12 hour day and a 30 day month (cm/month).

PE is monthly potential evapotranspiration (cm/month).

2. Evaporation Pan conversion. An evaporation pan has been installed at Lake St. Clair since 1960. Originally this was an Australian Sunken Pan but this was changed to an American Class A pan in 1964. An American Class A pan was installed at Liawenee in 1970.

Although the Water Resources Council (1970) was optomistic about the possibilities of applying pan conversion ratios for determining open water evaporation, the same optimism can hardly be extended to the reliability of the two gauges in the Tasmanian highlands.

The Lake St. Clair pan records reveal obvious discrepancies, such as 6.63" in April 1970, and 2.67" in August 1962. Many records, especially in winter months, are missing, and the gauge is suspect from a siting viewpoint. Consumption of water from the pan is obviously taking place by birds, and probably by marsupials.

The pan at Liawenee is also poorly sited on a concrete block previously comprising the foundation to a building. Advection effects are probably significant in this gauge, as well as obvious consumption of water by native animals.

In order to present the available pan evaporation data in the format of potential evapotranspiration, the following conversion ratios have been applied, (after discarding obviously erroneous data).

Australian Sunken : American Class A = 0.88 : 1 *

Open Water : American Class A = 0.7 : 1 *

Evapotranspiration : Open Water Evapn. = 0.7 : 1 **

i.e. Evapotranspiration = Australian Sunken Pan x 0.56

= American Class A Pan x 0.49

* Pan conversion ratios taken from Australian Water Resources Council (1970)

** From Penman (1963)

TABLE 15. Pan Conversion Estimates of Evapotranspiration (inches)

	L. St. Clair (1960-70)		Liawenee (1969-71)		Hobart (1908-57)	
	A°	B°°	A	B	A	B
J	2.60	3.72	3.06	4.38	2.66	3.80
F	1.99	2.85	2.83	4.05	2.07	2.96
M	1.72	2.46	2.64	3.78	1.74	2.49
A	1.00	1.43	1.66	2.37	1.11	1.59
M	0.82	1.17	0.77	1.10	0.77	1.10
J	0.47	0.67	0.6 E	0.86	0.51	0.73
J	0.52	0.74	0.56	0.80	0.53	0.76
A	0.45	0.64	0.79	1.13	0.73	1.04
S	0.98	1.40	0.95	1.36	1.10	1.57
O	1.35	1.93	2.09	2.99	1.64	2.35
N	2.07	2.96	2.48	3.55	2.06	2.95
D	2.46	3.52	3.08	4.40	2.41	3.45
Y	16.43	23.49	22.05	31.53	17.33	24.78

° A assumes conversion ratios as above.

°° B assumes evapotranspiration = open water evaporation.

3. Empirical formulae based on theoretical physics.

Formulae derived by Penman (1948, 49, 1956 (a), 1956 (b), Slatyer and McIlroy, (1961), Van Bavel (1966), Monteith (1965) have been applied by Slatyer (1960), Tanner and Pelton (1960), Fitzgerald and Richard (1960), Stanhill (1961), Prescott (1958) and others.

The Penman method is the most widely used of these and combines an aerodynamic and energy balance approach. Although more complicated than most other evaporation formulae, it still requires only standard meteorological data.

Essentially, the expression is:

$$E = \frac{\left[\frac{\Delta}{y} H + Ea\right]}{\left[\frac{\Delta}{y} + x\right]}$$

where Ea is an expression for the drying power of the air, involving wind speed and saturation deficit.

Δ is a temperature constant - the slope of the saturation vapour-pressure curve at mean air temperature.

y is the constant of the wet and dry-bulb psychrometer equation.

H is the heat budget which is partitioned into evaporation E, and sensible heat transfer to the air, Q.

Where H is not measured directly Penman used the following relationship in its derivation -

$$Ho = (1 - r) R_I - R_B \text{ mm/day}$$
$$= 0.95\, R_A \left(0.18 + 0.55 \frac{n}{N}\right) - \sigma T^4 \left(0.56 - 0.09\sqrt{ed}\right) \left(0.10 + 0.90 \frac{n}{N}\right)$$

where RA is the theoretical maximum solar radiation that could reach the site in the absence of the earth's atmosphere (obtainable from standard tables).

$\frac{n}{N}$ is the ratio of actual to possible hours of bright sunshine.

T^4 is the theoretical black-body radiation at mean temperature T (obtainable from standard tables).

ed is the mean vapour pressure of the atmosphere (mm Hg.) derived from routine humidity observations.

$$Ea = 0.35\ (0.5 + \frac{u}{100})\quad (ea - ed)\ \text{mm/day.}$$

where u = wind speed at a height of 2 metres in miles/day.

ea = saturation vapour pressure at mean air temperature (obtainable from standard tables).

ed = is as above, so ea - ed is the saturation defecit of the atmosphere at screen height.

Ho is the appropriate heat budget for open water. For a green crop Penman found empirically that the radio $\frac{E_t}{Eo}$ varied from 0.6 - 0.8, with daylength the dominant controlling factor.

Solutions to the Penman equation have been greatly simplified by electronic computer (e.g. Chidley and Pike, 1970) and by graphical solutions (e.g. Purvis, 1961, and Kohler et al 1959). Measurements of air temperature, sunshine percentage, relative humidity and wind speed are required.

In Tasmania, evapotranspiration data from Penman's equation has been calculated since 1965 for a number of important agricultural areas, by the Bureau of Meteorology. The original graphs by Purvis (1961) were modified initially for a reflection coefficient of 23%, but were reverted to 5% (as used by Penman) in 1968. The Meteorological Bureau found that the following substitutions provided what they considered more realistic figures for Tasmania and Victoria.

$(0.18 + 0.55 \frac{n}{N})$ replaced by $(0.26 + 0.50 \frac{n}{N})$

$(0.5 + 0.01\ u)$ replaced by $(1 + 0.01\ u)$

$(1 - r) = 0.95$ replaced by $1 - r = 0.77$

Although no measurements have been made on the Central Plateau because wind speed, humidity and sunshine records are lacking, the following comparisons with Class A Pan evaporation at Hobart have been calculated for later discussion of the relative merits of Penman's formula.

TABLE 16. Ratio of Evapotranspiration from Penman's formula to Pan Evaporation from an American Class A Pan at Hobart.

Year	J	F	M	A	M	J	J	A	S	O	N	D	Year
1966	.72	.77	.64	.68	.59	.37	.55	.68	.90	.88	.77	.89	.75
1967	.80	.76	.65	.62	.50	.31	.59	.66	.79	.73	.86	.88	.75
1968	.79	.76	.72	.63	.65	.47	.59	.65	.70	.75	.44	.85	.76
1969	.76	1.37	.78	.66	.72	.46	.39	.41	.58	.81	1.02	.90	.73
1970	.83	.80	.79	.62	.59	.53	.46	.53	.58	.74	.79	.86	.74
1971	.78	.82	.72	.67	.52	.27	.39	.55	.58	.76	.81	.87	.73

4. Water Budget Method.

It is possible to estimate the evapotranspiration of a catchment by measuring the difference between the precipitation input and outflow. The accuracy of this method is generally acknowledged to be low for short periods because of the difficulty in adequately sampling rainfall over a large area, and because of the possibility of leakage from the catchment through permeable bedrock.

In the highlands of Tasmania, rainfall is only measured in a few gauges and these certainly do not represent the average precipitation in any catchment. By averaging data over a number of years however, and making a number of assumptions, it is possible to apply the water budget method to the Central Plateau.

This method essentially establishes the relationship between rain-gauge precipitation and catchment precipitation in winter months by assuming an average evapotranspiration loss. Since evapotranspiration is almost certainly between 0.5" and 1.5" per month in winter, it is possible to calculate the monthly catchment precipitation as:

$$Rc = RO + E$$

where Rc = Average catchment rainfall in winter months

RO = Measured run-off converted to depth

E = Evapotranspiration which is between 0.5 and 1.5 inches per month.

Then $Rg = Rc.K.$

where Rg = raingauge precipitation at any site

K = constant to convert raingauge precipitation to catchment precipitation. (See page 84).

Using this approach it is possible to determine the relationship between raingauge precipitation at any site, and average catchment precipitation during winter months, and to extrapolate this relationship to the remainder of the year.

Although the validity of many of the assumptions inherent in this analysis are open to question, it is likely that they are less suspect than many of the assumptions in estimations of evapotranspiration using empirical formulae. That is, while the estimates of monthly catchment rainfall are only approximate, they do enable a direct measure of the evapotranspiration of a catchment. The method consequently takes into account soil water limitations in summer, stomatal closing under stress conditions, advection, and the numerous micro-environmental factors important in determining average water loss from a catchment.

A discussion of the assumptions inherent in the analysis, as was applied here, follows :-

(A) Evaporation is very low in winter and able to be estimated. If winter evapotranspiration losses can be estimated to approximately $\pm$ 0.3", then annual calculated evapotranspiration will be estimated to $\pm$ 3" (See Table 32). This is because the relationship between raingauge records and average catchment rainfall is determined in winter months, and extrapolated to summer months.

(B) No large delays in run-off occur. Soil is invariably at field capacity by the end of May, but the water table can fluctuate over the winter months and falling rain may take days and weeks in large catchments before being measured as streamflow, i.e., some rain falling in May will appear as run-off in June, and some rain falling in September will occur as run-off in October. Since September rainfall is, on average, approximately the same as May rainfall, errors due to delays in run-off should tend to cancel when averaged over a number of years.

In this study, winter months June, July, August and September have been used to determine the annual total evapotranspiration providing the best fit with expected evapotranspiration from month to month.

(C) Raingauge station records are directly proportional to average catchment rainfall when averaged over a number of years.

Table 33 presents the rainfall falling in winter months as a percentage of the annual totals for raingauge stations on the Central Plateau. It is apparent that stations near the north of the Plateau, such as Lake Mackenzie, Liawenee and Breona, have a higher percentage of their rainfall in winter, than stations in the mid-plateau region. The assumption is not valid then, when comparing run-off from catchments that are situated a long way from raingauge stations.

(D) Raingauge errors are constant and the same in winter as in summer. The efficiency of a raingauge in measuring snow is less than when measuring rain, so that this assumption is not likely to be strictly valid. Evaporation in summer of water from raingauges would tend to cancel this error, although the overall variation in precipitation measurement efficiency throughout the year is not known.

The errors inherent in this assumption, however, are likely to be slight compared to the previously mentioned factors. Variations in the amount of mist and other wind dependent precipitation forms, as a proportion of normal rainfall, may also induce minor errors.

Results: Tables 17 to 32 present the results of this analysis. It is assumed that the raingauge station records may be multiplied by a constant to arrive at the catchment rainfall for a year period, and that the constant is measured as -

$$K = \frac{\overline{RO} + \overline{E}}{\overline{R}}$$

where $\overline{R}$ = Average annual rainfall at raingauge station

$\overline{RO}$ = " " run-off at catchment under study

E = assumed annual evapotranspiration

Monthly evapotranspiration is determined for each month as -

$$Em = Rm.K - ROm$$

where Em = monthly evapotranspiration

Rm = monthly rainfall at raingauge station

ROm = " run-off (in depth units) at streamgauge

TABLE 17. Monthly evapotranspiration for an annual total of 20" in the Ouse River Catchment.

Reference Raingauge Station

	L. St. Clair	Bronte Park	Butlers Gorge	Liawenee
J	2.34	2.28	2.79	2.19
F	2.19	2.54	2.13	3.42
M	2.70	2.58	2.93	2.65
A	3.27	3.76	3.31	3.32
M	1.40	1.13	1.54	1.66
J	0.73	0.33	0.77	-0.18
J	0.26	0.14	0.14	0.91
A	-0.88	-0.58	-1.04	0.79
S	-0.23	-0.60	-0.50	-0.83
O	1.86	1.78	1.52	1.28
N	3.42	3.32	3.40	2.17
D	2.94	3.02	3.02	2.67

TABLE 18. Monthly evapotranspiration for an annual total of 24" in the Ouse River Catchment.

	L. St. Clair	Bronte Park	Butlers Gorge	Liawenee
J	2.52	2.46	2.99	2.36
F	2.39	2.76	2.32	3.70
M	2.91	3.10	3.14	2.85
A	3.67	4.19	3.70	3.72
M	1.80	1.50	1.95	2.02
J	1.12	0.69	1.16	0.15
A	-0.45	-0.14	-0.62	1.32
S	0.14	-0.25	-0.15	-0.55
O	2.24	2.15	1.87	1.42
N	3.81	3.71	3.79	2.48
D	3.24	3.31	3.32	2.94

TABLE 19. Monthly [illegible] for an annual total of 28" in the [illegible] River Catchment.

Reference Raingauge Station

	L. St. Clair	Bronte Park	Butlers Gorge	Liawenee
J	2.70	2.63	3.20	2.53
F	2.59	2.98	2.52	3.98
M	3.11	3.31	3.36	3.05
A	4.06	4.61	4.10	4.12
M	2.19	1.88	2.35	2.49
J	1.50	1.06	1.56	0.48
J	1.02	0.89	0.89	1.76
A	-0.03	0.31	-0.21	1.55
S	0.51	0.09	0.21	-0.22
O	2.61	2.52	2.22	1.96
N	4.20	4.09	4.13	2.79
D	3.53	3.61	3.62	3.22

TABLE 20. Monthly evapotranspiration for an annual total of 20" in the Travellers Rest Catchment.

Reference Raingauge Station

	L. St. Clair	Bronte Park	Butlers Gorge	Liawenee	Waddamana
J	2.10	2.02	2.70	1.89	2.06
F	3.20	3.63	3.11	4.88	1.28
M	3.19	3.44	3.49	3.12	3.84
A	3.59	4.26	3.64	3.66	4.61
M	1.53	1.15	1.71	1.88	1.77
J	1.43	0.90	1.49	0.19	1.03
J	0.81	0.66	0.65	1.70	0.44
A	-0.36	0.06	-0.57	1.91	0.24
S	-0.83	-1.34	-1.19	-1.71	-1.29
O	0.75	0.65	0.29	-0.03	0.66
N	2.50	2.38	2.48	0.80	2.83
D	2.09	2.20	2.20	1.72	2.54

TABLE 21. Monthly evapotranspiration for an annual total of 24" in the Travellers Rest Catchment.

	L. St. Clair	Bronte Park	Butlers Gorge	Liawenee	Waddamana
J	2.23	2.19	2.91	2.05	2.23
F	3.41	3.85	3.31	5.16	1.45
M	3.40	3.65	3.71	3.32	4.06
A	4.00	4.69	4.04	4.05	5.05
M	1.78	1.53	2.12	2.29	2.18
J	1.83	1.26	1.89	0.52	1.40
J	1.21	1.04	1.03	2.12	0.80
A	0.09	0.50	-0.16	2.45	0.68
S	-0.45	-0.99	-0.84	-1.38	-0.94
O	1.14	1.02	0.67	0.30	1.02
N	2.91	2.76	2.87	1.11	3.23
D	2.40	2.49	2.50	2.00	2.84

[illegible] [illegible] total of 28" in the [illegible]

[illegible]

	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
J	2.46	2.37	3.11	2.22	2.49
F	3.61	4.07	3.51	5.44	1.56
M	3.61	3.87	3.93	3.52	4.30
A	4.40	5.11	4.43	4.45	5.49
M	2.17	1.91	2.52	2.70	2.58
J	2.21	1.63	2.09	0.85	1.77
J	1.59	1.41	1.40	2.54	1.16
A	0.51	0.95	0.26	2.98	1.13
S	-0.29	-0.64	-0.49	-1.05	-0.59
O	1.52	1.39	0.99	0.64	1.40
N	3.30	3.15	3.26	1.42	3.63
D	2.69	2.79	2.79	2.27	3.16

[illegible] River catchment [illegible] of [illegible]".

[illegible]

	[illegible]	[illegible]	[illegible]	L. [illegible]
[illegible]	[illegible]	[illegible]	2.74	1.79
[illegible]	[illegible]	[illegible]	2.99	2.77
[illegible]	[illegible]	[illegible]	3.04	3.12
[illegible]	[illegible]	2.72	2.72	2.84
[illegible]	[illegible]	1.48	1.04	1.65
J	[illegible]	[illegible]	-0.60	0.94
[illegible]	-0.43	[illegible]	0.83	2.29
[illegible]	[illegible]	-1.97	0.23	[illegible]
[illegible]	[illegible]	[illegible]	-1.67	-1.25
[illegible]	[illegible]	1.71	1.47	0.67
[illegible]	[illegible]	[illegible]	3.16	1.78
D	4.03	4.11	3.44	2.50

TABLE 24. [illegible] evapotranspiration in the [illegible] River Catchment for annual evapotranspiration of 24".

	[illegible]	[illegible]	[illegible]	L. [illegible]
J	3.36	3.99	2.91	1.92
F	1.97	0.80	3.26	3.04
M	4.01	3.99	3.24	3.33
A	3.78	3.12	3.12	3.24
M	1.36	1.91	1.46	2.09
J	[illegible]	[illegible]	-0.07	1.34
J	[illegible]	[illegible]	[illegible]	2.78
A	[illegible]	[illegible]	[illegible]	1.72
S	[illegible]	[illegible]	[illegible]	[illegible]
O	2.24	[illegible]	[illegible]	0.97
N	[illegible]	[illegible]	3.47	2.03
D	4.34	[illegible]	3.71	2.74

TABLE 25. Monthly evapotranspiration in the Fisher River Catchment for an average annual evapotranspiration of 28".

Reference Raingauge Station

	Bronte Park	Butlers Gorge	Liawenee	L. Mackenzie
J	3.55	4.21	3.08	2.04
F	2.19	0.98	3.54	3.31
M	4.24	4.23	3.44	3.53
A	4.21	3.52	3.52	3.65
M	1.77	2.35	1.87	2.53
J	0.09	1.31	0.06	1.74
J	0.31	0.55	1.68	3.27
A	0.04	-1.15	1.90	1.95
S	-0.42	-0.15	-1.01	-0.55
O	2.60	2.40	2.15	1.27
N	4.79	5.05	3.78	2.28
D	4.64	4.72	3.99	2.97

TABLE 26. Monthly evapotranspiration in the Nive River Catchment for an annual total of 20".

	Reference Raingauge Station		
	Bronte Park	Butlers Gorge	Liawenee
J	1.81	2.11	1.59
F	2.59	1.85	3.08
M	2.56	2.57	2.15
A	3.41	3.02	3.12
M	1.61	2.01	1.74
J	0.54	1.14	0.51
J	0.87	0.99	1.64
A	0.51	0.02	1.39
S	0.06	0.24	0.00
O	1.51	1.32	1.11
N	2.32	2.48	1.67
D	2.22	2.25	2.01

TABLE 27. Monthly evapotranspiration in the Nive River catchment for an annual total of 24".

	Bronte Park	Butlers Gorge	Liawenee
J	1.99	2.32	1.76
F	2.83	2.04	3.36
M	2.79	2.80	2.35
A	3.83	3.41	3.51
M	2.01	2.44	2.15
J	0.87	1.52	0.84
J	1.23	1.37	2.06
A	0.97	0.45	1.92
S	0.39	0.59	0.33
O	1.88	1.67	1.44
N	2.63	2.85	1.98
D	2.51	2.54	2.29

TABLE 29. Monthly evapotranspiration in the Nive River Catchment for an annual total of 28".

Reference Raingauge Station

	Bronte Park	Butlers Gorge	Liawenee
J	3.18	2.53	1.93
F	3.07	2.22	3.64
M	3.02	3.03	2.55
A	4.25	3.80	3.91
M	2.42	2.87	2.56
J	1.20	1.90	1.17
J	1.59	1.74	2.48
A	1.44	0.88	2.46
S	0.73	0.43	0.66
O	2.25	2.03	1.78
N	3.04	3.23	2.29
D	2.80	2.84	2.57

TABLE 29. Monthly evapotranspiration in the Derwent River Catchment for annual evapotranspiration of 20".

Reference Raingauge Station

	L. St. Clair	Bronte Park	Butlers Gorge
J	2.08	1.98	2.72
F	3.03	3.52	2.92
M	2.69	2.94	3.01
A	3.09	3.78	3.13
M	1.33	1.07	1.67
J	0.60	0.00	0.65
J	0.81	0.62	0.62
A	0.68	1.15	0.43
S	-0.09	-0.64	-0.49
O	1.32	1.18	0.80
N	2.11	1.96	2.08
D	2.35	2.44	2.45

TABLE 30. Monthly evapotranspiration in the Derwent River Catchment for annual evapotranspiration of 24".

	L. St. Clair	Bronte Park	Butlers Gorge
J	2.26	2.16	2.93
F	3.23	3.75	3.12
M	2.89	3.15	3.22
A	3.49	4.21	3.52
M	1.72	1.44	2.08
J	0.99	0.36	1.04
J	1.19	0.99	1.00
A	1.11	1.59	0.85
S	0.28	-0.29	-0.14
O	1.70	1.55	1.16
N	2.50	2.34	2.47
D	2.64	2.74	2.75

TABLE 31. Monthly evapotranspiration in the Derwent River Catchment for annual evapotranspiration of 28".

Reference Raingauge Station

	L. St. Clair	Bronte Park	Butlers Gorge
J	2.44	2.34	3.14
F	3.43	3.97	3.32
M	3.10	3.37	3.44
A	3.88	4.64	3.92
M	2.11	1.83	2.49
J	1.38	0.73	1.43
J	1.57	1.38	1.37
A	1.53	1.99	1.26
S	0.66	0.06	0.22
O	2.07	1.93	1.51
N	2.90	2.73	2.86
D	2.94	3.04	3.05

TABLE 32. Mean Winter evapotranspiration for months June, July, August and September (inches per month).

Catchment	Annual Et*	L. St.Clair	Bronte Park	Butlers Gorge	Liawenee
	20	0.03	-0.18	-0.16	0.16
Ouse	24	0.36	0.31	0.23	0.56
	28	0.75	0.59	0.61	0.97

Catchment	Annual Et*	Waddamana	L.St. Clair	Bronte Park	Butlers Gorge	Liawenee
	20	0.11	0.26	0.07	0.10	0.52
Travellors Rest	24	0.49	0.67	0.45	0.48	0.93
	28	0.87	1.06	0.84	0.86	1.33

Catchment	Annual Et*	L. Mackenzie	Bronte Park	Butlers Gorge	Liawenee
	20	0.72	-0.75	-0.63	-0.15
Fisher	24	1.16	-0.37	-0.25	0.25
	28	1.60	0.01	0.14	0.66

Catchment	Annual Et*	Bronte Park	Butlers Gorge	Liawenee
	20	0.50	0.60	0.89
Nive	24	0.87	0.98	1.29
	28	1.24	1.36	1.69

Catchment	Annual Et*	L. St.Clair	Bronte Park	Butlers Gorge
Derwent	20	0.50	0.28	0.30
	24	0.89	0.66	0.69
	28	1.29	1.04	1.07

* Et = Evapotranspiration

TABLE 33. Percentage of annual rainfall falling in winter months (% per month).

Lake St. Clair	9.01
Bronte Park	9.56
Butlers Gorge	9.60
Waddamana	9.75
Miena	9.77
Lake Mackenzie	11.08

Discussion: Evapotranspiration losses are the most fundamental reason for the difference between precipitation input and streamflow, and are basic to an understanding of the hydrological cycle. The literature dealing with evapotranspiration is voluminous and there are many alternative methods of measurement. Reviews of measurement techniques are given by Lincere (1963), Penman (1963), Ward (1972), Australian Water Resources Council (1970a and 1970b), U.S.G.S. (1961).

The Australian Water Resources Council (1970a) concluded that the only method suitable for the measurement of evaporation from most types of land surfaces, was based on an evaluation of the surface energy balance. This method essentially consists of measuring net radiation, sensible heat transfer to soil and air, and the proportion of radiation partitioned into latent heat. Sensors are placed at two height levels, as close as possible to the crop surface, to measure temperature and humidity gradients over the same height level. The ratio of the two fluxes, the Bowen ratio, determines the partitioning of the radiant energy into sensible and latent heat, and measurements of net radiation and ground heat transfer enable evaporation rate to be determined.

It is apparent that even with the most sophisticated apparatus incorporating approximately $30,000 worth of installation and data processing equipment (AWRC, 1970a) plus a supervising technician, evapotranspiration can only be determined at a point location with a reasonable degree of precision.

On the Central Plateau the range of vegetation types is wide, the range of climates is continuous from the most exposed, to mild and sheltered sites; and the rainfall with associated cloud cover, is marked across the plateau, both from south to north and from east to west. Ground cover ranges from water to bare rock, and various vegetation forms, which must have a significant influence on both the reflection coefficient of incoming radiation, and the availability of soil moisture for evaporation, particularly in summer months.

In order to adequately sample evapotranspiration on the Central Plateau catchments then, it would be necessary to install an extensive network of radiation instruments, sufficiently dense to enable a representative sampling of vegetation types having different albedo, different Bowen ratios, and different advection effects. Any method of determining evapotranspiration can at best give a rough indication if sampling is inadequate, no matter how accurate the method at the site of measurement.

The formula of Penman's, as applied to Tasmanian conditions, emphasises the difficulties in estimating evapotranspiration, even where meteorological records are of a reliable nature. The data for Hobart, as shown in Table 16, averages 75% of evaporation from an American Class A pan, whereas Penman (1963) expected this ratio for open water evaporation, and an average of approximately 50% of pan evaporation for a crop surface.

The use of the Penman equation on the Central Plateau is not a promising line of approach for the following reasons:

1. The effect of pressure on evaporation. Gale (1972), pointed out that not only the psychrometric constant, but other terms as well, are pressure dependent in many semi-empirical formulae for estimating evapotranspiration from meteorological data.

2. Evapotranspiration is not maintained at the "potential" rate throughout summer months in the eastern catchments because of soil moisture limitations. In other areas where bare ground and rock are exposed, advection is likely to be important. Only in the wetter western catchments is water expected to be lost at the potential rate during average summer conditions, and even here unusually dry seasons would present complications.

3. Evaporation from wet leaves is likely to be more efficient than transpiration that would normally be suppressed while free water is evaporating.

The effect of aerodynamic roughness on the turbulent transfer of moisture and energy from the vegetation surface was recognised by Van Bavel (1966). The coefficient of turbulent exchange increases with height of vegetation even in normally transpiring vegetation with no free surface water (Rijtema 1968).

Hewlett (1969) summarized evidence to suggest that intercepted water does evaporate much faster than the apparent short term potential transpiration. The energy for vaporizing intercepted water may come from advection, from reduced albedo in wet versus dry leaves, and from a reduction in the Bowen ratio.

On the Central Plateau much of the precipitation occurs in the form of frequent light showers which are associated with strong winds. It is likely that the resulting losses of water from wet foliage are considerable, even in winter.

Many of the arguments against use of the Penman semi-empirical formula for estimating evapotranspiration also apply to conversion ratios for evaporation pans. Advection, microenvironmental variation and super-efficient evaporation from wet leaves, in addition to the previously mentioned errors associated with the evaporation pans, effectively invalidate any conclusive conversion ratios applying to large areas of the Central Plateau from two poorly sited evaporation pans.

The evaporation formulae of Thornthwaite and Blaney and Criddle must also be viewed with scepticism for an area like the Central Plateau, far removed from the locations of derivation of the formulae, and in an area where reduced pressure may significantly alter the relationship between temperature and evapotranspiration. Pelton, King and Tanner (1960), pointed out that any correlation between temperature and evaporation must be indirect, resulting from the fact that both are determined by radiation.

The Thornthwaite equation includes an adjustment for the general variation in net radiation with latitude, but does not account for either the lag of temperature behind radiation, fluctuating Bowen ratio, or advection.

The formula of Blaney & Criddle's shares the disadvantage of the Thornthwaite equation, without having the advantages. It takes no account of variations in radiation with latitude or with altitude, and even assume that evaporation is directly proportioned to temperature down to 0°C. In an area such as the Central Plateau then, any good correlation between actual water losses from evapotranspiration and that estimated from the formula of Blaney and Criddle must be considered unlikely.

The water budget method is a promising line of approach for the Central Plateau because there is little likelihood of any significant leakage through the underlying dolerite, and because it takes into account all the factors which complicate theoretical and empirical estimates of evapotranspiration. These include advection, evaporation from wet leaf surfaces, aerodynamic roughness, and large local variations in albedo, soil moisture and bare ground.

