internal report **366**

Hydrology of the Ngarradj catchment, Northern Territory: 1998-1999 and 1999-2000 Wet season monitoring - Interim report

Moliere DR, Evans KG, Saynor MJ & Boggs GD

July 2001

supervising scientist

Hydrology of the Ngarradj catchment, Northern Territory

1998-1999 and 1999-2000 Wet Season Monitoring: Interim Report

DR Moliere[1], KG Evans[1], MJ Saynor[1&2] & GS Boggs[1&3]

[1]Erosion and Hydrology Group.
Environmental Research Institute of the Supervising Scientist
Locked Bag 2, Jabiru NT 0886

[2]The University of Western Australia
Nedlands, WA

[3]The Northern Territory University
Darwin NT 0901

July 2001

eriss

ENVIRONMENTAL RESEARCH INSTITUTE OF THE SUPERVISING SCIENTIST

Table of Contents

Acknowledgements

Currumbene Hydrological installed the gauging stations and Mr B Smith, Mrs E Crisp and Mr A Ralph assisted with data collection. Mr G Fox assisted with rainfall data analysis and preparation of appendices. Dr W Erskine, NSW State Forests, provided advice on monitoring design and strategies and constructively criticised and improved this report.

1. Introduction

The Jabiluka uranium mine is located in the catchment of Ngarradj[1] in the wet dry tropics of the Northern Territory, Australia (fig 1). Ngarradj is a major downstream right-bank tributary of Magela Creek, which flows directly into the Magela Creek floodplain. The Magela Creek and floodplain are listed as Wetlands of International Importance under the Ramsar Convention and recognised under the World Heritage Convention. The Ngarradj catchment will be the first to be affected should any impact occur as a result of mining operations at Jabiluka.

This report describes two years of hydrology data collected from three stream gauging stations within the Ngarradj catchment (fig 1) as part of a long-term study of the impact of mining at Jabiluka on the Ngarradj catchment. The stream gauging stations were established in 1998 both upstream (ET-East Tributary and UM-Upper Main) (fig 1) and downstream (SC-Swift Creek) (fig 1) of the mine to collect data on rainfall, runoff and sediment transport in the Ngarradj catchment (Erskine et al 2001). The ET and UM gauging stations, upstream of the mine, provide data from unimpacted parts of the catchment. If a change occurs at SC, downstream of the mine, that is not observed at ET or UM then it can be assumed that this change arises from that part of the catchment where the mine is located and may be due to mine site activity.

Oenpelli rainfall data were used in the analysis of the two years of rainfall data from the Ngarradj catchment in section 3. The derivation of rating tables used to convert stage height data collected at each gauging station to discharge data is described in section 4. Section 5 describes the discharge data for the two years of monitoring at Ngarradj catchment, including a partial-series flood frequency analysis. In section 6, eight separate rainfall-runoff events that occurred during the two wet seasons of flow were selected for further analysis.

---

[1] **Ngarradj**: Aboriginal name for the stream system referred to as "Swift Creek" in earlier studies. Ngarradj means sulphur crested cockatoo. The full term is Ngarradj Warde Djobkeng. Ngarradj is one of several dreaming (Djang) sites on or adjacent the Jabiluka mine lease (A Ralph, Gundjehmi Aboriginal Corporation 2000)

It is recommended that several more years of rainfall and streamflow data are collected from these gauging stations to improve the expected accuracy of this type of analysis.

2. Study area

The Ngarradj catchment is located approximately 230 km east of Darwin and 20 km north-east of Jabiru (fig 1). Oenpelli, Arnhem Land, is a further 20 km north-east of the Ngarradj catchment.

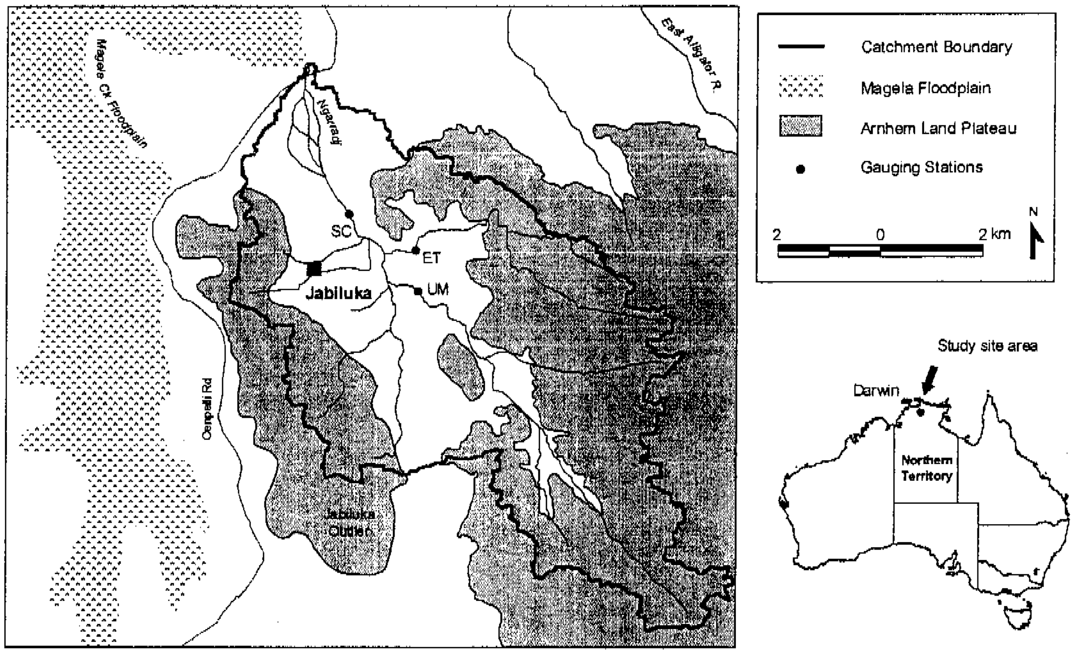

Figure 1 The location of the Jabiluka mine and the gauging station sites within the Ngarradj catchment.

Ngarradj main channel flows in a well-defined valley in a northwesterly direction from the Arnhem Land plateau to the Magela Creek backplain with one major right bank tributary (East Tributary) (fig 1). Both the upper reaches of the Ngarradj main channel and East Tributary flow in essentially a bedrock confined channel on the escarpment (fig 1). There are several left bank tributaries that drain predominantly wooded lowland areas and do not have the areas of bedrock and escarpment that are present in the main channel and East Tributary. The catchment areas of the three gauged streams within the Ngarradj catchment (SC, UM and ET) are 43.61 km^2, 18.79 km^2 and 8.46 km^2 respectively. The catchment area contributing to the left bank tributaries is therefore approximately 16.36 km^2.

3. Rainfall data

A 0.2 mm tipping bucket rain gauge was installed at each gauging station within Ngarradj catchment and readings were taken at 6 minute intervals. The rain gauges were installed at each station in mid-November 1998 and as a consequence, early wet season rainfall data (Sept – Nov) were not recorded at these sites. Rainfall data measured at the Jabiluka mine by Energy Resources of Australia were used to estimate the early wet season rainfall data for the three stations.

Linear regression analysis of the total monthly rainfall figures observed at Jabiluka and each of the three gauging stations during the 1998/99 and 1999/00 wet seasons was used to derive linear relationships for rainfall at SC, UM and ET (eqns 1 to 3).

$$SC_{rain} = 0.998\ Jab_{rain} \qquad (r^2 = 0.97) \qquad (1)$$

$$UM_{rain} = 1.021\ Jab_{rain} \qquad (r^2 = 0.92) \qquad (2)$$

$$ET_{rain} = 1.006\ Jab_{rain} \qquad (r^2 = 0.96) \qquad (3)$$

Equations 1 to 3 indicate that the monthly rainfall data recorded at Jabiluka mine is very similar to that observed at the three gauging stations. As a result, the total rainfall figure recorded at Jabiluka mine from 1 September to mid-November 1998 was simply transposed to the SC, UM and ET rainfall record (table 1).

Table 1 Total Jabiluka rainfall used to infill gaps in the rainfall record at SC, UM and ET (Sept – Nov 1998).

Station	Gap in the rainfall record	Total infilled rainfall from Jabiluka (mm)
SC	1 Sept - 23 Nov* 1998	293.2
UM	1 Sept - 22 Nov* 1998	293.2
ET	1 Sept - 11 Nov* 1998	224.8

* The final day of the gap in the rainfall record corresponds to the date that the raingauge was installed at the station.

The total daily rainfall at each gauging station during the period of flow for the two wet seasons is shown in Appendix A. The total annual rainfall at each gauging station (SC, UM and ET) and Jabiluka mine during 1998/99 and 1999/00 wet seasons are shown in Table 2.

The total rainfall over the Ngarradj catchment during 1998/99 and 1999/00 (September to August) was determined using the Thiessen Polygon method (Thiessen 1911, as cited in Ward & Robinson 1990) to spatially average the total rainfall measured at the three gauging stations and Jabiluka mine. The total rainfall at each site is weighted in proportion to the area the gauge represents (table 2). The Ngarradj catchment received 1826.1 mm and 2047.4 mm during 1998/99 and 1999/00 respectively (table 2).

Table 2 Total rainfall over the Ngarradj catchment area derived using the Thiessen Polygon method.

Station	Rainfall 98/99 (mm)	Rainfall 99/00 (mm)	Polygon area (% of total area)	Rainfall fraction 98/99 (mm)	Rainfall fraction 99/00 (mm)
SC	1788.6[1]	1997.2	0.324	579.5	647.1
UM	1855.2[1]	2105.0	0.482	894.2	1014.6
ET	1733.6[1]	2069.6	0.105	182.0	217.3
Jabiluka	1914.4	1892.0	0.089	170.4	168.4
Total [ARI]			1.00	1826.1 [1:15]	2047.4 [1:87]

[1] Data partly provided by Energy Resources of Australia

Figure 2 shows the diurnal cycle of mean rainfall in one hour bins for two years of rainfall data collected at the SC gauging station within Ngarradj catchment. Rainfall at the Ngarradj catchment exhibits a strong diurnal cycle with a peak in the late afternoon (fig 2). The diurnal cycle over the Ngarradj catchment is similar to that found over the Darwin region (Li et al 1996, Soman et al 1995).

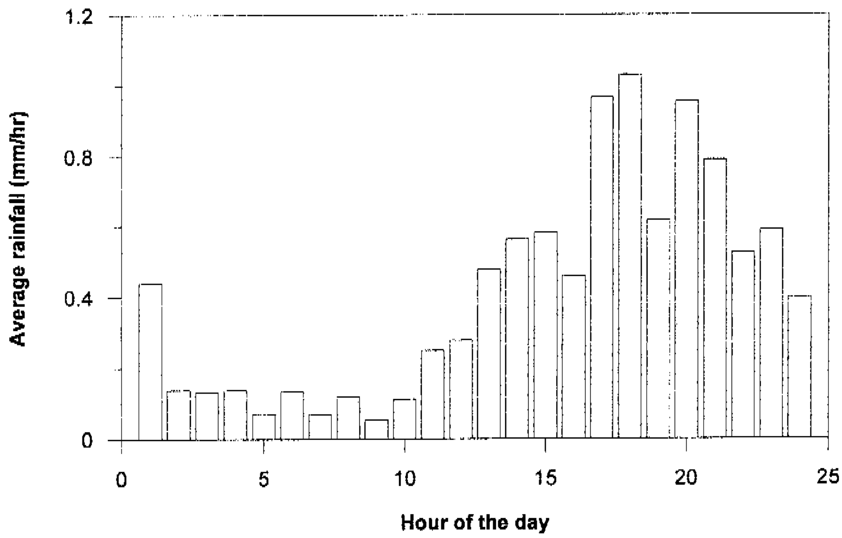

Figure 2 Diurnal variation of mean rainfall for the SC gauging station within Ngarradj catchment.

During the two year monitoring period there were 17 rainfall events that occurred at all three gauging stations with an intensity greater than 20 mm/hr. All of these rainfall events contributed to a peak in the hydrograph. The 17 rainfall events occurred between 14:00 h and 03:30 h, with an average start of rainfall time of 19:00 h, and generally lasted between one and two hours. The average time taken from the start of rainfall to the peak of runoff at SC, UM and ET for the 17 rainfall events was 5.75, 3.9 and 2.75 hours respectively. This 'lag' time for each catchment area is approximately proportional to stream path length (11.5 km, 9 km and 6.5 km for SC, UM and ET respectively). Rodriguez-Iturbe and Rinaldo (1997) discuss in detail the relationship between stream path length and the time of runoff response to a rainfall event.

The understanding of the diurnal cycle of rainfall over the Ngarradj catchment and the corresponding lag time for runoff after a storm event has important implications for stream monitoring sampling within the Ngarradj catchment. For example, a sampling regime that samples the streams within Ngarradj catchment only in the morning is unlikely to capture peak discharge events.

3.1 Analysis of annual rainfall

There are two rainfall stations with long-term data close to the Ngarradj catchment – Jabiru airport, 20 km south-west of the Jabiluka mine site, and Oenpelli, 20 km north-east of the Jabiluka mine site. The length of the rainfall records for Jabiru airport and Oenpelli are approximately 30 years (1971-2000) and 90 years (1910-2000) respectively. The mean annual rainfalls (September to August) for both locations are given in table 3 (Bureau of Meteorology pers. comm. 2000).

Table 3 Mean annual rainfall for Jabiru airport and Oenpelli.

Location	Period of record	Mean annual rainfall (mm)	Standard deviation (mm)
Jabiru airport	1971-2000	1511	309.2
Oenpelli	1910-2000	1402	283.7

The average annual rainfall for Oenpelli over the same period of record as Jabiru airport (1971-2000) is 1510 mm, very similar to the mean annual rainfall recorded at Jabiru airport (1511 mm) (table 3). As the rainfall data at the two locations are relatively similar, the rainfall data for Oenpelli will be used for analysis in the Ngarradj catchment area because it has a longer period of record. Previous studies on rainfall analysis in the Jabiluka mine site region have also used Oenpelli rainfall data (ie Chiew and Wang 1999).

The annual rainfall data for Oenpelli fit a normal distribution for the period of record (Bureau of Meteorology 1999). Therefore, an annual exceedence probability (AEP) was calculated for each year for the period of record at Oenpelli using a z-score transformation formula (eqn 4) and a standard normal table.

$$z = (x - X)/\sigma \quad (4)$$

where x is the annual rainfall, X is the mean annual rainfall (table 3) and σ is the standard deviation (table 3).

From standard normal tables the AEP for each year is determined using the corresponding z value (eqn 4). The annual distribution of rainfall for Oenpelli showing the AEP and the average recurrence interval (ARI) is given in figure 3. The total annual rainfall for the Ngarradj catchment during 1998/99 and 1999/00 (table 2) is also shown in figure 3.

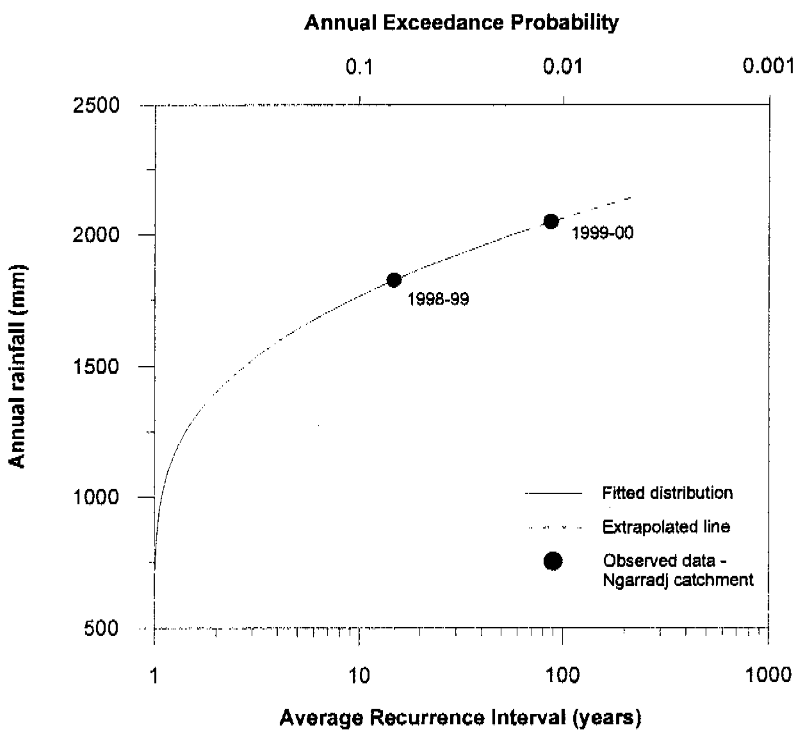

Figure 3 Annual distribution of rainfall for Oenpelli. The two years of rainfall for the Ngarradj catchment (table 2) are also shown.

The total annual rainfalls for the Ngarradj catchment for 1998/99 and 1999/00 (table 2) are above average for both Oenpelli and Jabiru (table 3). Figure 3 shows the distribution of annual rainfall for Oenpelli. The total rainfall in the Ngarradj catchment during 1998/99 and 1999/00 plot on this distribution as approximately 1:15 and 1:87 rainfall years respectively (table 2).

The total annual rainfall at Oenpelli during 1998/99 and 1999/00 was lower than that recorded in the Ngarradj catchment, particularly during 1999/00 (table 4). The annual rainfall at Oenpelli during 1998/99 and 1999/00 was also much lower than that recorded at Jabiru (table 4). Despite the good relationship between Oenpelli and Jabiru rainfall data (Chiew and Wang 1999) the annual rainfall at these two sites during 1998/99 and 1999/00 (table 4) highlights the variance from year-to-year between the two stations. Therefore, it may be assumed that there is also variance from year-to-year between rainfall data recorded in the Ngarradj catchment and at Oenpelli, and that although the annual rainfall in the Ngarradj catchment during 1998/99 and 1999/00 is greater than that at Oenpelli (table 4), it cannot be assumed that this is consistently the case. It is recommended that several more years of rainfall data in the Ngarradj catchment are required to determine the quality of the relationship between Ngarradj catchment and Oenpelli rainfall data.

Table 4 Total annual rainfall for Ngarradj catchment, Oenpelli and Jabiru during 1998/99 and 1999/00. The ARI of the rainfall at each location compared to the annual distribution of rainfall at Oenpelli is also shown.

Location	Rainfall 98/99 (mm) [ARI]	Rainfall 99/00 (mm) [ARI]
Ngarradj catchment	1826.1 [1:15]	2047.4 [1:87]
Oenpelli	1616.0 [1:4]	1667.5 [1:6]
Jabiru airport	1838.0 [1:16]	1923.0 [1:30]

3.2 Analysis of monthly rainfall

During the 1998/99 wet season, 6 of the 7 months of the rainfall period recorded for the Ngarradj catchment were above the monthly average (fig 4), particularly early in the wet season (Oct) where rainfall was equivalent to a monthly total with an ARI of greater than 1 in

1000 years (fig 5). During the 1999/00 wet season, every month of the rainfall period, except for January, was above average (fig 4). Early in the 1999/00 wet season (Oct-Nov) total monthly rainfall was equivalent to a monthly total with an ARI of greater than 1 in 100 years (fig 5) and late in the wet season (April) rainfall was equivalent to a monthly total with an ARI of approximately 1 in 30 years (fig 5). During both wet seasons the 3 month period (Jan-Mar) normally associated with the highest rainfall in the region (fig 4) consisted of total monthly rainfalls that corresponded to an ARI of less than 1 in 5 years (fig 5). Therefore, the relatively high total annual rainfall for the Ngarradj catchment, particularly during 1999/00, was attributed to the length of the high rainfall period, rather than a significant monthly rainfall total during the wet months of January to March. Carter (1990) found that high rainfall years generally result from rain spread over several months and not from one extremely wet month, which supports the results in this study.

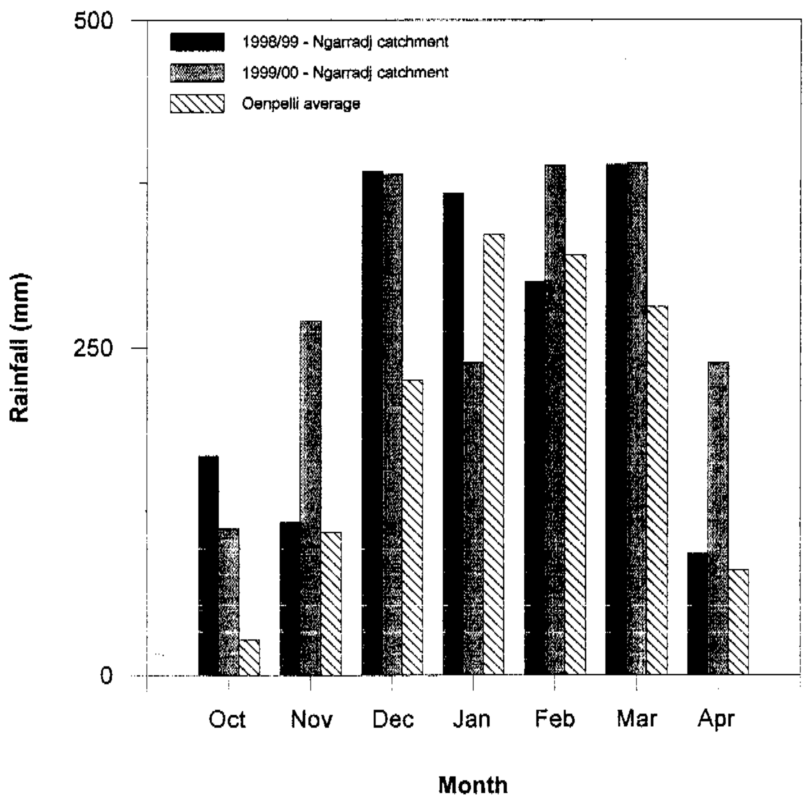

Figure 4 Total monthly rainfall for the Ngarradj catchment. Average monthly rainfall for Oenpelli is also shown.

