SIX-MINUTE RAINFALL INTENSITY DATA FOR AN EXCEPTIONALLY HEAVY TROPICAL RAINSTORM

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IN his comprehensive review of tropical rainfall, Jackson (1977) noted that there was a lack of information on precipitation intensities for periods of less than 24 hours. The principal cause is a shortage of autographic recorders in tropical areas. Such detailed rainfall data are required not only for tropical climatology but also for hydrological purposes. It has been graphically and statistically demonstrated elsewhere that the lag response between rainfall, overland flow and stream discharge can be as small as 6–12 min (Bonell and Gilmour 1977). This means that if hydrological models, concerned with the runoff generation process, are to be applied successfully then the availability of short-term intensity information is essential. The object of this paper is to give details of six-minute rainfall intensities for an exceptionally heavy storm event which took place in a 25 ha catchment of tropical rainforest in north-east Queensland, Australia. The experimental area is located 5 km east of Babinda (17°20′S) adjacent to the Coral Sea (Fig. 1). The significance of the storm is more easily seen against the perspectives of the synoptic climatology, the rainfall characteristics and the method of measurement.

CLIMATIC BACKGROUND

The experimental catchment is located in the midst of the wet tropical coastal belt of north-east Queensland. The catchment has recorded a mean annual rainfall of 4239 mm for the eight-year period 1970 to 1977. The monthly distribution is shown in Fig. 2. It is evident that the regime is very seasonal with frequently half of the annual total falling during the 'wet season' months of January to March. It is at this time of the year when the inter-tropical convergence zone (ITCZ), or monsoonal trough as it is locally known, reaches its most southerly limit of seasonal movement. When the ITCZ is active it develops tropical lows which often intensify into tropical cyclones over the Coral Sea and Gulf of Carpentaria. These well-organised systems ensure the occurrence of high intensity rainfall events as well as high rainfall totals. Daily falls in excess of 250 mm are fairly common. Later in the year moist on-shore south-easterly winds occur sporadically during the

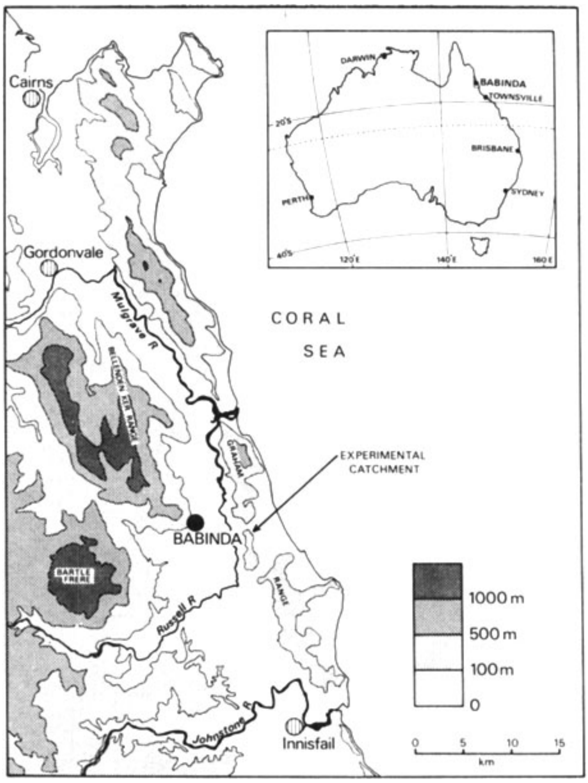

Fig. 1. The location of the experimental catchment in north-east Queensland

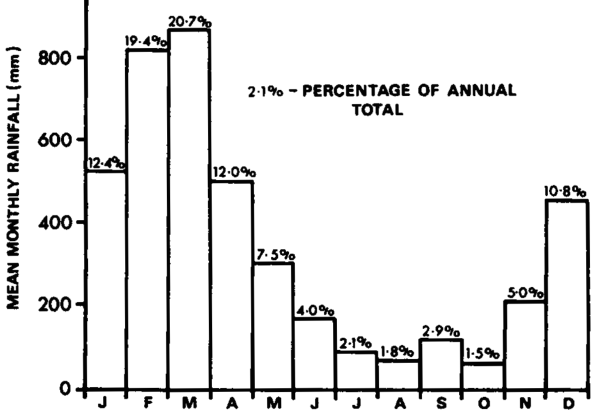

Fig. 2. Frequency diagram of mean monthly percentage contribution to the annual rainfall total, 1970 to 1977