The main error components in this analysis are likely to arise from delays in run-off between the time rain falls and its measurement as streamflow, and from the increase in percentage rainfall falling in winter months on the northern and western extremities of the Plateau.

The latter error is well illustrated in Table 32, showing evapotranspiration losses each month in the Fisher River catchment, a small (78 sq. Km, 30 sq. miles) catchment in the north-west corner of the plateau. The monthly evapotranspiration estimates based on rainfall at Bronte Park, Butlers Gorge, and to a lesser degree, Liawenee; all show negative values for winter evapotranspiration where annual losses were assumed to be 20" and 24". The equivalent data based on Lake Mackenzie rainfall, is 0.72"/month winter evapotranspiration for an annual total of 20", 1.16" for annual total of 24", and 1.60" for an annual total of

30" evapotranspiration. Since Lake Mackenzie is in the approximate centre of this relatively small catchment, and the other rainfall stations are at least 10 miles away, the estimate based on Lake Mackenzie must be considered the most realistic.

In the Travellers Rest Catchment the total area is only 56 sq. km. (19 sq. miles) and the slopes of the catchment grade steeply to the Travellers Rest Lake, in the approximate centre of the catchment. In this catchment then, the delay in run-off is likely to be at a minimum. Evapotranspiration estimates here are relatively constant for all nearby raingauge stations, averaging approximately 0.15" per winter month for annual evapotranspiration of 20", 0.53inches per month for 24" annual evapotranspiration, and 0.92inches per month for 28" annual evapotranspiration (For reference stations Lake St. Clair, Bronte Park and Butlers Gorge).

In this method of analysis, the monthly evapotranspiration calculated is actually evapotranspiration plus storage since it is calculated as rainfall-runoff. In winter the quantity of water stored in the soil is equal to or greater than the soil water in other months of the year, so that the winter evaporation is, if anything, an overestimate. For example 1" calculated evapotranspiration per winter month may be derived from 0.75" actual evapotranspiration and 0.25" water storage.

If it is accepted then, that evapotranspiration must total at least 1" per month in winter, then the annual loss must approach 30" in the Travellers Rest Catchment if the previously mentioned assumptions are valid.

In the Ouse River Catchment, 1" evapotranspiration per winter month is shown in Table 32. to correspond to approximately 25" evapotranspiration per year when based on the nearby Liawenee rainfall, or over 30" per year when based on the rainfall stations Lake St. Clair, Bronte Park and Butlers Gorge.

In the Nive River Catchment, 1" per winter month evapotranspiration corresponds to approximately 24" per year, indicating that evapotranspiration losses in this catchment are less than in the Ouse and Travellers Rest Catchments. Since most of this large catchment is in a lower rainfall zone than the Ouse and Travellers Rest catchments, the reduced evaporation is to be expected in summer when soils become depleted of moisture and evapotranspiration drops below the potential rate. It is also possible in this large catchment, that delays in run-off are greater than the smaller watersheds of the Ouse, Travellers Rest and Fisher, so that part of the measured evapotranspiration is due to increases in the water table ie, catchment storage.

In the Derwent River catchment at Lake St. Clair, the pattern is the same as in the Ouse and Travellers Rest catchments. 1" winter evapotranspiration per month corresponds to approximately 23" annual evapotranspiration with only minor variation between the three reference rainfall stations - Lake St. Clair, Bronte Park and Butlers Gorge.

It may be noted that use of the Lake St. Clair rainfall station is considered valid for monthly data when averaged over the 21 years from

1950 - 1970 wherea it was not for comparing annual totals before 1960 with those after 1960. (See next Chapter). This is because the change co-inciding with the 1960-1961 fire was presumably due to a change in raingauge site, or removal of a sheltering object, i.e. due to a factor that is constant from month to month.

Conclusions:

Evapotranspiration losses of water from the Central Plateau have been estimated from a number of methods. Estimates based on empirical formulae, relating evapotranspiration to -

(a) temperature,

(b) pan evaporation, and

(c) physical principles of evaporation,

have been calculated for the Central Plateau.

All empirical methods of estimating evapotranspiration from potential evaporation formulae have been considered at best unreliable for a heterogeneous unit such as the Central Plateau, and at worst very misleading. The main reasons for their breakdown are :

1. The complex relationships between pressure and evaporation leading to greater evaporation at high altitudes for unit temperature and radiation data, compared to lower altitudes.

2. The greater efficiency of evaporation from wet foliage compared to transpiration from dry foliage.

3. The complex pattern of vegetation cover with varying albedo and soil moisture retention, leading to a complex relationship between advection, wind speed, and evaporation, which varies greatly with locality.

4. The difficulty in measuring evapotranspiration even at a single locality due to a lack of reliable meteorological data.

It is considered that the best method of estimating actual catchment evapotranspiration on the Plateau is from the water budget approach. Since the average catchment rainfall is not accurately sampled anywhere on the Central Plateau, it has to be estimated by assuming an average annual evapotranspiration figure to add to measured run-off. By assuming that for periods averaged over approximately 20 years, raingauge station records are directly proportional to catchment rainfall, it is possible to calculate monthly evapotranspiration estimates for varying annual totals. Since evapotranspiration can be estimated most accurately in winter months, the yearly assumed evapotranspiration with monthly pattern best fitting expected winter evapotranspiration, is taken to represent the most probable annual evaporation loss from any catchment.

It is believed that evapotranspiration in winter months must average at least 1" per month. Standard empirical formulae and pan conversion ratios give calculated evapotranspiration as follows for the months June, July, August and September:

Blaney and Criddle :	Miena	0.35"/m	
	Lake St. Clair	0.94	
Thornthwaite :	Lake St. Clair	0.90	
	Miena	0.68	
Pan Conversion :	Liawenee	0.73 (a)	1.04 (b)
	Lake St. Clair	0.61	0.86

(a) Assumes $Et = Ep \times 0.49$

(b) " $Et = Ep \times 0.70$

where Et = Evapotranspiration

Ep = American Class A Pan evaporation

In winter months moisture is always freely available for evaporation at the potential rate. Although winter temperatures are, on average, very low (2.4° at Miena for June, July, August and September), there are many quite warm and sunny days where evaporation must occur at a high rate. In addition, wind speeds are commonly strong and foliage is frequently wet so that evaporation must exceed the rate for an extensive open water surface for periods after the frequent showers. Although snow is common in winter and effectively seals the low ground cover from transpiration it is of sporadic occurance, rarely lies more than a few days below 1200 m (4,000') and leaves exposed the taller shrubs and trees which constitute the main ground cover. On the Central Plateau then, the general effect of snow, in increasing the albedo and reducing evapotranspiration (as in higher mountains above the tree line such as at Kosciusko National Park) is absent and it must be assumed that evapotranspiration losses are significant despite the average low temperatures.

By assuming that monthly winter evapotranspiration is at least 1" on average, the analysis has indicated that annual losses must exceed 30" over large areas of the Plateau. Despite probable errors attributable to changes in storage within catchments, inaccuracies in raingauge records and errors in extrapolating raingauge readings to catchment rainfall, it is believed that this analysis has produced data which substantiates the theory that evaporation at high altitudes is at least as great as at lower altitudes despite the reduced temperature.

CHAPTER 4.

THE EFFECT OF A SEVERE FIRE ON STREAMFLOW

SUMMARY:

A severe fire in the summer of 1960 - 61 burnt 310 sq. Km. (120 sq. miles) in the highest and most exposed western portion of the Central Plateau. The fire burnt 70% of the 78 sq. Km. (30 sq. miles) Fisher River Catchment, 34% of the 286 sq. Km. (110 sq. miles) Ouse River catchment, 28% of the 733 sq. Km. (283 sq. miles) Nive River catchment, and 32% of the 47 sq. Km. (18 sq. miles) Travellors Rest catchment.

Hydrological records for the 10 year period before and after the fire have been analysed to detect changes in streamflow pattern. Evidence is presented to show that run-off in the post fire decade has been reduced in the Ouse, Nive and Fisher catchments by 4.3 inches, 2.3" and 2.7" per year respectively. In the lower Travellors Rest Catchment a slight increase of 0.3" per year has been recorded after the fire. The reduction was significant in the Ouse River Catchment ($P=0.02$), almost significant in the Nive River Catchment ($P=0.08$) and non significant in the Fisher and Travellors Rest Catchments.

The change in run-off co-inciding with the fire is attributed to destruction of vegetation by the fire, which razed the highest portions of the catchments. It appears that the ability of highland vegetation to increase snow deposition, intercept rime deposits, and to strain out

fine water droplets in mist, low cloud and fog, has been reduced by burning. The net loss in catchment run-off occurred despite a probable decrease in evapotranspiration in the post fire period.

INTRODUCTION:

A number of fires in the summer of 1960-61 burnt an extensive area on the western side of the Central Plateau. The area burnt had not been documented, although Mitchell (1962) referred to an area estimated at over 500 sq. miles (1295 sq. Km.) that had been burnt. This study has documented the true area burnt as approximately 310 sq. Km. (110 sq. miles). (See page 111). The fires were severe and generally razed the vegetation on the highest parts of the plateau, including Eucalypt woodland, Arthrotaxis coniferous forest, proteaceous shrubland, and peat bog. Burning continued for at least 6 months from October until April.

Sporadic burning of grazing leases has been practiced for many years in lower sections of the plateau, but this was the first fire that had touched the western catchments for decades at least, and possibly centuries. *Arthrotaxis cupressioides* (Pencil Pine) is an extremely slow growing conifer common on the western side of the Central Plateau and is a sensitive indicator of fire, since it has no adaptive mechanism to survive burning, as have the Eucalypts. The presence of extensive numbers of these trees which now remain as dead trunks (plate 7) is strong evidence that the western side of the plateau had not been severely burnt for a long time before the 1960-61 conflagration.

H.E.C. water catchments that were burnt or partially burnt in this fire are listed on page 10. Streamflow records for at least 6 years before the fire and 10 years after the fire are available for three catchments that were severly burnt (Ouse, Nive and Travellors Rest). The Fisher River catchment has records extending back to 1956, and the Lake St. Clair catchment, which was untouched by the fire, has records from 1937. Rainfall records are also available from most areas burnt.

The availability of hydrological data both before and after 1960-61, then, has provided a unique opportunity to determine the effect of a severe fire on run-off in an alpine region.

Mapping of the Fire Boundary. The total area burnt was mapped from a number of ground reconnaisance trips. These basically comprised:

a. 4-day trip from Lake Mackenzie to Lake St. Clair.
b. 3-day trip from Lake Augusta to Clarence Lagoon.
c. 2-day trip from Lake Mackenzie to Lake Augusta via Forty Lakes Peak and Wild Dog Tier.
d. 5-day trip from Lake Augusta to Mt. Jerusalem via Great Pine Tier and return to Lake Augusta via Pillans Lake.
e. 2-day trip to Julian Lakes via Stumps Lake and return via The Throne and Little Split Rock.

Fig. 15 depicts the area traversed during mapping.

The fire edge is still clear in most places on the western plateau, 10 years after the fire. Near Pillans Lake the pattern is less distinct and a number of smaller fires have created a mosaic pattern, with small unburnt areas intermingled with burnt patches.

The fire burnt a total area of approximately 310 sq.Km. (120 sq.m), most of which included the highest, most exposed portions of the plateau. Approximately 30% of the burnt section was above 1200 m. (4000') and 90% above 1050 m. (3500'). Fig. 15 shows the areas burnt in each catchment, and the percentages are listed in description of catchments on page 10.

The plant associations burnt include all those listed on page 7. Recovery since 1960 varies with vegetation type and with altitude. A summary is given below.

1. Arthrotaxis cupressioides open forest. Most of the original stands of Arthrotaxis have been killed and regrowth in all areas is nil. Stands killed include a comparatively large forest of approximately 60 hectares (150 acres) near a long, unamed lake, east of Mt. Jerusalem, and several small areas of 0.1 to 1 hectare in extent. Many isolated living trees remain fringing the shores of lakes and tarns, and in sheltered sites, on islands, that have missed the main onslaught of the fire. These remaining trees should act as a source of seed for regeneration, but no recolonisation is evident 12 years after the fire. It is probable that seedling establishment is hampered by frost heaving in winter and by browsing.

2. Eucalyptus coccifera open woodland. Eucalyptus coccifera is the main tree in the highest parts of the plateau, occuring extensively over the freely drained, rocky hill tops west of Lake Augusta. Since Eucalyptus coccifera stands dominate in the most exposed locations, they

have suffered heavy damage from the fire over large areas. Regrowth from seedlings and lignotubers has occurred but in many localities subsequent insect damage (plate 10) has killed the foliage. Regrowth from lignotubers is less than 20% in many sites and seedlings are sparse in the most extreme climatic zones. Height of lignotuber regrowth above 1200 m. altitude is less than 1 metre, 12 years after the fire. Near Lake Norman, regrowth is approximately 3 metres high in sheltered aspects while on the slopes above Travellors Rest Lake, it reaches 6 - 7 metres.

3. Heath. Extensive stands of Orites acicularis - Orites revoluta tall heath have been burnt, but regrowth is evident in most areas although it is less than 30 cm. high after 12 years. Many of the associated species such as Richea acerosa, Epacris gunnii, Grevillea australis and Cyathodes dealbata show a similar rate of recovery but large areas of bare ground still remain between the recolonising bushes. Helichrysum hookeri, Olearia algida and Olearia ledifolia have colonised extensively after the fire and moss covers large areas.

4. Sedge. Sedgeland communities of Restio australis, Carpha alpina, Astelia alpina, Lepidosperma filiformae, Richae scoparia, Richea gunnii, Gleichenia circinnata and associated minor species, have suffered to a varying degree according to the severity of the fire and species composition. Many peat bogs have been destroyed to the base of the peat layer, while other sites show almost complete recovery. Presumably the sites with a water table near ground level at the time of the fire have been able to recover, while slightly drier sites have been severly burnt where the fire was able to penetrate through the peaty root system.

Assumptions Inherent in Statistical Analysis Techniques:

Classical experiments on the effect of a treatment, such as clearing or burning, on a catchment have used paired catchments. Extrapolation of the relationship between the streamflow from the two watersheds before the fire, to a period after the fire, then enables the difference between observed and calculated run-off to be attributed to the treatment (e.g. Bates and Henry, 1928).

The paired catchment method can give misleading results if climatic conditions before and after the treatment vary, and can detect only large differences without refined analysis to allow for fluctuations in rainfall and evaporation, both in space and in time.

There is no generally accepted method of analysing the effect of a treatment on streamflow. In many cases run-off is merely presented both before and after treatment, with any obvious differences being ascribed to the treatment, (e.g. Maruyama and Inose, 1956; Hoyt and Troxell, 1934; Rowe and Colman, 1951). Most of the experiments on catchment areas reviewed by Penman (1963) are of this nature. Rainfall is sampled with a minimum number of raingauges and run-off subtracted to estimate the water loss through evapotranspiration. A change in calculated evapotranspiration coinciding with the date of treatment is subsequently attributed to the treatment without rigid statistical verification. Although in some situations statistical methods of analysis may be unnecessary, there are many cases where non-random patterns of rainfall, and rare events of extreme amounts of rainfall could account for differences in calculated evapotranspiration from year to year.

Statistical methods of approach have basically used regression analysis, although multi-variate analysis has been proposed by some workers. Before outlining the procedures normally adopted using regression analysis, the assumptions tacit in such statistics will be briefly reviewed, in order to demonstrate the difficulties in fitting hydrological data to statistical analysis :-

1. Errors occur only in the dependent variables, and not in the independent variables. That is, in the regression of y on x, the line of best fit is such that the sum of the deviations squared (of observed y values from expected y values) is minimal, and all x values are measured exactly. Alternatively, the regression of x on y assumes y values to be measured correctly.

The presence of error is obvious in all hydrological data involving measurements of rainfall, run-off, temperature and other climatic parameters. Time is the only truly independent parameter for many regression equations. Where error exists in both the x and y variates, the underlying relationship is unidentifiable and lies somewhere between the regression line of y on x and that of x on y. This difficulty is irrelevant if the relationship is desired purely for prediction. For example, the regression of run-off on rainfall is a valid estimate for predicting run-off from rainfall but not rainfall from run-off (Bulmer, 1967).

In a simple bi-variate case such as this, the methods of multivariate analysis are considered by Snyder (1962) to be preferable to regression. Where the error variance of x and y are equal:

$$b = W + \sqrt{1 + W^2}$$

where $$W = \frac{\sum (y - \bar{y})^2 - \sum (x - \bar{x})^2}{2\sum\left[(x - \bar{x})\ (y - \bar{y})\right]^2}$$

b = slope of regression.

2. The variance of the dependent variables does not depend on the values of the independent variables (Sharp et al, 1960).

This assumption is violated where the parameters rainfall or run-off are used as "independent" variables. The size of the variance in most hydrological data is proportional to the size of the event, and the size of individual events in the dependent variable influences the size of the independent variable. For example, small values of precipitation are associated with low values (and variance) of run-off, but high precipitation results in high values of run-off with associated large variance. Similarly, run-off in one catchment tends to be associated with run-off in an adjacent catchment because both catchments are controlled by incident precipitation, which is strongly correlated in adjacent catchments.

3. The observed values of the dependent variables are uncorrelated random events (Riggs, 1968).

This assumption does not hold for many hydrological parameters because the occurance at any time influences the occurance of the same parameter for successive periods of time. Both run-off and to a lesser extent, rainfall may be influenced by previous occurances. For instance, if streamflow is high in one month, then because of saturated soils and a high water table, there is a high probability that run-off in the next month will also be high. Sharp et al (1960) give a correlation coefficient of 0.616 for run-off in the Deloware River for June and July, which compared with 0.412 for precipitation.

Long period cycles in weather patterns may also occur, and can correspond to a catchment treatment such as clearing or burning. However stringent the precautions taken, the risk of changing conditions coinciding with application of a treatment, remains.

In addition to the danger due to weather cycles, is the possibility of measuring apparent change in a hydrological parameter (which is in fact, due to a calbiration change in the measuring device). In this respect the risk is high in determining changes due to fire, because fire frequently destroys raingauges and stream recording devices, or at least alters the exposure of raingauges by destroying nearby vegetation. Rain gauge replacement invariably changes the measured rainfall, because of the sensitivity of raingauge input to exposure as expressed through height of installation, shielding from vegetation, and gauge type. Streamflow gauges may be influenced by fire (which may sufficiently alter the relationship between measured discharge and stage level), by sedimentation in the vicinity of weirs, by increased peak flows which cannot be calibrated accurately, or by replacement of the measuring unit.

4. The population of the dependent variable is normally distributed about the regression line for any fixed level of the independent variables

under consideration. (Sharp et al, 1960). Since the period of record in any hydrological analysis is usually limited, it is difficult to prove that this assumption holds. The presence of one or two extreme events have a disproportionate effect on regression slopes and correlation co-efficients, and may give misleading significance levels. The magnitude of this effect increases as rainfall decreases, so that in arid regions most of the run-off can result from extreme rainfall and storms. On the Central Plateau, rainfall is relatively high with an even distribution so that skewness of this nature is unlikely to be important.

An important source of skewness however, can arise from erroneous values that have been included in meteorological records. For example, evaporation from an Australian Sunken Pan at Lake St. Clair for 1962 is listed in records as 40.72" which includes 2.7" in August and 2.1" in July. This data is unrealistically high and presumably occurred because of a leakdge, or water consumption from the pan by native animals. The reliability of records for many of the isolated Tasmanian highland localities is low and it is considered that all events differing markedly from normal, (or from nearby stations recording the same parameter) should be recognised as anomalies, rather than occasional extreme values expected from a normal distribution.

Brown (1970) pointed out that it is rare for all the above requirements to be fulfilled, but that minor departures will not affect the validity of results. It is clear however, that all significance tests applied to regression models must bear in mind the possible errors in interpretation arising from extreme events, from possible changes in rain-gauge and run-off calibration due to gauge replacement or removal of shielding vegetation, and from invalid assumptions of independence of individual events.

Methods of Analysis:

In all experiments in which the effects of a treatment on a catchment are being observed, it is desirable to view changes over a number of time intervals. This is done most simply by plotting a regression of the dependent character on time, or by a mass curve, in which the sum of the dependent character on time is plotted. A mass curve provides a convenient visual display of data, since a change in the mean of the dependent character per unit time interval is represented by a slope change in the regression. Extreme values are not given undue emphasis in a line of best fit by the method of least squares in a mass curve, and year to year fluctuations resulting from delays in run-off and changes in storage, are evened out. In a normal regression on the other hand, the slope for any series of time intervals is largely determined by extreme events, and a change in the mean values per unit time interval is not readily depicted visually.

In this thesis, data is presented in the mass curve format for most illustrations. It is important to bear in mind that statistical tests of significance on the slope of a mass curve are invalid because consecutive points on the graphs are not independent estimates of the dependent variable.

Methods of analysis adopted by various workers are described below:

1. Multiple Regression Analysis. Regression analysis with a number of dependent variables is valid for purposes of prediction, and

regression analysis has commonly been adopted, using as many variables as can be obtained that are correlated with the variable under study. Significance tests are limited by the validity of the assumptions previously mentioned. The procedure has been adopted by many workers including Wicht (1968), Sharp et al (1960), Brown (1970, 1972), Wilm (1943, 1949), Brakensiek and Amerman (1960), Anderson and Hobba (1959) and Johnson and Kovner (1956).

The procedure outlined by Brown (1970) using electronic computer is basically as follows:

a. Partial and multiple correlation coefficients and regression equations are obtained for both linear and logarithmic relationships with increasing number of independent variables from the simple two variable case until the addition of a further independent variable does not yield any significant improvement.

b. The adopted regression equation is used to calculate estimates of the dependent variable. Departures of calculated from observed values for the period used in the derivation of the equation (before the treatment) and a nominated period after the treatment are determined.

c. Deviations of the values predicted by the equations from the recorded values for both the pre-treatment and post-treatment periods are plotted in chronological order, and obvious differences are attributed to the treatment.

The methods of analysis adopted by Brakensiek and Amerman (1960) and by Wicht (1967) were designed to remove variations in observed run-off due to year to year fluctuations. This was done by using an index watershed to document uncontrolled climatic factors. The basic procedure is as follows:

1. A control catchment, known to have suffered no major vegetation changes for a number of years, is chosen as an index watershed. The linear regression of run-off on time is plotted by standard methods, and the deviation of observed from expected run-off for each year is calculated.

2. Deviations from expected run-off in the index watershed are added to the observed run-off in the treated catchments, enabling an "adjusted" streamflow figure to be calculated for each year, which is independent of year-to-year variations in precipitation.

3. A linear regression of adjusted run-off on time in the treated catchments then enables a statistical test on the slope of the regression to detect long term changes which are attributed to the treatment.

Brakensiek and Amerman (1960) believed that significance tests could be made on the regression co-efficients "by the usual procedures". Wicht, on the other hand recognised that valid estimates of significance had yet to be evolved, although he believed that general trends could be detected in the procedure outlined above. The whole procedure is considered invalid by this writer because the regression equation of best fit for the index watershed is rarely significant in itself, being altered in a major manner by one or two of the extreme sets of data.

Since the adjusted run-off regression in the treated catchment is determined by the deviation of the data on the index watershed from expected values on the regression line, the final adjusted catchment run-off trend is, in effect, determined by one or two extreme values in the index catchment. This can be illustrated by an example:

Using the Lake St. Clair Catchment as an index watershed in Tasmania, and the Ouse Catchment as a treated catchment, the relevant unaltered data for Lake St. Clair is presented on Fig. 16. The calculated adjusted regression for the Ouse River catchment run-off on time is shown in Fig. 17. The procedure adopted by Brakensiek and Amerman has been slightly amended by reducing Lake St. Clair data by a constant percentage to bring the average run-off of 133 cm. down to the same as the Ouse Catchment (110 cm.). In Fig. 18 the index watershed regression has been recalculated with data for 1950 and 1968 omitted. The Ouse Catchment adjusted time trend is seen to have changed markedly so that it is in fact "significant" of the 5% level. The significance is clearly meaningless since the basis of the significance test has been violated in calculating the adjusted values from the index watershed.

Multivariate Analysis:

Multivariate analysis allows association of error with more than one variable in a quantitative manner. For the simple mean and variance of a single variable, there is substituted the concept of a vector of means and a matrix of covariances of several variables. In hydrological data analysis there is an obvious need for estimates of the independent effect of various factors and multivariate analysis techniques. Snyder (1962) described some possibilities of multivariate analysis for a simple two variable relationship and compared multivariate analysis with multiple regression analysis in establishing a relationship between rainfall and run-off.

A general review of multivariate techniques is given by Kendall (1957), including component analysis, factor analysis, and discriminatory analysis. Snyder (1962) concluded that further development of numerical solutions to multivariate analysis, as applied to hydrology, was necessary. Riggs (1968) believed that multiple regression analysis was preferable to multivariate analysis for determining cause-and-effect relationships in hydrology. Matalos and Recher (1967) concluded that factor analysis is questionable in its applicability to hydrological data.

Methodology Adopted:

In this thesis two methods of analysing the effect of the 1960-61 fire on run-off have been adopted:

1. The first method involves standard multiple regression analysis in which run-off in each burnt catchment is correlated with a number of independent characters before the fire, and then the relationship is extrapolated to determine expected run-off after the fire. Observed run-off is then compared with expected run-off and obvious differences attributed to the fire. The method is described on page 119.

2. The second approach has been developed in an attempt to reduce two inherent difficulties in measuring run-off changes due to a treatment. Firstly, the year to year variability in run-off caused by

variability of precipitation, and secondly, the variability in the relationship between run-off in any one year in adjacent catchments of differing average precipitation. For example, catchment A with average annual run-off of 125 cm (50") will average approximately 200 cm (80") of precipitation, while an adjacent catchment B may average 90 cm (35") run-off from precipitation of 165 cm (65"), assuming that evapotranspiration in both catchments averages 76 cm (30"). In a year of below average rainfall then, for example, when rainfall is reduced in both catchments by 30%, the run-off in catchment A is reduced by 48% and in catchment B by 56%, again assuming 76 cm evapotranspiration per year. In practice, further complications arise because evapotranspiration is normally less in a dry year because of limited soil water availability in summer. This does not necessarily occur, especially where rainfall has a winter maximum and where summer rainfall is adequate to maintain soils near field capacity, as in the wetter mountain catchments of Tasmania.

The method measures changes in evapotranspiration from year to year, thereby reducing a major source of variability due to changes in precipitation. This is because evapotranspiration is relatively constant from year to year, and is, in fact, the parameter that is ultimately required as the causative agent in any change in run-off due to the fire.

Basically, the analysis procedure is as follows:

1. Measured discharge is converted to depth over the catchment and an approximate constant value for evapotranspiration (for example, between 50 and 75 cm per year) is added to enable determination of

of average catchment rainfall.

2. Measured rainfall in all nearby precipitation stations is assumed to be proportional, for any complete year, to the average catchment precipitation. The conversion constant (K) for mean measured precipitation ($\bar{R}$) at any raingauge station to average catchment precipitation ($\overline{RO + E}$) is calculated from the average of all years of record as $K = \frac{\overline{RO + E}}{\bar{R}}$ Actual calculated catchment precipitation for any single year is then determined by multiplying the measured rainfall at the raingauge site by the constant.

3. Evapotranspiration in each year is calculated as -

$E = R.K. - RO$, where RO is depth of run-off.
R is rainfall at raingauge station.

4. Mean evapotranspiration before and after the fire is tested for significant differences with a 't' test, and a regression of sum evapotranspiration on time is plotted to visually determine obvious progressive effects in the first few years after the fire.

5. Independent checks on evapotranspiration changes with time are calculated from all available temperature, wind - speed, humidity and radiation data.

The assumptions inherent in the method are as follows:

1. Raingauge and run-off gauge characteristics do not change coincidentally with the treatment. This can be tested in the case of raingauge stations by cross correlating all gauges after converting annual rainfall to a percentage of normal. With streamflow gauges it is

difficult to eliminate the possibility that measured changes are due to a gauge calibration change, especially if a gauge has been replaced after a fire. No streamflow gauges on the Central Plateau were destroyed during the 1960 - 61 fires although the possibility remains that unreliable peak flow calibrations with stage level may have led to measured run-off which would be attributed to the fire.