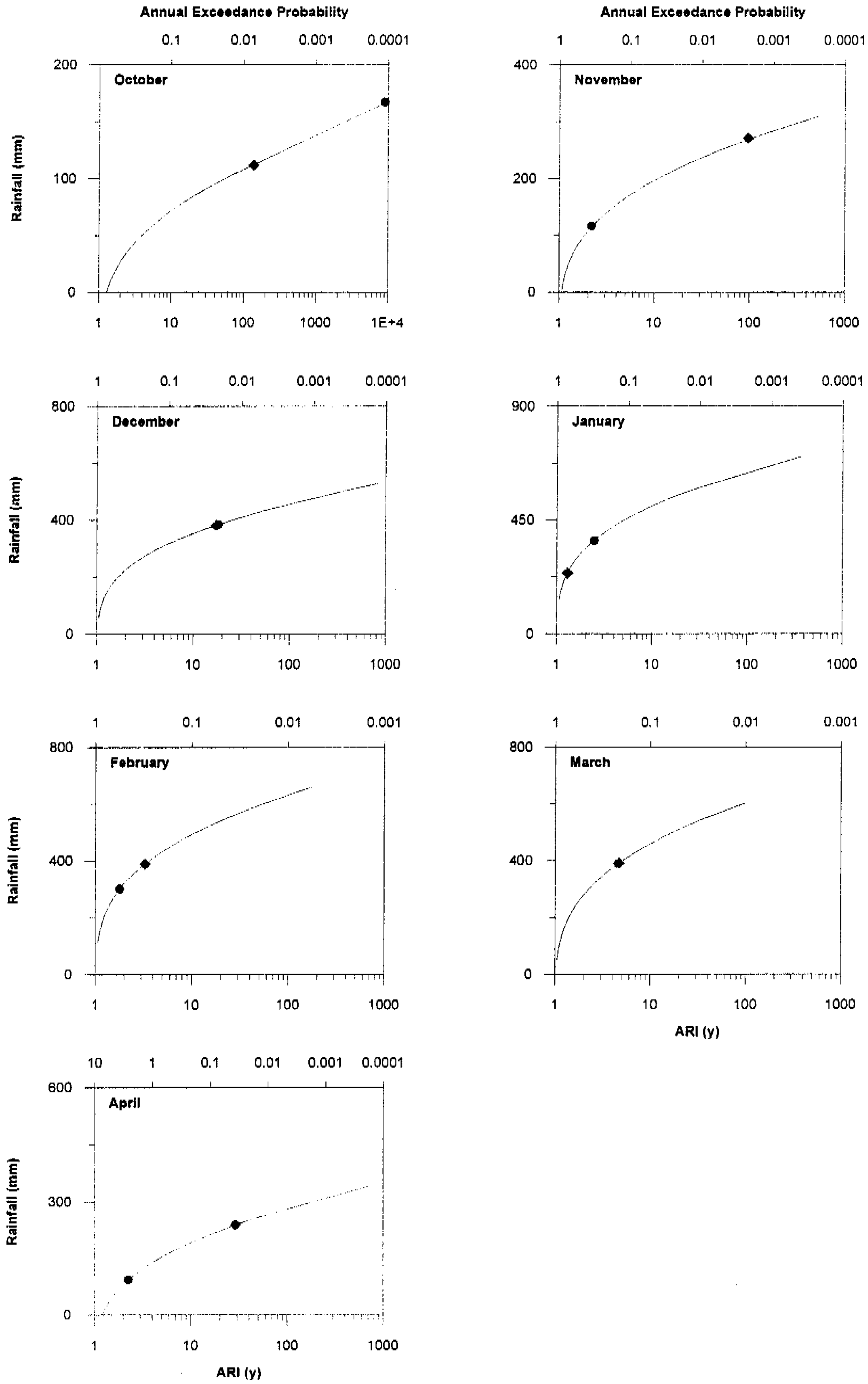

Figure 5 Monthly rainfall distribution for Oenpelli. The 1998/99 and 1999/00 rainfall data for the Ngarradj catchment are also shown (● and ♦ respectively).

Figure 6 shows the cumulative rainfall for Ngarradj catchment during 1998/99 and 1999/00 wet seasons compared to the cumulative rainfall at Oenpelli in a 1:5, 1:10, 1:20, 1:50, 1:100 and an average year.

As discussed above, rainfall during the early months of both wet seasons was particularly high (figs 4 and 5). As a result, total cumulative rainfall by the end of December is approximately equal to, and greater than, a 1-in-100 year rainfall value for the 1998/99 and 1999/00 wet seasons respectively (fig 6). During the period of high rainfall (Jan-Mar) the monthly rainfall figures for both wet seasons only corresponded to an ARI of less than 1 in 5 years (fig 5). However, total cumulative rainfall by the end of March for both years remained high, approximately equivalent to a 1-in-20 year rainfall value (fig 6). April 1999/00 rainfall was well above average (fig 4) and subsequently the final total annual rainfall value for the 1999/00 wet season was equivalent to a 1-in-87 year rainfall figure (fig 6). Figure 6 highlights the effect high rainfall early and late in the wet season has on the total annual rainfall figure, particularly during the 1999/00 wet season.

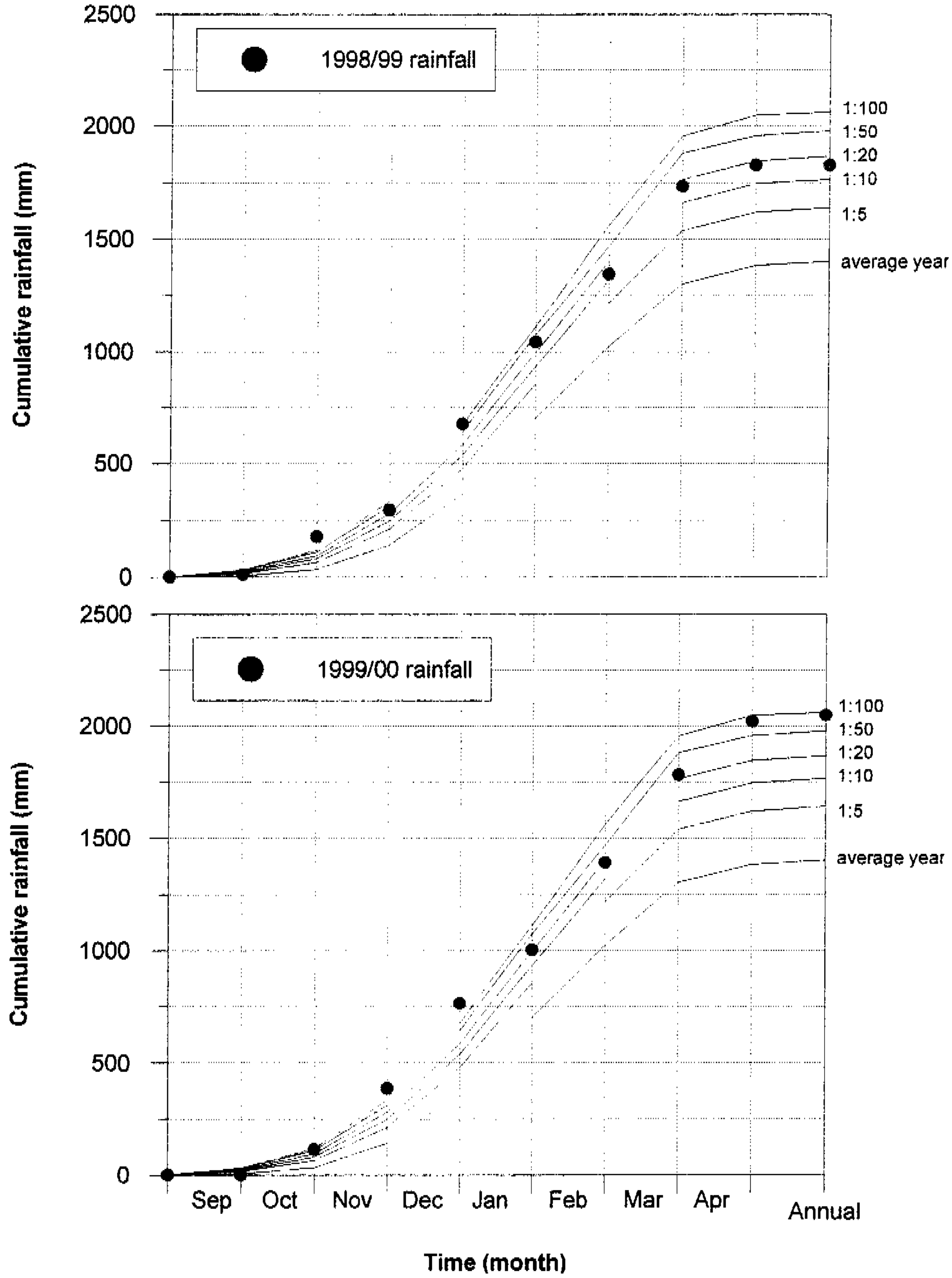

Figure 6 Cumulative rainfall for the Ngarradj catchment during 1998/99 and 1999/00 compared to that at Oenpelli during a 1:5, 1:10, 1:20, 1:50, 1:100 and an average year.

4. Rating table derivation

A differential pressure transducer and an optical shaft encoder were installed at each station and used as the primary and secondary water level sensors respectively. These sensors recorded stage height (m) of the flow at 6 minute intervals throughout the wet season.

A rating table used to convert the stage height data to continuous discharge data is required for each gauging station. The derivation of these rating tables, using velocity-area gaugings taken along a stable cross section at each of the gauging stations at various times throughout the period of flow (Appendix B), is described below.

The range of continuous stage height data and the highest and lowest gauging made during the two year monitoring period at each gauging station is given in table 5.

Table 5 The range of stage heights and gaugings at each gauging station.

Site	SC		UM	ET
	98/99	99/00	98-00	98-00
Cease to flow level (m)	0.19	0.24	0.089	0.06
Lowest gauging level (m)	0.33	0.32	0.17	0.21
Highest gauging level (m)	1.905	1.98	1.65	1.46
Highest stage height (m)	2.194	2.064	2.146	1.669

The computer software package HYDSYS was used to determine a rating table for each gauging station using the collected velocity-area gauging points. In this study HYDSYS was used to fit a 'point based' rating table, a collection of points each consisting of an input value (stage height) and a corresponding output value (discharge). Discharge values are determined for a particular stage height using interpolation techniques between table points. The fitted rating table can be applied over (1) a specified range of stage height values, and/or (2) a certain period of time.

4.1 SC gauging station

Figure 7 shows the cross sectional surveys taken along the gauging wire at SC before each wet season. There is a distinct change in cross section shape between 1998-1999 and 1999-2000 resulting in a change in cross sectional area. Although one rating table could be fitted for both years using HYDSYS, two separate and statistically significant rating tables were fitted using HYDSYS for each year of gauging data at SC to take into account the change in cross section area. The separate rating tables give more accurate discharges for each wet season of flow.

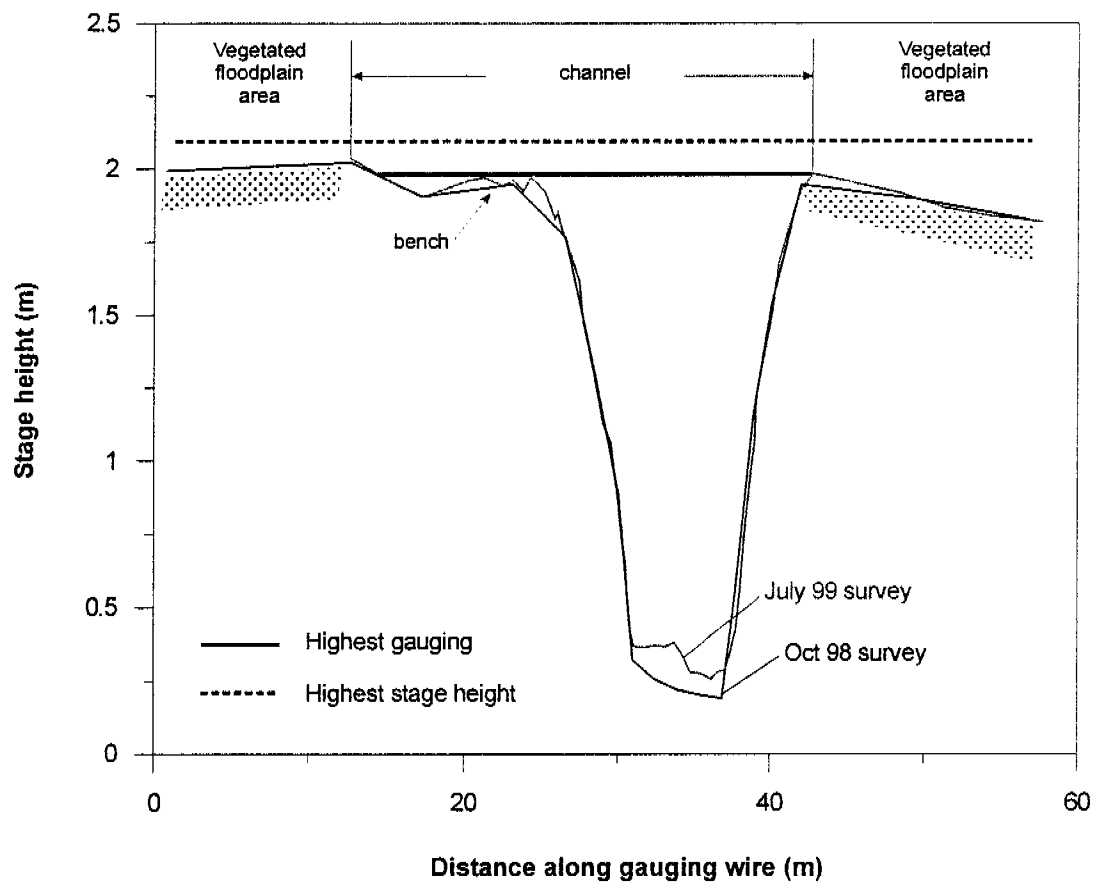

Figure 7 Cross section at SC showing the highest gauging and the highest measured stage height during the two year monitoring period. The dates at which the two cross sectional surveys were conducted are also shown.

During both wet seasons there were periods of flow that exceeded the highest gauging made at SC (table 5). The highest gauging and the highest measured stage height for the two year monitoring period at SC are indicated on figure 7. Extrapolation of the two rating tables was required in order to convert stage height data to continuous discharge data at stage heights greater than the highest gauging (Grayson et al 1996).

The channel at SC consists of a relatively deep main channel (fig 7) which accommodates most of the flow. Figure 7 shows that on the left side of this main channel is a bench which is considered to be part of the SC channel. Flow occurs in the overbank floodplain areas on both sides of the channel at times of very high flow only, and the floodplain level at SC is approximately equal to the highest gauging level.

Throughout the two year monitoring period at SC, there were eight events with a peak discharge greater than the floodplain level (~1.98 m) (table 5). Immediately after these periods of very high flow (> 1.98 m) there was little observed evidence to indicate that significant flow had occurred on the floodplain areas on either side of the channel (fig 7). The floodplain areas at SC are vegetated with sparse woodland and low grasses, particularly during the wet season, and therefore the effective boundary roughness is high and the flow is generally shallow on these areas. As a result, flow velocities on the floodplain areas would be relatively low compared to that in the channel (Pilgrim 1987). Therefore, it may be assumed that all flow at SC is confined to the channel, and that any flow on the floodplain areas either side of the channel is negligible.

Given that flow at SC is assumed to be confined to the channel, the channel at SC is considered to be of "simple" cross section (Pilgrim 1987) and therefore the fitted rating tables for each wet season were simply extrapolated to incorporate the entire range of stage heights (fig 8). The rating table extrapolation also included a minor lower-end extension from the lowest gauging to the 'cease to flow' level (table 5).

Figure 8 shows that there is a clear difference in the velocity-area gaugings taken during each wet season for the low to mid-range flows. The velocity-area gaugings taken during each wet season for the higher flows are similar. This trend in the gauging data is reflected in the fitted rating tables derived for each wet season of flow at SC (fig 8). To further refine the 1998/99 rating table in the higher flow rate region, the three highest gauging points measured during 1999/00 were included in the rating table derivation for 1998/99.

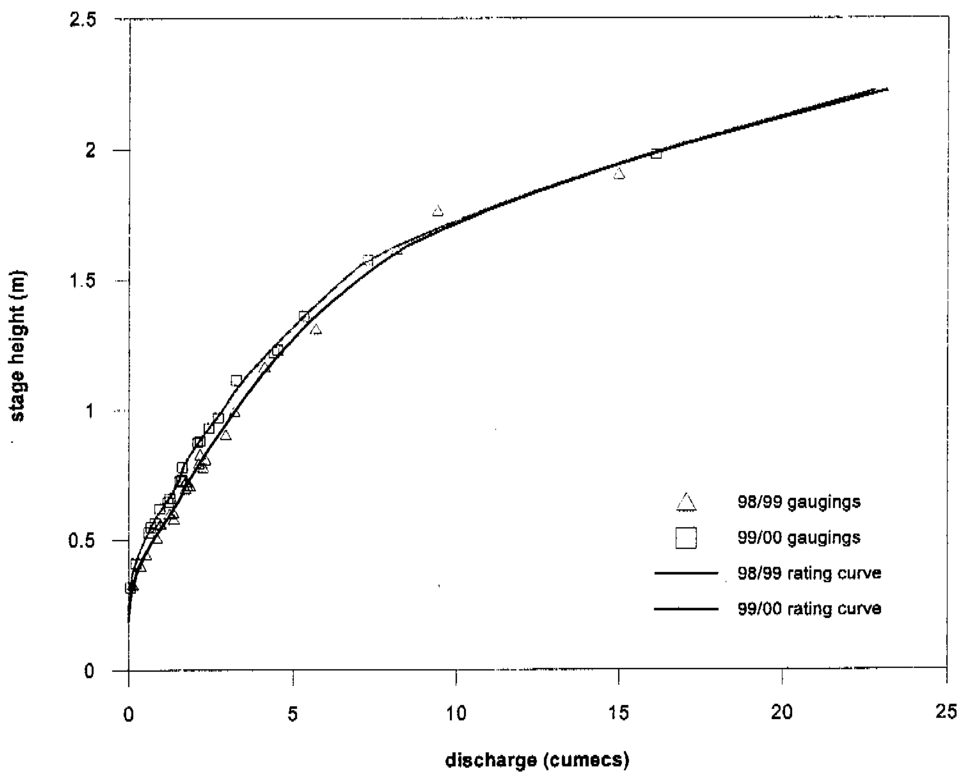

Figure 8 Rating curves constructed from the fitted rating tables for the SC channel for the 1998/99 and the 1999/00 wet seasons. The gauging points are also shown.

4.2 UM gauging station

One statistically significant rating table was fitted using HYDSYS from the two years of velocity-area gauging point data at UM. The fitted rating table can be applied to both years of continuous streamflow data at UM.

Similar to SC, there were periods of flow at UM during both wet seasons that exceeded the highest gauging (table 5 and fig 9). Therefore, it was necessary to extrapolate the rating table to estimate the stage-discharge relationship at flows higher than those observed in the channel at UM during a gauging.

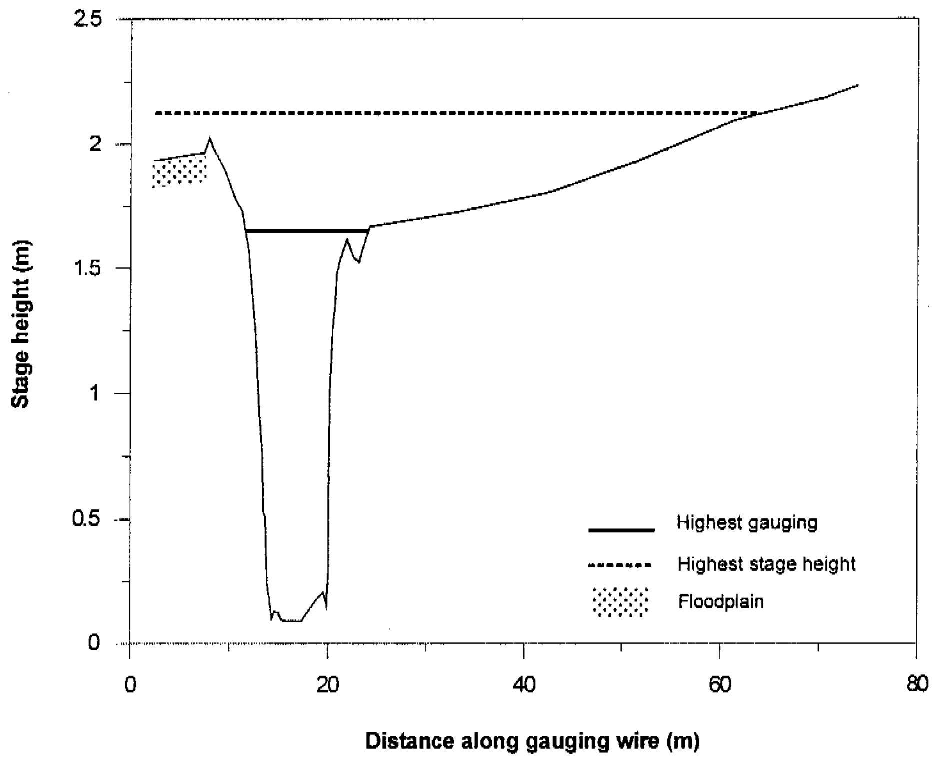

Figure 9 Cross section at UM showing the highest gauging and the highest measured stage height for the two year monitoring period.

