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Baseline hydrology characteristics of the Ngarradj catchment, Northern Territory

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Executive summary

The catchment of Ngarradj[1], located in the wet dry tropics of the Northern Territory, Australia, is a major right-bank tributary of the Ramsar-listed Magela Creek wetlands. The Ngarradj catchment will be the first to be affected should any impact occur as a result of mining operations at the Energy Resources of Australia Jabiluka Mine. As part of a long-term study of the impact of mining at Jabiluka on the Ngarradj catchment, an attempt has been made to estimate the baseline hydrological characteristics of the catchment.

General diurnal trends and analysis of high magnitude storm events at the Ngarradj catchment during the three year monitoring period (1998–2001) show that peak rainfall and runoff occur late in the afternoon to early in the morning. The average time taken from the start of low frequency, very intense rainfall periods to peak runoff at stream gauging stations within Ngarradj catchment ranged between 45 minutes to 5.2 hours. These lag-times were examined in relation to the hydrological and geomorphological characteristics of the catchment, which showed that stream length and mean channel slope were the most significant factors in predicting lag-time at each catchment outlet. 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 the design of an effective stream sediment monitoring regime within the Ngarradj catchment.

Hydrology model parameters for the Ngarradj catchment were fitted to the US Army Corps of Engineers Hydrologic Modelling System (HEC-HMS) using the three years of observed rainfall-runoff data collected at each gauging station. The calibrated model was then used to generate a long-term runoff record using 20 years of rainfall data collected at Jabiru airport and the Jabiluka Mine. Flood frequency analysis of these data indicate that during the 20 year period there were 2 very large peak discharge events (ARIs of 1:55 y and 1:18 y), while the rest had ARIs of less than 1:6 y. Further analysis of the large flood events showed that they were associated with the largest recorded storm event in Kakadu and two consecutive high-intensity rainfall events respectively. However, it is important that future work determines how well the model and the current parameters predict very large flood events (>1:10 y event) as they have high significance in the assessment of risk and geomorphological change.

[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).

Acknowledgments

Currumbene Hydrological installed the gauging stations and Mr B Smith, Mrs E Crisp and Mr M Grabham assisted with data collection. Mr G Fox assisted with data collection, rainfall data analysis and preparation of appendices. Trevor Spedding, Energy Resources of Australia, supplied rainfall data collected at Jabiluka mine site and some stage data collected at streams within the Ngarradj catchment. Professor TA McMahon (University of Melbourne) and Associate Professor RJ Loughran (University of Newcastle) constructively and comprehensively reviewed the draft report.

Note

Section 3 of this report has been published elsewhere and has been included here for completeness. When referring to this section of the report, please refer to:

Moliere DR, Boggs GS, Evans KG & Saynor MJ 2002. Hydrological response of Ngarradj — a seasonal stream in the wet-dry tropics, Northern Territory. In *The structure, function and management implications of fluvial sedimentary systems* (Proceedings. Alice Springs symposium, Australia, September 2002). IAHS Publ. 276, 281–288.

1 Introduction

The Jabiluka uranium mine is located in the catchment of Ngarradj[2] in the wet dry tropics of the Northern Territory, Australia (fig 1.1). 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. A significant potential impact on the environment as a result of mining involves the pollution of waterways through erosion of post-mining landforms and movement of the sediment into the surrounding streams (Evans 2000). In 1998 the Environmental Research Institute of the Supervising Scientist (***eriss***) established a stream gauging network to develop an understanding of contemporaneous catchment baseline conditions of sediment movement and hydrology in the Ngarradj catchment (fig 1.1). Stream gauging stations were installed upstream (Upper Main – UM; East Tributary – ET) and downstream (Swift Creek – SC) (fig 1.1) of the mine in order to assess possible impacts associated with mining at Jabiluka (as described in Erskine et al (2001)). Gauging stations were also operated at tributaries North, Central and South (TN, TC and TS respectively) (fig 1.1) by Energy Resources of Australia (ERA). As the ERA gauging stations only operated for a period of time during the 1998/99 Wet season, runoff data from these gauging stations were not used in most of the analysis presented in this report. Runoff data from these gauging stations were used only in section 3.3, 'relationship between lag-time and catchment characteristics'.