2. Raingauge station records are proportional to catchment rainfall. This assumption is obviously violated for short periods of time because rainfall is variable over short distances. When averaged over periods as long as a year, however, the correlation between the raingauge station and the annual catchment rainfall should be high.

3. Evapotranspiration can be estimated.

This assumption does not need to be highly accurate, so long as an order of magnitude for annual water losses can be determined. For instance, by assuming 50 cm (20") evapotranspiration per year, the variability induced in calculating catchment rainfall is not greatly different from that from an assumption of 76 cm (30"). (See Page 140.

The assumption of constant annual evapotranspiration is certainly not strictly valid. It does, nevertheless, enable estimates of departures from the assumed constant annual evapotranspiration each year so that a regression of measured Evapotranspiration on time shows the effect of the treatment. The assumed evapotranspiration figure is only used in determining the average catchment precipitation, and consequently departures of assumed from actual annual evapotranspiration only increase the variability of the precipitation estimate.

Results:

1. Preliminary analysis of rainfall pattern before and after the fire:

Since a change in raingauge site, type, or exposure, commonly results in a significant change in measured rainfall, a preliminary analysis of rainfall records before and after the fire was undertaken to detect any obvious discrepancies. Rainfall at all stations was converted to percentage of mean rainfall for all periods included in the analysis (1950 - 1970, where possible), and change was determined from mass curves where a change in mean rainfall is measured as a slope change. Rainfall data at all stations on the Central Plateau west of Great Lake was checked against at least one other station, and more than one where a change co-inciding with the fire was apparent. The following mass curves were constructed:

Bronte Park	x	Butlers Gorge
" "	x	Liawenee
" "	x	Shannon
" "	x	Waddamana
" "	x	Lake Mackenzie
" "	x	Lake St. Clair
Lake St. Clair	x	Shannon
Liawenee	x	Lake St. Clair
Lake Mackenzie	x	Lake St. Clair
Butlers Gorge	x	Lake St. Clair
Liawenee	x	Lake Mackenzie
"	x	Travellórs Rest

Figs. 11, 12, 13 and 14 show a sample of the graphs obtained. The magnitude of the change between any two stations for the 10 year period before the fire compared to a 10 year period after the fire, was determined by a standard t test for two regressions:

$$t = \frac{b_1 - b_2}{\sqrt{Vb_1 + Vb_2}}$$

where b = slope of regression
Vb = variance of slope

Although the significance of the t obtained is not strictly valid because the mass curve does not independently measure each data point, for the purpose of the analysis, a significant t difference was taken to indicate a suspicious raingauge station, whose data should not be used in future analysis. Lake St. Clair emerged as such a station. Comparisons with all other stations revealed that rainfall as recorded at Lake St. Clair has increased markedly for the period 1960 - 70 compared with 1950 - 60. It seems likely that this change was not real, but an anomoly due to the sampling technique, such as removal of a shielding tree, or renewal of the gauge at a different location. The analysis also revealed a reduction in rainfall at both Shannon and Waddamana in the post fire period, although the significance was marginal. It is likely that this reduction was due to a real rainfall reduction in this part of the plateau, since both stations measured a similar reduction.

Table 34 presents overall percentage changes in rainfall for the post fire period compared to the pre-treatment period.

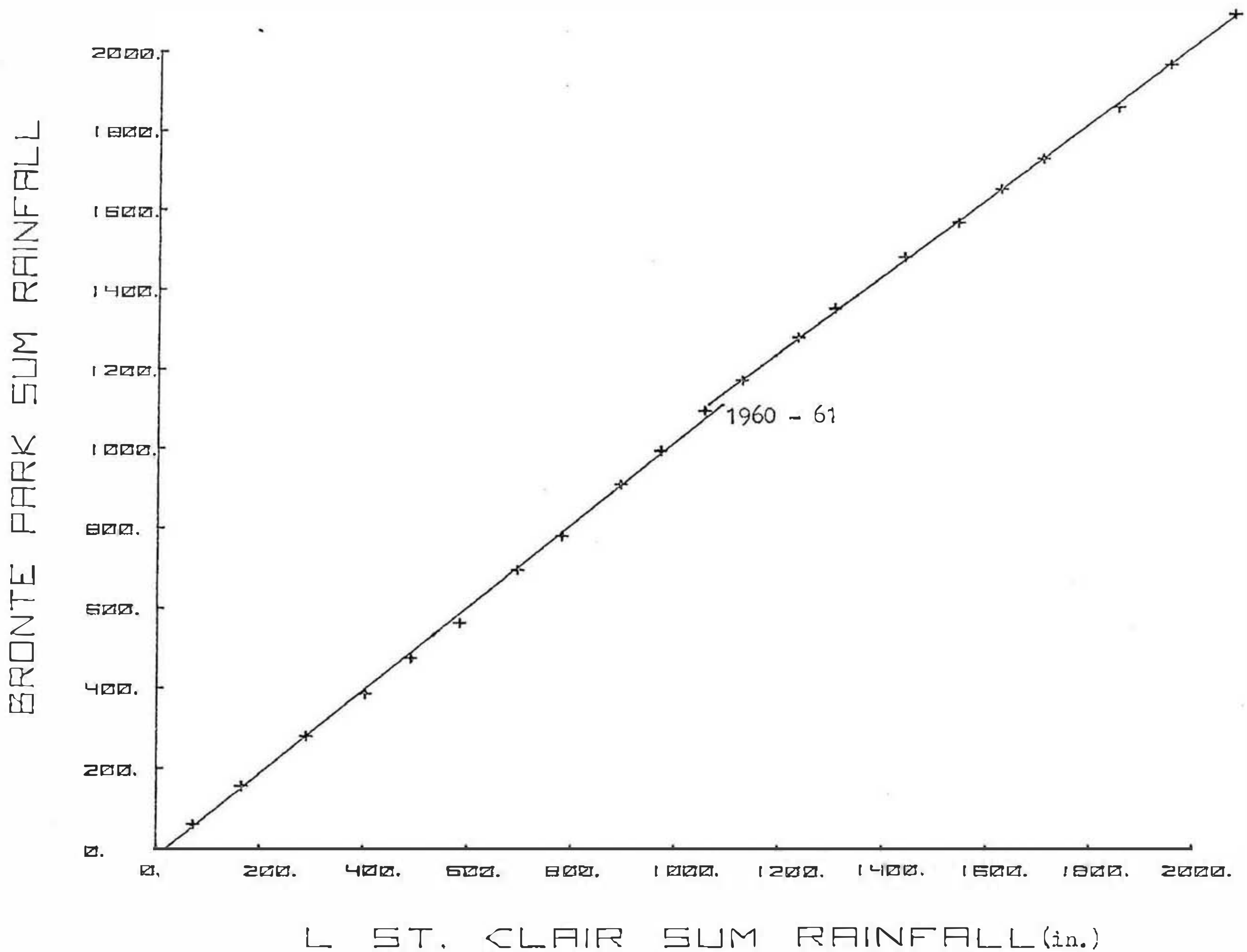

FIG. 11.

Regression of Bronte Park sum rainfall on Lake St. Clair sum rainfall for pre and post fire periods.

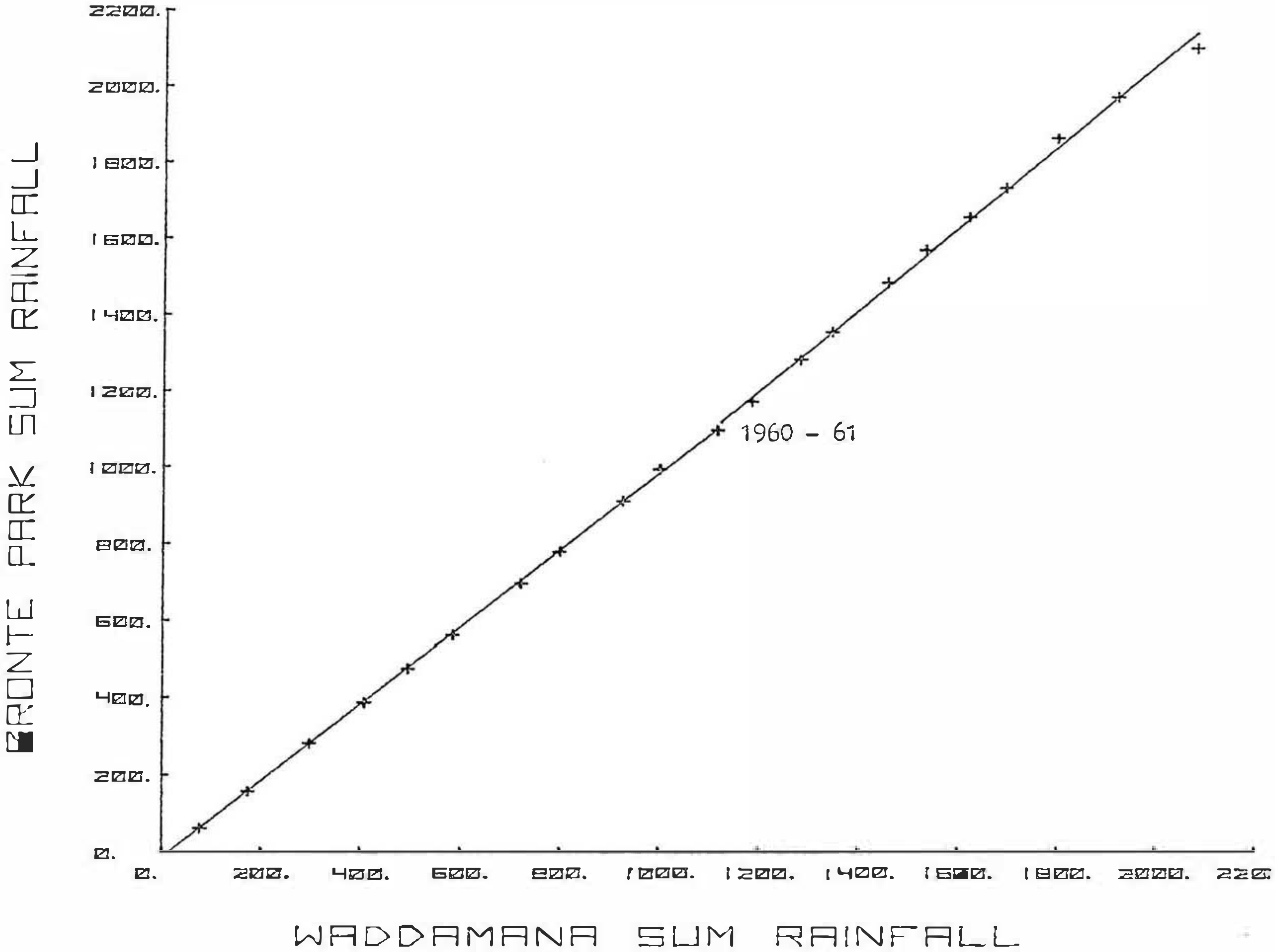

FIG. 12. Regression of Bronte Park sum rainfall on Waddamana sum rainfall, for pre and post fire periods.

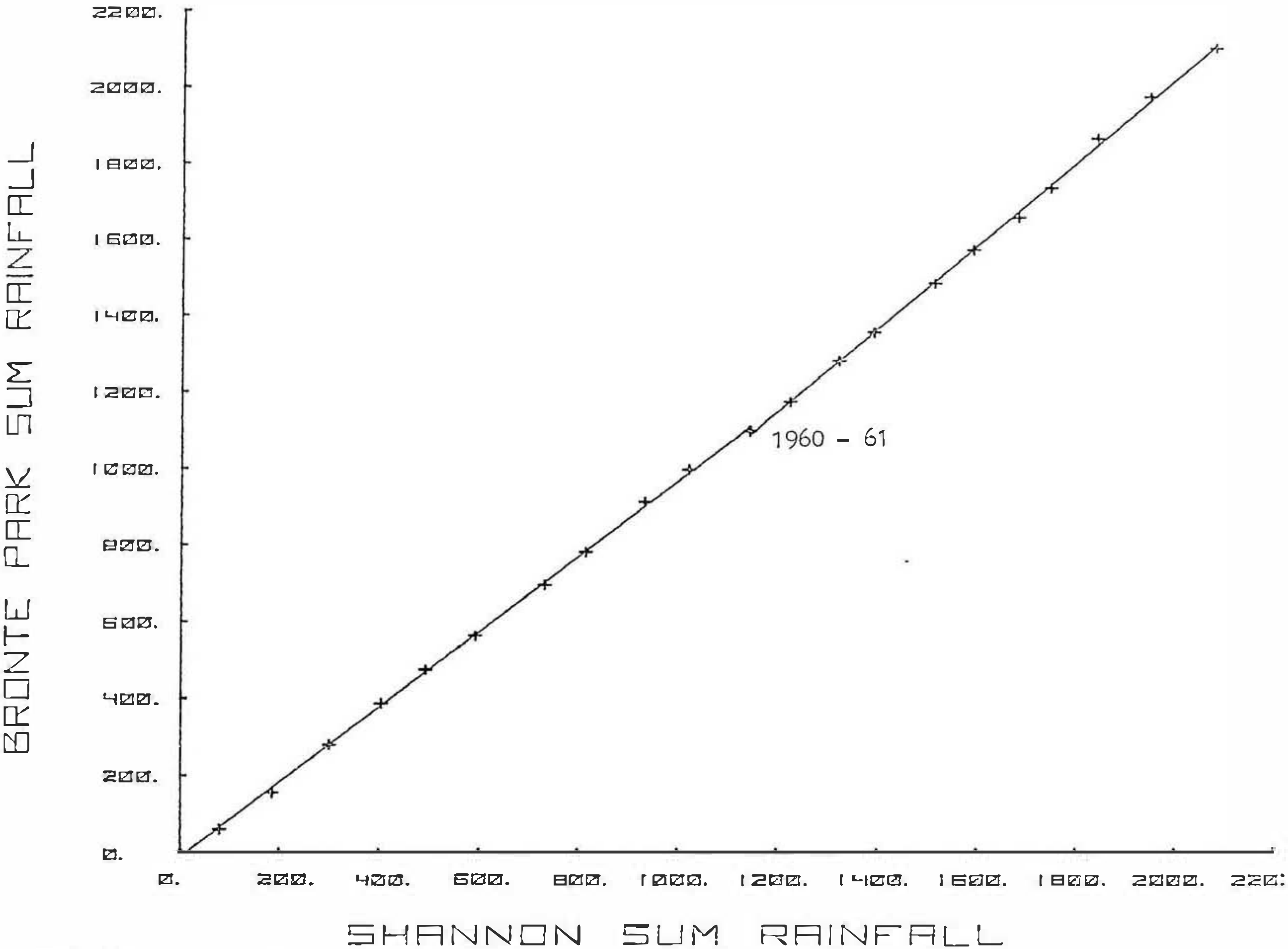

FIG. 13. Regression of Bronte Park sum rainfall on Shannon sum rainfall, for pre and post fire periods.

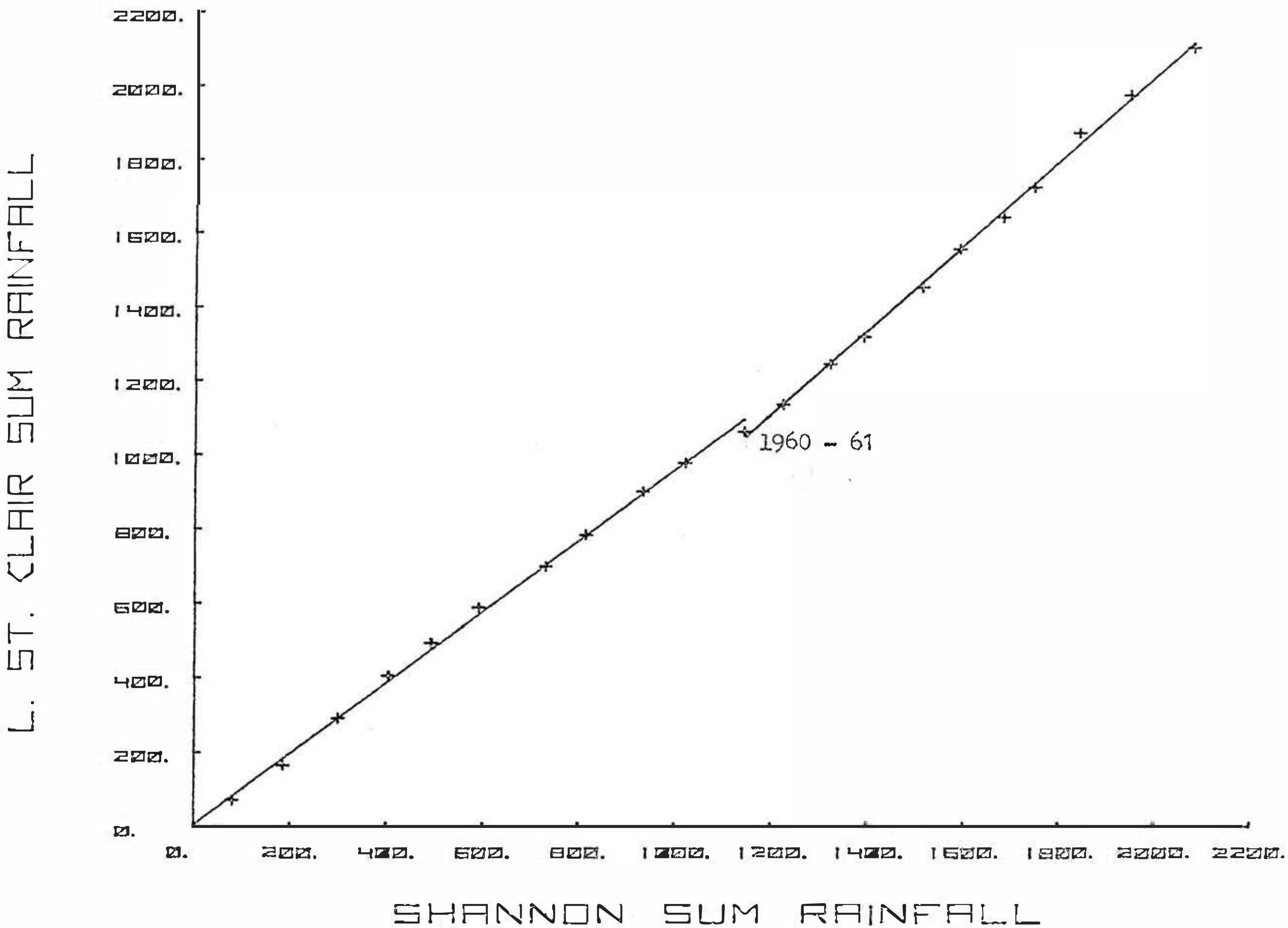

FIG. 14. Regression of Lake St. Clair sum rainfall on Shannon sum rainfall for pre and post fire periods.

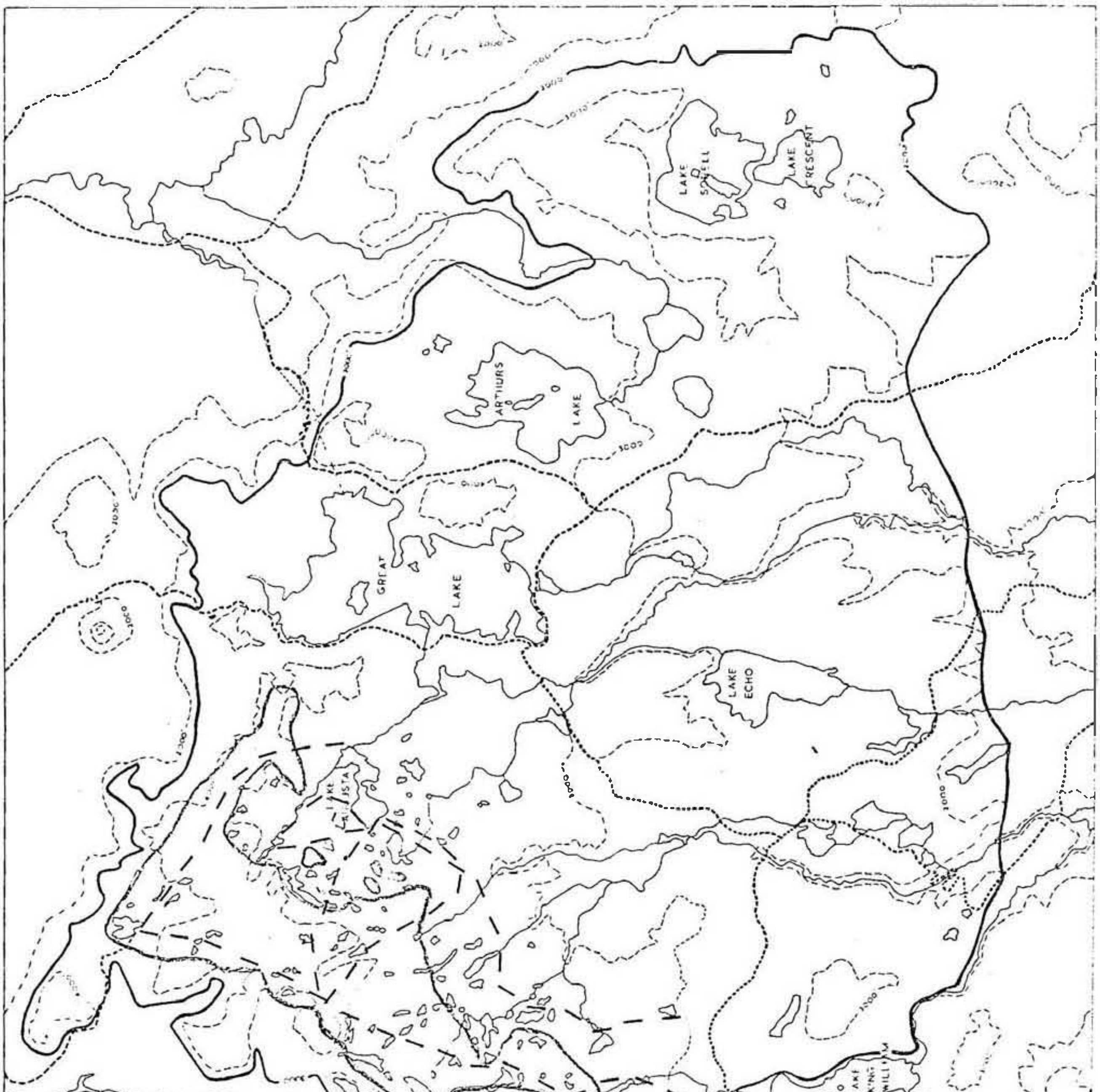

Fig. 15. Area severly burnt during 1960-61 fire. Broken lines indicate area traversed during mapping.

TABLE 34. Percentage change in rainfall for post fire period compared to pre fire period.

Station	% Change	
Butlers Gorge	0.26	Reduction
Bronte Park	0.70	Increase
Lake St. Clair	7.20	Increase
Lake Mackenzie	12.10	Reduction (only 5 years of record before fire)
Shannon	8.60	Reduction
Waddamana	4.20	Reduction

2. Multiple Regression Analysis:

Multiple regression equations were built up for the burned catchments using as independent variables -

x1 = Derwent River run-off at Lake St. Clair

x2 = Butlers Gorge Rainfall

x3 = Bronte Park Rainfall

All other rainfall station records were discarded because of insufficient length of record before the fire (Lake Mackenzie, Liawenee), suspected unreliable measuring technique (Lake St.Clair) or non random rainfall change co-inciding with the year of the fire (Shannon, Waddamana).

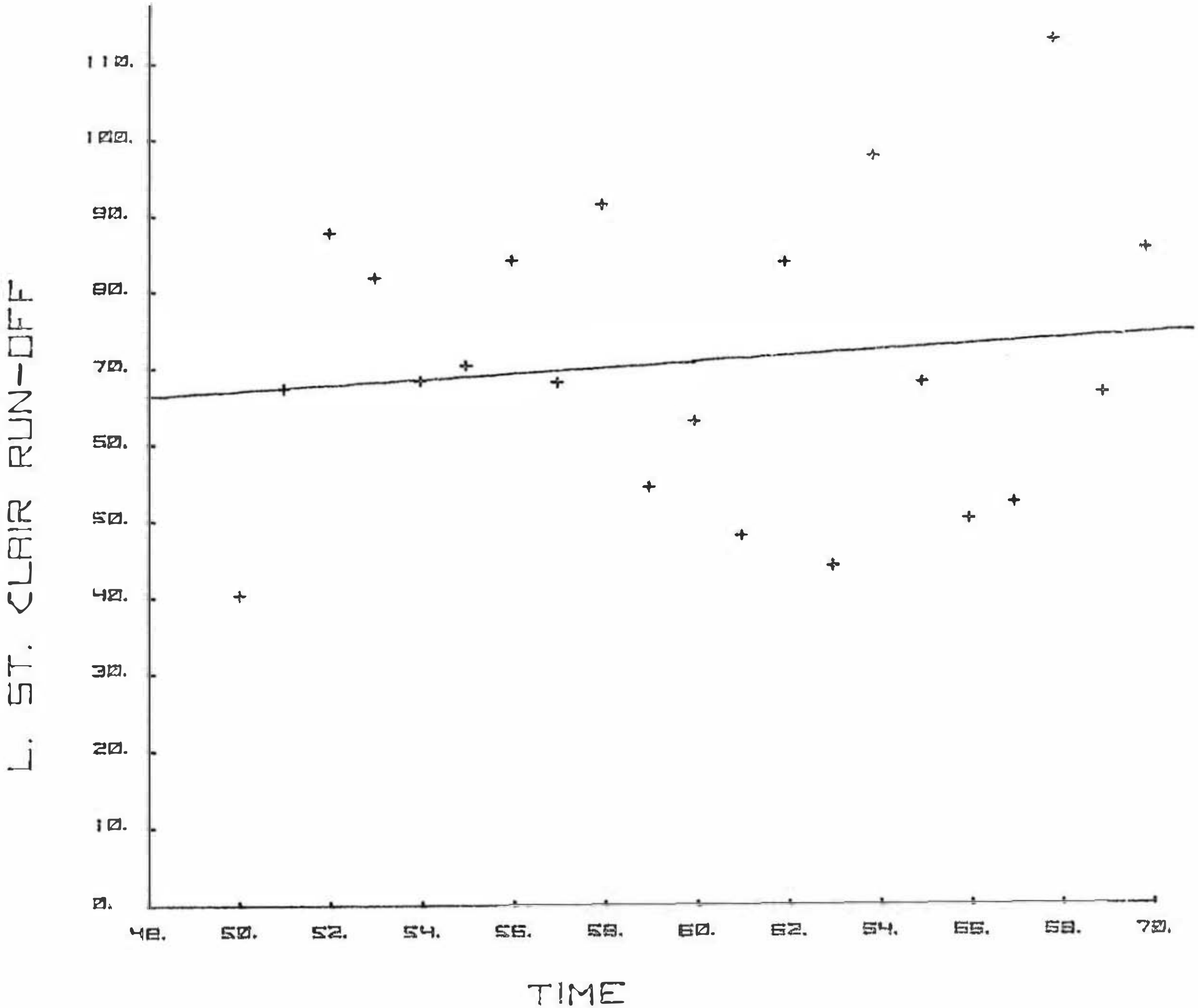

FIG.16. Regression of Lake St. Clair run-off (index watershed) on time.