Figure 9 shows that the channel at UM consists of a relatively deep and steep-sided main channel, an overbank flow area on the right side of the main channel and a floodplain area on the left side of the main channel. The main channel accommodates low and medium flows and flow only occurs on the overbank and floodplain areas during periods of high flow. It was evident from field observations that at flows much greater than the highest gauging, the flow on the overbank area on the right side of the main channel was significant. Therefore, the channel at UM is considered to be of "compound" cross section (Pilgrim 1987).

The following section describes the estimation of discharge values for two stage heights at high, overbank flow in the channel at UM. These estimated stage height-discharge values will be used to extrapolate the rating table at UM.

4.2.1 Rating table extrapolation

Discharge values were estimated for two stage heights, 2.023 m and 2.168 m (fig 10). The channel at UM is of compound cross section and therefore the overall cross section is subdivided into a number of subsections. According to Pilgrim (1987), imaginary vertical lines define the boundaries of each subsection and within each of these subsections large variations in flow depth or boundary roughness should not occur. Figure 10 shows the subdivision of arbitrary flow areas across the cross section at the given overbank flow levels at UM. Subsection 1 is the main channel; subsections 2 and 3 are overbank flow areas on the left and right side of the main channel respectively, and; subsection 4 is the floodplain area on the left side of the main channel.

Throughout the two year monitoring period at UM, flow in the floodplain area on the left side of the main channel (subsection 4) (fig 10) only occurred during four events. Immediately after these four periods of very high flow (> 2.023 m) there was little observed evidence to suggest that significant flow had occurred in this subsection. The floodplain area at UM is vegetated with sparse woodland and low grasses and therefore the surface roughness on this floodplain area is relatively high. As a result, it was assumed that flow on the floodplain area on the left side of the main channel was negligible.

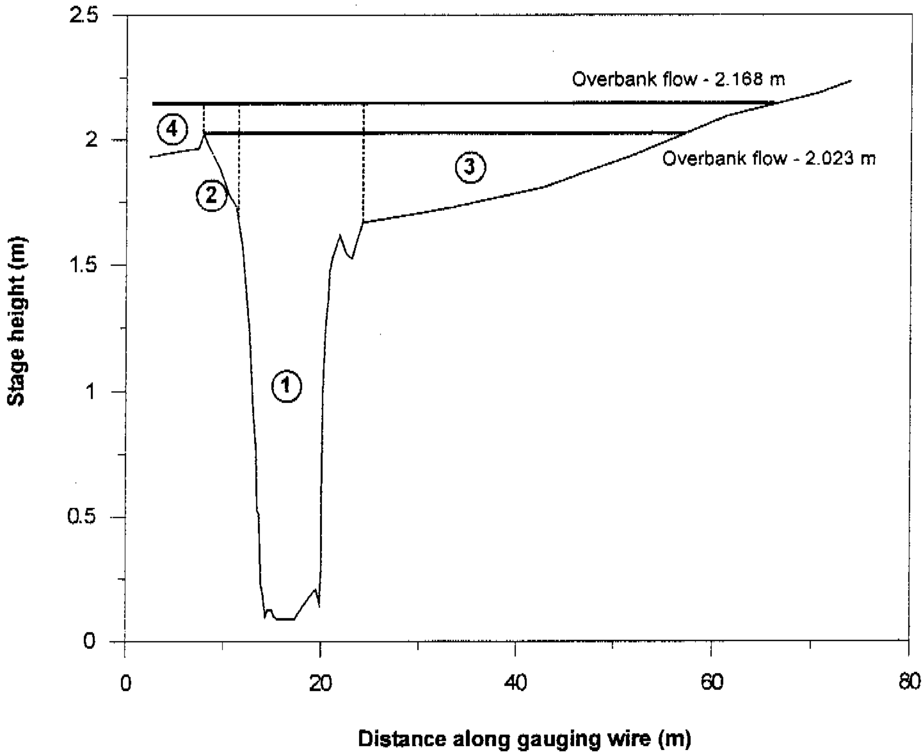

Figure 10 The compound cross section at UM. The subdivision of the cross section into subsections is shown. The two overbank flow levels used to extrapolate the rating table are also shown.

Table 6 Estimation of discharge values at overbank flow heights of 2.023m and 2.168m.

Stage height (m)	Sub-section	Height (m)	Area (m^2)	Manning's Roughness, *n*	Discharge coefficient, C_d	Discharge (m^3s^{-1}) (eqn 5)
2.023	1*	1.934		0.046	0.49	10.96*
	2	0.356	0.64	0.050	0.45	0.17
	3	0.356	5.86	0.071	0.32	1.10
					Total Q	**12.23**
2.168	1*	2.079		0.046	0.49	12.68*
	2	0.501	1.16	0.050	0.45	0.37
	3	0.501	11.15	0.071	0.32	2.49
	4	-	-	-	-	0[(1)]
					Total Q	**15.54**

* Main channel section – discharge determined by extrapolating the rating table

(1) There is assumed to be no overbank flow in subsection 4 (see above).

The discharges within the main channel section (subsection 1) (fig 10) at the two overbank flow levels were determined by extrapolating the rating table fitted using HYDSYS to the given stage heights (table 6). The discharges within the smaller subsections (subsections 2 and 3) (fig 10) were predicted using the Conveyance Method (Chester equation) (Grayson et al 1996) of the form:

$$Q = C_d A h^{0.5} \quad (5)$$

where Q = discharge (m^3s^{-1})

C_d = discharge coefficient

A = cross sectional area of the water flow (m^2)

h = flow depth (m)

The depth of flow, h, and the cross sectional area of flow, A, of subsections 2 and 3 at the two overbank flow levels are determined using cross sectional survey data and are given in table 6.

The velocity-area gauging points collected at UM during the two year monitoring period were all taken within the main channel (fig 9). A discharge coefficient, C_d (eqn 5), for the main channel at UM of 0.49 was derived using the velocity-area gauging data (Appendix B) and linear regression techniques. However, the surface roughness of subsections 2 and 3 differs from that of the main channel and therefore the C_d value for subsections 2 and 3 will vary from that derived for the main channel. The relationship between C_d and surface roughness can be written as:

$$C_d \propto 1/n \quad (6)$$

where n is Manning's roughness.

By determining the degree of surface roughness, n, of subsections 2 and 3 relative to the main channel, the C_d value for subsections 2 and 3 can also be derived. A procedure for estimating

n was developed by Cowan (1956) (as cited by Dingman 1984) and can be represented using the equation:

$$n = (n_0 + n_1 + n_2 + n_3 + n_4)m \quad (7)$$

The values of n_0 to n_4 take into account the runoff resistance added by the type of material involved; surface roughness; slope and size of channel cross section; flow obstructions; and vegetation, respectively. The value of m is determined by the degree of channel meandering (Dingman 1984) and this was assumed to be the same for each subsection of the channel.

A table of values to estimate each component of equation 7 given a set of corresponding channel conditions (Chow 1959, as cited by Dingman 1984) was applied to the surface conditions of the main channel and the overbank subsections at UM. Manning's roughness values, n, for each subsection are given in table 6. The corresponding C_d values for each subsection are also given in table 6.

Using equation 5, the discharge within each subsection, and hence the total discharge within the whole cross section, at the two overbank flow stage heights were estimated (table 6).

The derived rating curve for UM that incorporates the entire range of stage heights observed in the channel during the two wet seasons is shown in figure 11. A minor extension of the rating table from the lowest gauging to the 'cease to flow' level was also included in the extrapolation process (fig 11).

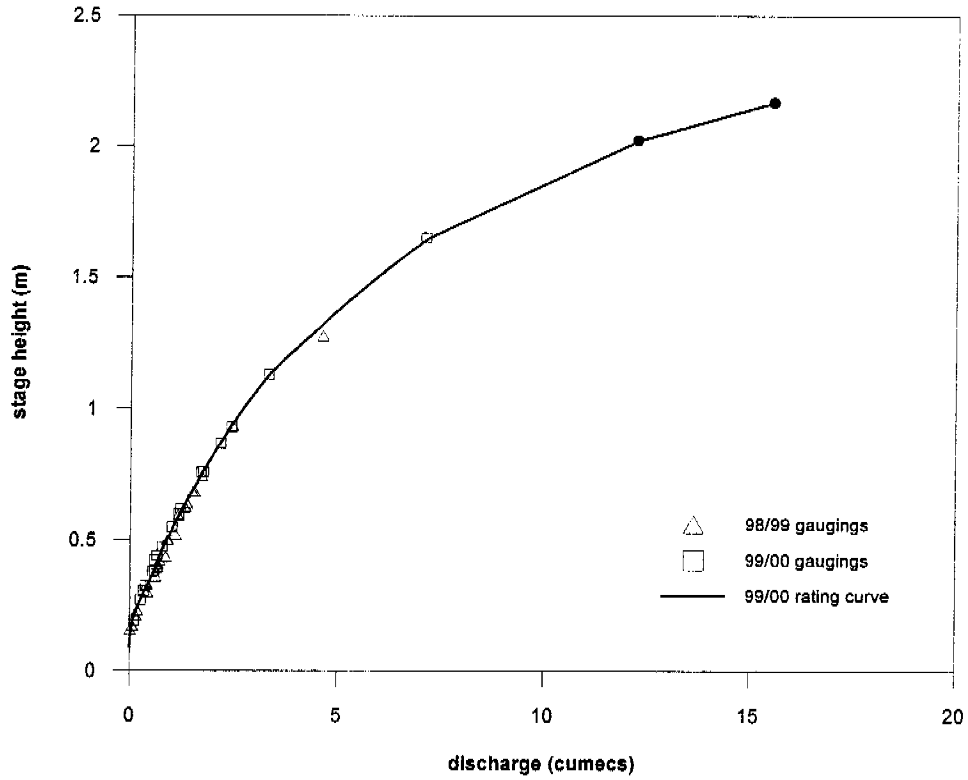

Figure 11 The rating curve constructed from the fitted rating table for the UM channel for the 1998/99 and 1999/00 wet seasons. The gauging points and the extrapolated overbank flow points (table 6) are also shown (•).

4.3 ET gauging station

One statistically significant rating table was fitted using HYDSYS from the two years of velocity-area gauging point data at ET. The fitted rating table can be applied to both years of continuous streamflow data at ET.

Similar to SC and UM, there were periods of flow at ET during both wet seasons that exceeded the highest gauging (table 5 and fig 12). Therefore, it was necessary to extrapolate the rating table fitted using HYDSYS to estimate the stage-discharge relationship at flows greater than the highest gauging.

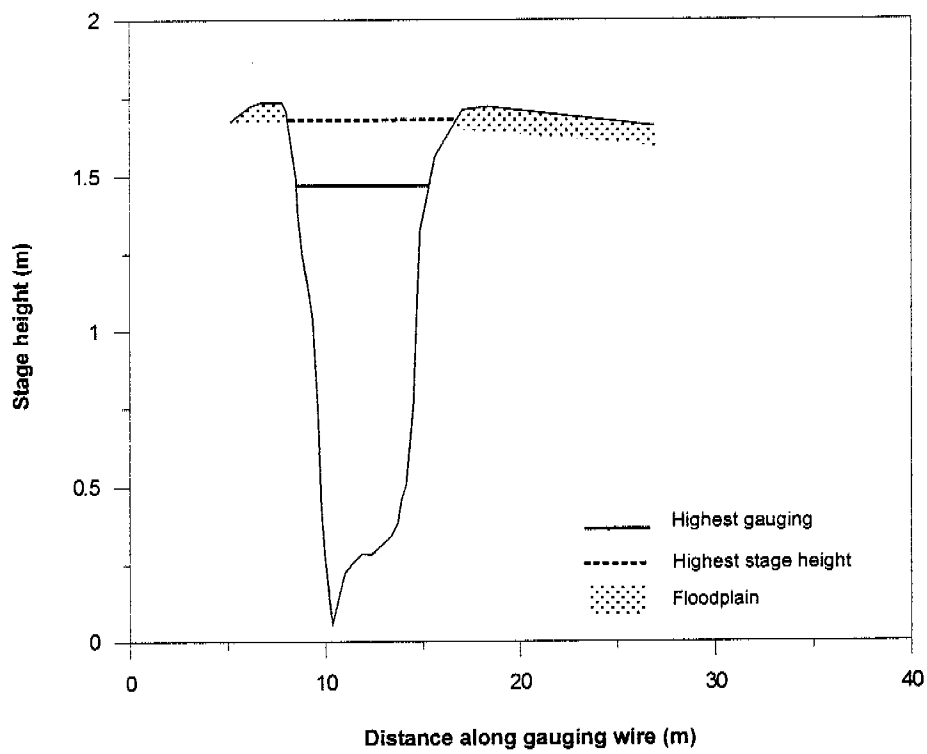

Figure 12 Cross section at ET showing the highest gauging and the highest measured stage height for the two year monitoring period.

Throughout the two year monitoring period at ET flow was confined to the deep, steep-sided main channel (fig 12). There was no evidence of any flow occurring on the floodplain areas on either side of the main channel. The channel at ET is considered to be of "simple" cross section (Pilgrim 1987) and therefore the rating table fitted using HYDSYS was simply extrapolated to incorporate the entire range of stage heights (fig 13). The rating table extrapolation also included a minor lower-end extension from the lowest gauging to the 'cease to flow' level (fig 13).

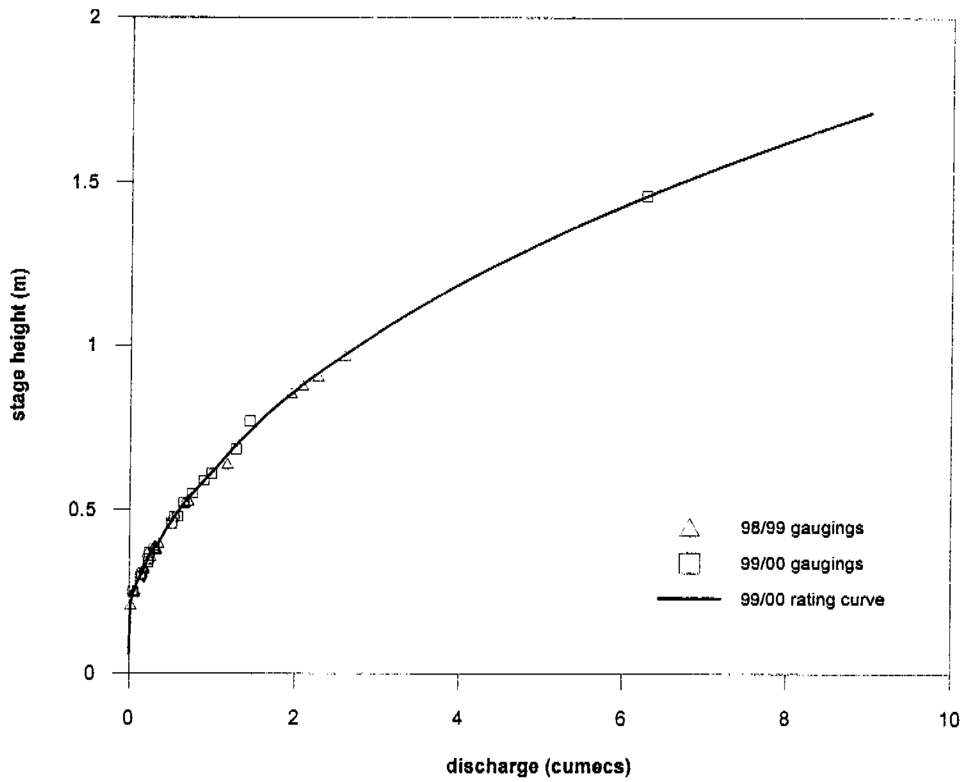

Figure 13 The rating curve constructed from the fitted rating table for ET for the 1998/99 and 1999/00 wet seasons. The gauging points are also shown.

5. Runoff data

The fitted rating tables were used to convert the stage height (m) data to continuous discharge ($m^3 s^{-1}$) data for each gauging station for the 1998/99 and 1999/00 wet seasons. The complete hydrograph for each gauging station for the two wet seasons is shown in Appendix A. The total runoff for each wet season at the gauging stations, estimated as the area under the hydrograph, is given in table 7. Total rainfall and the date when rainfall and runoff started and ended for each wet season at the gauging stations is also given in table 7. The time that runoff ended was estimated from field observations and is accurate to within 2-3 days (table 7).

Table 7 Total rainfall and runoff at each gauging station for the 1998/99 and 1999/00 wet seasons.

Year	Station	Rainfall period	Total rainfall (mm)	Antecedent rainfall (mm)	Runoff period	Total runoff (ML) [Peak discharge ($m^3 s^{-1}$)]
1998/99	SC	20 Sep – 28 Apr	1788.6[1]	430[1]	9 Dec – 27 May	33665.3 [22.3]
	UM		1855.2[1]	440[1]	12 Dec – 10 Jun	15665.6 [15.0]
	ET		1733.6[1]	415[1]	9 Dec – 27 May	7621.0 [8.5]
1999/00	SC	14 Oct – 24 May	1997.2	260	20 Nov – 14 Jul	34898.9 [18.1]
	UM		2105.0	305	20 Nov – 20 Jul	17425.8 [12.2]
	ET		2069.6	280	20 Nov(2) – 25 Jun	8531.6 [8.1]

1 Data partly provided by Energy Resources of Australia

(2) A small surge of runoff occurred on 8 Nov, 1900 – 2300 h (Appendix A)

The average antecedent rainfall for the Ngarradj catchment was approximately 430 mm during the 1998/99 wet season and 280 mm during the 1999/00 wet season.

The total runoff for each month during the period of flow at each gauging station is given in figure 14. The highest monthly runoff figure for each gauging station for both years of monitoring clearly occurred in March (fig 14), however, monthly rainfall figures indicate that during the wet months (Jan – Mar) rainfall was relatively consistent for both years (fig 4).

Figure 14 also shows that total runoff for each month is similar for each wet season of flow. The small difference between total annual runoff figures for 1998/99 and 1999/00 for each gauging station (table 7) may be attributed to the difference in length of the period of flow (fig 14 and table 7).

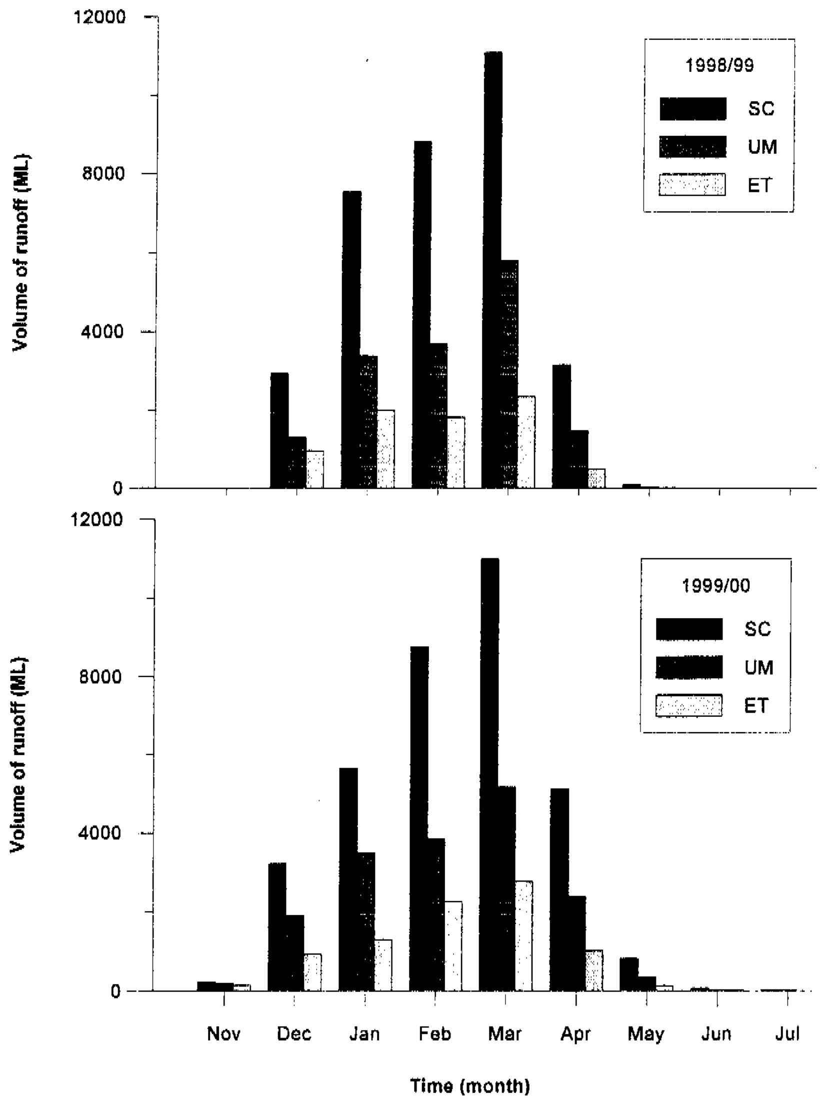

Figure 14 Total monthly runoff for the Ngarradj catchment.

Both annual and monthly runoff figures are similar for each year of monitoring at each station (table 7 and fig 14). However, a standard flow duration curve for the period of flow each year (fig 15) indicates that, in general, instantaneous discharge is higher during 1998/99 than 1999/00 at each gauging station. This result supports the difference in peak annual discharge between the two wet seasons at each gauging station (table 7). The standard flow duration curves indicate a reduction in instantaneous discharge at SC, but there is also a reduction in instantaneous discharge at ET. It is difficult to assess if the reduction at SC is due to mine site construction/activity using two years of data. It is likely that the change at SC is a catchment response as a similar trend in discharge is observed at ET, a gauging station upstream of the mine.