'dry season' bringing relatively low intensity rain to the area, although daily totals can still occasionally exceed 100 mm. The meteorological systems usually responsible for these lighter rains are coastal ridges of surface high pressure; but whether rainfall occurs or not seems to depend on the lower easterlies gaining sufficient depth at the expense of the upper westerlies. It should be emphasised that a significant proportion of rainfall events in both seasons results from lows in the upper atmosphere which are not detectable on the surface chart. Furthermore the orographic effect is highly significant in the area as the easterly winds are uplifted over the Bellenden Ker-Bartle Frere mountain range (*c.* 1600 m OD) immediately to the west of Babinda (Fig. 1).

It is clear from this brief review that most rainfall results from well-organised meteorological systems originating over the sea rather than from localised thunderstorms resulting from diurnal heating. In fact thunderstorms tend to be more prevalent over the higher mountain range west of Babinda during the occasional north-westerlies resulting from the southward movement of the monsoonal trough, or northerlies preceding the onset of the summer wet season. This is a significant point to bear in mind when considering the short-term rainfall characteristics.

DATA

Records for the catchment commenced late 1969. The rainfall data were collected in a cleared area below the catchment outlet in a meteorological station which is located 3 km from the Coral Sea at an elevation of 12 m OD. Information is continuously monitored by a Rimco digital event recorder in conjunction with a tipping bucket rain-gauge which tips every 0·25 mm. The movement of the bucket activates a circuit by means of a reed switch sending an electrical impulse to the recorder. This in turn punches the number of tips for a specified channel on paper tape. The instrument records on a time base of six minutes thus allowing an accurate study to be carried out relating storm intensity, duration and amount. The paper tape is translated by a computer program written for the CSIRO Cyber 76 computer in Canberra. This gives rainfall totals for six-minute periods past the hour, e.g. 6·06, 6·12 etc. If the paper tape time marks are not coincident with these periods, e.g. 6·04, 6·10, 6·16, etc., then this is achieved by the computer on a proportional basis. This means that rainfall data will not necessarily be in 0·25 mm increments. The system has worked very well and there has been little record lost during eight years of use in the prevailing tropical climate.

ANALYSIS

The weekly maximum six-minute intensities were evaluated for the 1976 'wet season' for the purposes of statistically relating precipitation to overland flow generation in the tropical rainforest catchment. This information is presented in Fig. 3. The histogram is bimodal, with the first two

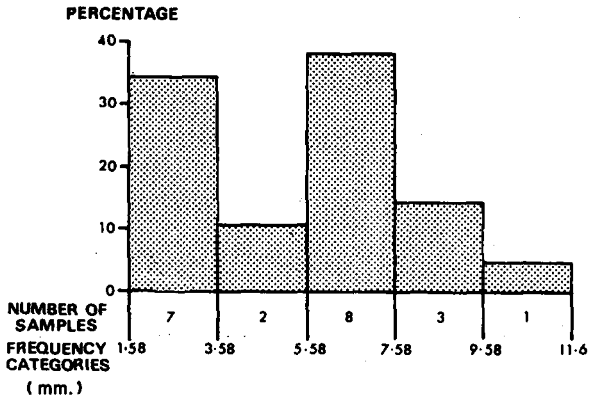

Fig. 3. Frequency diagram of maximum weekly six-minute rainfall intensity for the period 14 January–16 June 1976

categories depicting the low intensity 'winter' situation and the remainder depicting the summer situation. Thus in the latter case, weekly maximum six-minute intensities of between 6–10 mm frequently occur.