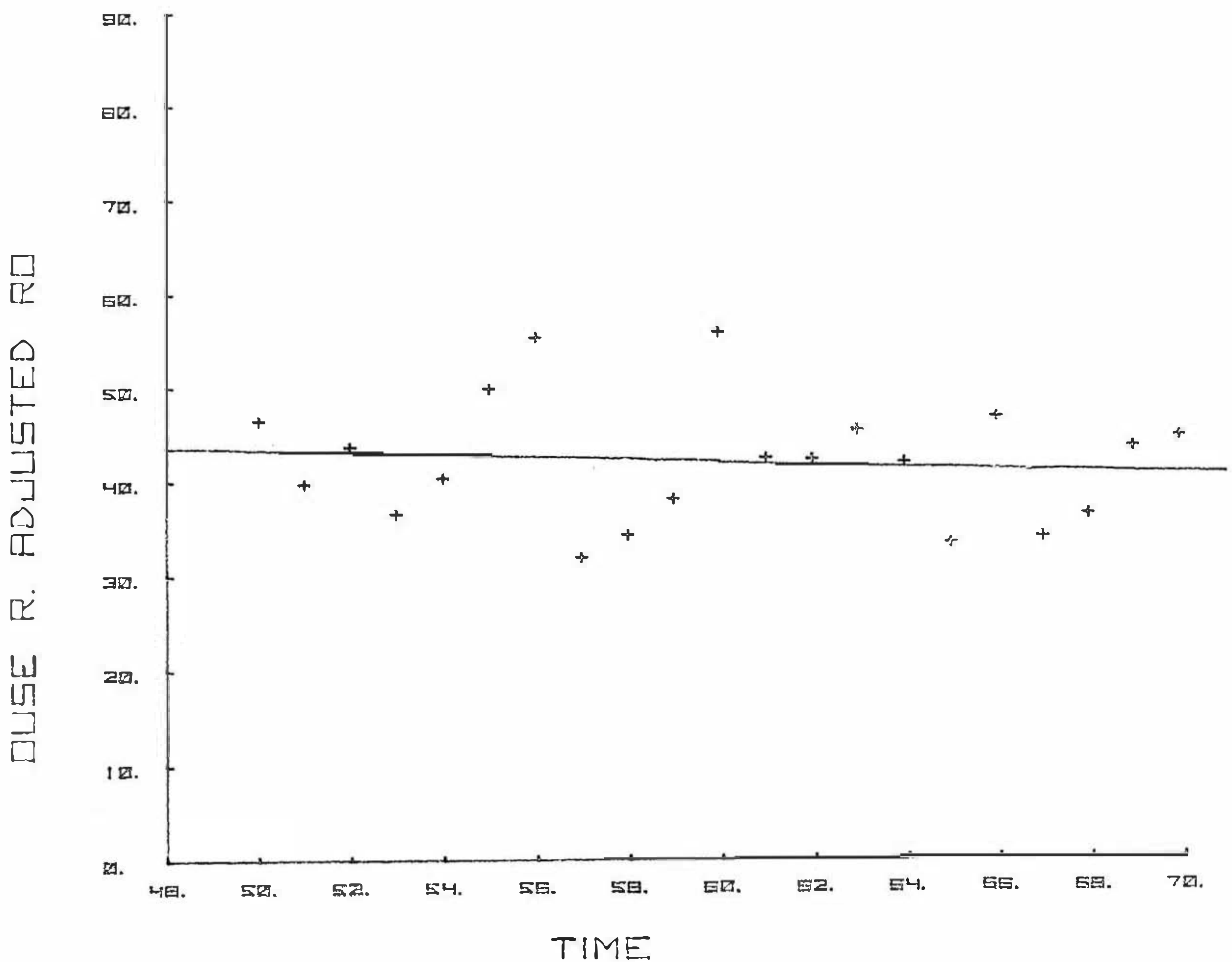

FIG. 17. Regression of Ouse River adjusted run-off on time.

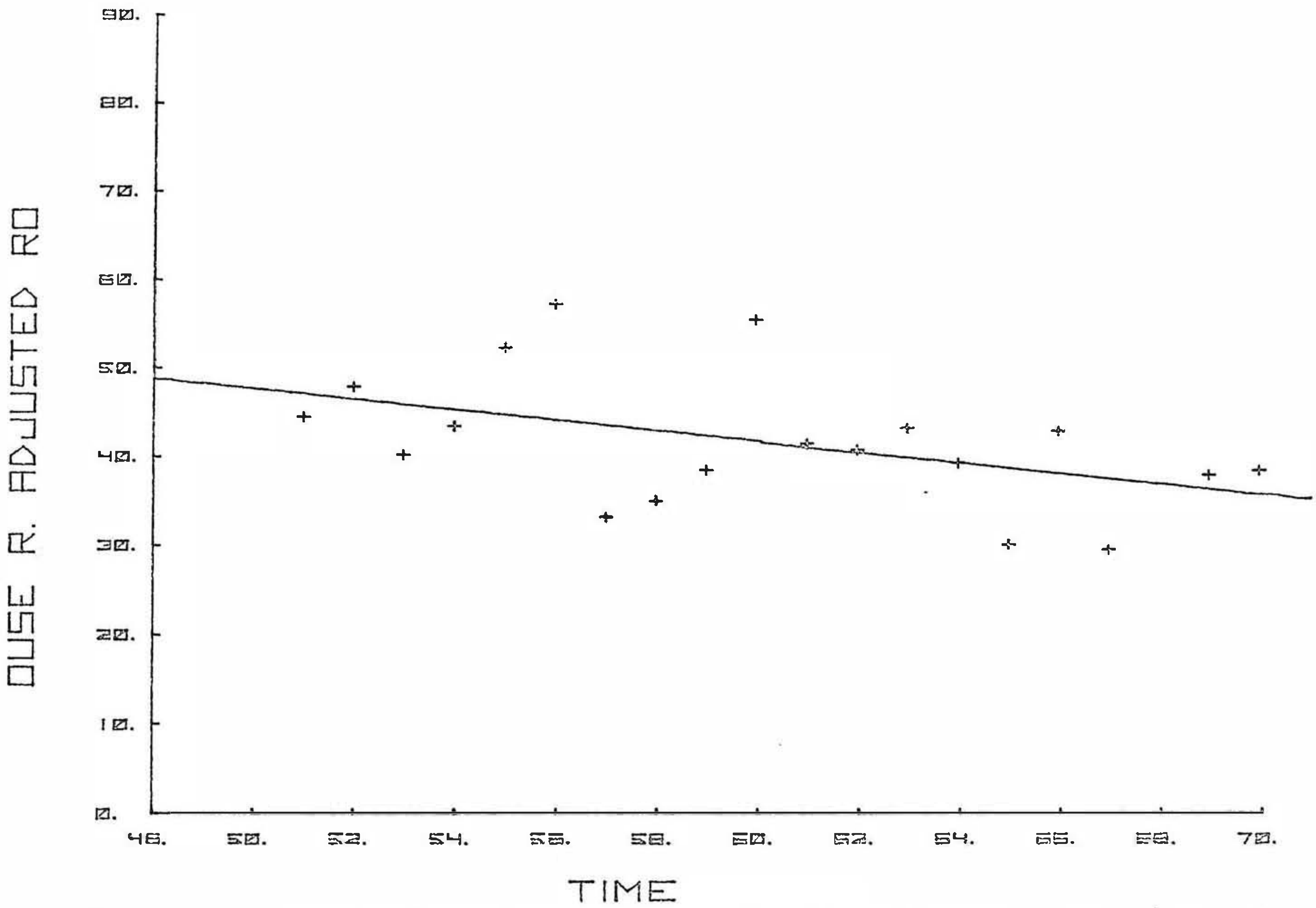

FIG. 18. Regression of Ouse River adjusted run-off on time, with years 1950 and 1968 omitted.

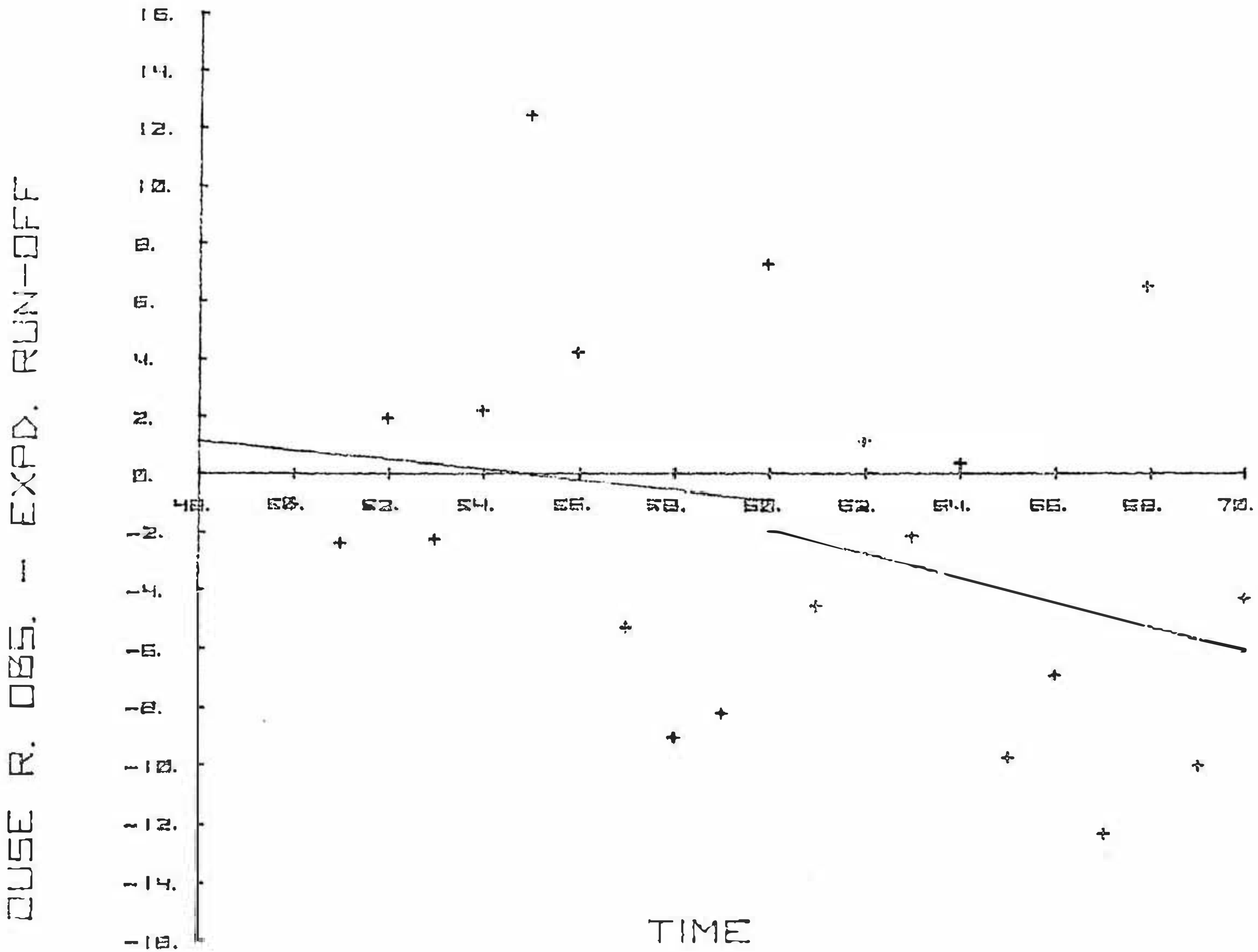

FIG. 19. Regression of Ouse River annual observed minus expected run-off, on time. Relationship based on linear multiple regression equation established during pre fire years and extrapolated to post fire years (1950 - 70).

All comparisons were taken from the period 1950 - 1960 except the Nive River catchment, where records start in 1954. All values of x and y are expressed in inches depth per annum. The derived equation with the best multiple correlation coefficient for each burnt catchment has been extrapolated to the post fire decade, by assuming the same relationship with the independent variables after the fire, as before. Deviations of calculated run-off from measured run-off have been determined and a t test for differences in mean deviation for pre and post fire periods has been applied:

A. Ouse River Catchment:

Table 35 presents correlation coefficients and equations for linear regressions up to 4 variable.

Deviations from observed run-off are plotted in Fig. 19. The regression lines drawn represent the statistical lines of best fit from the method of least squares.

A t test for differences in mean deviations of observed from calculated values in pre and post fire periods is shown in Table 42.

TABLE 35. Correlation Coefficients and multiple regression equations for annual run-off in the Ouse Catchment (1950 - 60).

Independent Variables		Mult. Corr. Coeff. (r)	Mult. Reg. Eqn.
Nive	RO (54-60)	0.91	
Travellors Rest	RO	0.737	
Derwent	RO	0.01	
Butlers Gorge	R	0.753	
Derwent RO, Butlers Gorge R		0.766	$y = -17.231 - .452x_1 + 1.413x_2$
Derwent RO, Bronte Park R		0.803	$y = 4.407 - .106x_1 + 1.364x_3$
Bronte Park R, Butlers Gorge R		0.801	$y = 2.647 + .040x_2 + 1.222x_3$
Derwent RO, Bronte Park R, Butlers Gorge, R.		0.807	$y = 6.566 + .264x_1 - .327x_2 + 1.175x$

Where R = rainfall, RO = run-off.

Multiple regression equations have also been derived for monthly run-off data in the Ouse Catchment, using Travellors Rest run-off and Derwent run-off at Lake St. Clair as independent variables. Both linear and logarithmic relationships were calculated. Results are given in Table 36.

TABLE 36. Correlation coefficients and multiple regression equations for monthly run-off in the Ouse Catchment.

r	Mult. Reg. Eqn.
.750	$y = 0.244 \times 0.333^{x1} \times 0.692^{x2}$
.816	$y = -4.080 + 0.848\, x_1 + 0.582\, x_2$

where x_1 = Travellors Rest run-off (cusecs)

x_2 = Derwent River run-off (cusecs)

y = Ouse River run-off (cusecs)

Period of comparison = 1954 - 1960.

Fig. 20 shows observed - expected run-off from the linear equation for monthly data during the period from which the equation was derived (1954 - 60) and the post fire decade assuming the same relationship.

A 4 variable multiple regression equation for run-off in the Ouse Catchment in terms of rainfall at Bronte Park, Butlers Gorge and Liawenee was calculated for annual data from 1955 - 60. The resulting equation, with all data expressed in inches depth/annum is shown in Table 37.

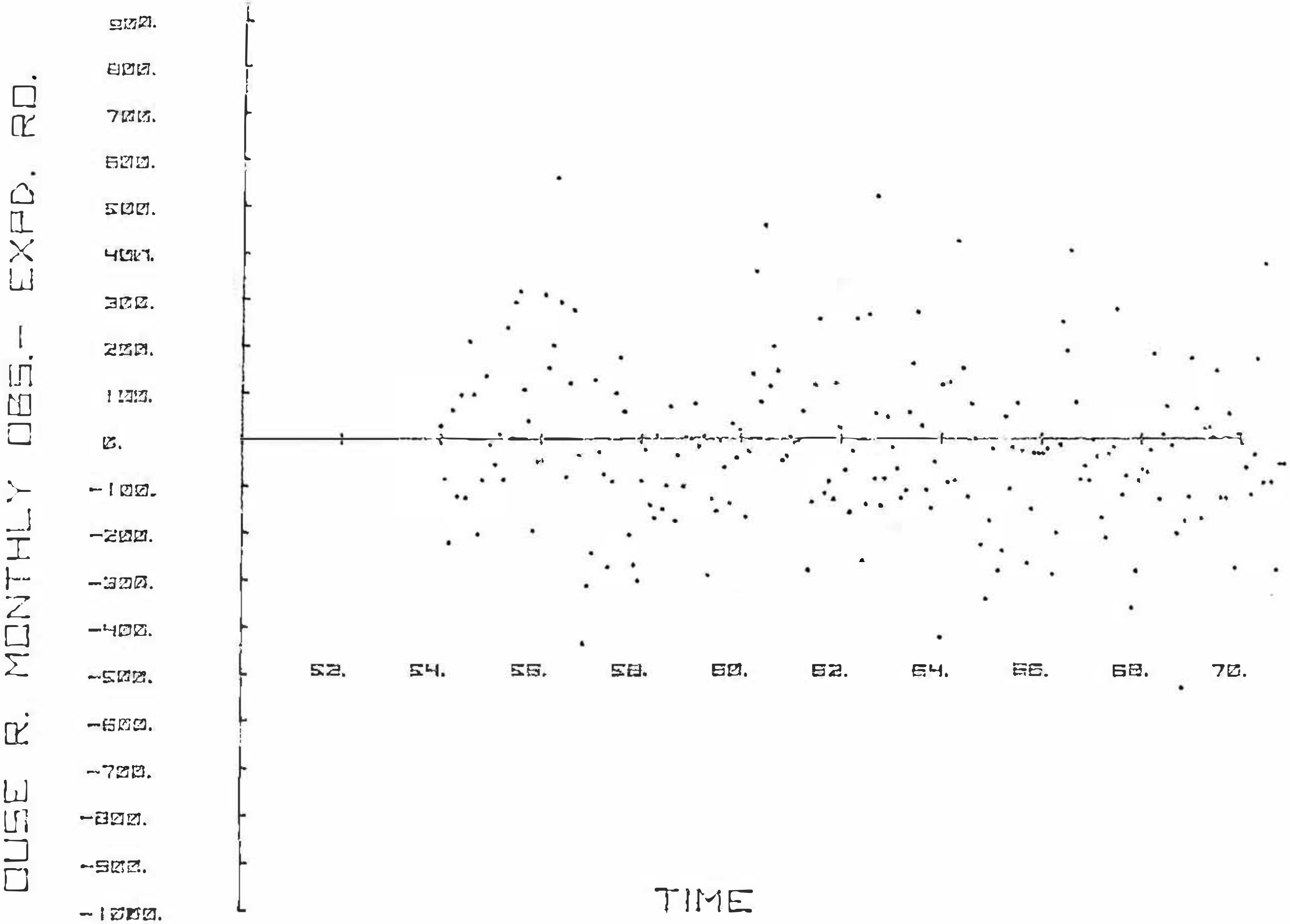

FIG. 20.

Regression of Ouse River monthly observed minus expected monthly run-off, on time. Relationship based on linear multiple regression equation established during pre fire period, and extrapolated to post fire period (1950 - 70).

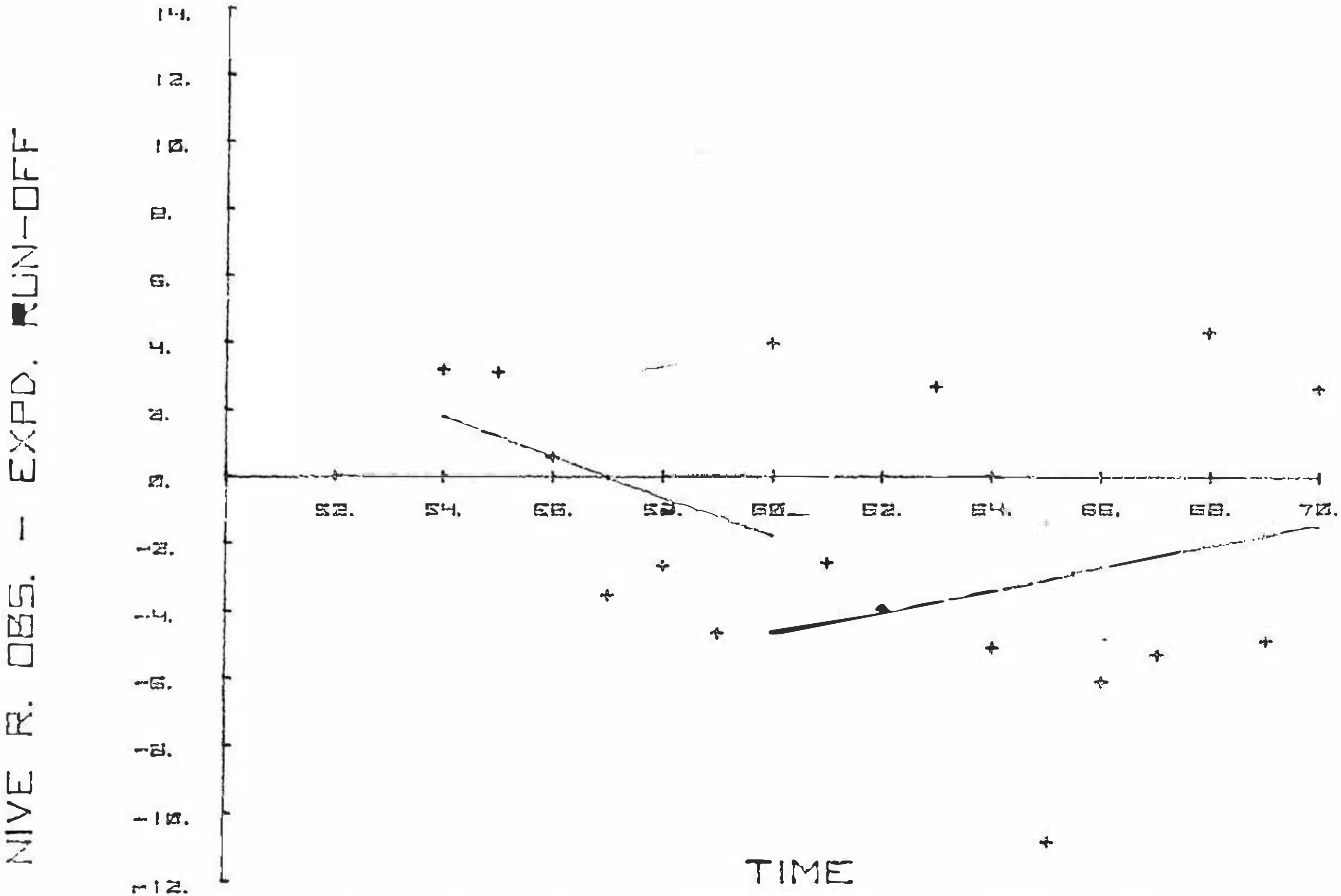

FIG. 21. Regression of Nive River annual observed minus expected run-off, on time. Relationship based on linear multiple regression equation established during pre fire years and extrapolated to post fire years (1954 - 70.)

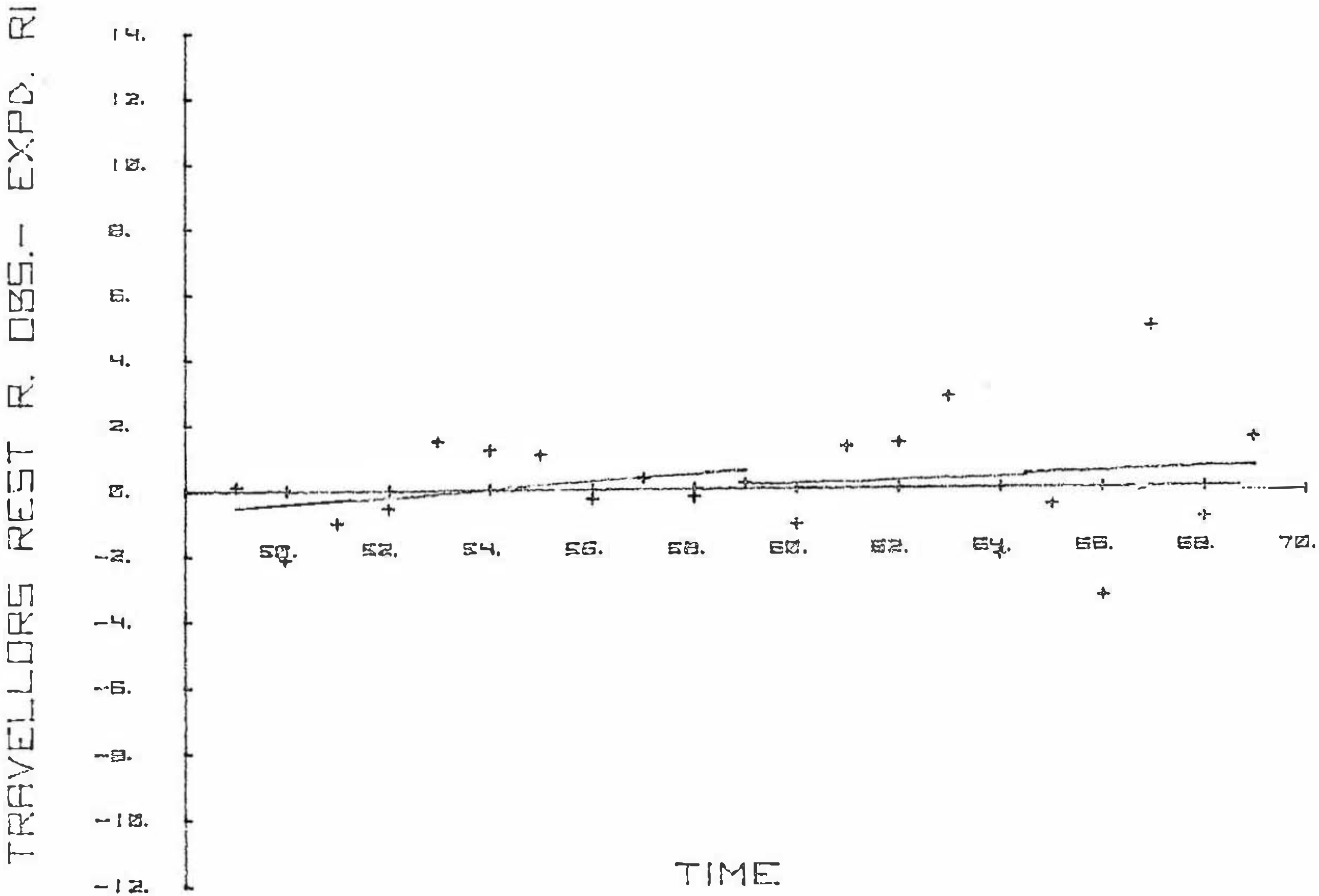

FIG.22. Regressions of Travellors Rest Catchment annual observed minus expected run-off, on time. Relationship based on linear multiple regression equation established during pre fire years and extrapolated to the period following the fire (1950-70).

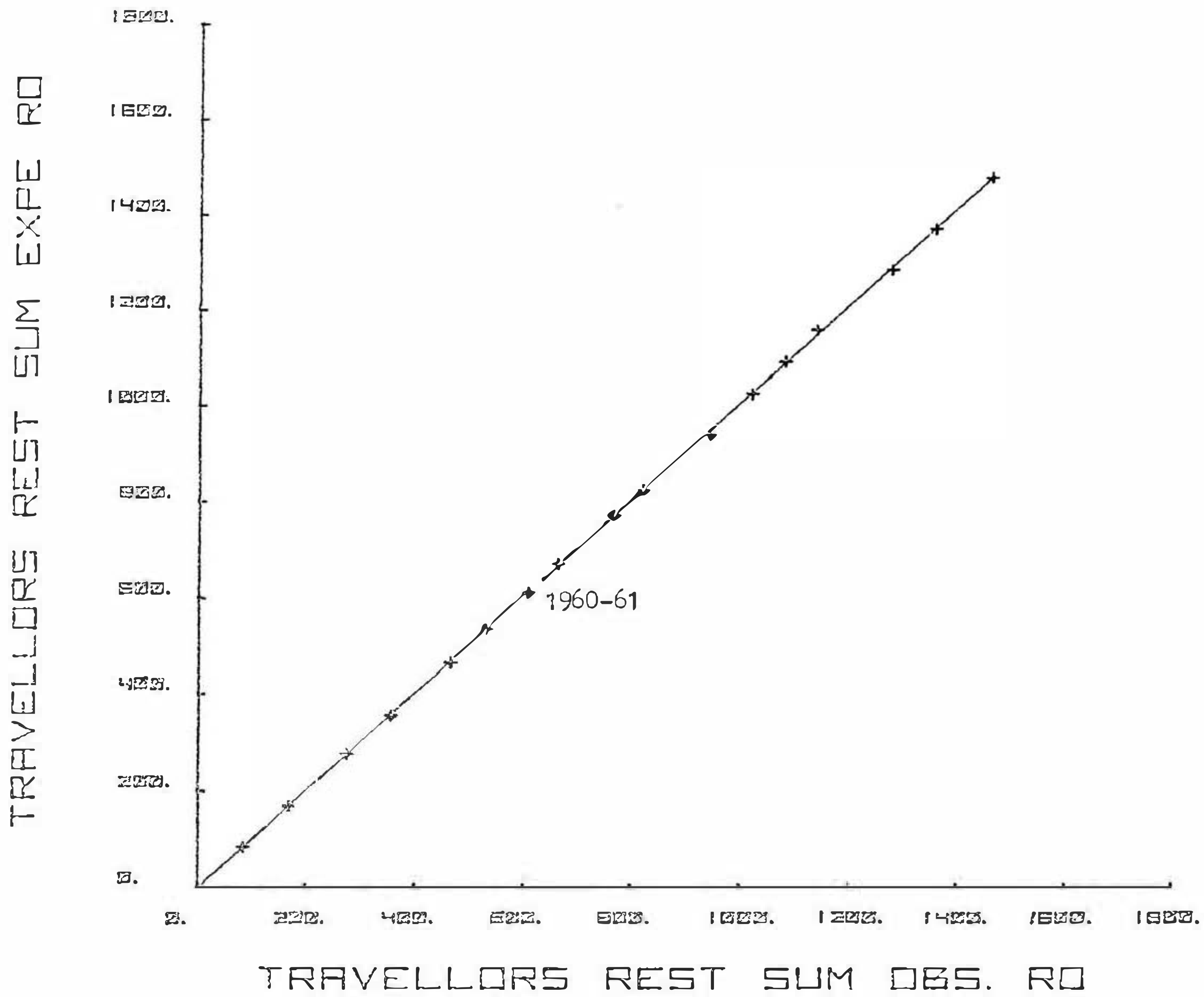

FIG. 23. Regression of Travellors Rest Catchment sum expected annual run-off, on sum observed annual run-off. Relationship based on linear multiple regression equation established in pre fire years and extrapolated to post fire years (1954-70).