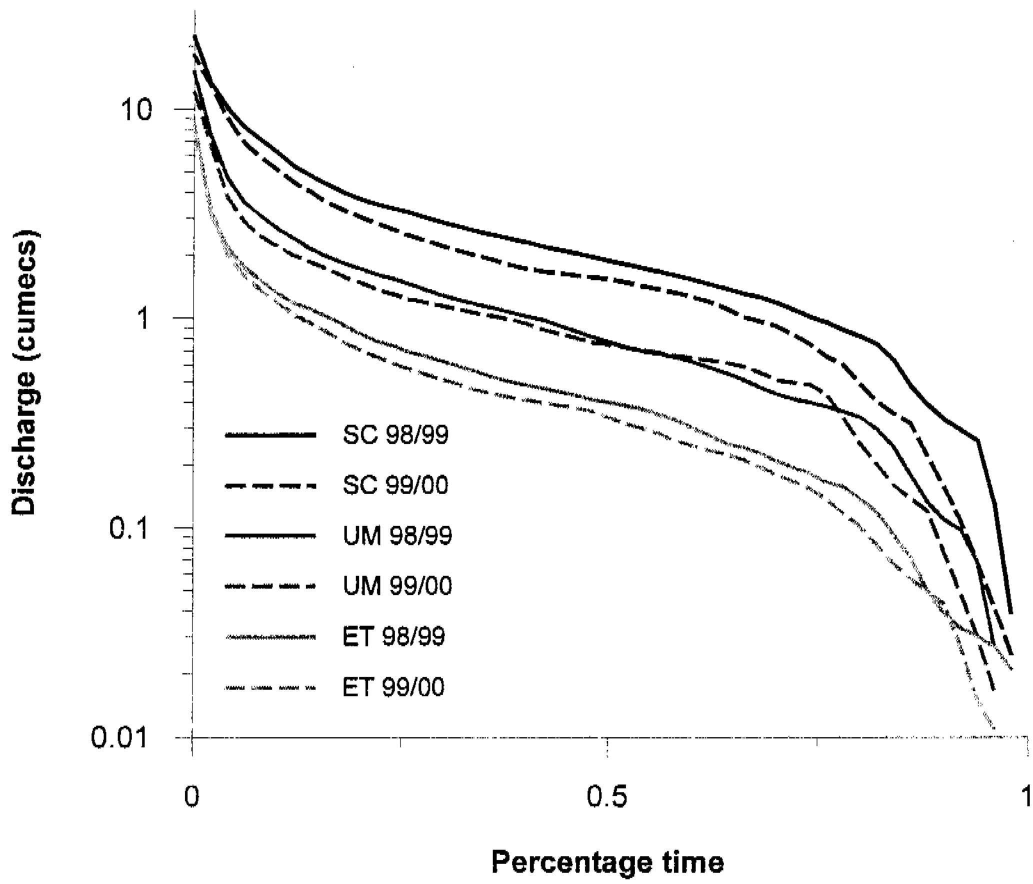

Figure 15 Standard flow duration curves for Ngarradj catchment.

5.1 Flood frequency analysis

Flood frequency analysis is used to estimate the magnitude of a flood of a particular probability of exceedance. The analysis in this section is applied to the peak discharges of runoff events. As there are only two years of continuous streamflow data available at the three gauging stations within the Ngarradj catchment the partial series of events was adopted. The partial series of events was assumed to conform to an exponential distribution (Pilgrim 1987).

Flood frequency analysis for partial series requires a selection of events with a peak discharge greater than a selected base discharge. The base discharge is generally selected so that the number of floods is at least 2 to 3 times the number of years of record (Pilgrim 1987). For each gauging station in this study, a base discharge was selected so that eight flood events were observed in the analysis for the two years of streamflow data.

A criterion for independence of successive peaks was also applied in the selection of the eight flood events. Pilgrim (1987) cited a wide range of criteria used in past studies to illustrate that the criteria is often site specific and subjective by nature. In this study, two flood peaks were considered to be independent if separated by periods of baseflow. For events separated by a period of baseflow it is assumed that overland flow from the catchment has ceased (Moliere et al 2001). In hydrology, this is a suitable criteria of independence between flood peaks (Hoggan 1997). The baseflow at each gauging station is shown in Appendix A and was determined by applying the Lyne and Hollick digital filter (Nathan & McMahon 1990, Grayson et al 1996) to the two years of observed discharge data.

The eight highest ranked flood events for each gauging station for the two year period are listed in Table 8. The date of occurrence is also shown. The plotting position ($YP(m)$) of an event in terms of ARI is (Pilgrim, 1987):

$$YP(m) = \frac{N + 0.2}{m - 0.4} \tag{8}$$

where N is the number of years of record and m is the rank of the flood event in the series.

Table 8 Frequency analysis of partial series floods – Ngarradj catchment 1998-2000.

Rank	SC		UM		ET		$YP(m)$
m	Date	Peak Q ($m^3\ s^{-1}$)	Date	Peak Q ($m^3\ s^{-1}$)	Date	Peak Q ($m^3\ s^{-1}$)	(y)
1	12 Mar 99	22.25	31 Jan 99	15.00	31 Jan 99	8.50	3.66
2	31 Jan 99	20.74	11 Mar 99	14.70	9 Feb 99	8.43	1.38
3	10 Feb 99	20.48	10 Feb 99	13.41	11 Mar 99	8.39	0.85
4	29 Dec 99	18.14	29 Dec 99	12.15	11 Mar 00	8.13	0.61
5	22 Mar 00	17.07	7 Mar 99	12.00	29 Dec 99	7.89	0.48
6	2 Mar 00	16.91	16 Feb 00	11.63	21 Mar 00	7.81	0.39
7	7 Mar 99	16.60	10 Apr 00	11.50	2 Mar 00	7.60	0.33
8	16 Feb 00	16.43	2 Mar 00	11.46	9 Mar 99	7.26	0.29

The ARI for each of the eight flood events at each gauging station is given in Table 8. The partial series flood discharges were plotted at the calculated plotting positions of ARI values (Table 8) for each gauging station on a log-normal graph (fig 16). The line of best fit for the data (fig 16) constitutes the fitting of an exponential distribution to the data (Pilgrim, 1987).

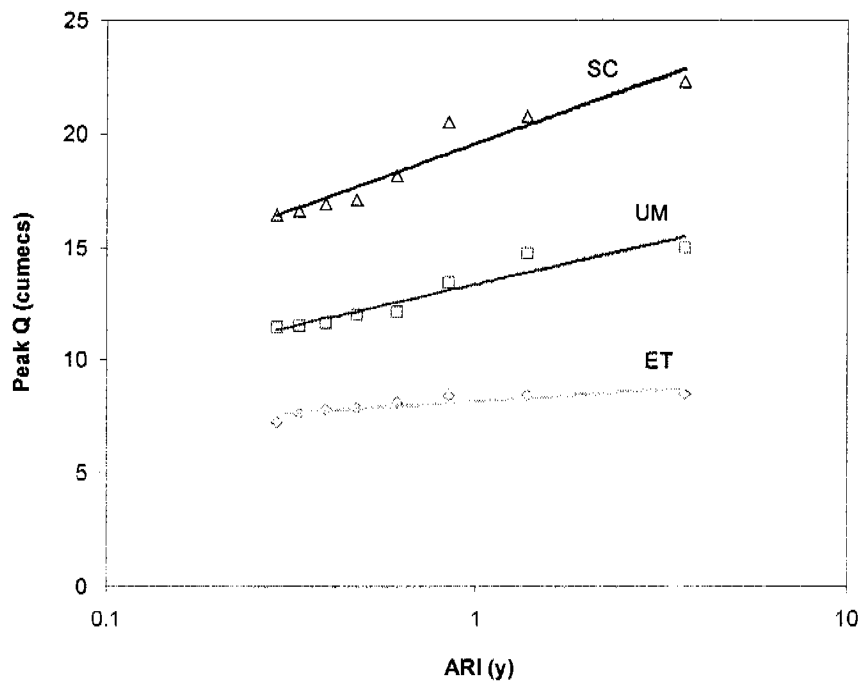

Figure 16 Frequency curves of partial series floods at SC, UM and ET.

The exponential distribution of the partial series for SC, UM and ET can be expressed as:

$$Q_{SC} = 2.545\text{Ln}(YP(m)) + 19.55 \qquad (r^2 = 0.92) \qquad (9)$$

$$Q_{UM} = 1.631\text{Ln}(YP(m)) + 13.35 \qquad (r^2 = 0.91) \qquad (10)$$

$$Q_{ET} = 0.448\text{Ln}(YP(m)) + 8.172 \qquad (r^2 = 0.75) \qquad (11)$$

Using equations 9 to 11, flood estimates for each gauging station within the Ngarradj catchment for various year return periods up to 10 years were summarised in table 9.

Table 9 Summary of the fitted flood frequency distribution for each gauging station.

ARI (y)	Flood estimate Q_Y ($m^3 s^{-1}$)		
	SC	UM	ET
1.053	19.68	13.44	8.19
1.111	19.81	13.52	8.22
1.25	20.11	13.72	8.27
2	21.31	14.48	8.48
5	23.64	15.98	8.89
10	25.41	17.11	9.20

5.1.1 Average recurrence interval of bankfull flow

Bankfull flow is simply defined as the discharge at which the channel just begins to overflow onto the floodplain (Grayson et al 1996). The floodplain level at each gauging station, determined from cross-sectional survey data (figs 7, 9 and 12), is given in table 10.

It should be noted that the bankfull level at SC is assumed to be the floodplain level at the left bank (fig 7). There was more evidence of sediment deposition and flood debris on the floodplain area on the left side of the main channel after periods of overbank flow at SC than that observed on the floodplain area on the right side of the main channel.

Using the fitted rating tables derived above (section 4), the corresponding discharges at which flow reaches the floodplain level for each gauging station were determined (table 10). The number of times that overbank flow occurred during the two wet seasons, and the average duration of overbank flow, at SC and UM is also shown in table 10.

Table 10 Bankfull flow for each gauging station.

Station	Floodplain level (m)	Bankfull flow (m^3 s^{-1}) [ARI (y)]	No. of times peak discharge exceeds bankfull flow		Average duration of overbank flow (h)
			1998/99	1999/00	
SC	2.035	17.36 [0.42]	3	1	6.1
UM	2.023	12.28 [0.52]	3	0	4.8
ET	1.711	9.00 [6.4]	0	0	-

During the two year monitoring period overbank flow occurred at SC and UM four and three times respectively. The overbank events at UM and SC occurred during the same periods of runoff on the hydrograph in 1998/99. During 1999/00 overbank flow occurred once at SC and, during this same event, flow at UM reached floodplain level and was the maximum peak discharge for the year.

Using equations 9 and 10, the recurrence interval for bankfull discharge at SC and UM is approximately 0.42 and 0.52 years respectively (table 10). In other words, bankfull discharge is expected to occur approximately twice a year at SC and UM, which corresponds well to the the number of times overbank flow occurred during the two year monitoring period (table 10). However, the predicted ARI of bankfull flow at SC and UM is relatively frequent compared to that previously determined in other studies for tropical regions where the ARI of bankfull discharge is generally closer to 1 year (Pilgrim 1987, McDermott & Pilgrim 1983).

The recurrence interval for bankfull discharge at ET is approximately 1 in 6.4 years (eqn 11) (table 10). However, this figure may not accurately reflect the ARI of bankfull discharge for the catchment of the stream, but rather the location at which the cross sectional survey was taken. From field observations immediately after periods of very high flow, it was evident that flow had exceeded bankfull level at a point approximately 400 - 500 m upstream of the ET gauging station and this overflow had subsequently flowed into a floodplain area approximately 20 m downstream of ET near the main channel (fig 17). This would suggest that the ET gauging station is located at a high point along the stream and therefore the AEP of bankfull discharge at ET is relatively low.

During the events when flow exceeded bankfull discharge at UM and SC throughout the two year monitoring period it was assumed that overbank flow on the floodplain at UM and SC was neglible (section 4). Therefore, assuming that peak discharge exceeded bankfull discharge upstream of ET during the same flood events that occurred at UM and SC, it may be assumed that this overbank flow within the anabranch (fig 17) was also neglible. The location of the ET gauging station should not result in a significant underestimation of discharge during very high rainfall/runoff events.

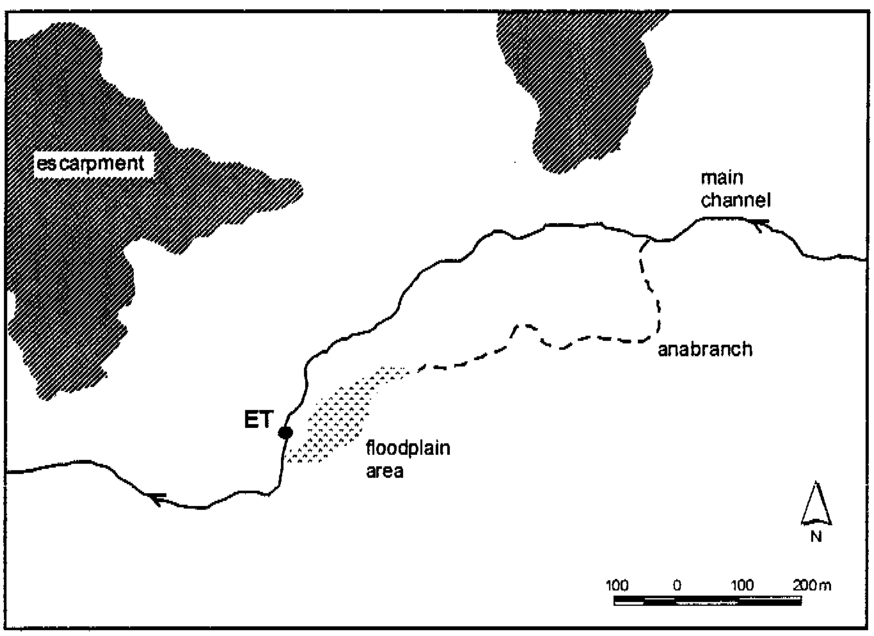

Figure 17 Schematic diagram of the flow path of the anabranch formed upstream of the ET gauging station.

6. Selected event hydrology

Table 11 shows total rainfall and runoff for selected events that have occurred at each gauging station throughout the monitoring period – four during 1998/99 and four during 1999/00. These particular events were selected because (1) there was a distinct runoff response to recorded rainfall at each of the gauging stations (Appendix C), and (2) the peak discharge and the volume of runoff for these events were relatively high compared to other events that occurred during the two year monitoring period.

The rainfall and runoff data at each of the gauging stations for the event on 26 Dec - 6 Jan 2000, the event with the highest peak discharge at each station during 1999/00, is shown in figure 18. The rainfall and runoff data collected at each gauging station for all of the selected events are shown in Appendix C. An event was considered to be a runoff period that started and ended at approximate baseflow conditions. The baseflow at each gauging station is shown in Appendix A.

The computer software package HYDSYS was used to determine maximum rainfall intensities over various durations for each of the selected runoff events. Maximum 6 min, 10 min, 20 min, 30 min, 1 hr, 4 hr, 12 hr and 72 hr intensities during each of the runoff periods are shown in table 12. The Thiessen Polygon method was used to spatially average the maximum rainfall intensities measured at the three gauging stations over each of the above durations. These rainfall intensities are assumed to be for the entire Ngarradj catchment during the selected runoff events. Total rainfall and maximum rainfall intensities over the various durations recorded at each individual gauging station are shown in Appendix D.

Tabulated intensity-freqency-duration (IFD) data for the Ngarradj catchment region (12.500°S 132.925°E) is shown in table 13 (Bureau of Meteorology pers. comm. 2000). The IFD data extend from 6 min to 72 hours and ARIs from one year to 100 years.

Table 11 Total rainfall and runoff for selected events during the two year monitoring period.

Year	Event No.	Date	Total rainfall* (mm)	SC		UM		ET	
				Runoff (ML) [Peak discharge (m^3s^{-1})]	Runoff Coefficient (RoC)	Runoff (ML) [Peak discharge (m^3s^{-1})]	Runoff Coefficient (RoC)	Runoff (ML) [Peak discharge (m^3s^{-1})]	Runoff Coefficient (RoC)
1998/99	1	6 - 12 Jan	58.4	1721.9 [13.9]	0.68	865.6 [10.1]	0.79	388.3 [4.8]	0.79
	2	26 Jan – 6 Feb	223.5	4343.7 [20.7]	0.45	1955.2 [15.0]	0.47	960.4 [8.5]	0.51
	3	6 - 18 Feb	187.1	5207.3 [20.5]	0.64	2113.1 [13.4]	0.60	1108.5 [8.4]	0.70
	4	7 - 22 Mar	261.6	7937.4 [22.3]	0.70	4040.8 [14.7]	0.82	1693.3 [8.4]	0.77
1999/00	1	26 Dec – 6 Jan	147.2	2499.2 [18.1]	0.39	1449.5 [12.2]	0.52	592.7 [7.9]	0.48
	2	9 – 26 Feb	231.6	6110.3 [16.4]	0.61	2674.0 [11.6]	0.61	1536.6 [6.7]	0.78
	3	26 Feb - 10 Mar	216.6	6555.8 [16.9]	0.69	3313.5 [11.5]	0.81	1635.1 [7.6]	0.89
	4	21 Mar – 6 Apr	107.2	2941.9 [17.1]	0.63	1340.0 [9.9]	0.67	624.5 [7.8]	0.69

* Event rainfall calculated using the Thiessen Polygon method using rainfall measured at each station (Appendix D)

Table 12 Maximum 6 min to 72 hr rainfall intensities for each selected runoff event (table 11) during the two year monitoring period. Approximate ARIs for the various durations for each event are also shown (ARIs are not shown where intensity is less than a 1 in 1 year event).

Maximum rainfall intensity for various durations
(mm h-1) [ARI (y)]

		Duration (minutes)							
Year	**Event No.**	**6**	**10**	**20**	**30**	**60**	**240**	**720**	**4320**
1998/99	1	56.4	50.5	42.0	33.6	21.6	6.35	2.74	0.75
	2	131 [1.1]	123 [1.6]	106 [2.5]	89.3 [2.9]	53.8 [1.8]	15.6	6.73	1.60
	3	86.3	81.0	54.9	44.5	31.0	14.5	5.59	1.84
	4	119	113 [1.2]	96.9 [1.8]	87.7 [2.6]	66.1 [4.4]	21.0	8.22 [1.6]	2.14 [1.3]
1999/00	1	90.9	86.4	77.5	68.9 [1.1]	61.1 [3.1]	22.9	7.82 [1.4]	1.60
	2	121	104	82.0 [1.1]	67.0 [1.0]	39.3	10.2	3.40	1.26
	3	136 [1.2]	112 [1.2]	81.5 [1.1]	60.9	32.5	9.71	3.88	1.80
	4	127	119 [1.4]	106 [2.5]	95.9 [4.0]	65.3 [4.2]	16.6	6.32	1.09

Table 13 Tabulated IFD data for the Ngarradj catchment region (Bureau of Meteorology pers. comm. 2000) showing maximum rainfall intensities for various durations and return periods.

Maximum rainfall intensity for various durations and return periods (mm h^{-1})

ARI (y)	**Duration (minutes)**							
	6	**10**	**20**	**30**	**60**	**240**	**720**	**4320**
1	128	106	80.2	66.3	44.6	27.7	7.14	1.96
2	163	135	102	84.1	56.6	35.0	8.96	2.59
5	200	165	124	102	68.7	42.2	10.8	3.40
10	223	183	137	113	75.9	48.4	11.6	3.93
20	254	209	156	129	86.2	52.5	13.1	4.62
50	297	244	182	150	99.9	60.7	15.0	5.61
100	331	271	202	166	111	67.1	16.4	6.40

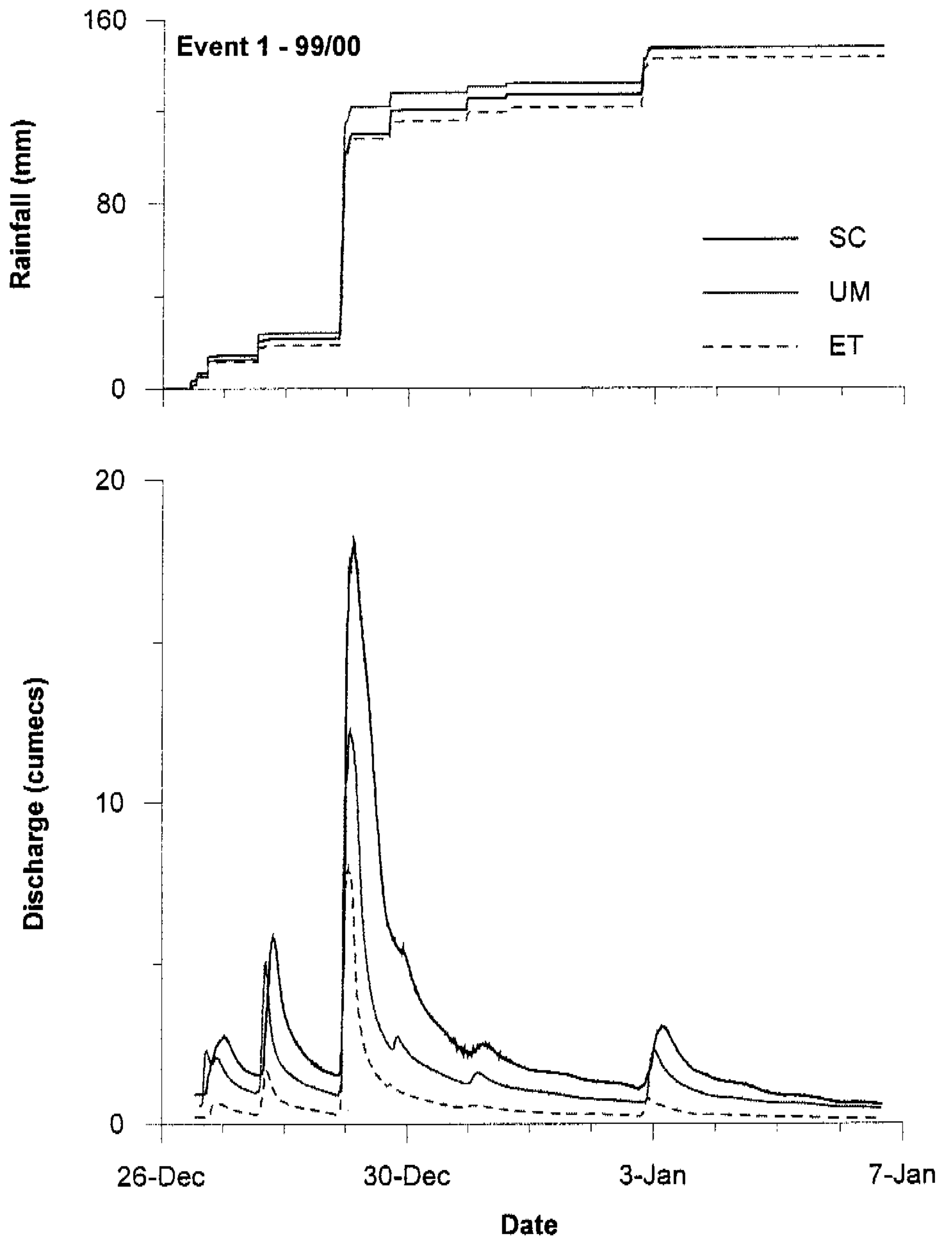

Figure 17 Cumulative rainfall and hydrograph at each gauging station during an event on 26 Dec – 6 Jan 2000 (table 11).