Chapter 2 of this report describes the three years of rainfall and runoff data collected from the three ***eriss*** stream gauging stations within the Ngarradj catchment (fig 1.1) as part of a long-term study of the impact of mining at Jabiluka on the Ngarradj catchment.

In chapter 3 the observed hydrology data were used to characterise the hydrological response of streams within the Ngarradj catchment. In particular, the diurnal variation in rainfall and runoff was studied and a relationship between lag-time and catchment characteristics of high intensity rainfall events was determined.

Finally, in chapter 4, the observed rainfall-runoff data at the three ***eriss*** stream gauging stations were used to derive hydrology model parameters for the Ngarradj catchment using the software package HEC-HMS. Chapter 4 documents the process of HEC-HMS parameter derivation using site hydrology data and catchment form data. The fitted hydrology model parameters were then used to (1) establish a long-term runoff record for each gauging station, and (2) derive a flood frequency curve for each station.

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[2] **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).

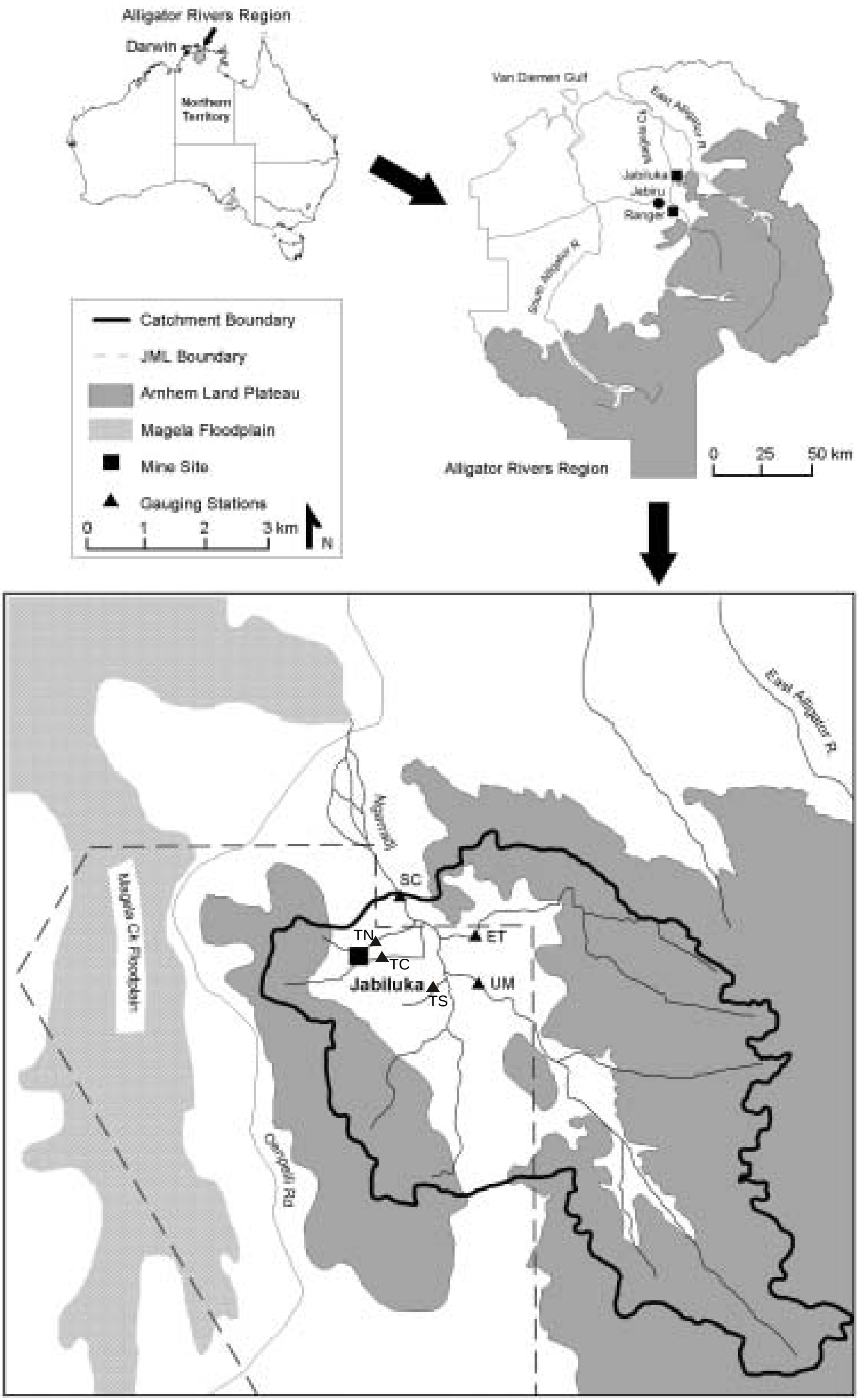

Figure 1.1 The Ngarradj catchment showing the location of the Jabiluka mine and the gauging station sites

1.1 Study area

The Ngarradj catchment is located approximately 230 km east of Darwin and 20 km north-east of Jabiru (fig 1.1). Oenpelli, Arnhem Land, is a further 20 km north-east of the Ngarradj catchment. Located in the monsoon tropics climatic zone, the catchment experiences a distinct Wet season from October to April, and a Dry season for the remainder of the year. Stream flow, as a consequence, is highly seasonal. The average annual rainfall for the region is approximately 1410 mm (Bureau of Meteorology pers comm 2001).