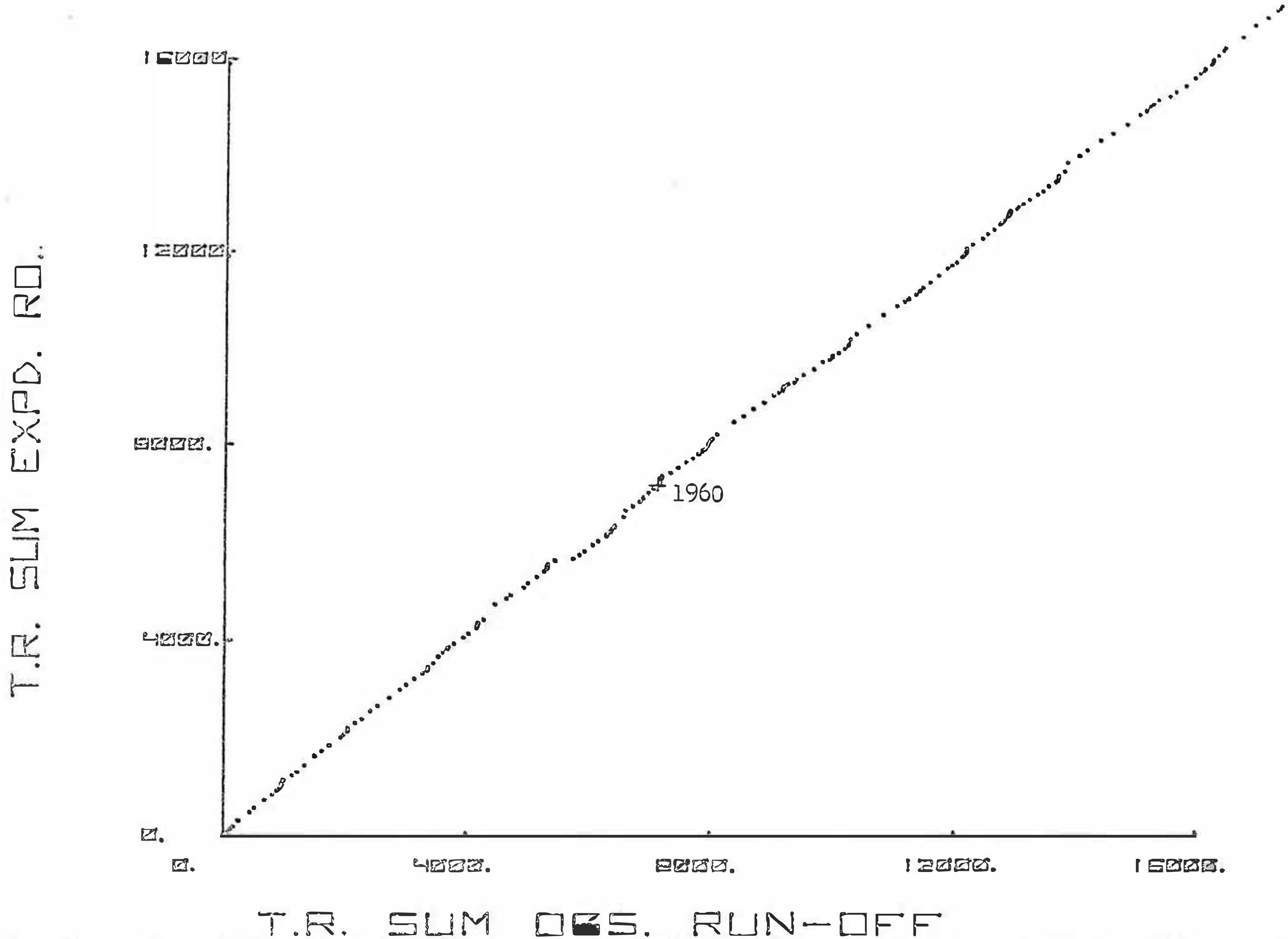

FIG. 24. Regressions of Travellors Rest Catchment sum expected monthly run-off, on sum observed monthly run-off in pre and post fire periods. Relationship based on linear multiple regression equation established in pre fire period and extrapolated to post fire period (1954-70).

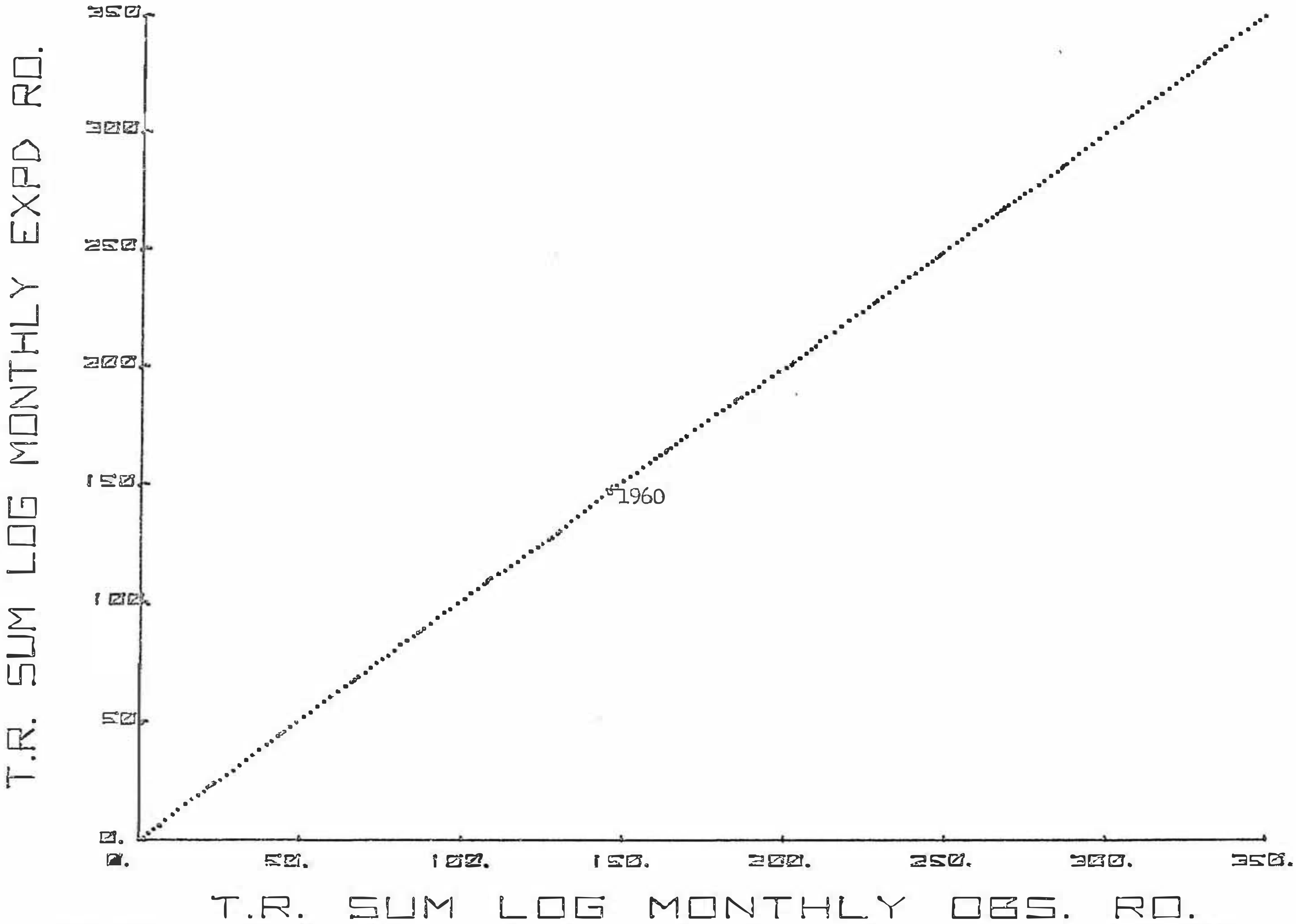

FIG. 25. Regressions of Travellors Rest Catchment log sum expected monthly run-off, on log sum observed run-off in pre and post fire period. Relationship based on log multiple regression equation established in pre fire period and extrapolated to post fire period (1954-70).

TABLE 37. Multiple Regression equation for run-off in the Ouse Catchment.

$$y = -26.263 - 0.325x_1 + 0.276x_2 + 1.630x_3$$

$$r = 0.987$$

where x_1 = Bronte Park Rainfall

x_2 = Butlers Gorge Rainfall

x_3 = Liawenee Rainfall

y = Ouse River run-off

Period = 1955 - 1960.

B. Nive River Catchment:

Data for the Nive River Catchment is presented in Tables 38 and 42 and in Fig. 21.

TABLE 38. Correlation coefficients and multiple regression equations for annual run-off in the Nive Catchment (1954 - 60).

Independent Variables	Mult. Corr. Coeff (r)	Mult. Reg. Eqn.
Ouse RO	0.91	
Travellors Rest RO	0.89	
Derwent RO	0.858	
Butlers Gorge R	0.900	
Bronte Park R	0.848	
Derwent RO, Butlers Gorge R	0.907	$y = -19.089 - .412\ x_1 + 1.238\ x_2$
Derwent RO, Bronte Park R	0.892	$y = -6.828 - .661\ x_1 + .194\ x_3$
Bronte Park R, Butlers GorgeR	0.901	$y = -14.844 + .641\ x_2 + .156\ x_3$
Derwent RO, Bronte Park R, Butlers Gorge	0.907	$y = -19.958 - .449\ x_1 + 1.324\ x_2 - 0.063\ x_3$

Where x_1 = Derwent River run-off (inches)

x_2 = Butlers Gorge run-off (inches)

x_3 = Bronte Park run-off (inches)

y = Nive River run-off (inches)

C. Travellors Rest Catchment:

Data for the Travellors Rest Catchment is shown in Tables 39 - 42 and in figs. 22 - 25.

TABLE 39. Correlation coefficients and Multiple Regression equations for Annual Run-off in the Travellors Rest Catchment (1950-60)

Independent Variables	Mult. Corr. Coeff.	Mult. Reg. Eqn.
Ouse RO	0.737	
Nive RO	0.89	
Derwent RO	0.996	
Butlers Gorge R	.980	
Bronte Park R	.921	
Derwent RO, Bronte Park R	.997	$y = 1.036 + .813\ x_1 + .181\ x_3$
Derwent RO, Butlers Gorge R	.997	$y = -3.070 + .719\ x_1 + .259\ x_2$
Butlers Gorge R, Bronte Park R	.980	$y = -16.819 + 1.197x_2 + .080\ x_3$
Derwent RO, Bronte Park R, Butlers Gorge R	.997	$y = -1.992 + .721x_1 + .184\ x_2 + 0.107x_3$

Multiple regression equations have also been calculated on monthly data for Travellors Rest run-off (y), on Butlers Gorge rainfall (x_1), Nive River run-off (x_2) and Ouse River run-off (x_3), for both logarithmic and arithmetic relationships from 1954 - 1960. Data is presented in Table 40 together with equivalent equations and correlation co-efficients for annual data. All data is expressed in cusecs except Butlers Gorge rainfall which is in points.

Monthly arithmetic and logarithmic relationships for Travellors Rest Catchment established in the pre fire period have been used to calculate expected values in the post fire period. Data is presented in fig. 24 in the format of a sum observed and sum expected graph. A change in the relationships after the fire would be expressed as a slope difference. Fig. 25 presents data for the monthly logarithmic expression.

TABLE 40. Monthly and annual Multiple Regression relationships for Travellers Rest Catchment based on Butlers Gorge Rainfall, Nive River Run-off and Ouse River Run-off.

	r	Mult. Reg. Eqn.
Monthly	0.914	$y = -0.577 \times 0.073^{x_1} \times 0.866^{x_2} \times -0.054^{x_3}$
Monthly	0.764	$y = 35.545 - 0.020_{x_1} + 0.101_{x_2} - 0.019_{x_3}$
Annual	0.995	$y = -.239 + 0.114_{x_1} + 0.047_{x_2} - 0.053_{x_3}$
Annual	0.997	$y = -0.914 \times 0.319^{x_1} \times 0.994^{x_2} \times -0.222^{x_3}$

A 4 variable multiple regression analysis is presented in Table 41, where :

x_1 = Derwent Monthly run-off (cusecs)
x_2 = Nive " " "
x_3 = Ouse " " "
y = Travellors Rest Monthly run-off (cusecs)

Period = 1954 - 60.

TABLE 41. Monthly multiple regression analysis for the Travellors Rest Catchment from 1954-1960.

r	Mult. Reg. Eqn.
0.932	$y = -0.585 \times 0.302^{x_1} \times 0.667^{x_2} \times -0.071^{x_3}$
0.771	$y = 23.876 \times 0.054_{x_1} \times 0.005_{x_2} - 0.005_{x_3}$

TABLE 42. t values and probability that mean deviations before and after 1960 fire, represent no change in Run-off pattern.

	t	Mean Decrease in Run-off After Fire (inches)	Probability
Ouse RO	1.54	3.84	0.1 - 0.2
Nive RO	1.37	2.92	0.1 - 0.2
Travellors Rest RO	0.46	0.37	

TABLE 43. Mean Maximum temperatures in pre and post fire periods (deg. F. 1950-70)

Station	1950-60	1960-70	Difference	t	Deg. Freedom	Prob.
Bronte Park	57.30	56.58	0.72	1.17	19	0.3
Shannon	52.20	52.58	- .30	.87	18	0.4
Lake St. Clair (52-70)	53.73	53.90	- .17	.32	16	0.7

TABLE 44. Mean summer rainfall (J, F, M, A, N, D) in pre and post fire periods (inches).

Station	1950-60	1960-70	Difference	t	Deg. Freedom	Prob.
Bronte Park	15.17	14.59	0.58	.39	19	.7
Butlers Gorge	29.32	26.65	2.67	1.09	19	.3

3. Rainfall - Run-off Analysis:

Catchment rainfall has been estimated as outlined on page 124 from all available rainfall stations and streamflow recorders. Results are presented in Tables 45 - 50. and Figs. 26 - 37.

TABLE 45. Mean Annual Rainfall - Run-off before and after the fire for the Ouse River Catchment, based on average evapotranspiration of 30" per annum (760 mm).

Reference Station	1950-60*	1960-70	Difference (inches)	t	Deg. Freedom	Prob.
Bronte Park Rainfall	27.80	32.42	- 4.62	1.32	19	0.2
Butlers Gorge "	28.14	32.04	- 3.90	1.16	19	0.25
Liawenee (55-70)	28.10	31.14	- 3.04	1.16	14	0.3
Lake Mackenzie (56-70)	30.95	30.34	0.61	.20	11	0.8
Travellors Rest	24.41	33.91	- 9.50	2.72	15	0.02
Derwent River run-off	27.98	32.22	- 4.24	1.28	19	0.2
Nive River run off (54-70)	28.91	30.76	- 1.85	.93	15	0.3
Fisher River run off (56-70)	29.97	30.02	- .05	.03	13	0.95
Travellors Rest "	27.83	32.39	- 4.56	1.49	19	0.15
Bronte Park rainfall, Butlers Gorge " & Derwent R run-off	27.98	32.28	- 4.30	2.30	61	0.02

TABLE 46. Mean annual rainfall - run-off before and after the fire for the Nive River Catchment, based on average annual evapotranspiration of 30" (760 mm).

Reference Station	1954-60	1960-70	Difference	t	Deg. Freedom	Prob.
Bronte Park Rainfall	28.86	30.80	- 1.94	0.71	15	0.5
Butlers Gorge "	28.46	31.08	- 2.62	1.14	15	0.25
Liawenee rainfall (55-70)	29.75	30.15	- 0.40	0.13	14	0.9
Ouse Run-off	31.10	29.17	1.93	0.96	15	0.4
Derwent "	28.69	30.92	- 2.23	1.12	15	.30
Travellors Rest Run-off	26.17	32.68	- 6.51	3.55	15	.005
Bronte Park Rainfall, Butlers Gorge " and Derwent run-off	28.65	30.93	- 2.28	1.76	49	0.08

TABLE 47. Mean annual rainfall - run-off in pre and post fire periods for the Fisher River Catchment, based on mean annual evapotranspiration of 30" (760 mm).

Reference Station	1956-60	1960-70	Difference	t	Deg. Freedom	Prob.
Butlers Gorge Rainfall	26.88	31.56	- 4.68	0.80	13	0.4
Bronte Park "	29.93	30.04	- 0.11	.02	13	.95
Liawenee "	27.08	31.46	- 4.38	.95	13	.35
Lake Mackenzie "	28.80	30.59	- 1.79	.45	13	.6
Butlers Gorge & Bronte Park Rainfall	28.41	30.80	- 2.39	.63	28	.50
Butlers Gorge, Bronte Park, Liawenee and Lake Mackenzie Rainfall	28.17	30.91	- 2.74	1.17	58	.25

TABLE 48. Mean annual rainfall - run-off in pre and post fire periods for the Travellers Rest Catchment, based on mean annual evapo-transpiration of 30".

Reference Station	1950-60	1960-70	Difference (inches)	t	Deg. Freedom	Prob.
Bronte Park Rainfall	29.96	30.04	.08	.02	19	.99
Butlers Gorge "	30.42	29.54	.88	.50	19	.6
Lake St. Clair "	27.02	33.28	-6.26	2.50	19	.02
Liawenee Rainfall (1955-70)	31.57	29.06	2.51	.36	14	.7
Shannon Rainfall	31.93	27.87	4.06	0.51	19	0.6
Derwent Run-off	30.20	29.77	0.43	0.63	19	0.5
Fisher " (56-70)	33.28	28.36	4.92	.8[illegible]	13	0.4
Nive " (54-70)	32.07	2[illegible].55	3.52	1.25	15	0.2
Butlers Gorge R, Bronte Park R, Derwent RO	30.19	29.78	0.41	0.29	61	0.8

TABLE 49. Mean annual rainfall - run-off in pre and post fire periods for the Travellers Rest Catchment, based on mean annual evapo-transpiration of 20".

Reference Station	1950-60	1960-70	Difference (inches)	t	Deg. Freedom	Prob.
Bronte Park Rainfall	20.00	20.00	-	-	19	1
Butlers Gorge "	20.41	19.55	.80	.53	19	.6
Lake St. Clair "	17.38	22.[illegible]3	-5.15	2.61	19	.02
Shannon "	20.41	19.55	.86	.53	19	.6
Derwent Run-off	20.21	19.77	.44	.63	19	.5
Fisher " (56-70)	23.26	18.37	4.89	.88	13	.4
Nive " (54-70)	22.24	18.44	3.80	1.38	15	.2
Ouse	23.54	16.11	7.43	1.99	19	.06

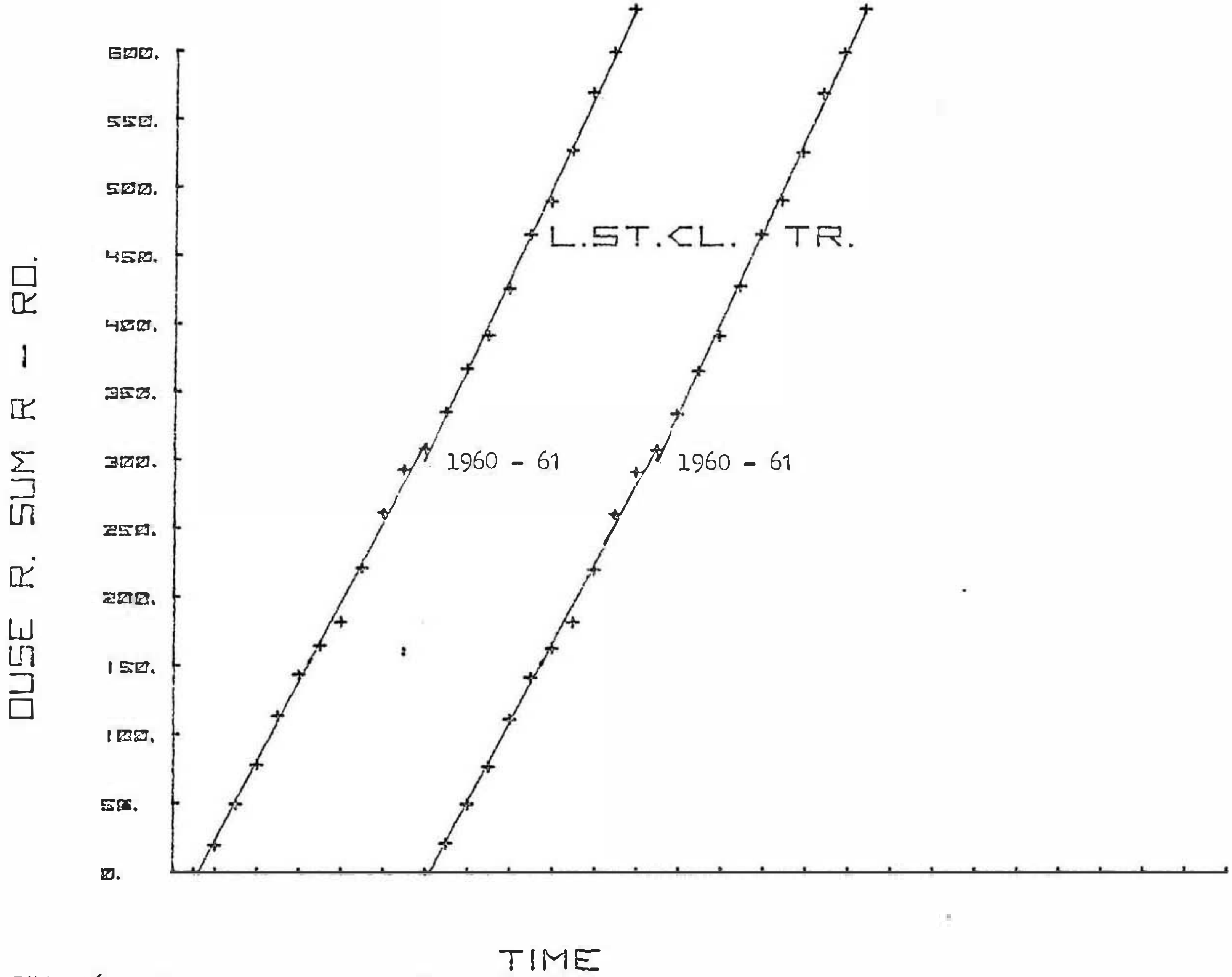

FIG. 26. Regressions of Ouse River Catchment sum rainfall minus run-off, on time, for pre and post fire years. Catchment rainfall estimated from rainfall at Lake St. Clair and Travellors Rest (1950-70). Assumed mean annual evapotranspiration of 30".

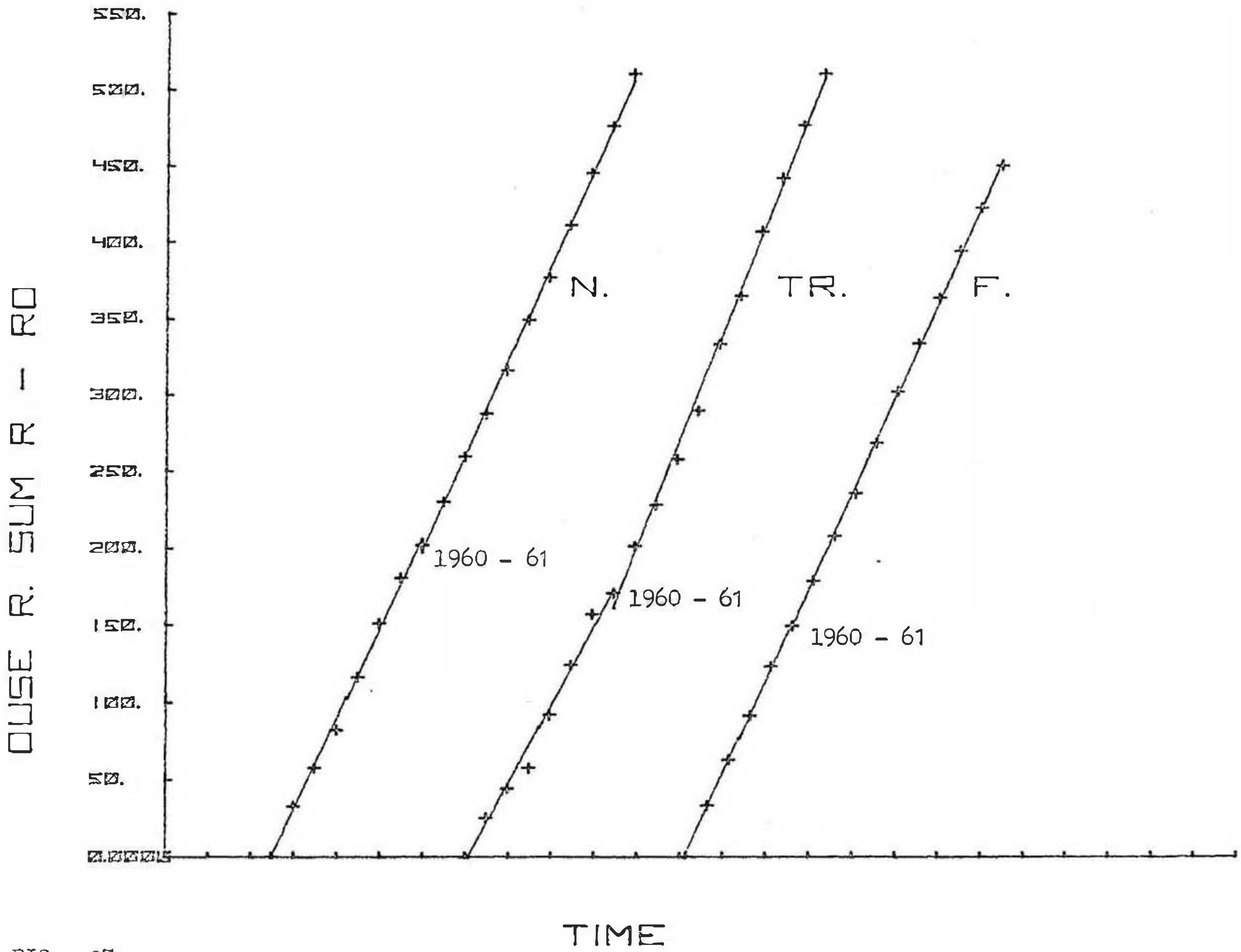

FIG. 27. Regressions of Ouse River Catchment sum rainfall minus run-off, on time, for pre and post fire periods. Data for catchment rainfall estimated from run-off in the Nive River Catchment (1954-70), Travellors Rest Catchment (1954-70), and Fisher River Catchment. Assumed mean annual evapotranspiration of 30".