With regard to 24 hour totals, Table 1 lists the number of days each year from 1970 to 1977 when the daily (midnight to midnight) rainfall exceeded 100 mm. It is evident that the rain occurring on only a few days makes up a large proportion of the annual total, e.g. in 1973, 41 per cent of the total precipitation occurred on only 13 days. Rain recorded on five consecutive days in February 1977 (6th to 10th inclusive) amounted to 1181 mm which was 23 per cent of the annual total of 5206 mm. More details on this period will be given later.

THE STORM IN DECEMBER 1976: SYNOPTIC ASPECTS

The storm under investigation occurred in December 1976 and generated the highest short-term intensities since records commenced. Brief details will be given of the synoptic situation at the time of the storm event.

TABLE 1. Number of days from 1970 to 1977 with rainfall exceeding 100 mm

Year	No. of days with rainfall > 100 mm*	Max. daily rainfall (mm)
1970	7	217
1971	8	153
1972	9	382
1973	13	300
1974	4	195
1975	6	328
1976	4	464
1977	12	423
Mean 8 yrs	7·9	307·75

*Rainfall period taken is midnight to midnight.

The surface chart at 0300 Eastern Standard Time (EST) on 20 December 1976 (Fig. 4) was dominated by severe tropical cyclone *Ted* which had previously crossed the Gulf of Carpentaria coast, north of Burketown at 1600 EST on 19 December. This was an unusually deep tropical cyclone for the Gulf, having a central pressure of about 950 mb at landfall. At 0300 on the 20th, the cyclone was located approximately 180 km south-east of Burketown with the monsoonal trough extending from the centre across the east coast near Port Douglas about 100 km north of Babinda. This trough subsequently moved southwards through the Babinda area at approximately 0900 on the same day.

The upper air charts (Fig. 5) show that the cyclone was beginning to lose its identity above the 400 mb level in the upper westerly circulation, after the previous existence of a closed circulation to 250 mb at 2000 on the 19th. This marked the transition to the rain depression stage whereby the mean winds eventually fell below cyclonic strength (<65 km hr^{-1}) but the system remained well organised producing widespread, heavy rainfall.

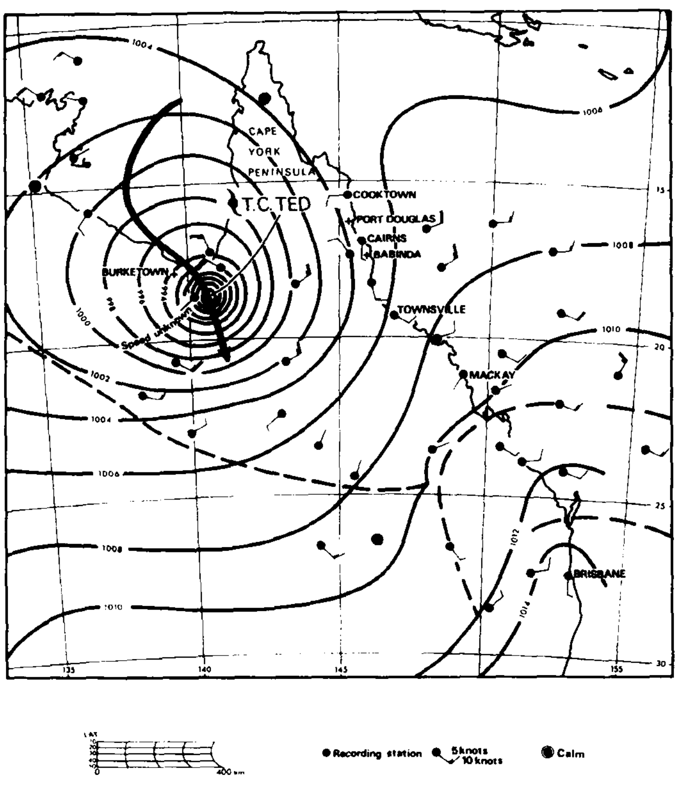

Fig. 4. The surface synoptic chart for 0300 EST 20 December 1976

Of greater interest to the Babinda area was a trough over Cape York Peninsula extending from the cyclone at 850 mb which was associated with the monsoonal trough and a second, much weaker feature, evident at the