Ngarradj main channel flows in a well-defined valley in a northwesterly direction from the Arnhem Land sandstone plateau to the Magela Creek floodplain with one major right bank tributary (East Tributary) (fig 1.1). Both the upper reaches of the Ngarradj main channel and East Tributary flow in essentially a bedrock confined channel on the plateau (fig 1.1). There are several left bank tributaries that drain predominantly wooded lowland areas and have significantly smaller areas of bedrock and escarpment than the main channel and East Tributary. The total catchment area of the Ngarradj catchment (upstream of SC) is approximately 43.6 km^2.

2 Hydrology data

2.1 Rainfall data

A 0.2 mm tipping bucket rain gauge was installed at each ***eriss*** gauging station within Ngarradj catchment and readings were taken at 6 minute intervals. Rainfall data were also collected at 10 minute intervals at Jabiluka mine (fig 1.1) by Energy Resources of Australia using a 0.5 mm tipping bucket rain gauge. The total annual rainfall at each gauging station (SC, UM and ET) and Jabiluka mine during 1998/99, 1999/00 and 2000/01 Wet seasons are shown in table 2.1.

The total annual rainfall over the Ngarradj catchment (September to August), determined using the Thiessen Polygon method (Thiessen 1911) to spatially average the total rainfall measured at the three gauging stations and Jabiluka mine, was 1826.1 mm, 2047.4 mm and 1896.9 mm for 1998/99, 1999/00 and 2000/01 respectively (table 2.1). It is assumed that these figures reflect the annual rainfall that occurred over the whole Ngarradj catchment, despite the fact that the rain gauges are all located in the wooded lowland areas of the catchment (fig 1.1). Due to the cultural significance of the Arnhem Land Plateau (fig 1.1), rain gauges were not allowed to be installed on the upper areas of the Ngarradj catchment.

Table 2.1 Total rainfall over the Ngarradj catchment area derived using the Thiessen Polygon method

Station	Rainfall 98/99 (mm)	Rainfall 99/00 (mm)	Rainfall 00/01 (mm)	Polygon area (% of total area)
SC	1788.6[1]	1997.2	1947.4	0.324
UM	1855.2[1]	2105.0	1861.0	0.482
ET	1733.6[1]	2069.6	1891.4	0.105
Jabiluka	1914.4	1892.0	1914.0	0.089
Total [ARI]	1826.1 [1:13]	2047.4 [1:71]	1896.9 [1:21]	1.00

1 Data partly provided by Energy Resources of Australia

2.1.1 Infilling rainfall data

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, 1999/00 and 2000/01 Wet seasons was used to derive linear relationships for rainfall at SC, UM and ET (eqns 2.1 to 2.3).