6.1 Discussion - discharge

For each of the selected events during the two year monitoring period (table 11) the average percentage volume of runoff at SC that is contributed by the upstream channels, UM and ET, is approximately 48 % (σ = 5 %) and 23 % (σ = 2 %) respectively, which is similar to the percentage contribution from the upstream channels for the whole two year monitoring period (48 % and 24 % respectively). It is therefore reasonable to assume that the percentage of total runoff at SC contributed by the two gauged channels upstream of the mine (UM and ET) varies little with flowrate.

The volume of runoff at SC that is contributed by the western and southern part of the Ngarradj catchment (left bank) (fig 1) is approximately 28 %. This volume of runoff from the left bank tributaries is relatively low given the catchment size (38% of the total Ngarradj catchment area) and reflects the difference in geomorphological characteristics between the left bank side of the Ngarradj catchment and the right bank side of the catchment (as discussed above in section 2 – Study area).

For each of the selected events (table 11) the peak discharge at the upstream sites, UM and ET, is on average 68 % (σ = 5 %) and 41 % (σ = 4 %) of the peak discharge at SC.

The relationship between peak discharge (m^3 s^{-1}) of a given frequency of occurrence and catchment area, A (km^2), can be expressed as follows:

$$Q = \beta A^m \qquad (12)$$

where β and m are parameters fitted by regression to available data.

The exponent m is generally in the range of 0.5 to 1.0 (Strahler 1964, Willgoose et al 1991). For mean annual flows the exponent, m, in the discharge-area relationship (eqn 12) is about 1.0 (Flint 1974, Rodriguez-Iturbe & Rinaldo 1997). For higher flows, x is usually less than unity (Flint 1974). For example, Leopold et al (1964) stated that for bankfull discharge, x is usually between 0.7 and 0.75.

Using the peak discharges of the eight selected events above (table 11) and the catchment areas upstream of the three gauging stations (see section 2 – Study area) the fitted discharge-area relationship (eqn 12) can be described as:

$$Q_{pc} = 0.132A^{0.543} \qquad (r^2 = 0.99) \qquad (13)$$

where Q_{pc} is the percentage peak discharge of that at SC. For example, using equation 13 the predicted peak flow at ET is 42 % of that at SC, very similar to that observed (41%).

Equation 13 may be used to determine peak flows at ungauged streams within the Ngarradj catchment as a percentage of the peak flow at SC. For example, the total area of the Ngarradj catchment at the outlet to the Magela floodplain is 66.6 km^2. Using equation 13 the peak discharge at the outlet of the Ngarradj catchment is 129 % of that at SC for an individual runoff event.

The exponent of area in the fitted discharge-area relationship (eqn 13) is within the range of values previously determined in the other studies (Strahler 1964, Leopold et al 1964, Willgoose et al 1991).

Using equations 9 to 11 (section 5.1 – Flood frequency analysis), an estimation of the ARI of the flood peaks for each of the selected events (table 11) is given in table 14.

Table 14 Approximate ARIs of peak discharge of the selected events (table 11).

Year	Event No.	Date	SC Peak discharge (m^3s^{-1}) [ARI (y)]	UM Peak discharge (m^3s^{-1}) [ARI (y)]	ET Peak discharge (m^3s^{-1}) [ARI (y)]
1998/99	1	6 – 12 Jan	13.9 [0.1]	10.1 [0.1]	4.8 [<0.1]
	2	26 Jan – 6 Feb	20.7 [1.6]	15.0 [2.7]	8.5 [2.1]
	3	6 – 18 Feb	20.5 [1.5]	13.4 [1.0]	8.4 [1.7]
	4	7 – 22 Mar	22.3 [3.0]	14.7 [2.3]	8.4 [1.7]
1999/00	1	26 Dec – 6 Jan	18.1 [0.6]	12.2 [0.5]	7.9 [0.6]
	2	9 – 26 Feb	16.4 [0.3]	11.6 [0.3]	6.7 [<0.1]
	3	26 Feb – 10 Mar	16.9 [0.4]	11.5 [0.3]	7.6 [0.3]
	4	21 Mar – 6 Apr	17.1 [0.4]	9.9 [0.1]	7.8 [0.4]

During the 1999/00 wet season there were no events at any of the gauging stations that were greater than 1 in 1 year floods (table 14). In terms of peak discharge, the largest three flood events occurred during the first year of monitoring (1998/99) at all three gauging stations (tables 8 and 14).

6.2 Discussion - rainfall

The highest rainfall intensity recorded at the Ngarradj catchment over any duration for the eight selected events was approximately equivalent to a 1 in 4.4 year storm event (table 12). The corresponding flood peak discharge for this event was equivalent to a 1 in 3 year flood at SC. In general, the selected events (table 11) had maximum rainfall intensities over the various durations that were relatively high compared to the peak discharges for the corresponding runoff events at each station, particularly during 1999/00 (tables 12 and 14). It is well documented that floods of given peak discharges may be the result of quite different rainfall events (Weinmann et al 2000).

The largest difference between the recurrence interval of the rainfall intensity and the peak discharge of an event occurred during Event 4 1999/00. During this event the maximum rainfall intensities over the 30 min and 60 min durations were equivalent to 1 in 4 year storm events (table 12). However, peak discharges at the three gauging stations during this storm corresponded to less than a 1 in 0.5 year flood event (table 14). This was the only selected event with a single-peaked hydrograph (Appendix C) where initial runoff at the commencement of the rainfall period was at baseflow. This implies that the catchment, before this single-peaked event, was relatively unsaturated and had a relatively high infiltration capacity (Moliere 2001). As a result, in this case, a high rainfall intensity storm event only resulted in a relatively small flood event.

The differences between the recurrence interval of the rainfall intensity and the peak discharge were less for the other seven selected events (tables 12 and 14). These events were multi-peaked runoff events (Appendix C) that were not separated by periods of baseflow. The peak discharge of these events occurred during the third or fourth peak of the hydrograph

(Appendix C), not during the first peak of the hydrograph when initial runoff was at baseflow. This implies that the peak discharge of these flood events occurred when the catchment was saturated. Therefore, in these cases, only a relatively moderate intensity rainfall period contributed to a high peak discharge of the flood event.

7. Summary

The total annual rainfall over the Ngarradj catchment during 1998/99 and 1999/00 is 1826.4 mm and 2047.4 mm respectively. Compared to annual rainfall data collected at Oenpelli, the annual rainfall for the Ngarradj catchment for 1998/99 and 1999/00 correspond to an ARI of 1:15 and 1:87 respectively.

Rating tables to convert stage height to discharge were derived for each gauging station using velocity-area gauging data. These rating tables incorporate the entire range of stage heights observed in each channel during two years of flow.

Using selected rainfall-runoff events that occurred simultaneously at each gauging station, the contribution from the two upstream sites (UM and ET) to the total volume of runoff at SC is approximately 48 % (σ = 5 %) and 23 % (σ = 2 %) respectively. The peak discharge at the upstream sites, UM and ET, is approximately 68 % (σ = 5 %) and 41 % (σ = 4 %) of the peak discharge at SC. A partial series flood frequency analysis showed that the recurrence interval for bankfull discharge at SC, UM and ET is approximately 0.42, 0.52 and 6.4 years respectively.

The average recurrence interval of rainfall intensities and peak discharges of eight selected events were determined for each gauging station. In terms of peak discharge the three largest flood events of the two year monitoring period occurred during 1998/99, the largest being a 1 in 3 year peak discharge event at SC. During the 1999/00 wet season there were no events at any of the gauging stations that were greater than a 1 in 1 year flood.

Further research requires direct rainfall intensity analysis to be conducted using rainfall data collected at the gauging stations within the Ngarradj catchment. There is also a need to further refine the flood frequency analysis at the gauging stations. It is recommended that several more years of rainfall and streamflow data are required from these gauging stations to improve the expected accuracy of this type of analysis.

8. References

Bureau of Meteorology 1999. *Hydrometeorological analyses relevant to Jabiluka.* Supervising Scientist Report 140, Supervising Scientist, Canberra.

Carter MW 1990. *The development of a regulatory mechanism for the control of water release from Ranger Uranium Mine.* Technical memorandum 30, Supervising Scientist for the Alligator Rivers Region, AGPS, Canberra.

Chiew FHS & Wang QJ 1999. *Hydrological analysis relevant to surface water storage at Jabiluka.* Supervising Scientist Report 142, Supervising Scientist, Canberra.

Chow VT 1959. *Open Channel Hydraulics.* New York: McGraw-Hill.

Cowan WL 1956. Estimating hydraulic roughness coefficients. *Agricultural Engineering* 37, 473–475.

Dingman SL 1984. *Fluvial Hydrology.* New York: WH Freeman and Company.

Erskine WD, Saynor MJ, Evans KG & Boggs GS 2001. *Geomorphic research to determine the off-site impacts of the Jabiluka Mine on Swift (Ngarradj) Creek, Northern Territory.* Supervising Scientist Report (in press), Supervising Scientist, Canberra.

Flint JJ 1974. Stream gradient as a function of order, magnitude and discharge. *Water Resources Research* 10 (5), 969–973.

Grayson RB, Argent RM, Nathan RJ, McMahon TA & Mein RG 1996. *Hydrological recipes: estimation techniques in Australian hydrology.* Cooperative Research Centre for Catchment Hydrology.

Hoggan DH 1997. *Computer-assisted Floodplain Hydrology and Hydraulics.* 2nd ed, New York: McGraw-Hill.

Leopold LB, Wolman MG & Miller JP 1964. *Fluvial Processes in Geomorphology.* Freeman, London.

Li Q, Bras RL & Veneziano D 1996. Analysis of Darwin rainfall data: Implications on sampling strategy. *Journal of Applied Meteorology*. 35, 372-385.

McDermott GE & Pilgrim DH 1983. A design flood method for arid western New South Wales based on bankfull estimates. *Civil Engineering Transactions*, Institution of Engineers, Australia. 25, 133-139.

Moliere DR, Evans KG, Saynor MJ & Erskine WD 2001. Estimation of suspended sediment loads downstream of the Jabiluka mine, Northern Territory, Australia. *Hydrological Processes* (in review).

Nathan RJ & McMahon TA 1990. Evaluation of automated techniques for baseflow and recession analyses. *Water Resources Research* 26 (7), 1465-1473.

Pilgrim DH 1987. *Australian rainfall and runoff.* Institution of Engineers, Australia, Barton, ACT Aust.

Rodriguez-Iturbe I & Rinaldo A 1997. *Fractal river basins: chance and self-organisation.* Cambridge University Press.

Soman VV, Valdes JB & North GR 1995. Satellite sampling and the diurnal cycle statistics of Darwin rainfall data. *Journal of Applied Meteorology* 34, 2481-2490.

Strahler AN 1964. Quantitative geomorphology of drainage basins and channel networks. In *Handbook of applied Hydrology*, McGraw-Hill, New York, pages 4.40-4.74.

Thiessen AH 1911. Precipitation averages for large areas. *Monthly Weather Review* 39, 1082-1084.

Ward RC & Robinson M 1990. *Principles of Hydrology* 3rd edition, McGraw-Hill, Book Company (UK) Limited, p32.

Weinmann PE, Rahman A, Hoang TMT, Laurenson EM & Nathan RJ 2000. Monte Carlo simulation of flood frequency tables from rainfall – the way ahead. In *Proceedings of the*

Hydro 2000 conference on Interactive Hydrology. Institution of Engineers, Perth, November 2000, 564-569.

Willgoose GR, Bras RL & Rodriguez-Iturbe I 1991. Results from a new model of river basin evolution. *Earth Surface Processes and Landforms* 16, 237–254.

Appendix A – Observed hydrographs and daily rainfall

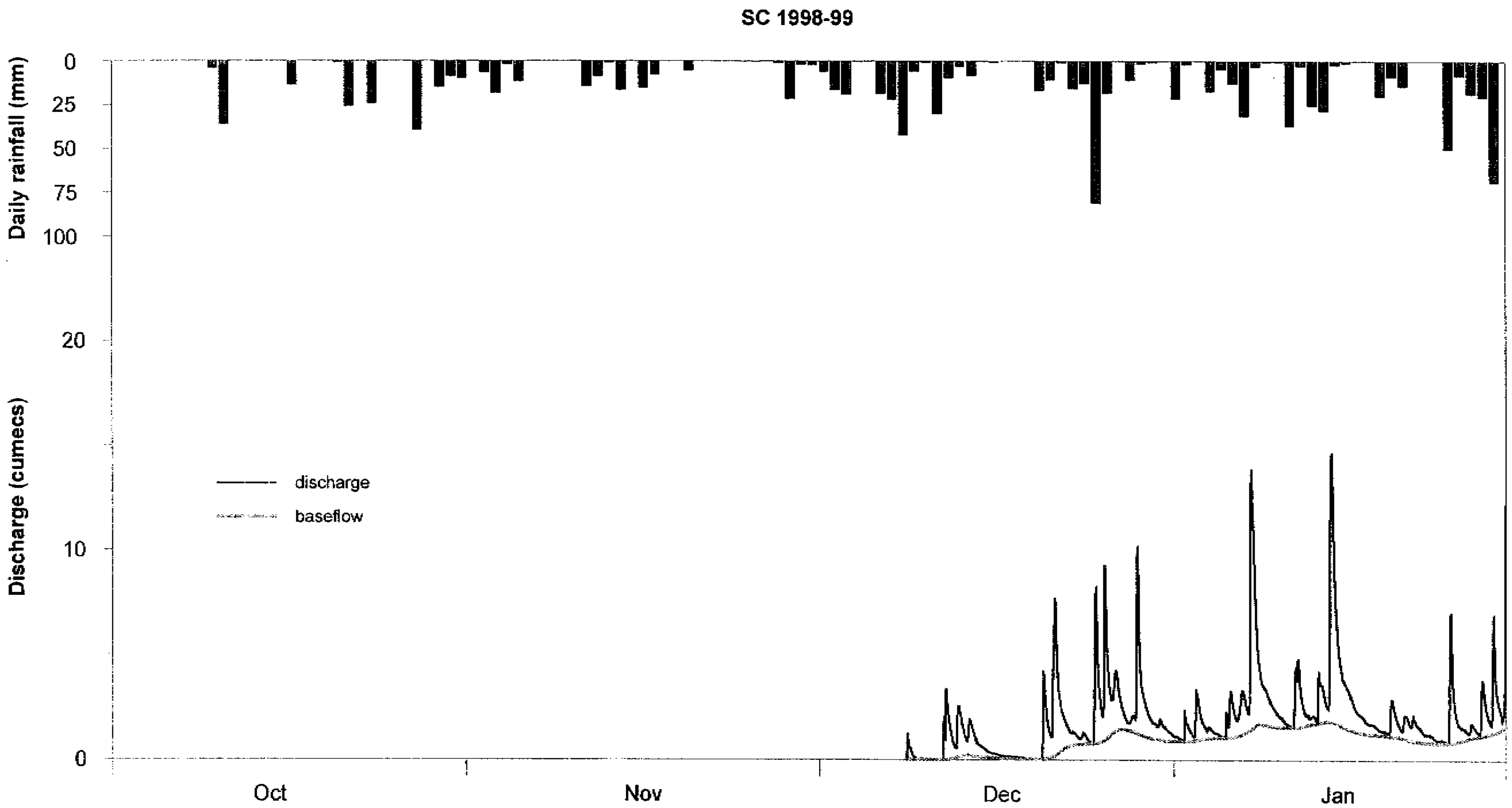

Figure A.1 Daily rainfall and the hydrograph for SC during 1998/99 wet season. The baseflow is also shown.

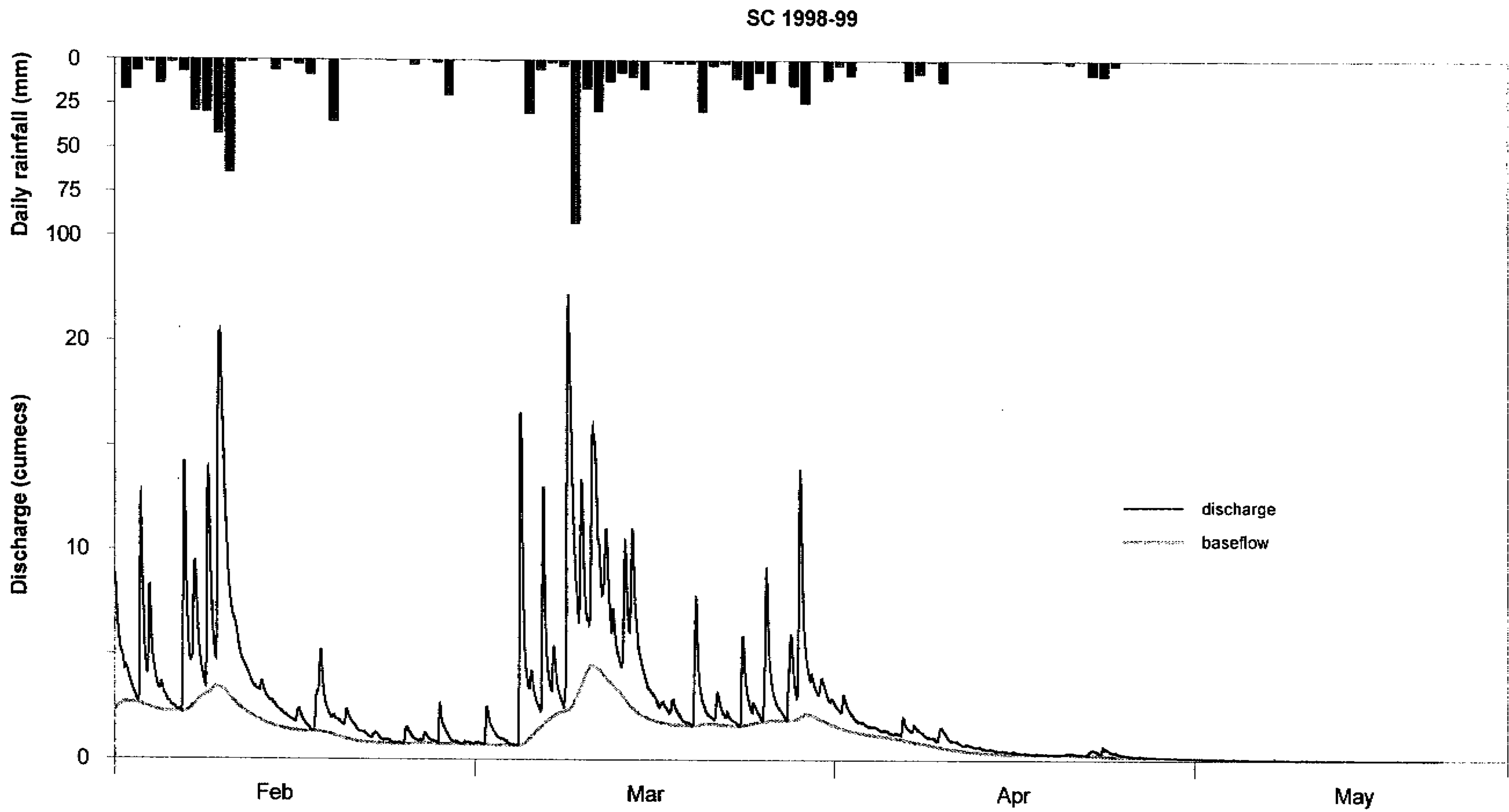

Figure A.1 (continued) Daily rainfall and the hydrograph for SC during 1998/99 wet season. The baseflow is also shown.