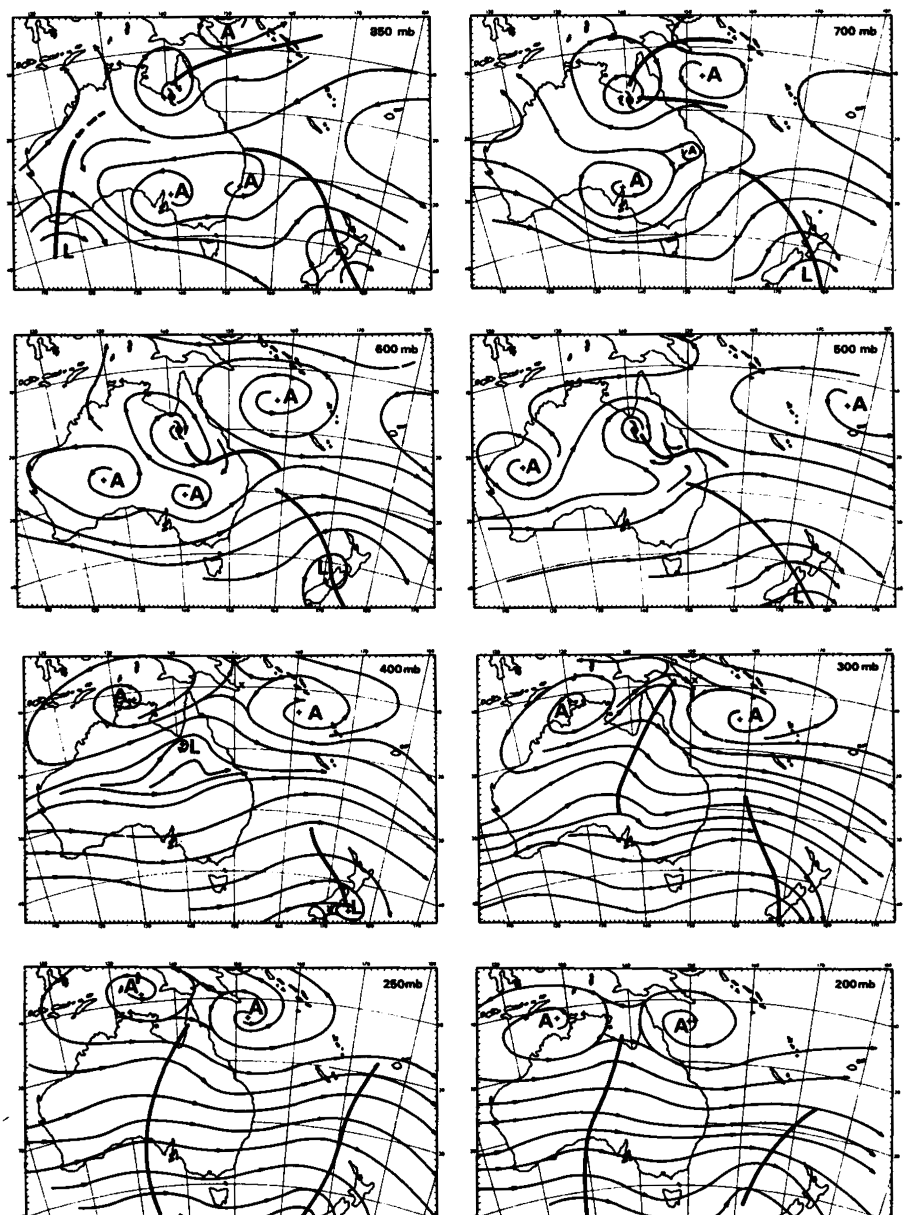

Fig. 5. Streamline charts for 0300 EST 20 December 1976 at various pressure levels