$$SC_{rain} = 0.998\ Jab_{rain} \quad (r^2 = 0.97;\ df = 24;\ p<0.001) \tag{2.1}$$

$$UM_{rain} = 0.996\ Jab_{rain} \quad (r^2 = 0.94;\ df = 20;\ p<0.001) \tag{2.2}$$

$$ET_{rain} = 0.991\ Jab_{rain} \quad (r^2 = 0.97;\ df = 24;\ p<0.001) \tag{2.3}$$

Equations 2.1 to 2.3 indicate that the monthly rainfall data recorded at Jabiluka mine are 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 was simply transposed to the SC, UM and ET rainfall record (table 2.2).

Table 2.2 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

An internal failure in the datataker at UM occurred on 6 February 2001 and, as a result, rainfall data collected at UM from 6 February 2001 until the end of the Wet season were unreliable. Rainfall data collected at ET, the nearest gauging station to UM (fig 1.1), were used to estimate the total rainfall during this period. Similar to above, linear regression analysis of the total monthly rainfall figures observed at both stations from December 1998 to February 2001 were used to derive a linear relationship for rainfall at UM (eqn 2.4).

$$UM_{rain} = 0.996\ ET_{rain} \qquad (r^2 = 0.97;\ df = 20;\ p<0.001) \qquad (2.4)$$

Equation 2.4 indicates that the relationship between monthly rainfall data recorded at UM and ET is significant and as a result, the total rainfall figure recorded at ET from 6 February to the end of the Wet season of 750.4 mm was simply transposed to the UM rainfall record.

2.1.2 Analysis of annual rainfall

To determine an annual recurrence interval (ARI) of the total annual rainfall volumes observed at the Ngarradj catchment, it was necessary to compare the observed data to long-term rainfall data collected in the region.

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 (fig 1.1). The length of the rainfall records for Jabiru airport and Oenpelli are approximately 30 years (1971–2001) and 90 years (1910–2001) respectively. Previous studies on rainfall analysis in the Jabiluka mine site region have used Oenpelli rainfall data because it has a longer record (ie Chiew & Wang 1999). However, for direct comparison between rainfall data at the Ngarradj catchment to rainfall data collected at Oenpelli, it was recommended that the correlation between the Ngarradj catchment and Oenpelli rainfall data should be determined (Moliere et al 2001).

Rainfall data were collected at 10 minute intervals at Jabiluka mine (fig 1.1) by Energy Resources of Australia since the 1994 Dry season. Assuming the rainfall data collected at Jabiluka mine between 1994–1998 represent the rainfall over the Ngarradj catchment, there are, in total, 7 years of rainfall data observed at the Ngarradj catchment. The rainfall data at Ngarradj were compared with both the Oenpelli and the Jabiru rainfall data using concurrent data between September 1994 to May 2001.

Figure 2.1 shows that the rainfall distribution throughout the Wet season is similar between (i) Ngarradj catchment and Oenpelli, although the rainfall is slightly higher at Ngarradj catchment during the wetter months of December to February, and (ii) Ngarradj catchment and Jabiru, although the average rainfall figure for January is higher at Jabiru. The slope of the relationship between monthly rainfall at Ngarradj catchment and Oenpelli and Ngarradj catchment and Jabiru is 0.98 and 0.95 respectively (fig 2.2). Figures 2.1 and 2.2 indicate that the relationships between monthly rainfall at Ngarradj catchment and the two long-term rainfall stations at Oenpelli and Jabiru are similar.