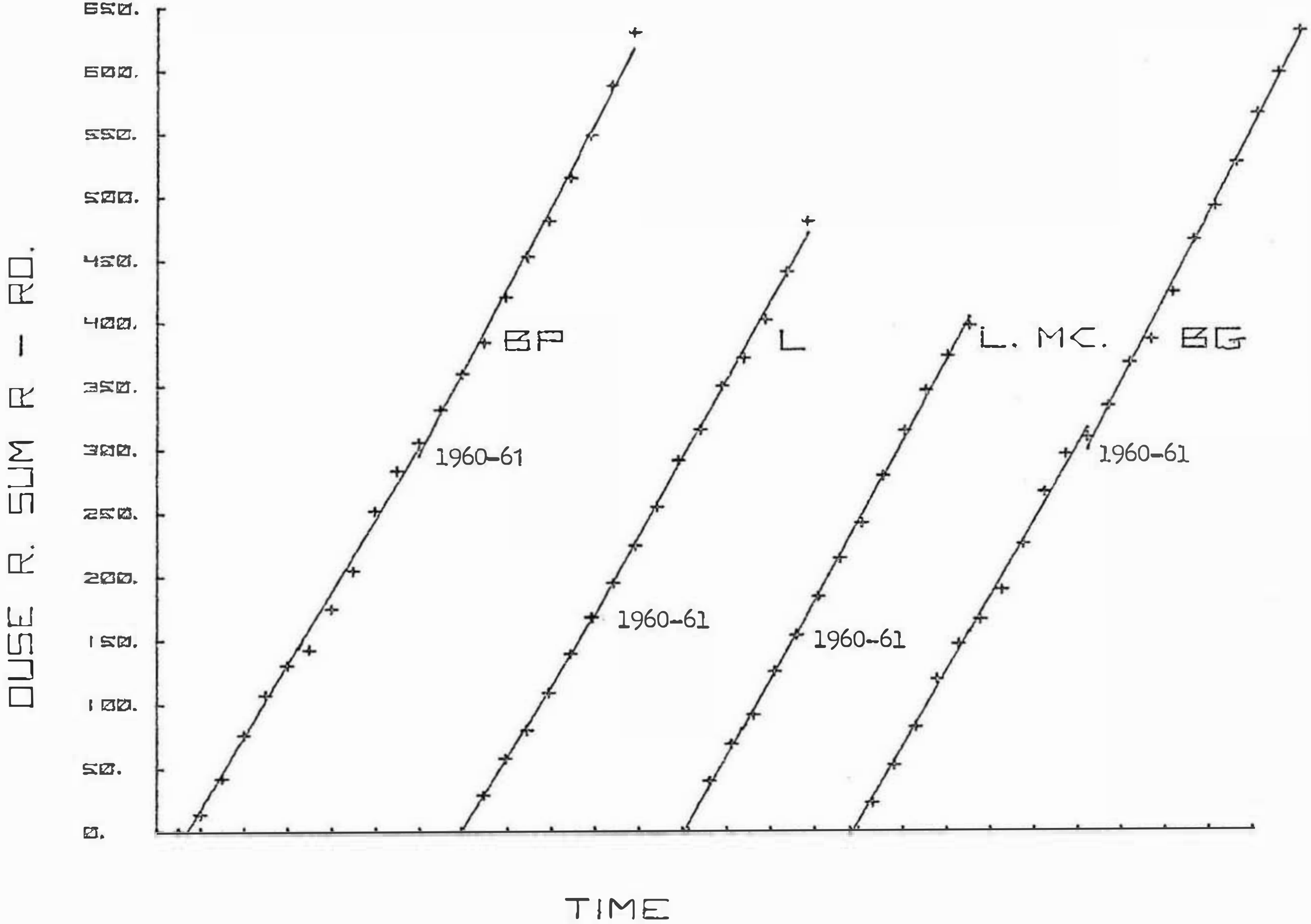

FIG. 28. Regressions of Ouse River catchment sum rainfall - run-off, on time, for pre and post fire years. Catchment rainfall calculated from rainfall at Bronte Park (1950-70), Liawenee (1955-70), Lake Mackenzie (1956-68) and Butlers Gorge (1950-70). Assumed mean annual evapotranspiration of 30".

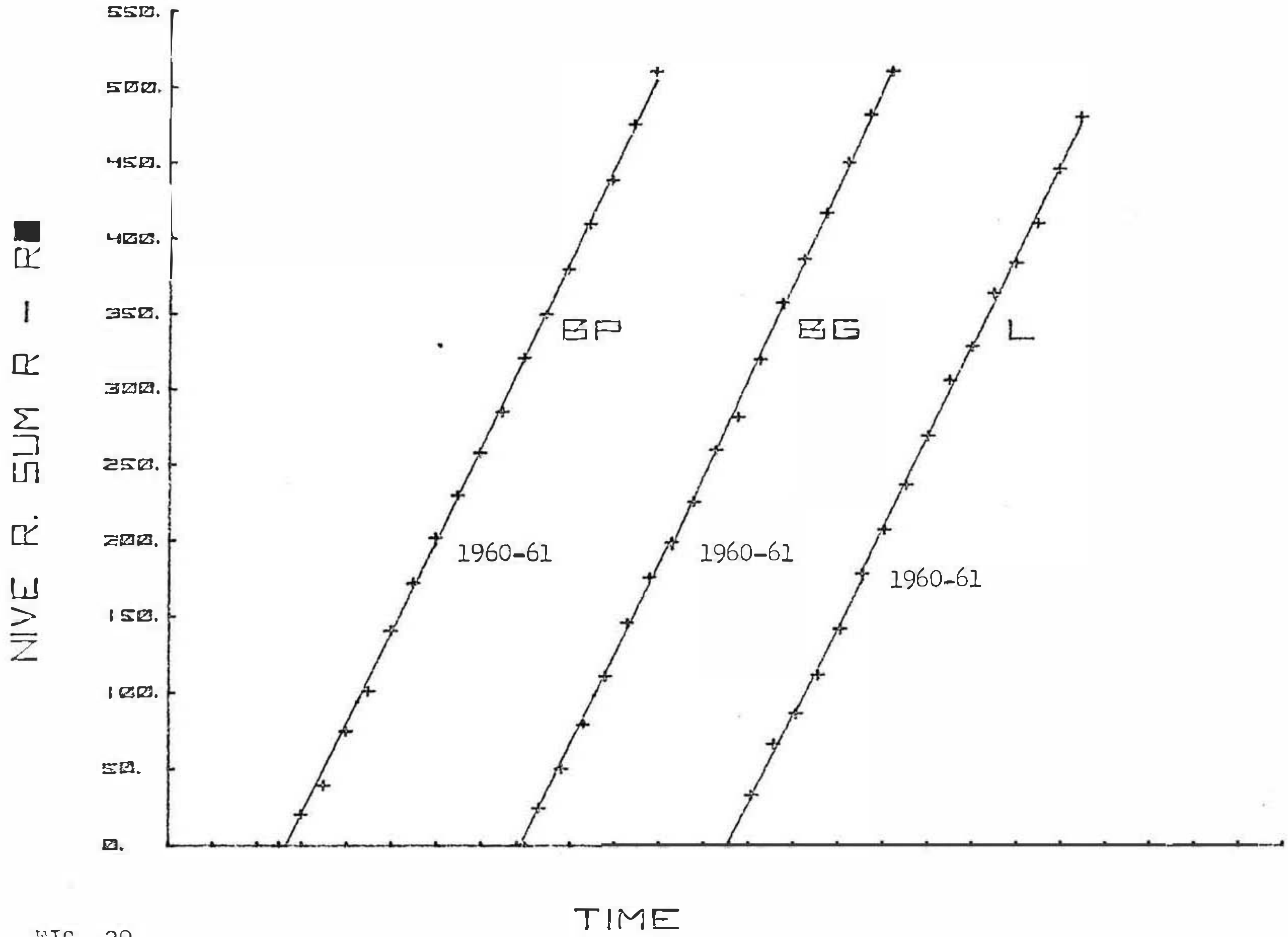

FIG. 29. Regressions of Nive River catchment sum rainfall - run-off, on time, for pre and post fire years. Catchment rainfall calculated from rainfall at Bronte Park (1954-70), Butlers Gorge (1954-70) and Liawenee (1955-70). Assumed mean annual evapotranspiration of 30".

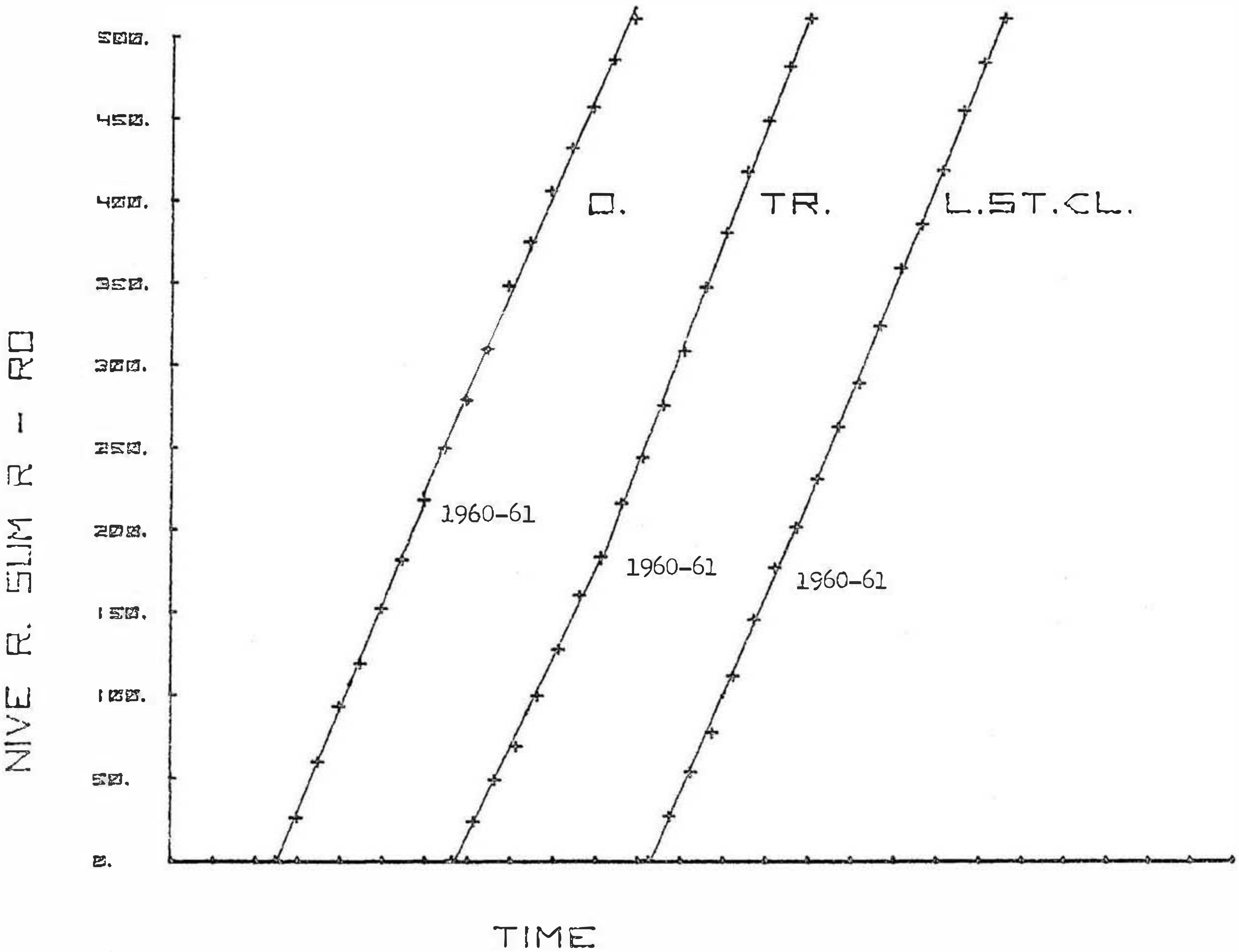

FIG. 30. Regressions of Nive River catchment sum rainfall - run-off, on time, for pre and post fire periods. Catchment rainfall calculated from run-off in the Ouse catchment (1954-70), Travellors Rest catchment (1954070) and Lake St. Clair catchment (1954-70). Assumed mean annual evapotranspiration of 30".

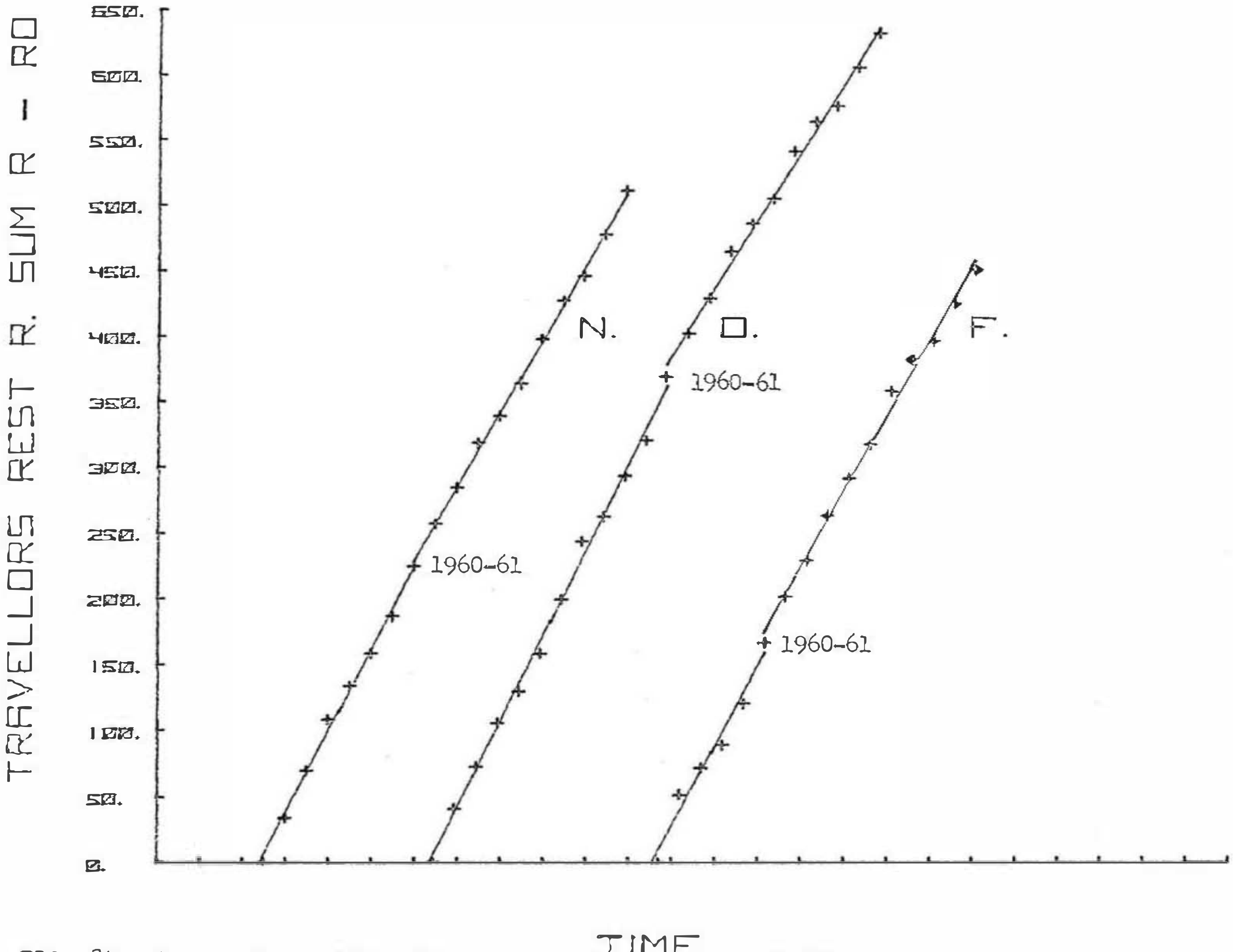

FIG. 31. Regressions of Travellors Rest catchment sum rainfall - run-off, on time, for pre and post fire years. Catchment rainfall calculated from run-off in the Nive River catchment (1954-70), Ouse River catchment (1950-70) and Fisher River catchment (1956-70). Assumed mean annual evapotranspiration of 30".

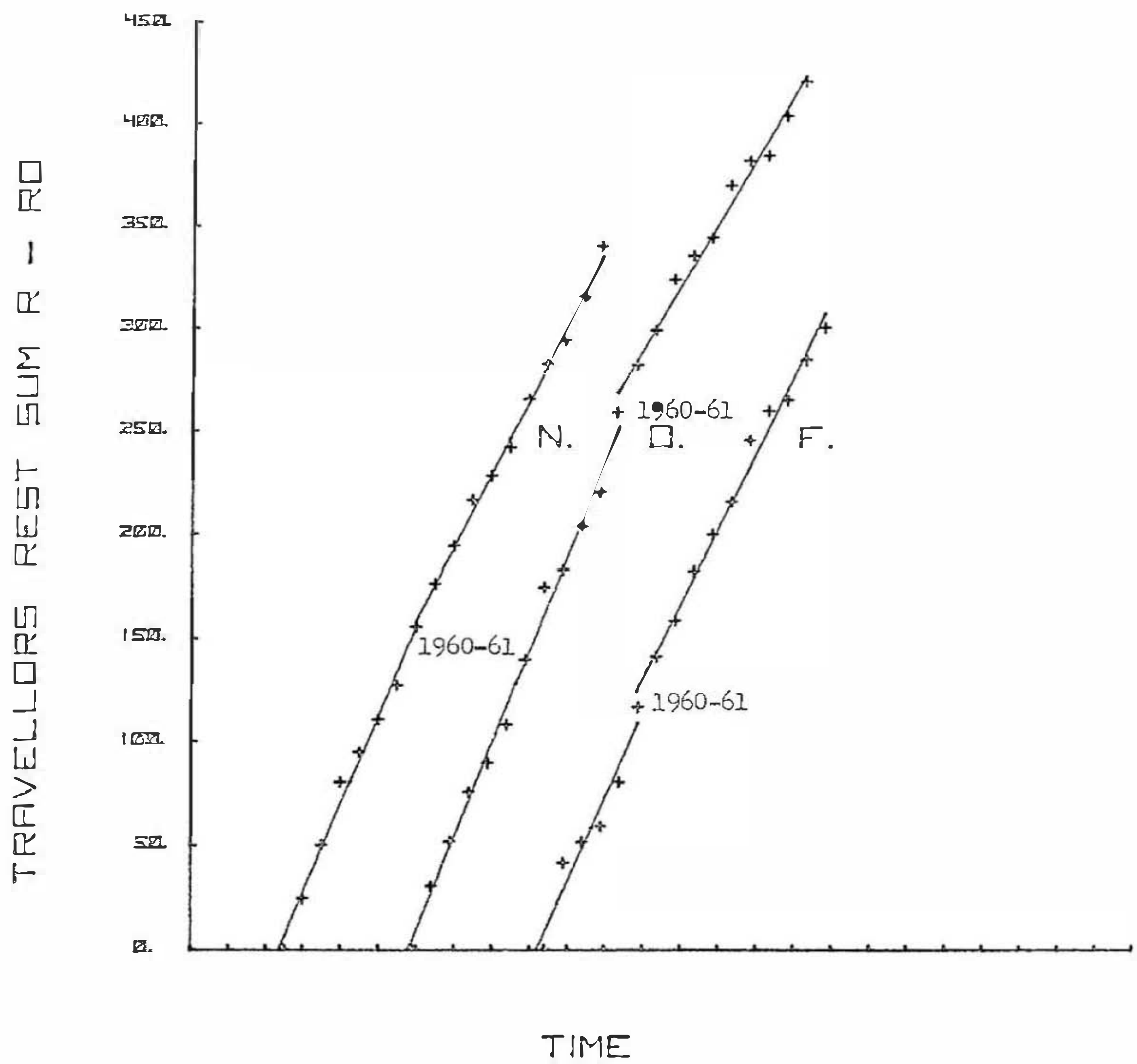

FIG. 32. Regressions of Travellors Rest catchment sum rainfall - run-off, on time, for pre and post fire years. Catchment rainfall calculated from run-off in the NiveRiver Catchment (1954-70), the Ouse River catchment (1950-70) and the Fisher River catchment (1956-70). Assumed mean annual evapotranspiration of 20".

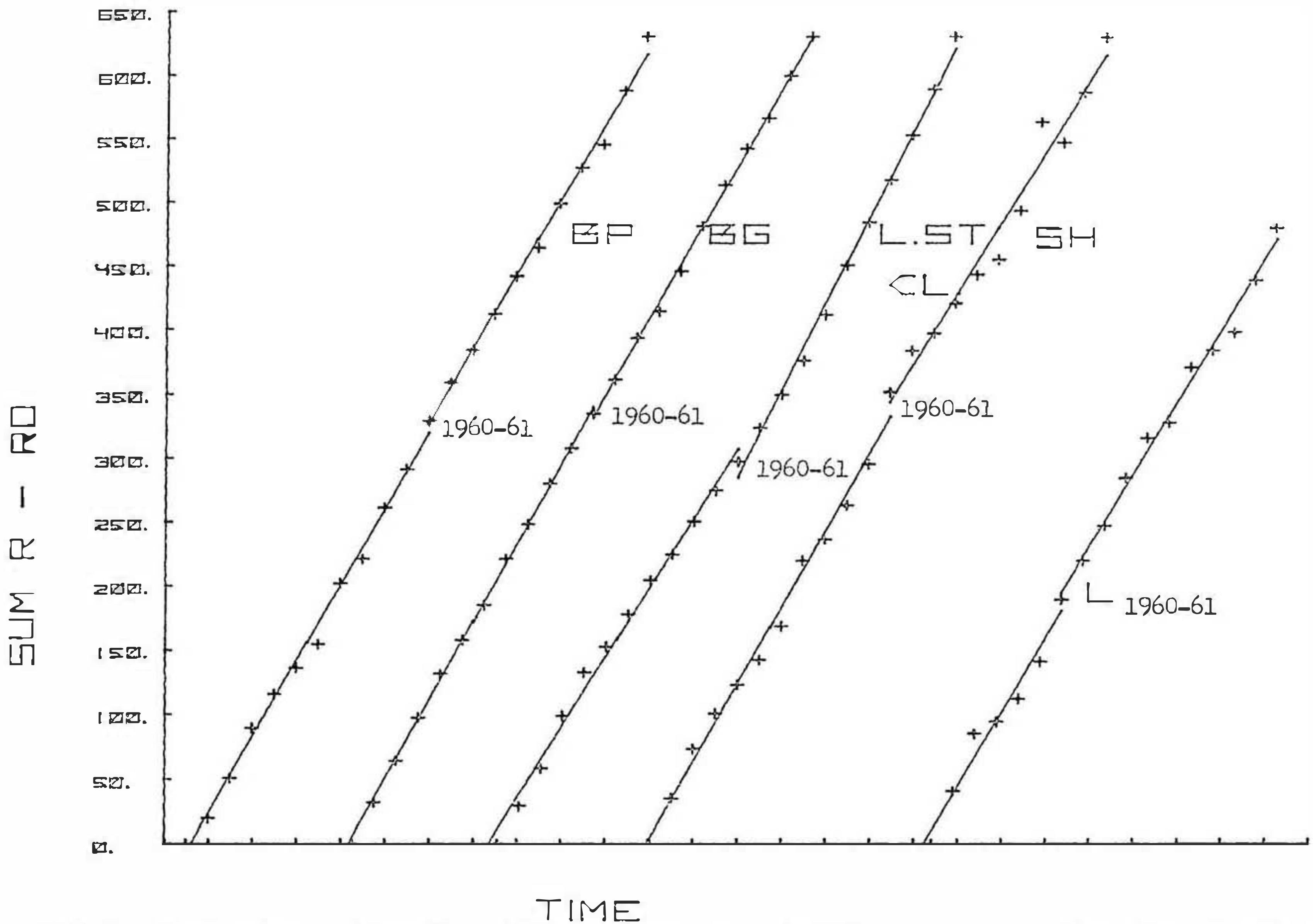

FIG. 33. Regressions of Travellors Rest catchment sum rain all - run-off, on time, for pre and post fire years. Catchment rainfall calculated from rainfall at Bronte Park (1950-70), Butlers Gorge (1950-70), Lake St. Clair (1950-70), Shannon (1950-70) and Liawenee (1955-70). Assumed mean annual evapotranspiration of 30".

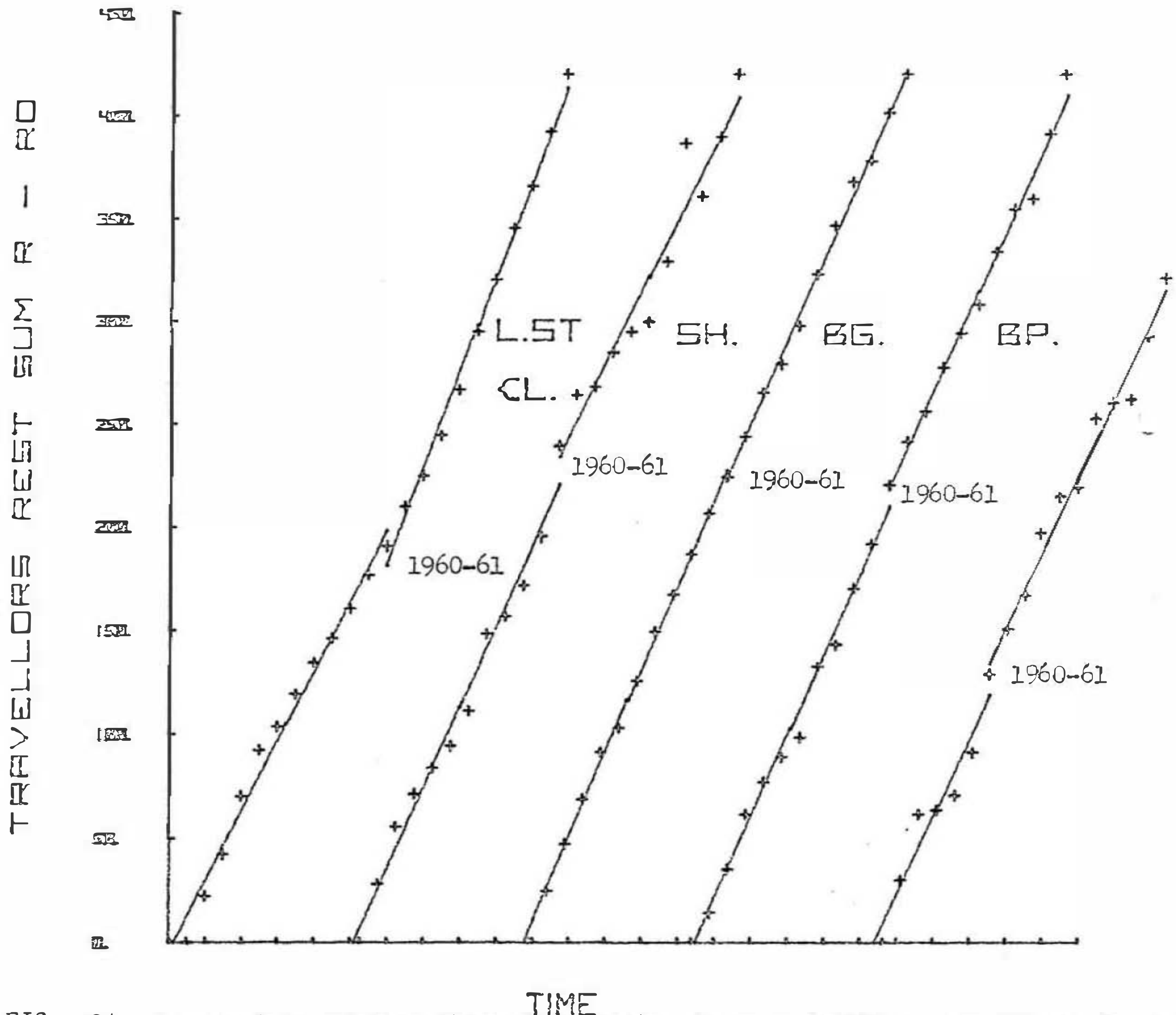

FIG. 34. Regressions of Travellors Rest catchment sum rainfall - run-off, on time, for pre and post fire years. Catchment rainfall calculated from rainfall at Bronte Park (1950-70), Butlers Gorge (1950-70), Lake St. Clair (1950-70), Shannon (1950-70) and Liawenee (1955-70). Assumed mean annual evapotranspiration of 20".