700, 600 and 500 mb levels in the Townsville–Mackay area. This was essentially the boundary between the drier easterly–south-easterly airstream to the south and the moist northerlies circulating around an anticyclone over the Coral Sea at these levels. However, radar echoes and the NOAA 5 satellite photograph of 2212 EST for 19 December suggest that the storm rainfall in the Babinda area was due to massive convergence resulting from tropical cyclone *Ted*, rather than to the upper troughs. This convergence formed part of a major spiral band from the cyclone along the coast north of Mackay which was accentuated in the Babinda area by orographic uplift over the mountains.

STORM RAINFALL

As regards the rainfall in the catchment, the moist inflow to the cyclone from the Coral Sea produced a total of 94·3 mm on the 19th which preceded the highest daily total so far recorded of 464 mm on the 20th. A detailed breakdown of six-minute intensities for these two dates is shown in Table 2. The rainfall of the 19th warrants inclusion in Table 2 as the intensity pattern is typical for a summer storm and will help to put the main event on the 20th in perspective. In addition, the maximum six-minute falls of 6·25 and 6·09 mm at 0554 and 0600 respectively are representative of the range depicted in Fig. 3 for this season. However, the main objective is to examine the first of two storms which gave rainfall on the 20th in the period 0136–0854. At this time the spiral band was best developed preceding the passage of the monsoonal trough at the surface.

The heavier precipitation did not commence until 0224 and terminated by 0832. The total rainfall for this shorter period was 356·45 mm in 6 hours 18 min which gives an average of 5·66 mm per 6 min. The total amount for the whole storm was 362·31 mm reducing the 6 min average intensity to 4·97 mm per 6 min. This is an exceptional total for a storm of this duration in the lowland rainforest catchment. Similar daily totals of this magnitude have occurred before but of much lower intensity and hence longer duration. Table 3 shows that about one-third of the storm had intensities greater than 6 mm per 6 min. But more important, 14·85 per cent of the events exceeded 10 mm per 6 min, which is the normal upper range of maximum weekly summer intensities.

It is evident from Table 2 that the storm had major peaks at 0318–0324 (13·5 mm) and 0448–0454 (14·4 mm). The latter occurred in the period of maximum intensities for this storm, i.e. 0407–0506. The intensities within this hour are summarised in Table 4, expressed in two ways, i.e. absolute intensities and their equivalent hourly rate. The absolute maximum 60-min amount shows an intensity of just over 100 mm hr^{-1} but the equivalent hourly rates of the maximum 6- and 12-min periods are greater than 140 mm hr^{-1} which are far in excess of normal values for this area.

TABLE 2. Six-minute rainfall totals (mm) for 19 and 20 December 1976 in the Babinda catchment

Date	Hours / Mins	00	01	02	03	04	05	06	07	08	09	10	11	12
19	06						3·30	4·20			0·05			0·23
	12						1·27	1·20			0·55			0·03
	18						1·41	0·68		0·02	1·05			0·25
	24						0·50			0·23	1·43			0·28
	30						0·48		0·02		0·80		0·03	0·45
	36						0·25		0·23		1·49		0·23	
	42						0·48		0·02		3·60			
	48	0·02				0·02	3·07		0·23		2·25			
	54	0·29				0·30	6·25		0·02		2·03		0·03	0·03
	60					1·00	6·09		0·23				0·25	0·23