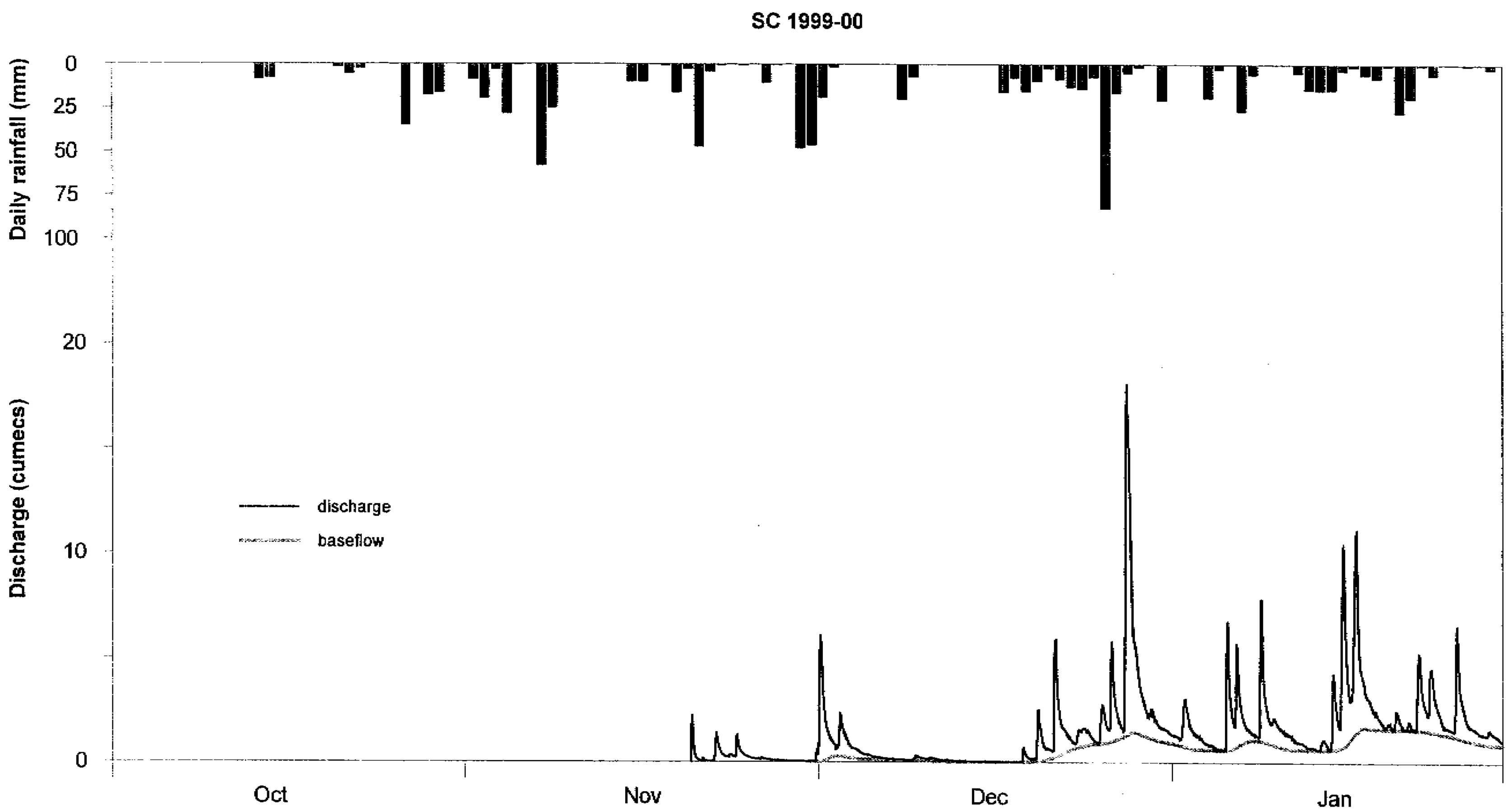

Figure A.2 Daily rainfall and the hydrograph for SC during 1999/00 wet season. The baseflow is also shown.

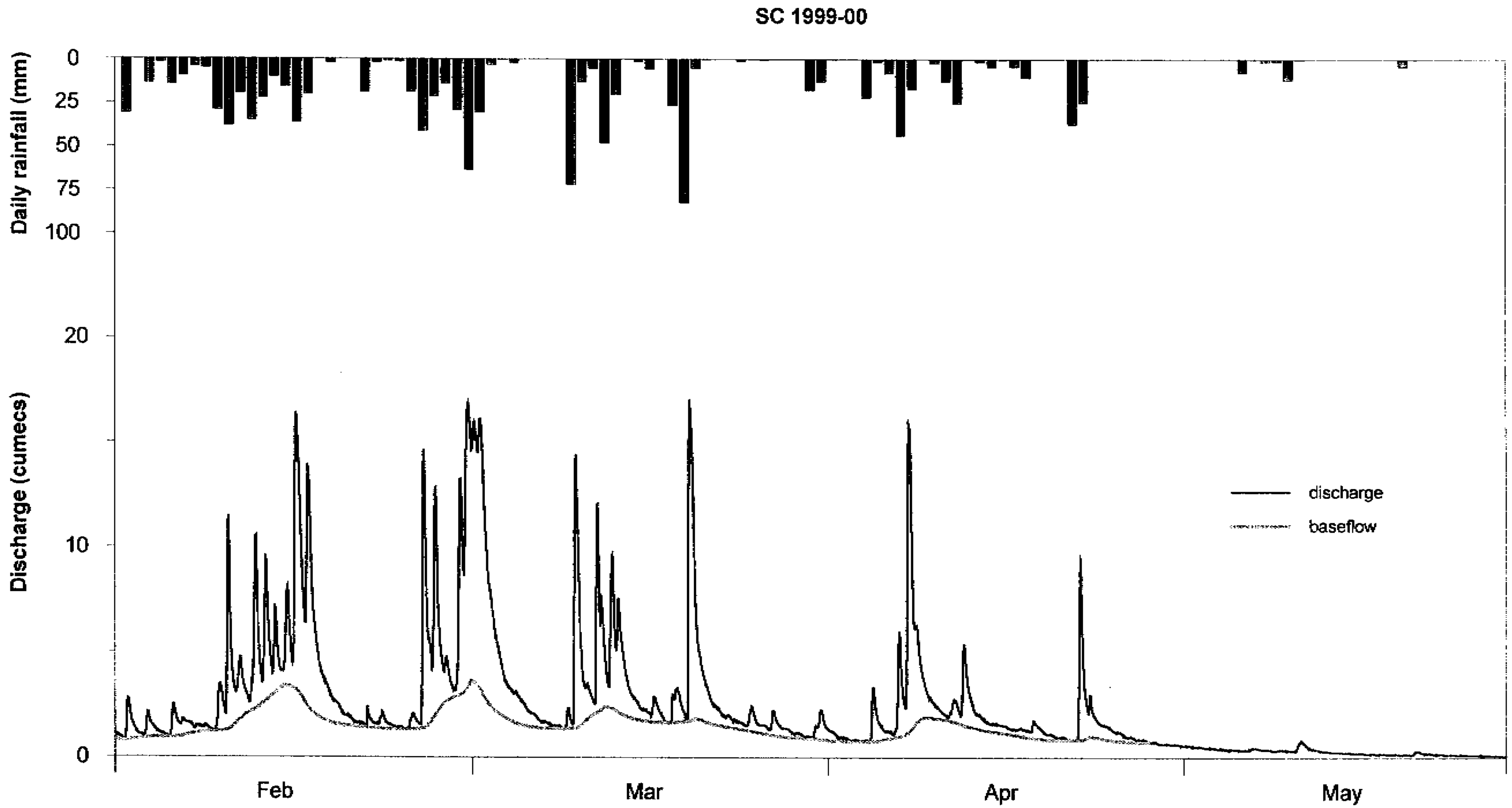

Figure A.2 (continued) Daily rainfall and the hydrograph for SC during 1999/00 wet season. The baseflow is also shown.

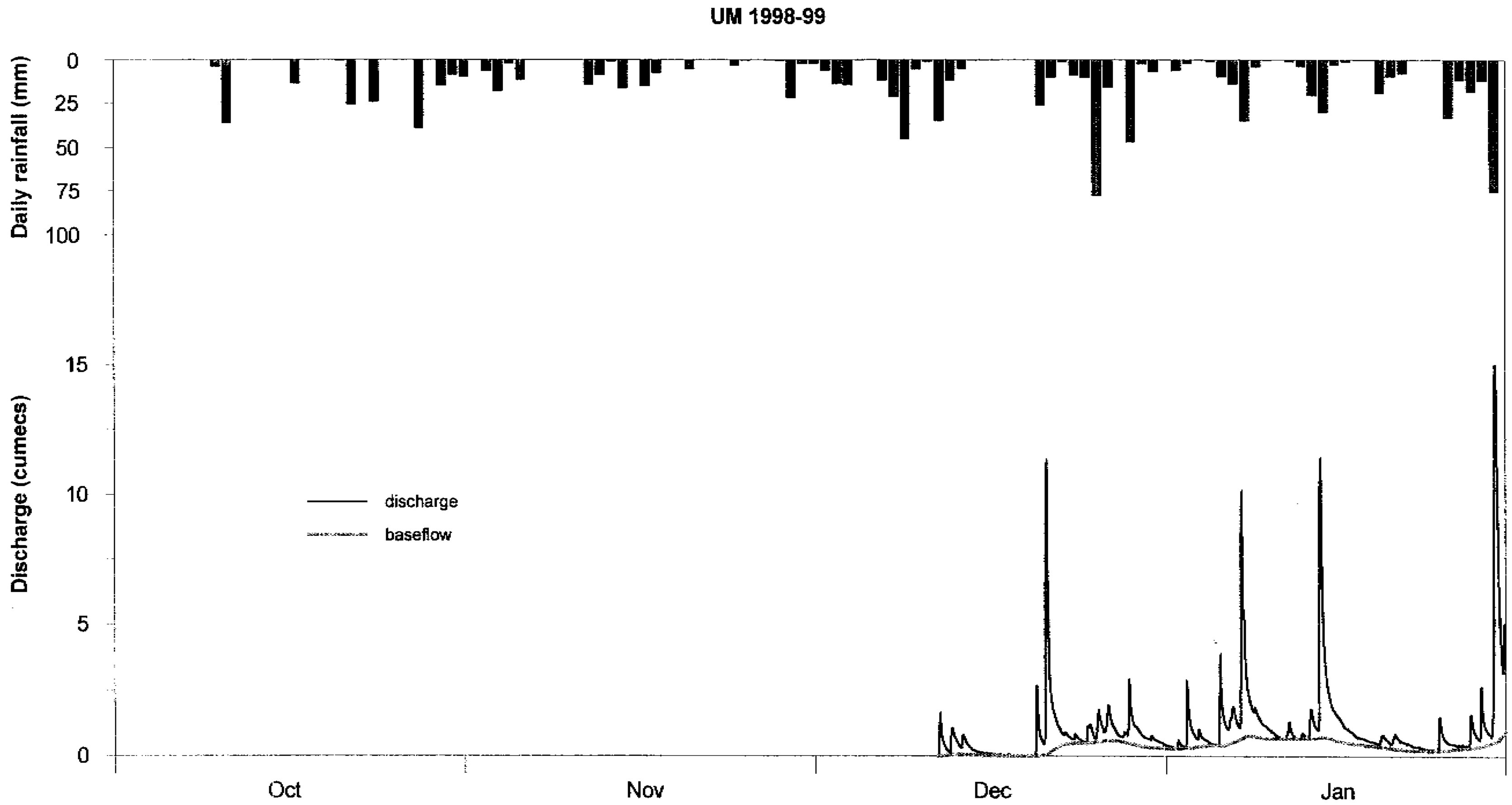

Figure A.3 Daily rainfall and the hydrograph for UM during 1998/99 wet season. The baseflow is also shown.

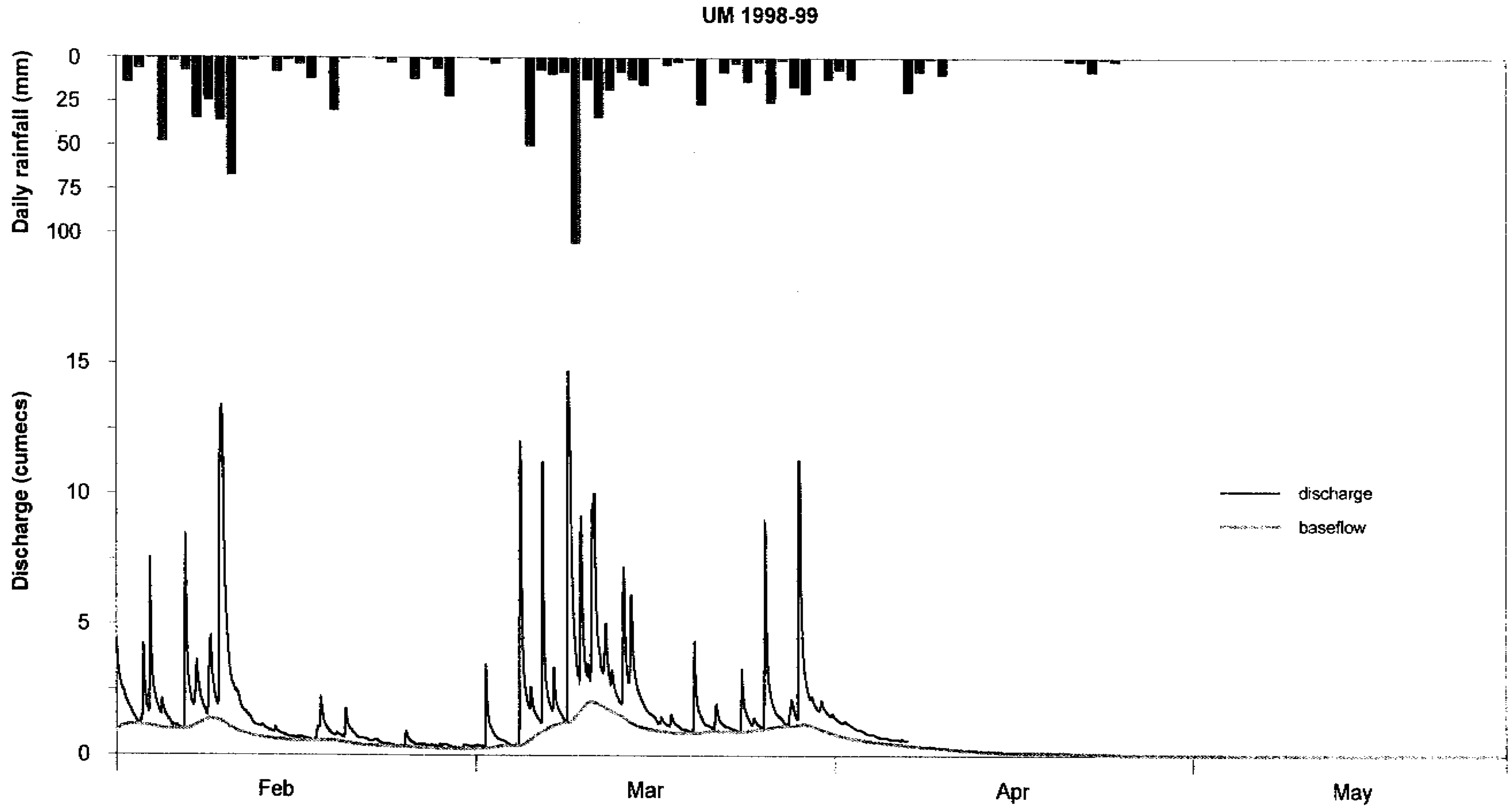

Figure A.3 (continued) Daily rainfall and the hydrograph for UM during 1998/99 wet season. The baseflow is also shown.

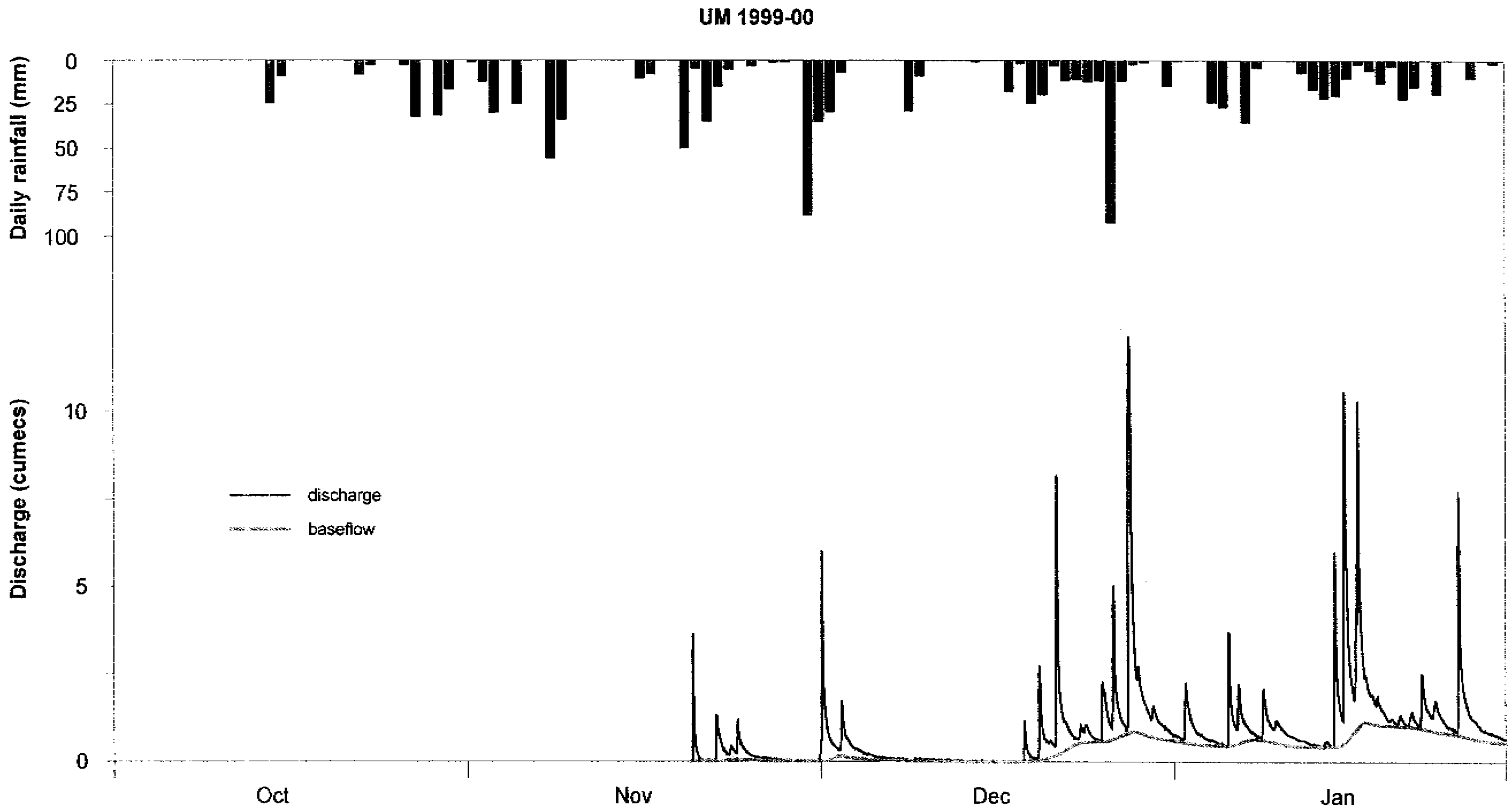

Figure A.4 Daily rainfall and the hydrograph for UM during 1999/00 wet season. The baseflow is also shown.

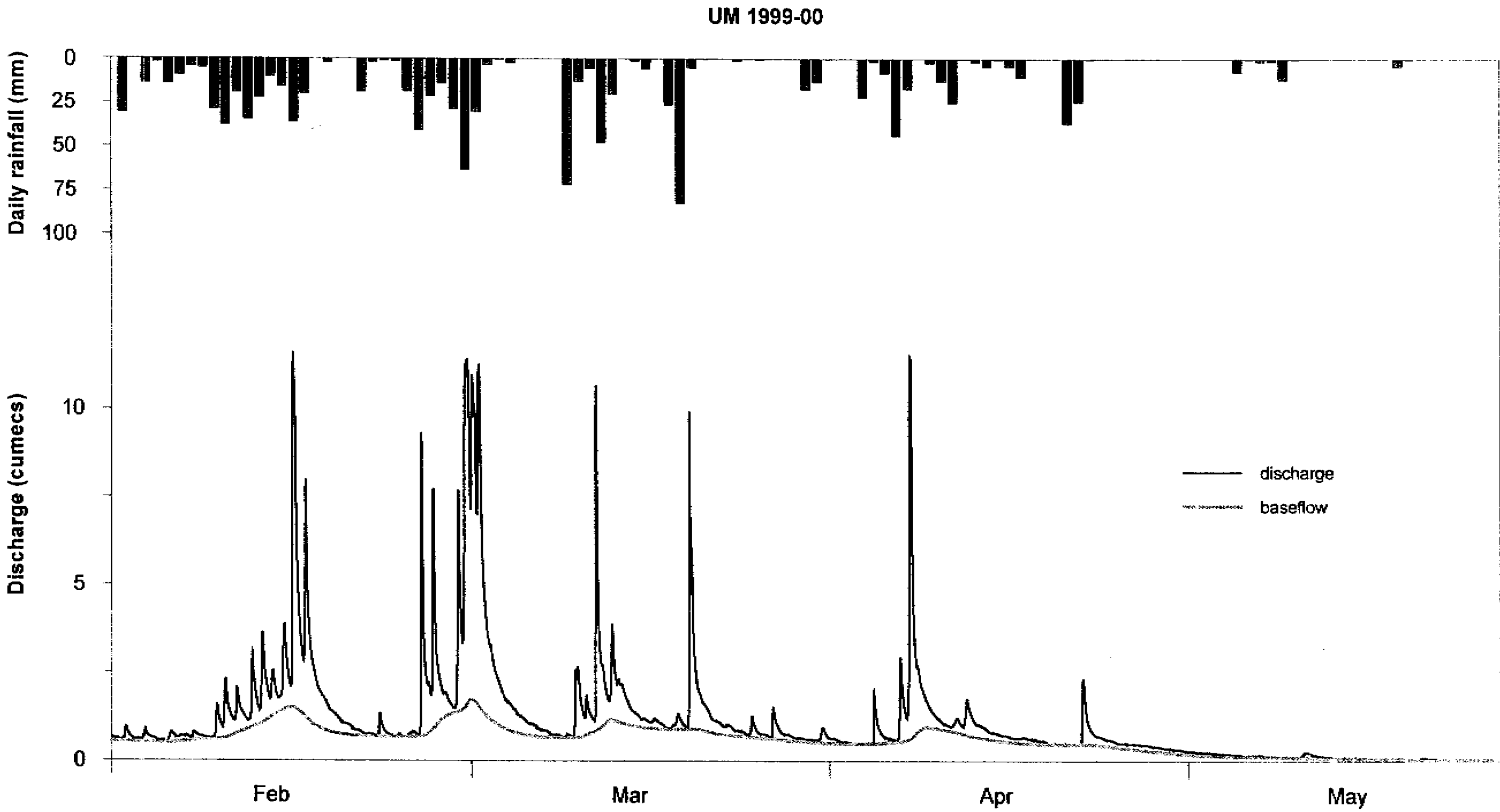

Figure A.4 (continued) Daily rainfall and the hydrograph for UM during 1999/00 wet season. The baseflow is also shown.