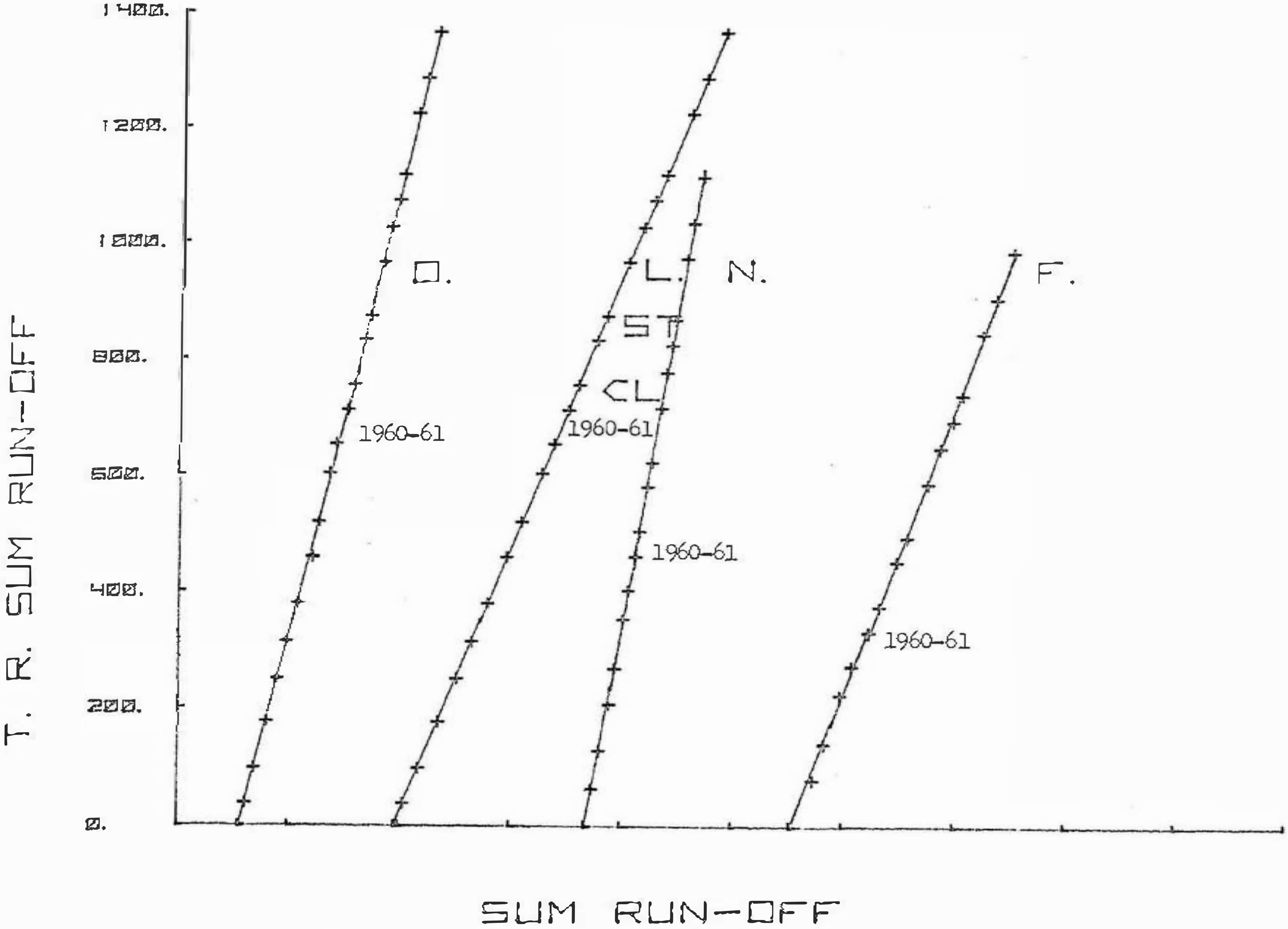

FIG. 35. Regressions of sum run-off in the Travellors Rest catchment, on sum run-off in the catchments Ouse, Lake St. Clair, Nive and Fisher. Regressions calculated for pre and post fire periods.

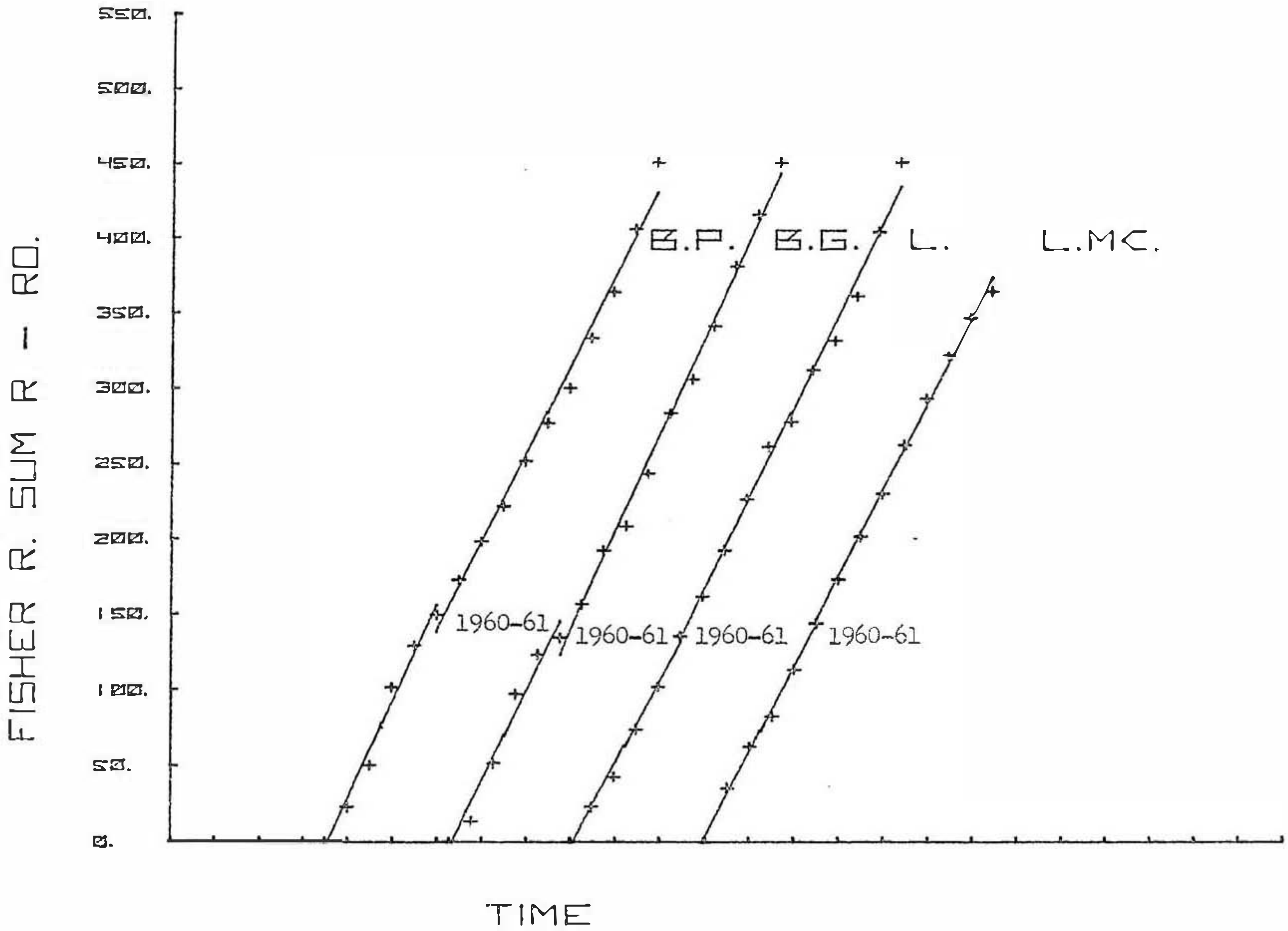

FIG. 36. Regressions of Fisher River catchment sum rainfall - run-off, on time, for pre and post fire years. Catchment rainfall calculated from rainfall at Bronte Park (1956-70), Butlers Gorge (1956-70), Liawenee (1956-70) and Lake Mackenzie (1956-68). Assumed mean annual evapotranspiration of 30".

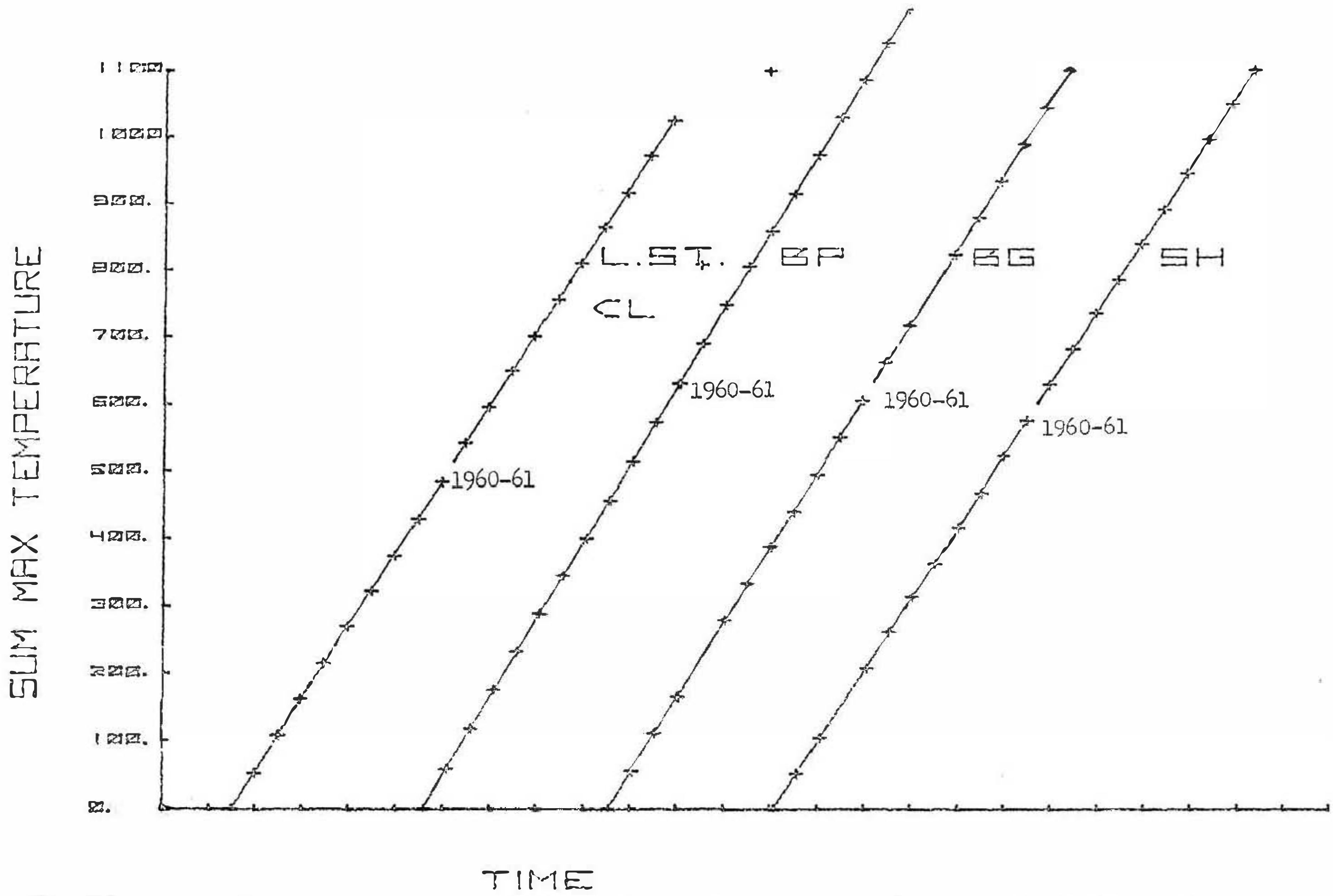

FIG. 37. Regressions of sum mean annual maximum temperature, on time, in pre and post fire years. Equations calculated for Lake St. Clair, Bronte Park, Butlers Gorge and Shannon (1950-70).

The overall pattern in evapotranspiration that has emerged from the analysis is presented in Table 50:

TABLE 50. Overall change in evapotranspiration in 10 years following a severe fire compared to pre fire period.

Catchment	Evapotranspiration Change (inches / year)	Prob.
Ouse	4.3 decrease	0.02
Nive	2.3 decrease	0.08
Fisher	2.7 decrease	0.25
Travellors Rest	0.3 increase	0.8

Discussion:

1. Rainfall - Run-off Analysis.

Data presented in Tables 45 - 49 is calculated from almost all raingauge and run-off stations on the Central Plateau west of Great Lake, and includes stations previously shown (Page 127) to be invalid. This was due to unreliability of raingauge records (Lake St. Clair) or to a change in rainfall co-inciding with the fire (Shannon and Waddamana). Other gauges, such as at Lake Mackenzie and Liawenee, have only been in operation since 1956 and 1955 respectively.

The final t test (Table 50) on all independent estimates of rainfall - run-off before the fire, compared with the period after the fire, has not used these stations. It was based on rainfall at Bronte Park and Butlers Gorge, and on run-off in the Derwent River at Lake St. Clair (for the Ouse, Nive and Travellors Rest catchments). For the shorter period of record in the Fisher River catchment, the reference stations used were rainfall at Butlers Gorge, Bronte Park, Liawenee and Lake Mackenzie.

The use of run-off stations to estimate catchment rainfall has assumed 76 cm. evapotranspiration per year, which has been added to the relevant catchment run-off to determine percentage catchment rainfall for any year, as was directly done for rainfall (see page 124).

The overall results have clearly indicated that the effect of the fire was to increase what is measured as rainfall-run-off, (and normally attributed to evapotranspiration) in the highest catchments. The sections of the Ouse, Nive and Fisher River catchments that were burnt are all over 1160 m. (3500') in altitude, while the altitude of the Travellers Rest catchment, which showed a slight increase in run-off attributable to the fire, is only approximately 950 m. (3000') in altitude.

Run-off records for the Fisher River catchment were only available since 1956, and although the general trend is the same as the Ouse and Nive catchments, the increase of 2 inches in evapotranspiration per year after the fire was not significant.

In the lower Travellers Rest catchment, the effect of the fire has followed that normally expected in a low altitude catchment where inputs from snow, rime and low cloud were not expected. The fire here has reduced the vegetation cover, and hence its ability to transpire water. This should result in an increase in run-off and this in fact did occur although it was non-significant.

The implication from these results is that in the highest catchments the fire has resulted in less run-off per unit rainfall, because the vegetation has been destroyed, i.e., because the ability of vegetation to increase snow deposition, collect rime deposits, and to strain out fine water droplets, has been drastically impaired. In lower catchments straining out of fine water droplets is not important and run-off may be expected to increase because of reduced transpiration.

The results confirm the results of the plot run-off experiments described in Chapter 2, in which run-off was increased when foliage projected into the atmosphere during conditions conducive to deposition from mist, rime and snow at high altitudes (above approximately 1130 m. (3700')).

Tables 48 and 49 show that the basic average evapotranspiration figure of 76 cm. (30") results in very slight differences in calculated values of observed-expected evapotranspiration compared to an assumption of 51 cm. (20") per year. Since annual losses through evapotranspiration most probably lie between these figures, the assumption of an annual evapotranspiration loss of 30" does not appear unreasonable.

The possibility that evapotranspiration would have increased (in the years 1960 - 70 compared to 1950 - 60) had the fire not occurred was briefly examined from available temperature and summer rainfall data on the Plateau. Temperature and summer rainfall are extremely crude parameters on which to estimate evapotranspiration but were used because there is a general lack of other climatic parameters which control evapotranspiration, (See Chapter 3). Tables 43 and 44 indicate that there is no evidence to suggest that the measured changes in evapotranspiration co-inciding with the fire were not caused by it.

2. Multiple Regression Analysis.

Multiple regression analysis provides the best method of correlating several factors for the purpose of predicting run-off in any single year. For example, a multiple regression equation linking rainfall and run-off at several stations with the dependent variable under study, gives an accurate model for predicting run-off in the dependent variable in terms of the other so called independent variables.

In doing so however, a number of possible independent estimates are lost, and consequently, the number of degrees of freedom for tests of significance is limited. This is demonstrated in all the multiple regression equations calculated. Even by using characters with a high correlation coefficient, the resulting deviations of calculated from observed results were too high for a significant difference (Table 42), although a trend was indicated.

Multiple regression analysis using monthly data, both in arithmetic and logarithmic form, has revealed no advantage over annual data. In general the logarithmic equation is superior to the arithmetic relationship when monthly data is used, but the increase in precision is not very great. Figs. 19 to 22 show that the deviations of observed from calculated values are too great for any change due to the fire to be detected.

Multiple regression equations were constructed for up to 4 variables. Generally speaking, the best independent variables for all comparisons were rainfall at Bronte Park and Butlers Gorge, and run-off in the Derwent River at Lake St. Clair. It may be noted that although a rainfall of x cm. in any year results in approximately x - 76 cm. run-off, the correlation coefficient is the same between rainfall and run-off, as between rainfall and run-off + 76, since constant additions or subtractions make no difference to the correlation co-efficients.

Data from the multiple regression equations has been presented in two formats. The first is a graph of sum observed against sum expected run-off and the second is a graph of deviations from observed and calculated values against time. The first graph shows any change in pattern due to the fire as a slope change, and the second shows actual changes from year to year i.e., the slope in the first graph corresponds to mean values in the latter. The sum graph has advantages in visual display, because it smooths out year to year fluctuations, especially where reduced or increased run-off in one year is compensated for in the subsequent year. Since each point on the sum graph has not been independently estimated, the slope on the sum graph may not exactly correlate with the mean in the deviation against time graph.

Conclusions:

The effects of the 1960 - 61 fire on streamflow are difficult to analyse accurately because of large variations, both in space and time, in the basic hydrological parameters rainfall, run-off, and evapotranspiration. The magnitude of any measured change in run-off depends to a large degree on the methods of analysis, especially on the reference stations used as independent controls.

This study has shown that the water budget method can be used to follow changes in the difference between rainfall and run-off following the fire. The method is preferable to multiple regression analysis because it estimates directly the parameter ultimately required, i.e. the difference between rainfall v run-off, which is normally evapotranspiration, but in alpine areas includes input from mist, rime and snow. These are not measured very efficiently in raingauges and are very dependent on vegetation for their collection. Since the year to year variability in evapotranspiration and fog deposits, are much less than the variability in run-off, the method can detect much smaller mean changes than any method that measured changes in run-off. The other advantage of the method is that it allows independent comparisons from a number of reference stations, thereby increasing the number of degrees of freedom for a significance test of changes due to the fire.

The method does, however, make a number of assumptions concerning the uniformity of a catchment. The most important assumption is that for periods as long as a year (or more), records from a raingauge station are proportional to catchment rainfall. This assumption is certainly not correct to a number of decimal places, but has proved a workable assumption in this study. Departures from the assumption only increase the variability in the rainfall-runoff estimate, and do not introduce bias or skewness into the results.

The tests of significance applied to the overall results of the analysis have demonstrated a reduction in run-off after the fire in the highest catchments, although not in the Lower Travellors Rest catchment. The higher catchments contrast with the normal expected pattern of low altitude catchments were evapotranspiration is reduced for the first few years following a fire until a vegetation cover is again established. In the area burnt on the Central Plateau there is still very little recovery of vegetation 12 years after the fire. The results are most logically explained as being caused by the fire destroying the most alpine vegetation, which can no longer strain out the small diameter droplets of water in rime and mist, that drift with air currents, and require a projecting object for their deposition.

The multiple regression analysis has measured approximately the same quantitative charge in run-off in the post fire decade, as the water budget method, but the results were non-significant.

PLATE 20. View looking west from above Pillans Lake showing the limited recovery of vegetation, 12 years after burning.

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APPENDIX I. Note on Computing Facilities

All calculations of regression equations, rainfall - runoff analysis, and tests of significance, were conducted with a Hewlett-Packard Model 10A programmable calculator. The calculator had a capacity of 500 programme steps and 52 memory registers, and was equipped with an Alpha Printer.

Graphs were drawn using a Hewlett-Packard Plotter linked with the calculator.

Programmes for most of the analyses and plotting were compiled by the writer. Programmes for standard calculations, such as t tests, were taken from a catalogue of programmes supplied by Hewlett Packard. Programmes involving more than 500 steps, such as the multiple regression equations, were modified from the catalogue to enable the calculator to compute the data in a number of stages.

APPENDIX 2. Paper on Tipping Bucket Run-off Gauges.

TIPPING BUCKET GAUGES FOR MEASURING RUN-OFF FROM EXPERIMENTAL PLOTS

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ABSTRACT

Tipping bucket gauges for directly measuring run-off from small catchment areas are described. Theoretical and experimental design considerations and sources of error are discussed for bucket capacities up to 12 litres. The principal errors are attributed to variable entry rates of water whilst the buckets are tipping and flow turbulence within the bucket. Surface tension effects are the major source of error in very small tipping bucket gauges. The most important design considerations on large capacity gauges are tipping time and the collision impulse of the buckets on tipping. Practical solutions to these design considerations are given.

INTRODUCTION

We are interested in the measurement of discharge rates and volumes from small catchment areas, usually less than 5 ha. The conventional methods of flow measurement in small plot work may be summarized as follows:

(a) measurement of depth of flow through calibrated structures such as orifices, weirs and flumes and integration with time.

(b) measurement of volume increment in a container of known dimensions.

Less conventional methods which have been applied in special circumstances are:

(c) mass measurement.

(d) estimation of velocity in a flow path of known dimension, e.g. magnetic flow meters.

The common methods involve serious problems at very low flow rates and very high flow rates, and so dividers or flow splitters are often introduced and/or cascades of metering devices (ANONYMOUS, 1959; TROSKOLANSKI, 1960; TOEBES and OURYVAEV, 1970). The less conventional methods usually require a high input of energy and technology, and often neither energy or large sums of money are available at hydrological sites. The tipping bucket offers a robust and relatively cheap form of mass rate measurement. It also produces a digital output which lends itself to simple on site integration or transmission to event recorders.

It is appropriate here to examine the problems and accuracy of the conventional stream flow measuring devices, particularly at low flow rates. A 22.5 degree V notch weir is quoted by TOEBES and OURYVAEV (1970) as having a minimum flow capacity of 0.6 litres per second which corresponds with a head of 8 cm. Actual discharge relationships below this rate are subject to changes in calibration with time and uncertainty as to the magnitude of surface tension effects (KING, 1964: BENTZ and AMERMAN, 1968). It is therefore not realistic to use notched weirs for run-off areas smaller than 2000 m^2 (where 0.6 l sec.$^{-1}$ corresponds to 1 mm. hr.$^{-1}$, or 24 mm. per day run-off rate from the catchment) except of course for high rate surface run-off events.

The Greib multislot divider was designed to simplify measurement of large volumes of water by separating run-off into a number of aliquots, one of which is diverted into a volumetric sampler (WILTSHIRE, 1947). HUDSON (1947) reported drawbacks with this device because of sediment blockage, and difficulty in devising a satisfactory method of installing the multi-divider plate so that it could be accurately leveled and then fixed rigidly. He improved the design by using a flat stainless steel plate with horizontal and vertical rows of holes, let into the side of a tank. The water passing through the central row of holes was measured. TOEBES and OURYVAEV (1970) concluded that the most accurate method of measuring low flows was to use such orifices in a tank, providing adequate head (approximately 1.2 m) is available.

It is therefore concluded that there is a need for a simple and reasonably accurate device for measuring sustained but low rates of run-off, from areas of less than 1000 sq. metres, and requiring limited head loss. It is believed that the tipping bucket fulfils these requirements.

THE TIPPING BUCKET PRINCIPLE

The tipping bucket or self-emptying bucket is widely used in rain gauges (W.M.O., 1961). It is also used in mechanical engineering to monitor small flows (TROSKOLANSKI 1960) for example, discharge from a solar still (PROCTOR, 1973). PILSBURY et al. (1962) reported the use of large tipping bucket devices on run-off plots at San Dimas, California, and MONKE et al. (1967) described their use to measure flows from tile drain experiments. BENTZ and AMERMAN (1968) used a 450 ml. tipping bucket to measure low flows from a 0.8 HS flume, whilst WHITE and RHODES (1970) described a bucket of capacity 100 ml. used in stem flow studies. Fig. 1 is a generalized drawing of a tipping bucket device. The basic instrument consists of two chambers, symmetrical about a central wall. It is pivoted about an axis on the line of symmetry and rests in either of two stable positions on appropriate stops. Since the centre of gravity is above the pivot there is also a metastable position when the centre of gravity lies on the vertical through the pivot.

If fluid is allowed to enter through a nozzle on the vertical axis, the uppermost chamber fills with water. At any level, L_1 etc., the appropriate position of the centre of gravity, of the buckets plus fluid, is indicated as M_1 etc. As the bucket fills, the centre of gravity approaches the vertical axis and at a critical level, L_c, the mechanism becomes metastable and any further increase in fluid level makes it unstable, and it tilts into the other stable configuration. In doing so the full bucket discharges the fluid and presents an empty bucket for fluid inflow.

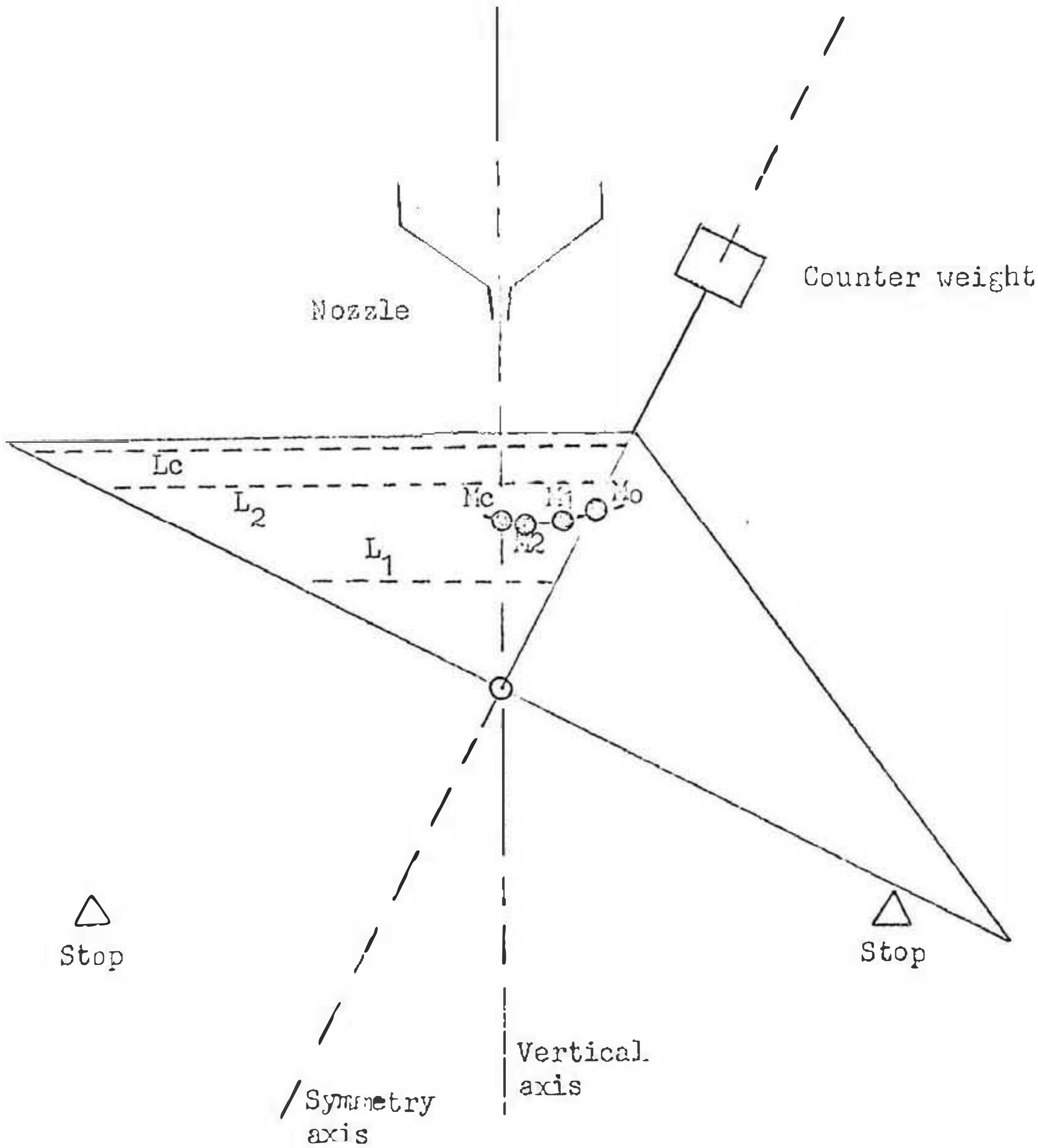


Fig. 1. A generalized drawing of a tipping bucket device. M_o, M_1 etc., are the positions of the centre of mass corresponding to bucket levels, empty, L_1 etc.