Date	Hours / Mins	13	14	15	16	17	18	19	20	21	22	23
19	06		0·22	0·50	4·60	0·97	0·22					
	12		0·03	0·55	1·46	0·72						
	18		0·25	0·95	3·12	0·47				0·03		
	24		0·25	0·50	1·89	0·28			0·03	0·25		
	30		0·30	0·58	1·05	0·53			0·25	0·22		
	36		0·98	1·30	1·45	0·72			0·22	0·03		0·06
	42		3·08	1·88	0·97	0·47				0·22		0·44
	48		3·44	2·97	0·80	0·25						
	54		0·70	2·59	1·22	0·22						
	60	0·03	0·28	1·65	1·00	0·03						0·03

Date	Hours / Mins	00	01	02	03	04	05	06	07	08	09	10	11	12
20	06	0·22		1·03	3·78	7·93	4·94	6·19	4·53	0·38				
	12			1·22	4·69	10·0	3·18	5·34	4·47	1·60				
	18			0·97	10·2	4·13	5·54	2·47	2·56	4·19		0·23	0·17	
	24			0·87	13·5	12·3	1·18	2·03	2·97	5·57		1·68	1·15	
	30			2·08	11·5	12·1	6·50	0·50	3·20	6·10		1·22	0·63	
	36		0·03	4·53	11·0	7·62	9·38	0·82	6·28	6·27		0·90	1·67	
	42		0·22	4·45	5·34	10·7	5·16	3·63	6·05	2·71		0·48	2·82	
	48	0·15	0·06	2·34	6·46	13·7	6·10	7·50	2·65	0·69	0·03	1·80	3·05	
	54	1·13	0·44	2·82	9·63	14·4	4·94	4·10	0·25	0·22	0·22	0·43	1·62	
	60	0·22	0·12	1·77	8·60	11·2	4·72	4·72	0·25				0·65	0·03

Date	Hours / Mins	13	14	15	16	17	18	19	20	21	22	23
20	06	0·22				0·04	1·14	0·21	1·93	1·68	0·32	
	12					0·29	2·04	0·11	1·32	1·10	0·86	
	18					0·47	2·25	0·71	0·32	0·25	1·80	
	24	0·03				0·43	2·53	0·89	1·00	0·25	3·09	
	30	0·22			0·04	1·40	4·07	3·11	2·79	0·25	0·68	
	36				0·60	0·68	2·68	2·00	4·68	0·25	0·32	
	42				2·54	0·25	0·75	0·46	5·57	0·29	0·68	
	48				1·11	0·22	1·07	0·25	4·76	0·54	0·21	
	54				0·29	0·07	2·61	0·25	5·74	0·71		
	60				0·43	0·57	0·25	0·50	2·60	0·46		

The second major storm which took place in the evening of 20 December presents a marked contrast to the one just described. The later event is of much lower intensity, as shown in Table 2.

This heavy precipitation event can be put into perspective in another way when it is considered that an additional 2156 mm was later recorded in a 17-day period dating from 31 Jan to 16 Feb 1977. This included the very

TABLE 3. The frequency distribution of six-minute rainfall totals for the period 0136–0854 EST, 20 December 1976

Frequency categories (mm)	Total no. of events	Percentage of total
0–1·99	19	25·68
2–3·99	13	17·57
4–5·99	17	22·98
6–7·99	11	14·86
8–9·99	3	4·05
10–11·99	6	8·1
12–13·99	4	5·4
14–15·99	1	1·35

TABLE 4. Maximum absolute intensities, 6 mins to 1 hr and equivalent hourly rate

Duration (in min)	Absolute totals (mm)	Equivalent hourly rate (mm)
6	14·4	144
12	28·1	140·5
18	39·3	131
24	50	125
30	57·62	115·24
36	69·72	116·2
42	82·02	117·17
48	86·96	108·7
54	91·09	101·21
60	101·09	101·09

close passage to Babinda of Tropical Cyclone *Keith* on 31 January which produced 423 mm, followed by additional high daily totals of 315 mm (6th), 252 mm (9th) and 270 mm (10th). The latter totals were generated by low pressure systems embedded in an active monsoonal trough in the Cairns region. All these events were characterised by low intensity precipitation of long duration and apart from the cyclone, the remainder occurred for the full 24-hour period. The maximum 6-min intensities for each storm were in the quoted 1976 wet season weekly range with the majority of remaining values less than 3 mm per 6 min. This is the more typical situation in this region during heavy rainfall resulting from well-organised disturbances.