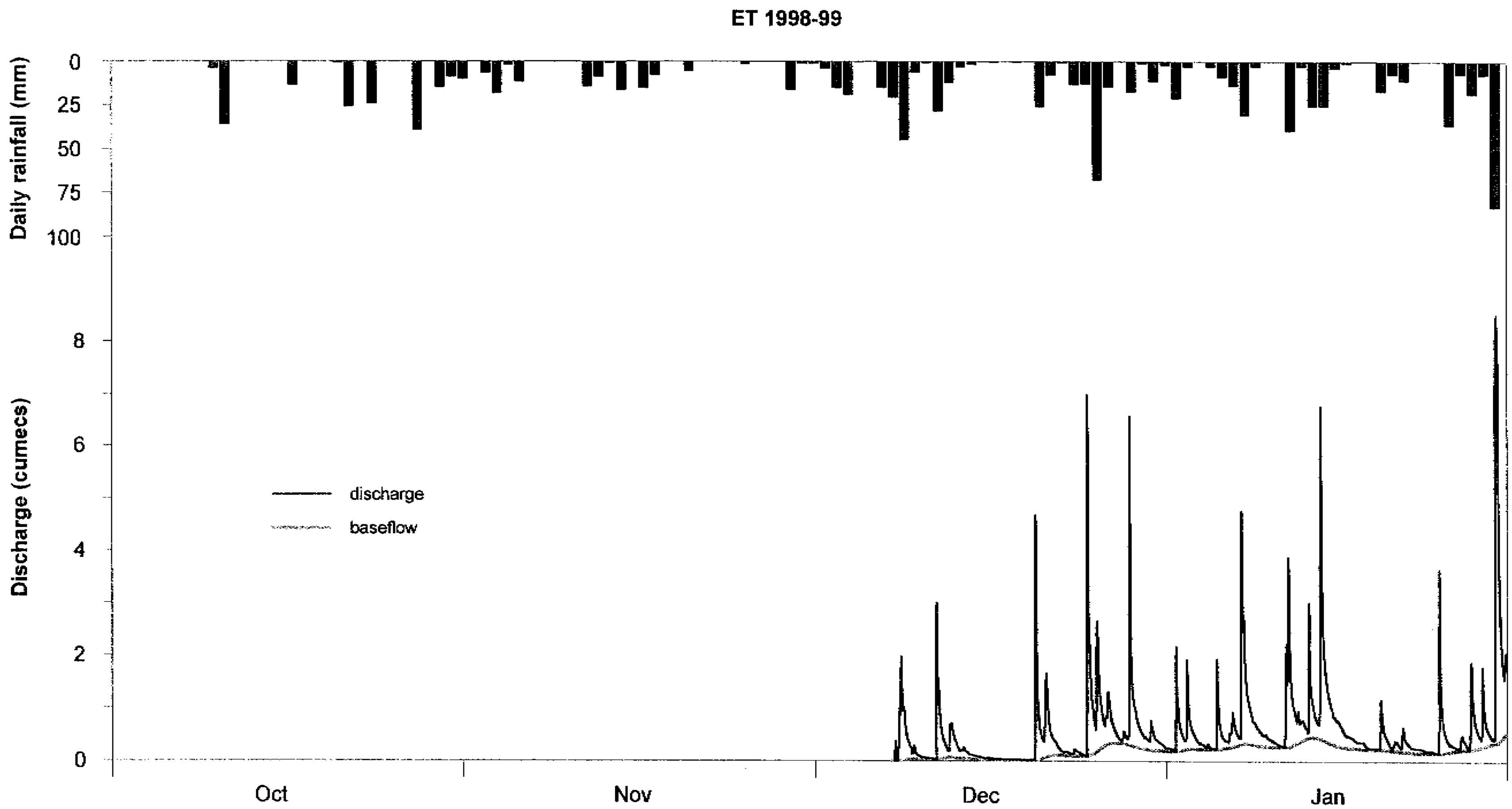

Figure A.5 Daily rainfall and the hydrograph for ET during 1998/99 wet season. The baseflow is also shown.

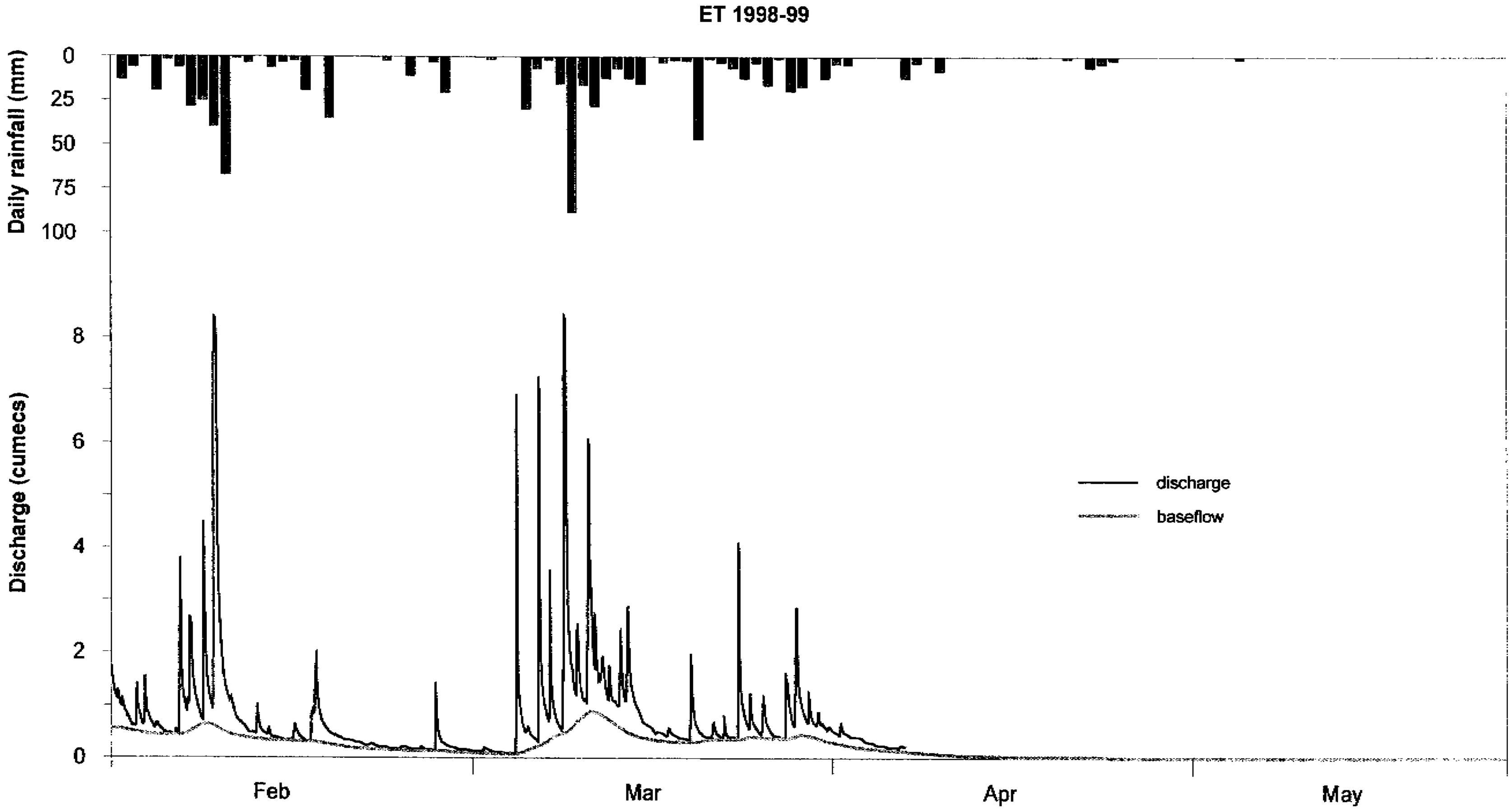

Figure A.5 (continued) Daily rainfall and the hydrograph for ET during 1998/99 wet season. The baseflow is also shown.

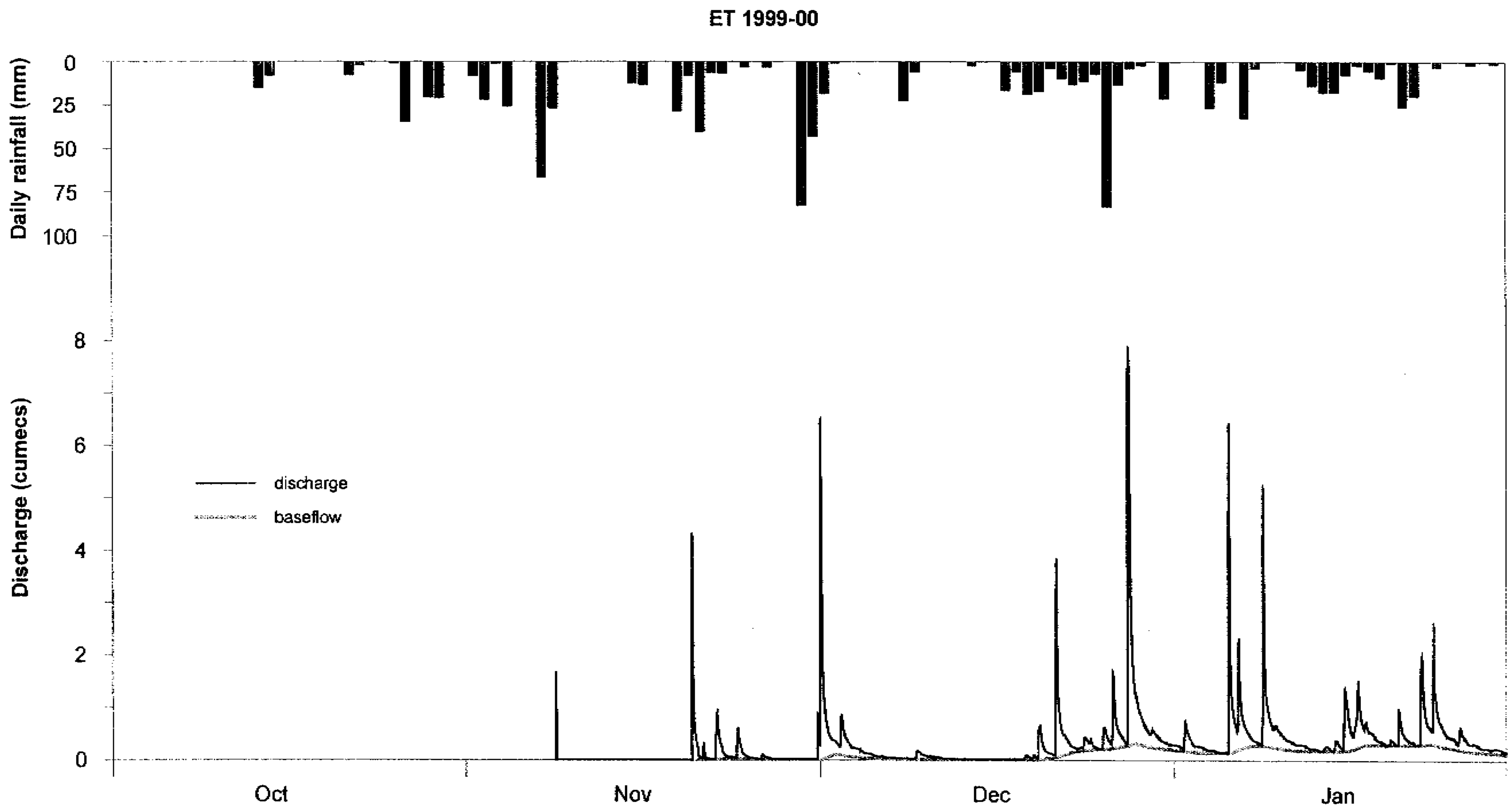

Figure A.6 Daily rainfall and the hydrograph for ET during 1999/00 wet season. The baseflow is also shown.

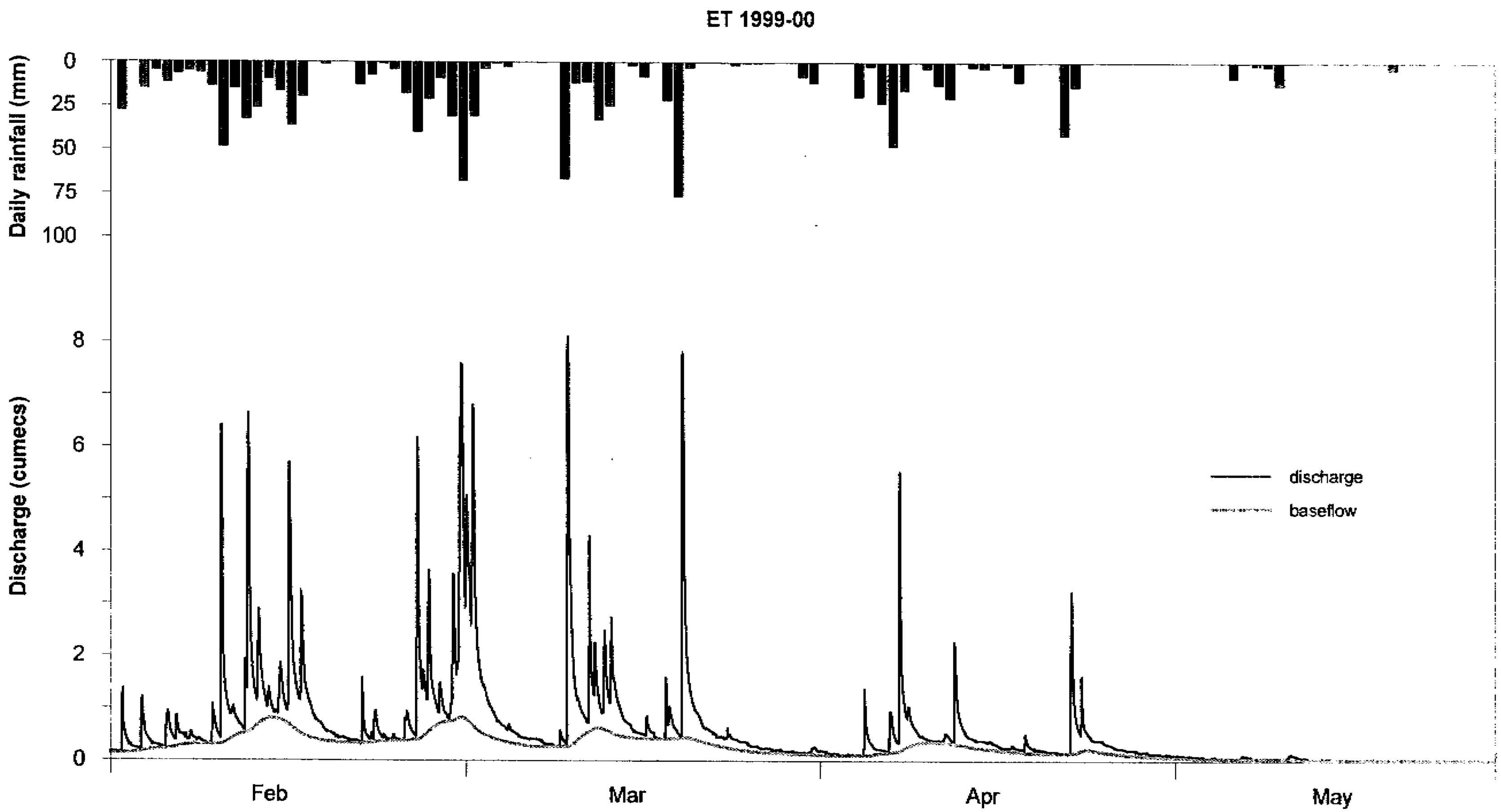

Figure A.6 (continued) Daily rainfall and the hydrograph for ET during 1999/00 wet season. The baseflow is also shown.

Appendix B – Velocity-area gauging data

Table B.1 Velocity-area gauging data at SC – 1998/99

Date	Stage height (m)	Discharge (m^3s^{-1})	Cross sectional flow area (m^2)
06-Jan-99	0.6	1.238	2.755
06-Jan-99	0.56	0.976	2.355
11-Jan-99	0.725	1.729	4.297
11-Jan-99	0.725	1.742	5.519
13-Jan-99	0.78	2.259	4.952
20-Jan-99	0.605	1.346	2.584
26-Jan-99	0.995	3.219	5.121
03-Feb-99	1.615	8.160	12.280
03-Feb-99	1.31	5.683	9.350
10-Feb-99	1.765	9.418	15.578
10-Feb-99	1.905	14.983	19.813
17-Feb-99	0.698	1.716	3.256
19-Feb-99	0.81	2.329	4.456
23-Feb-99	0.58	1.368	2.861
02-Mar-99	0.51	0.853	2.025
09-Mar-99	0.83	2.158	5.536
18-Mar-99	1.165	4.126	8.260
23-Mar-99	0.905	2.948	5.342
30-Mar-99	0.795	2.117	4.848
06-Apr-99	0.71	1.764	3.198
06-Apr-99	0.71	1.842	3.264
12-Apr-99	0.56	0.956	2.139
20-Apr-99	0.4	0.368	0.992
27-Apr-99	0.445	0.532	1.291
04-May-99	0.33	0.123	0.442

Table B.2 Velocity-area gauging data at SC – 1999/00

Date	Stage height (m)	Discharge (m^3s^{-1})	Cross sectional flow area (m^2)
03-Dec-99	0.55	0.671	1.874
21-Dec-99	0.875	2.085	4.812
04-Jan-00	0.645	1.190	2.554
18-Jan-00	1.36	5.317	9.803
25-Jan-00	0.93	2.426	5.078
01-Feb-00	0.62	0.943	2.073
08-Feb-00	0.725	1.552	3.302
15-Feb-00	1.23	4.524	9.277
22-Feb-00	0.78	1.617	3.074
29-Feb-00	1.22	4.405	8.858

03-Mar-00	1.98	16.120	20.553
07-Mar-00	0.97	2.718	4.584
14-Mar-00	1.575	7.257	12.569
21-Mar-00	0.88	2.155	5.548
28-Mar-00	0.73	1.597	3.202
06-Apr-00	0.565	0.804	1.759
11-Apr-00	1.115	3.270	7.859
20-Apr-00	0.66	1.249	2.575
02-May-00	0.53	0.601	1.599
16-May-00	0.41	0.221	0.765
30-May-00	0.32	0.047	0.245

Table B.3 Velocity-area gauging data at UM – 1998/99

Date	Stage height (m)	Discharge (m^3s^{-1})	Cross sectional flow area (m^2)
23-Dec-98	0.595	1.164	3.461
05-Jan-99	0.405	0.675	2.329
12-Jan-99	0.435	0.863	2.128
20-Jan-99	0.36	0.629	2.311
26-Jan-99	0.52	1.095	3.010
02-Feb-99	0.685	1.502	4.636
09-Feb-99	0.935	2.460	5.514
16-Feb-99	0.42	0.717	2.493
23-Feb-99	0.395	0.672	1.773
03-Mar-99	0.3	0.430	1.210
09-Mar-99	0.625	1.326	3.869
17-Mar-99	1.275	4.631	8.393
23-Mar-99	0.685	1.544	3.163
30-Mar-99	0.64	1.366	3.106
31-Mar-99	0.745	1.723	3.676
06-Apr-99	0.5	0.907	2.425
06-Apr-99	0.5	0.912	2.415
13-Apr-99	0.33	0.420	1.244
20-Apr-99	0.23	0.181	0.569
27-Apr-99	0.21	0.145	0.501
04-May-99	0.17	0.065	0.311
25-May-99	0.155	0.006	0.076

Table B.4 Velocity-area gauging data at UM – 1999/00

Date	Stage height (m)	Discharge (m^3s^{-1})	Cross sectional flow area (m^2)
03-Dec-99	0.305	0.326	1.116
04-Jan-00	0.44	0.658	2.292
18-Jan-00	1.13	3.324	7.052
25-Jan-00	0.62	1.209	2.809
01-Feb-00	0.385	0.589	1.459
08-Feb-00	0.425	0.597	1.586
15-Feb-00	0.76	1.749	4.230
22-Feb-00	0.475	0.780	2.813
29-Feb-00	0.87	2.170	4.983
03-Mar-00	1.65	7.101	12.261
07-Mar-00	0.6	1.168	3.653
14-Mar-00	0.93	2.431	4.903
21-Mar-00	0.55	1.009	2.084
28-Mar-00	0.44	0.658	1.625
06-Apr-00	0.325	0.371	1.014
11-Apr-00	0.76	1.698	4.213
20-Apr-00	0.38	0.545	1.456
02-May-00	0.27	0.258	0.870
16-May-00	0.19	0.095	0.442