During the tipping process, fluid continues to discharge into the full bucket until the dividing wall on the axis of symmetry passes the vertical position. The actual volume discharged each tip is therefore a function of the inflow rate and the time, t_c, which it takes for the dividing wall to rotate to the vertical position. The time to tip, t_c, is a function of the geometry of the mechanism, as are various other important gauge characteristics. Below is set out an approximate analysis of a simplified mechanism which highlights the scaling problems associated with the design and construction of a graded set of bucket sizes.

APPROXIMATE ANALYSIS OF A TIPPING BUCKET

Consider a 90 degree isosceles triangular bucket of negligible weight and on friction-less bearings (Fig. 2.). This rests in the metastable position and is filled with water and then given a slight displacement into an unstable position. The mechanism now rotates through 90 degrees to come to rest on the alternative stop. The time to tip, t_c, as previously defined represents the time to sweep out the first 45 degrees. The time to stop, t_s, represents the time to sweep through 90 degrees.

If we define the length of the bucket base as d, and the distance to the centre of gravity of the fluid as h, then an approximate analysis is as follows.

Change in potential energy during roation is equal to Mgh where M is mass of fluid and g is the gravitational constant. This also represents the kinetic energy to be absorbed in the stop which may also be expressed in terms of the rotational motion

$$Mgh = 0.5\ I\ w^2 \qquad (1)$$

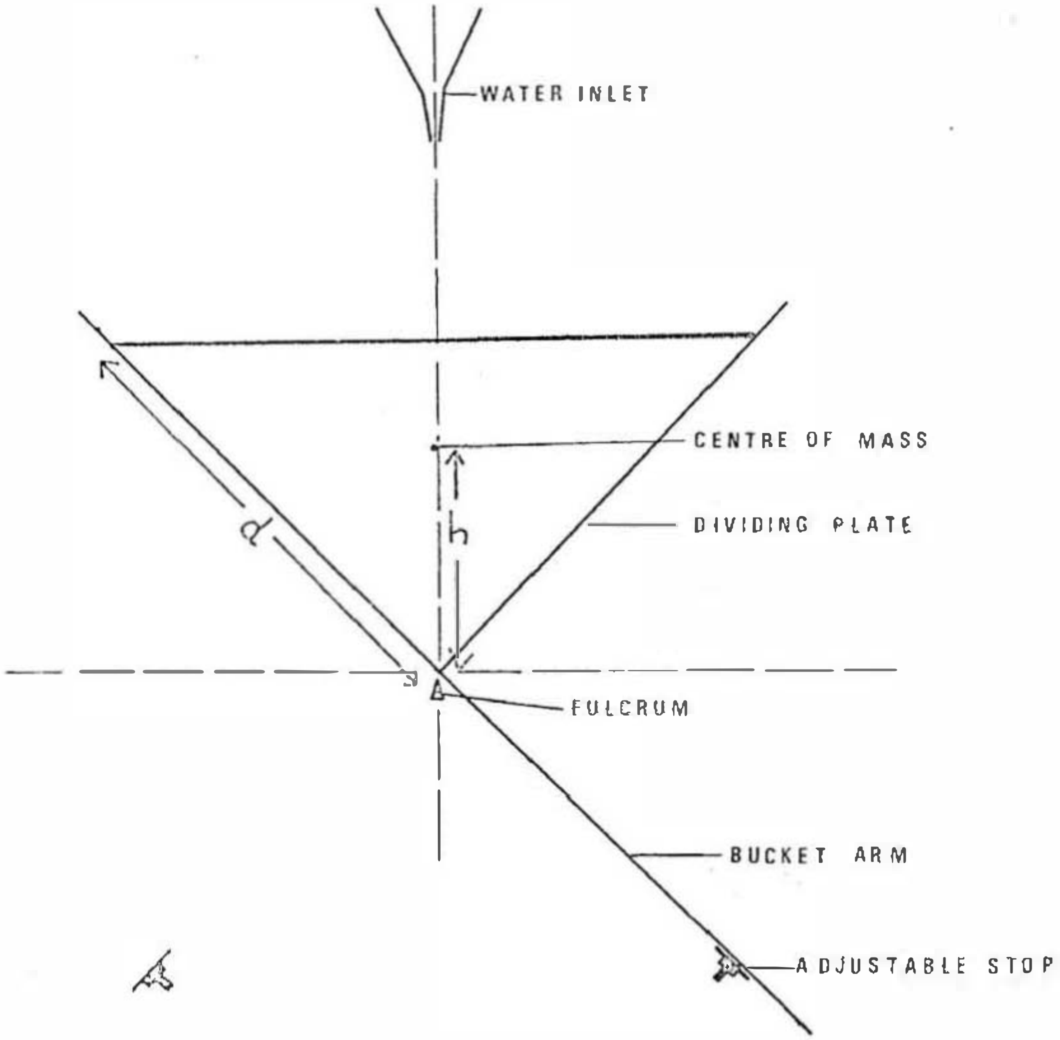


Fig. 2. A right-angled isosceles triangle tipping bucket. h is height of centre of mass of fluid in a full bucket of base length d.

where I, the rotational inertia, equals Md^2/d, and w is terminal angular velocity

Now $h = \frac{\sqrt{2}}{3} d$

hence

$$w = (2 . \sqrt{2} \ g/d)^{\frac{1}{2}} \qquad (2a)$$

or more generally

$$= (2 . \sqrt{2} \ g \cos \theta \ / \ d)^{\frac{1}{2}} \qquad (2b)$$

where θ is the angle turned through.

Initially the accelerating couple on the overturning mechanism is $Mgh \sin \theta$, or $(\sqrt{2} \ Mgd \sin \theta)/3$. The overturning mass is a fluid and is therefore unstable. The angle turned through to time, t_s, is also large, being 90 degrees in the case under consideration. Therefore a not unreasonable approximation to the motion is rotation with constant angular acceleration.

The general case for time to reach stop, t_s, is then

$$t_s = \theta/(g \cos \theta \ / \ \sqrt{2}d)^{\frac{1}{2}} \qquad -(3)$$

This means as the size of the bucket increases, the tipping time increases, as does the energy at impact. If we consider a bucket of width equal to side length, d, then doubling the volume increases dimension d, by 26%, the tipping time by 12% and impact energy by 152%.

It is also interesting to note the relationship between the periodic time, T, of the bucket considered as a compound pendulum and, t_s.

$$t_s = \frac{T\theta}{\sqrt{2}\,\pi} \qquad (4)$$

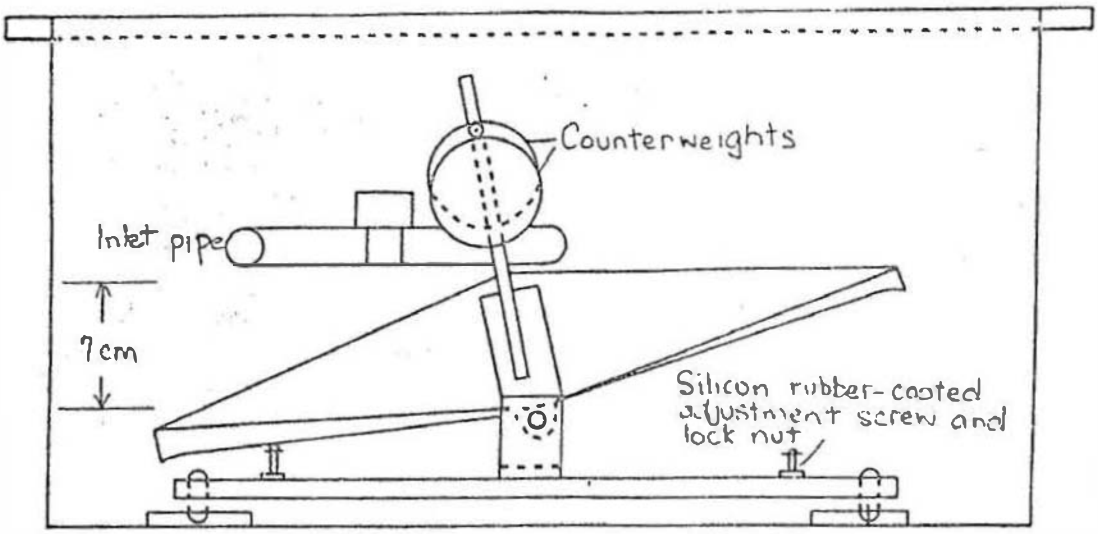
This relationship provides a simple method for determining approximate tipping time of alternative bucket configurations using rigid models suspended as compound pendulums.

CHARACTERISTICS OF REAL TIPPING BUCKET GAUGES

In the special case used in the approximate analysis the bucket is in a metastable position during the whole of the filling period. This is of course undesirable in a real gauge since any stray impulse such as the turbulence of entering fluid can trigger a tip. Real gauges are therefore constructed in a number of possible ways so that the centre of mass of the added water is clearly on the unstable side of the pivot. This ensures that the centre of mass of the whole instrument, as water is added, approaches the vertical axis by an orthogonal path or as nearly so as possible.

(i) An elongated right angled bucket shape with fixed counterweight. This is the most common method of construction, the counterweight being built into the dividing wall and the bucket walls. Fine adjustment of tipping capacity is made with additional adjustable weights above the dividing wall but still on the axis of symmetry, or by adjustment of the bucket stops (Fig. 3). The elongated shape has the apparent advantage of reducing the critical tilt angle, θ_c, from the 45 degrees of the isosceles shape. It should be noted, however, that the simplified analysis of equation 3 no longer applies because the relationship between the rotational inertia and the centre of mass distance from the pivot is altered.

If a counterweight is attached to the axis of symmetry as in Fig. 1., then clearly its mass needs to be inversely proportional to its



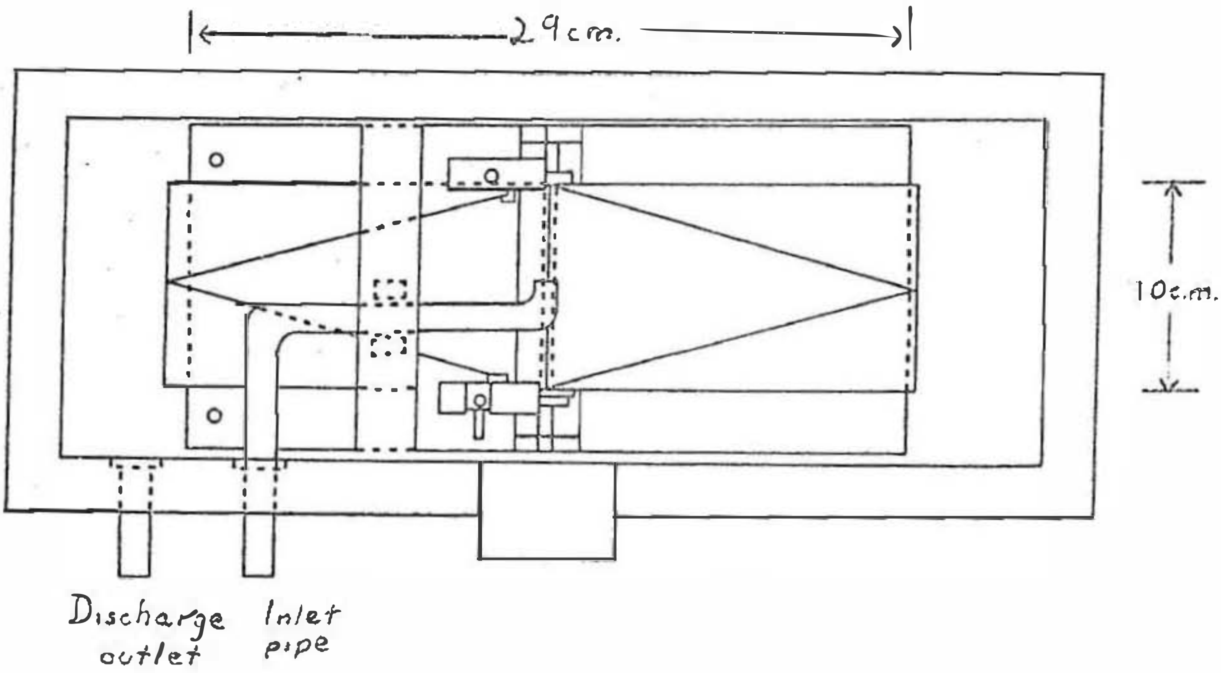


Fig. 3. General arrangement drawing of 0.5 litre tipping bucket designed to measure output from a solar still (see Proctor 1973).

horizontal distance from the pivot. For equal counter-balance effect, however, a gauge with a heavy weight near the pivot has less rotational inertia and will accelerate faster than one with a lighter weight a long way from the pivot, although the collision impulse of the bucket assembly on striking the stop will be the same.

(ii) An elongated rightangled bucket with sliding or liquid counterweight. As an alternative to the fixed counterweight a sliding counterweight, or a tube partially filled with a fluid, as in Fig. 4, may be attached near the plane of the bottom of the buckets.

By appropriate bucket modifications a counterweight can alternatively be provided by part of the incoming liquid. In each of these cases, in contrast to the fixed counterweight, some of the potential energy of the counterweight does not pass the vertical axis until some time after the initial impact of a bucket against the stop. For a given tipping time then, this type of counterweighted bucket strikes the resting stop with less collision impulse than does to a bucket with fixed counterweight.

(iii) An acute angled bucket shape. The use of acute angled buckets offers some advantages with respect to reduced amount of inertia and more effective positioning of the empty centre of mass. Here the angle between the dividing wall and the bucket base is less than 90 degrees and the stops can be positioned so that the base of the resting bucket is nearly horizontal. Even this restriction on tipping angle could be removed by the incorporation of a siphon emptying device, with the angle turned through being only that necessary to prime the siphon. The inertia and impact relations vary with the exact configuration adopted but are generally more desirable than the 90 degree situation.

(iv) Pivot points part-way along the axis of symmetry. This is another modification which reduces the rotational inertia, both of the empty buckets, and of the water in a full bucket, compared to an alternative with pivot at the normal position. Impact energy relations, tipping time and counterweight requirements vary with bucket configuration and the proportions of the total rotational inertia in the water and the buckets but a substantial reduction in collision impulse should occur over most alternative designs with the pivot at the angle between the bucket base and the dividing wall.

Rain gauges

Here the counterweight is effectively the material in the sidewalls and the dividing wall, on the axis of symmetry. Fine adjustment is made by altering the tilting stops. The energy dissipation requires no special treatment.

The real problem in small gauges is to ensure proper emptying due to surface tension effects, and the impact shock helps. The buckets are often gold or nickel plated and may carry a drip tip to encourage complete emptying. An example incorporating these and other features is the RIMCO gauge*.

Gauges of capacity 0.5 - 2.0 litres capacity

Bucket drainage is no longer a problem once bucket capacity exceeds about 0.5 litres, but impact energy becomes increasingly important. The design used by PROCTOR (1973) and illustrated in Fig. 3 incorporates

* Manufactured by RIMCO, 12 Monomeeth Drive, Mitcham, Vic. Aust.

counterweights on the axis of symmetry and uses no damper or energy absorbing stops. A 1.2 litre design developed by the senior author with bucket shape approximating a right-angled isosceles triange did not require counterweights and had an excellent calibration to quite high flow rates. A 1.0 litre design developed in New Zealand (J. Patterson private communication) incorporates a single, double-acting damper, which operates over the last part of the tipping action.

Gauges above 2 litre capacity

The senior authors have constructed a gauge of capacity 12 litres, (see Plate 1). The features of this design are shown in Fig. 4 and incorporate a fluid counterweight, surging baffles and a combined airdamper and adjustable stop. These features have allowed successful operation at inflow rates high enough to fill the bucket in 10 seconds.

MONKE et al. (1967) reported an ingenious design of bucket capacity about 5 litres but arranged to fit within a 24 inch (60 cm) diameter observation well. The paper infers tipping rates as high as ten tips per minutes. Huggins (private communication) has indicated that considerable effort was expended on calibration but no special modifications incorporated to improve the non-linear nature of the calibration.

Although the authors have only had experience with buckets pivoted at the base of the dividing wall and with right-angled triangle shapes, the analysis presented above suggests that very large gauges could benefit from construction with raised pivots, liquid counterweight provided by part of the entering fluid and buckets shaped to minimize rotational inertia, collision impulse and time of tipping.

Plate 1 A 12 litre tipping bucket with cover and inlet pipes removed. The recorder is adapted from a tipping bucket raingauge and the pipe chamber for the fluid counterweight is clearly visible.

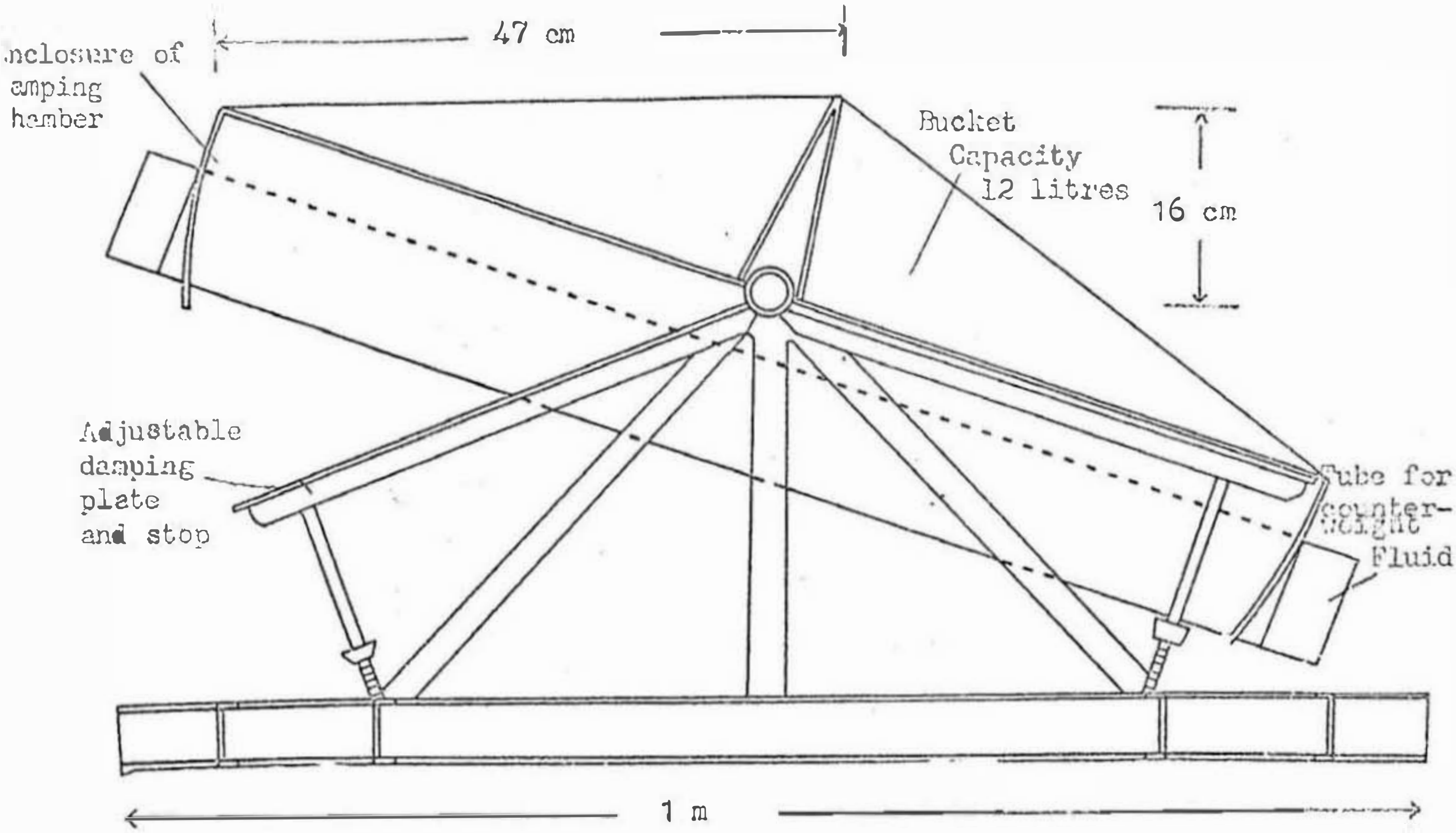


Fig. 4. Cross-section of the 12 litre tipping bucket illustrated in Plate 1.

OPERATION AND CALIBRATION OF TILTING BUCKET GAUGES

In the above sections it has been apparent that one of the major problems in the calibration of tilting bucket gauges is the characteristic of continued inflow into the discharging bucket after tipping has commenced. This means that the volume metered in a single tip is a function of inflow rate, and tends to increase with increasing inflow rate.

The turbulence inherent in high inflow rates acts in the opposite sense and tends to increase the chance of premature tipping although it also increases the variation in volume at initiation of tipping. Fig. 5, which is the calibration graph for a 12 litre gauge shows:

(i) Increasing error with increasing flow rate.

(ii) Increasing scatter with increasing flow rate.

If the operations of tilting bucket gauges are recorded against time, on a chart or data logger, then the mean inflow rate for each tip can be used to correct the nominal value of inflow and an extremely accurate record can be obtained, although the instantaneous flow at tipping is the critical factor. Of course at very high inflow rates the random error increases significantly. However if the operations are merely accumulated on a counter (KNEDLANDS, 1970), then an average tipping volume has to be assumed and errors in individual events can be quite large.

One solution, which has proven most effective in rain gauges, is to introduce an intermediate store of about three quarters bucket capacity between the source and the gauge. If this store is emptied at constant outflow rates equal to maximum designed inflow rate then the

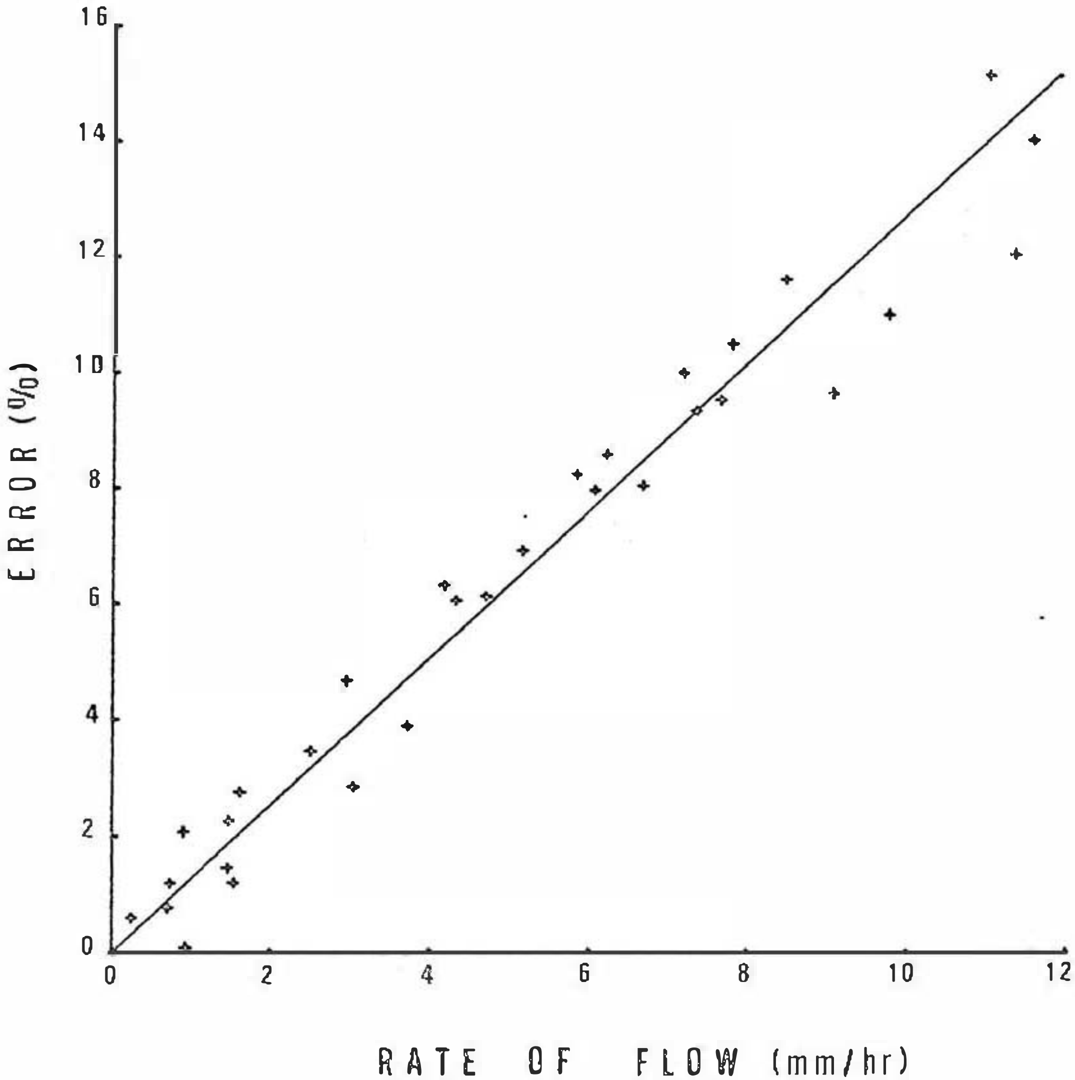


Fig. 5. Calibration graph for the 12 litre tipping bucket shown in Fig. 4 and Plate 1. Error percentage equals percentage by which tipped volume exceeds static calibration volume. Rate of flow for 500 sq. m. catchment area (1 mm per hr. = 8 l./min.)

inflow condition into the bucket is constant and so is the calibration. This has been incorporated in the RIMCO tilting bucket rain gauge, in the form of a siphon device.

In large capacity buckets, e.g. 12 litres, it is apparent from Fig. 5 that turbulence effects at maximum flow rates would make this solution undesirable. However a constant inflow rate of 50 litres per minute would appear to offer real improvement in accuracy and gauge behaviour over the whole range of runoff intensities.

Under low temperature conditions the fluid in the buckets can freeze and the empty bucket may freeze to the stop. These problems are no worse than those associated with ice in any other measuring systems and are rather more easily overcome by the provision of heaters than for many other gauging methods. In all gauges it is important to minimize the possibility of adhesion of buckets to stops and to minimise friction at the pivot.

DISCUSSION AND CONCLUSIONS

The tilting bucket principle can be readily extended to larger volumes than tipping bucket raingauges, and provides a simple digital integrator of mass flow of fluid. As bucket volume increases, tipping time increases and the variation in metered mass with inflow rate becomes important. The collision impulse of the falling bucket as it strikes the resting stop becomes the over-riding design consideration when bucket volume exceeds 2-5 litres. Solutions to these design problems have been offered in the form of fluid counter-weights, varying bucket shapes, alternative pivot positions and air dampers.

In buckets of raingauge size, surface tension effects cause the most significant er ors. Any water left in the bucket after tipping constitutes a variable counter-weight and also reduces the mass required to tip when the nominally empty bucket returns for filling.

It is the experience of the authors that bucket cycle times should not be reduced below about ten times the tipping time. This represents 2 seconds for raingauges which tip in approximately 0.2 seconds and 12 seconds for 12 litre buckets tipping in 1.2 seconds. In raingauges the bucket volume is usually set at the minimum amount to be recorded on a daily basis, which in Australia is usually 0.01 inches or 0.25 mm over the catch orifice area. The World Meteorological Organization (W.M.O. 1961) recommends 0.1 mm bucket volume. The maximum rainfall rate recommended above, is 30 bucket volumes per minute or 1800 volumes per hour.

As catchments increase in area, bucket capacities equivalent to approximately 0.025 mm over the catchment are used by the authors as a compromise between the errors inherent at high flow rates and the difficulties in constructing large gauges. This means that peak measurement rates of acceptable accuracy, measured in runoff depth, are significantly less than that of the companion raingauges.

There are therefore limitations to the situations where single bucket installations may be used. However it is believed that within these limitations the tipping bucket gauge offer real advantages with its simplicity and digital output.

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