DISCUSSION

The description of this storm event raises many problems. The foremost point is a sampling problem with regard to the presented data but as the instrument is the only digital event recorder in the area there is no immediate solution. It is likely that these records represent only the narrow 'lowland' strip of the humid, tropical coast of north-east Queensland. Only a short distance inland the orographic influence becomes even more pronounced producing much higher annual totals and therefore potentially greater short-term intensities.

Another question is how do these intensity values of fine-time resolution compare with other tropical areas, particularly in similar rainforest environments? For two reasons it is not possible to make an effective comparison. The Babinda record is too short to calculate a reliable frequency-amount-duration relationship which would provide a common base for comparison with other areas. Furthermore there is a dearth of similar information from other tropical stations. One of the few examples available is that quoted by Griffiths (1972) for the Lower Congo (Kinshasa) rainfall. It is generally accepted that the highest 24-hr totals of lower return period are found in higher tropical latitudes such as the Babinda area where the increase in Coriolis parameter enables well-organised systems such as tropical lows and cyclones to develop. This is evident when the current rainfall data are compared with daily precipitation frequency either of West Malaysia (Lockwood 1967; 1974) or Lower Congo (Griffiths 1972). However, it is uncertain whether the high frequency of thunderstorms in the Equatorial regions, say 5°N–5°S, resulting from all year round abundance of moisture, corresponds with the highest short-term intensities which occur in the Tropics. Apart from the scarcity of data, complicating factors such as orographic effects can apply equally across the entire Tropics.

CONCLUSION

To answer some of the preceding points requires the installation of more event recorders within both the north-east Queensland area and throughout the Tropics in general. Up to the present time, such an idea has been prohibitive due to the high cost of such instruments. However, much cheaper versions are in the process of being developed and perfected. Such an example is the CSIRO Ross recorder produced in Australia (Ross 1975). This particular model is currently showing promise in rainfall measurement in semi-arid tropical conditions (Williams 1977). Once this model has proved to be reliable there is no reason why it could not be adapted to rain-forest environments, on the condition that the electronics are properly sealed against sustained high moisture values in such areas. This may provide the initial opportunity to accomplish the objective of increasing the spatial resolution of the data.

In the meantime, high short-term rainfall intensities have been demonstrated for an event typical of the severe flood-producing rains which are experienced on the north tropical coast. While it was certainly a major storm event it was by no means extreme, as the nearby town of Babinda has recorded several daily falls in excess of 500 mm. When the length of the catchment record is sufficient, it is intended to produce a frequency-amount-duration analysis for various periods ranging from 6 min to 24 hrs.

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SCOTTISH SNOW BEDS IN SUMMER 1978

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TABLE 1 shows that a comparison of the Highland winter period January–March 1978 with that of the corresponding period in 1977 (Spink 1978) emphasises the notably cold January–February period and much higher precipitation (171 per cent). A reverse of this trend occurred in April and May but the high snowfalls of the first three months resulted in an overall snowy appearance during my late July visit, despite a warm May and snowless June.

From Inverdruie, a mile from Aviemore, Iain Hudson (1978) reported that in January snow fell on 20 days and sleet on two and in February, when the Inverdruie monthly mean was as low as $-3{\cdot}5$°C, ice was 23 cm thick on Loch Morlich by the 17th. Dynamite had to be used to clear ice blockages and consequent floods between Inverdruie and the River Spey. He also noted that 215 cm (85 in.) of snow fell on the Cairngorms between 20 January and 22 February leading to 'an extreme avalanche state'. (several occurred on the 19th).