Table B.5 Velocity-area gauging data at ET – 1998/99

Date	Stage height (m)	Discharge (m^3s^{-1})	Cross sectional flow area (m^2)
04-May-99	0.21	0.015	0.237
27-Apr-99	0.248	0.055	0.395
20-Apr-99	0.255	0.061	0.387
13-Apr-99	0.325	0.182	0.676
06-Apr-99	0.39	0.313	0.976
06-Apr-99	0.39	0.308	0.972
23-Mar-99	0.48	0.523	1.499
17-Mar-99	0.97	2.590	4.031
17-Mar-99	0.905	2.274	3.761
09-Mar-99	0.4	0.354	0.931
02-Mar-99	0.32	0.181	0.663
23-Feb-99	0.36	0.257	0.780
16-Feb-99	0.38	0.318	0.862
09-Feb-99	0.64	1.174	2.212
02-Feb-99	0.53	0.704	1.584
26-Jan-99	0.525	0.665	1.656
19-Jan-99	0.385	0.325	1.020

12-Jan-99	0.88	2.085	3.545
12-Jan-99	0.855	1.947	3.175
05-Jan-99	0.37	0.218	0.723

Table B.6 Velocity-area gauging data at ET – 1999/00

Date	Stage height (m)	Discharge (m^3s^{-1})	Cross sectional flow area (m^2)
03-Dec-99	0.37	0.243	0.837
29-Dec-99	0.77	1.443	3.132
04-Jan-00	0.34	0.227	0.770
18-Jan-00	0.55	0.753	1.837
25-Jan-00	0.52	0.652	1.660
01-Feb-00	0.305	0.150	0.651
15-Feb-00	0.59	0.890	2.198
22-Feb-00	0.38	0.301	1.202
29-Feb-00	0.61	0.983	2.292
03-Mar-00	1.46	6.273	6.808
07-Mar-00	0.46	0.509	1.341
14-Mar-00	0.685	1.282	2.456
21-Mar-00	0.48	0.539	1.512
28-Mar-00	0.35	0.238	1.169
06-Apr-00	0.3	0.146	0.957
11-Apr-00	0.48	0.580	1.627
20-Apr-00	0.34	0.225	0.908
02-May-00	0.295	0.129	0.620
16-May-00	0.25	0.041	0.450

Appendix C – Rainfall and runoff data for selected events

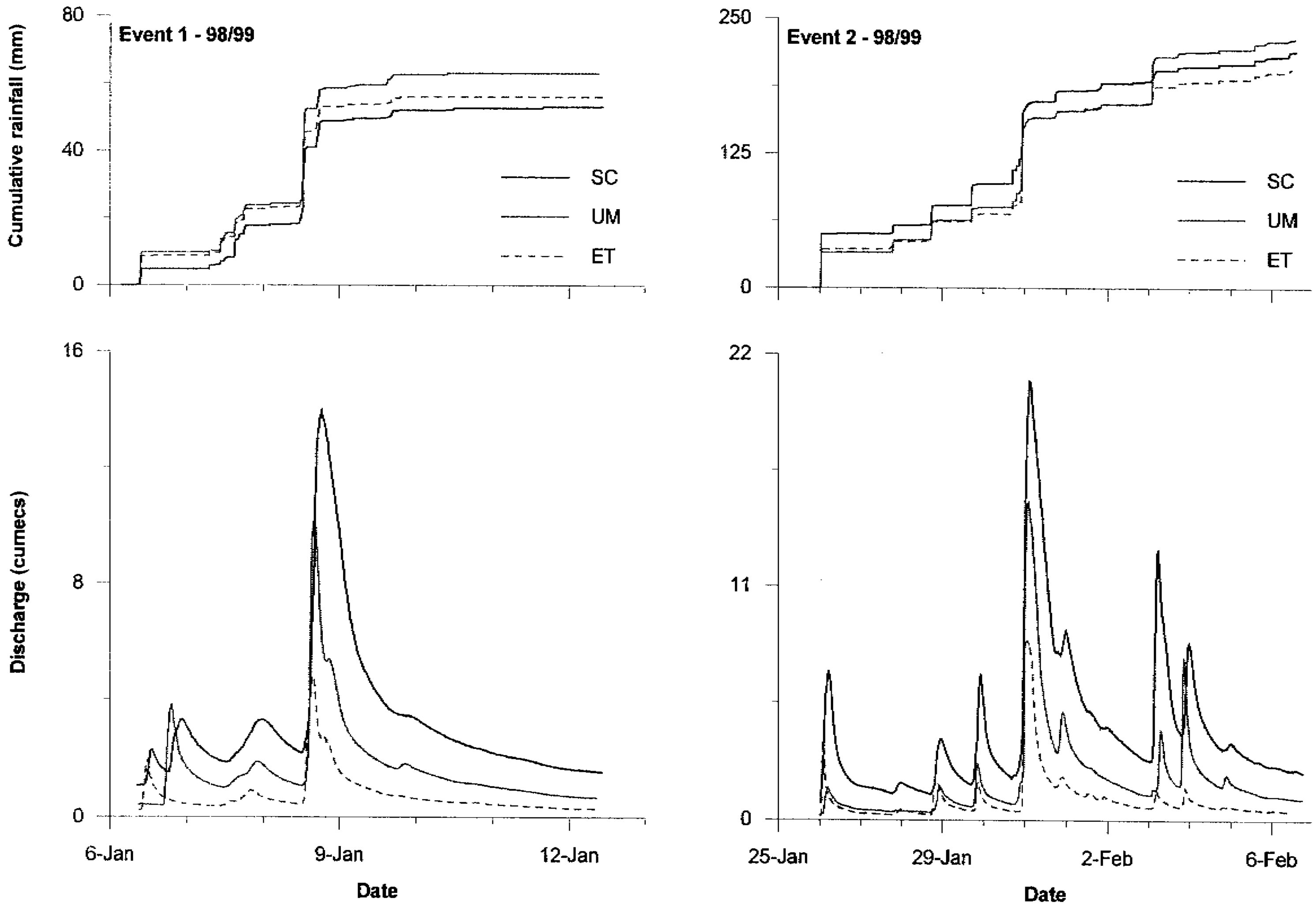

Figure C.1 Rainfall and runoff data for selected events at each of the gauging stations within Ngarradj catchment – 1998/99.

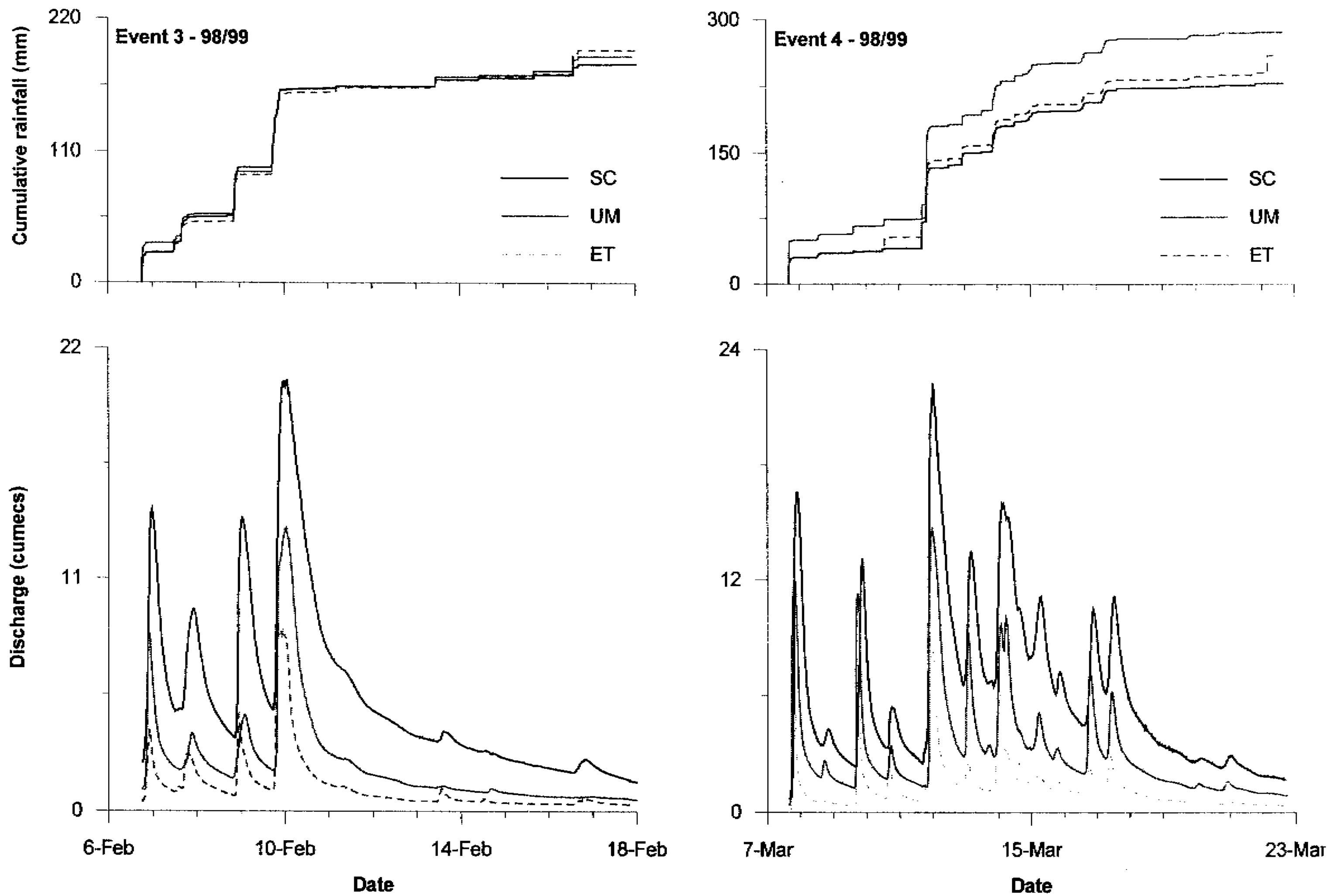

Figure C.1 (continued) Rainfall and runoff data for selected events at each of the gauging stations within Ngarradj catchment – 1998/99.

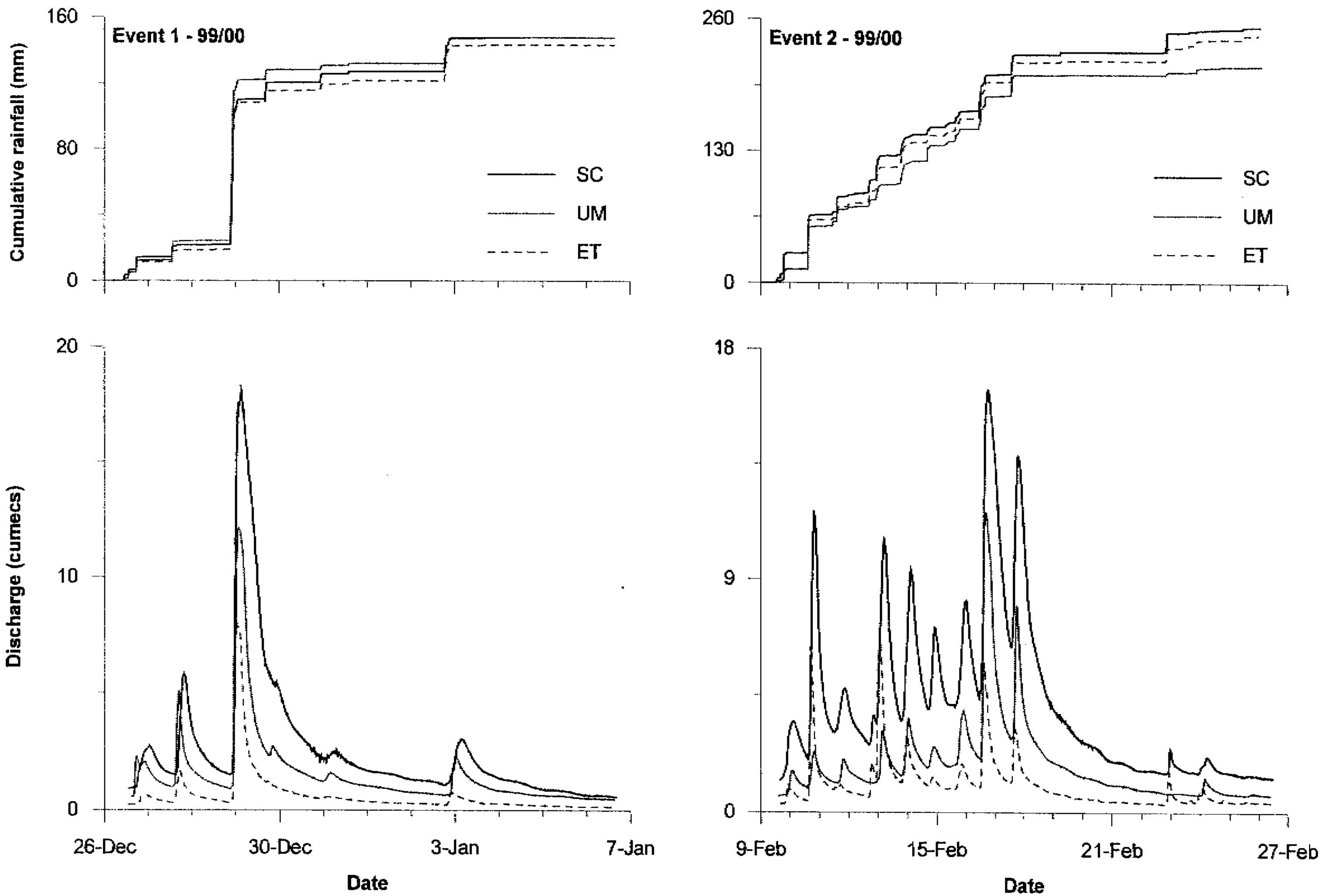

Figure C.2 Rainfall and runoff data for selected events at each of the gauging stations within Ngarradj catchment – 1999/00.

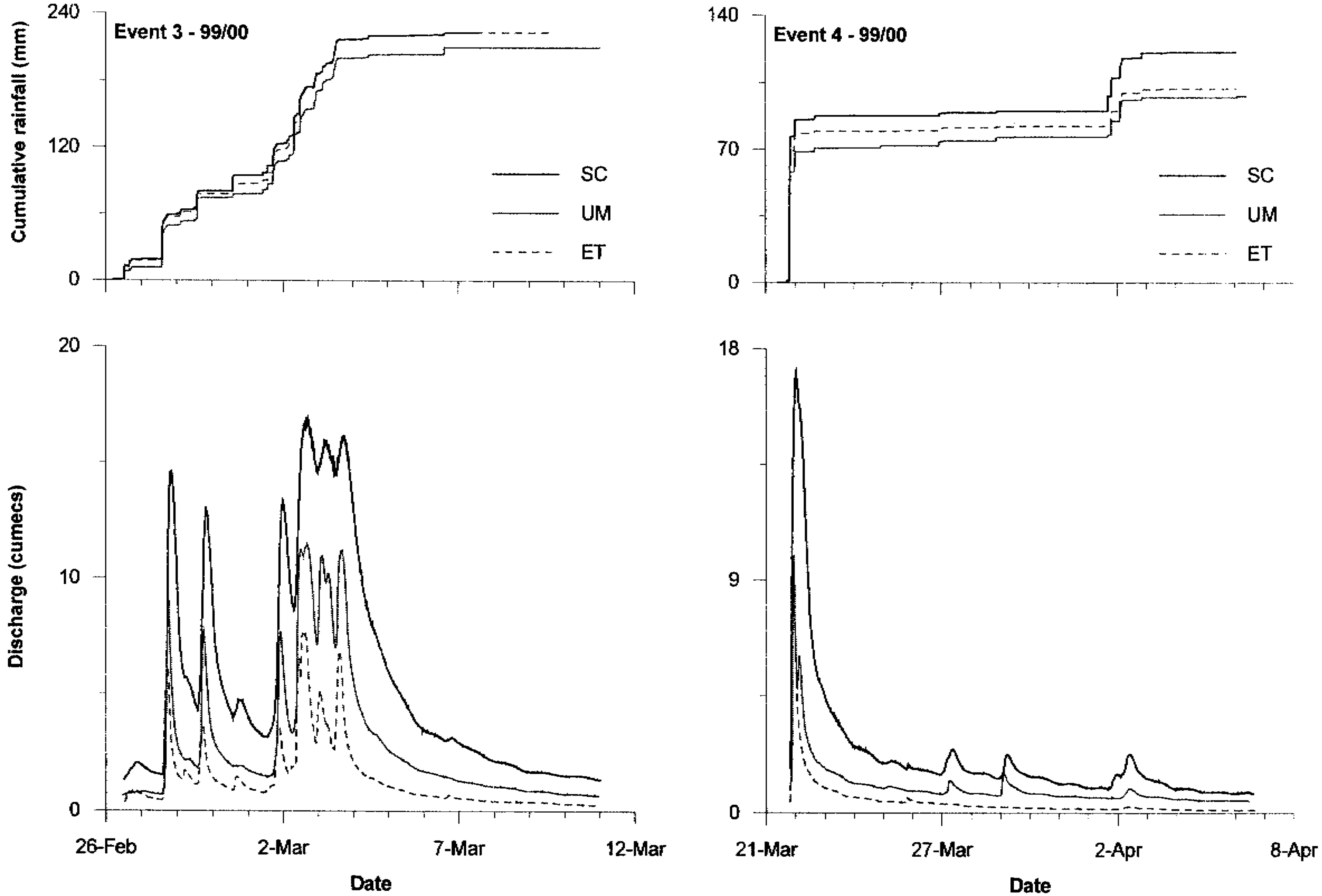

Figure C.2 (continued) Rainfall and runoff data for selected events at each of the gauging stations within Ngarradj catchment – 1999/00.

Appendix D – Maximum rainfall intensities for selected events

Table D.1 Total rainfall and maximum 6 min to 72 hr rainfall intensities for each runoff event during the two year monitoring period at SC.

Year	Event No.	Rainfall (mm)	I_6 (mm h^{-1})	I_{10} (mm h^{-1})	I_{20} (mm h^{-1})	I_{30} (mm h^{-1})	I_{60} (mm h^{-1})	I_{240} (mm h^{-1})	I_{720} (mm h^{-1})	I_{4320} (mm h^{-1})
1998/99	1	53.0	48.0	43.2	40.0	32.8	19.0	5.7	2.6	0.7
	2	219.4	158.0	150.8	130.0	98.8	49.6	13.6	6.3	1.6
	3	182.5	70.0	60.0	47.0	46.4	33.2	13.6	5.4	1.9
	4	228.8	130.0	115.6	81.8	66.0	52.2	19.0	7.7	2.0
1999/00	1	147.6	88.0	83.2	75.4	64.0	61.0	21.5	7.4	1.5
	2	252.0	106.0	89.2	71.4	58.8	35.6	9.3	3.1	1.3
	3	223.4	142.0	116.4	81.0	62.0	33.0	10.1	4.0	1.9
	4	120.8	134.0	122.4	119.4	114.4	75.2	19.1	7.1	1.2

Table D.2 Total rainfall and maximum 6 min to 72 hr rainfall intensities for each runoff event during the two year monitoring period at UM.

Year	Event No.	Rainfall (mm)	I_6 (mm h^{-1})	I_{10} (mm h^{-1})	I_{20} (mm h^{-1})	I_{30} (mm h^{-1})	I_{60} (mm h^{-1})	I_{240} (mm h^{-1})	I_{720} (mm h^{-1})	I_{4320} (mm h^{-1})
1998/99	1	63.0	64.0	56.4	43.8	34.8	24.2	7.0	2.9	0.8
	2	230.8	112.0	104.0	90.1	82.3	54.6	16.4	6.9	1.6
	3	189.2	101.5	100.1	61.9	43.0	29.2	15.1	5.7	1.8
	4	286.6	114.0	113.2	110.2	105.6	78.6	23.0	8.8	2.3
1999/00	1	147.8	92.0	91.2	81.8	74.0	61.6	24.1	8.2	1.7
	2	213.6	126.0	110.0	86.2	70.8	40.6	10.5	3.5	1.2
	3	210.0	134.0	107.6	81.4	60.0	32.0	9.4	3.7	1.7
	4	98.0	122.0	117.2	96.0	81.2	57.2	14.5	5.7	1.0

Table D.3 Total rainfall and maximum 6 min to 72 hr rainfall intensities for each runoff event during the two year monitoring period at ET.

Year	Event No.	Rainfall (mm)	I_6 (mm h^{-1})	I_{10} (mm h^{-1})	I_{20} (mm h^{-1})	I_{30} (mm h^{-1})	I_{60} (mm h^{-1})	I_{240} (mm h^{-1})	I_{720} (mm h^{-1})	I_{4320} (mm h^{-1})
1998/99	1	56.0	50.0	48.4	41.0	30.8	18.6	5.6	2.5	0.7
	2	202.8	124.0	116.0	99.0	88.6	65.3	19.2	7.5	1.6
	3	194.2	72.7	64.8	49.5	45.2	31.5	14.7	5.7	1.8
	4	260.8	106.0	99.2	87.2	80.0	56.2	18.2	7.3	1.9
1999/00	1	143.2	96.0	75.2	64.2	62.4	59.0	21.9	7.5	1.5
	2	244.2	154.0	126.8	100.8	78.8	46.4	11.9	4.0	1.4
	3	223.8	120.0	116.0	83.4	61.6	33.0	9.8	4.3	1.9
	4	101.8	128.0	116.0	103.2	99.2	68.2	17.3	6.5	1.1