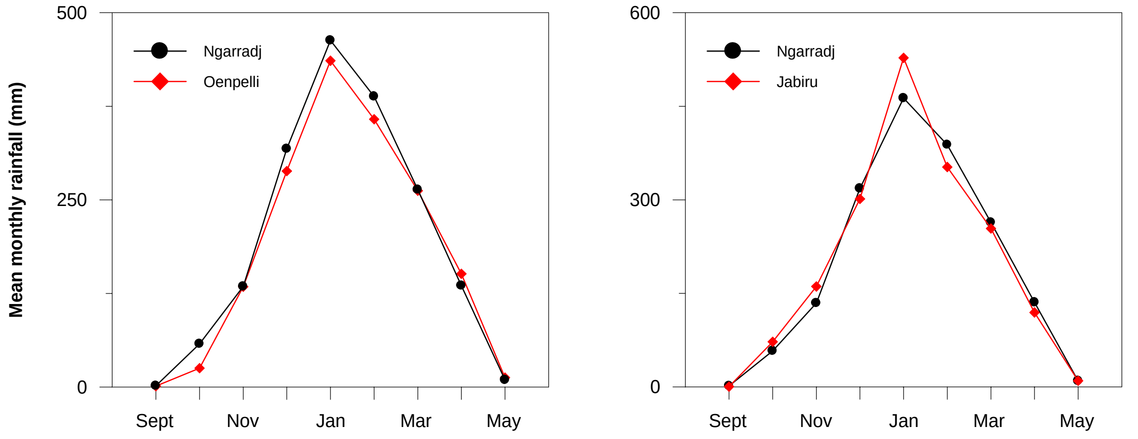

Figure 2.1 Mean monthly rainfall at (i) Ngarradj catchment and Oenpelli (Left), and (ii) Ngarradj catchment and Jabiru (Right) between September 1994 and May 2001

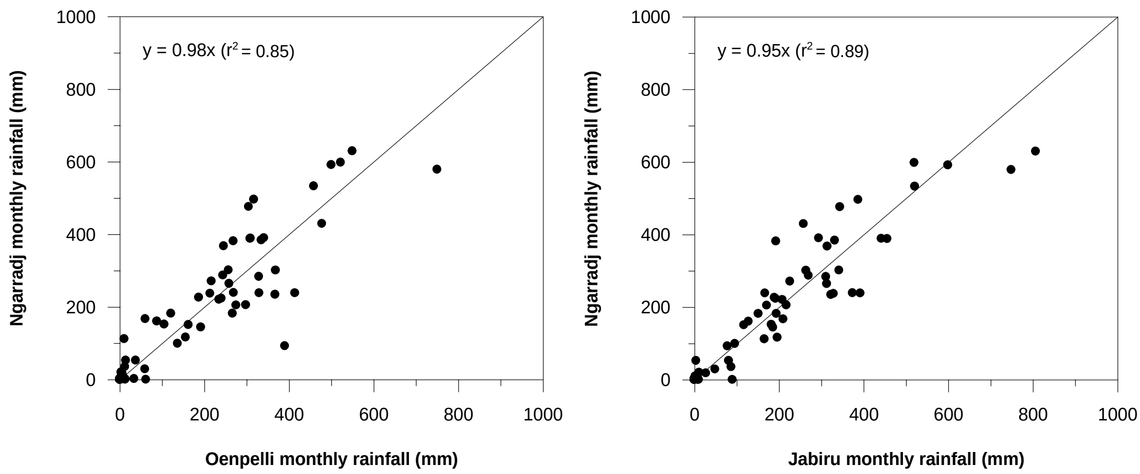

Figure 2.2 Comparison of monthly rainfall at (i) Ngarradj catchment and Oenpelli (Left), and (ii) Ngarradj catchment and Jabiru (Right) between September 1994 and May 2001

Figures 2.1 and 2.2 show that, although there is demonstrated variance from year-to-year between annual rainfall data recorded at all three locations (Moliere et al 2001), it may be assumed that rainfall at Ngarradj catchment, Oenpelli and Jabiru is not significantly different. In this study, the annual rainfall at Ngarradj catchment recorded during 1998/99, 1999/00 and 2000/01 (table 2.1) was compared with the Oenpelli rainfall distribution (fig 2.3), which has a longer period of rainfall record than Jabiru. The annual rainfall data for Oenpelli fit a normal distribution for the period of record (Bureau of Meteorology 1999). The total annual rainfall in the Ngarradj catchment during 1998/99, 1999/00 and 2000/01 plot on this distribution as approximately 1:13, 1:71 and 1:21 rainfall years respectively (fig 2.3, table 2.1).

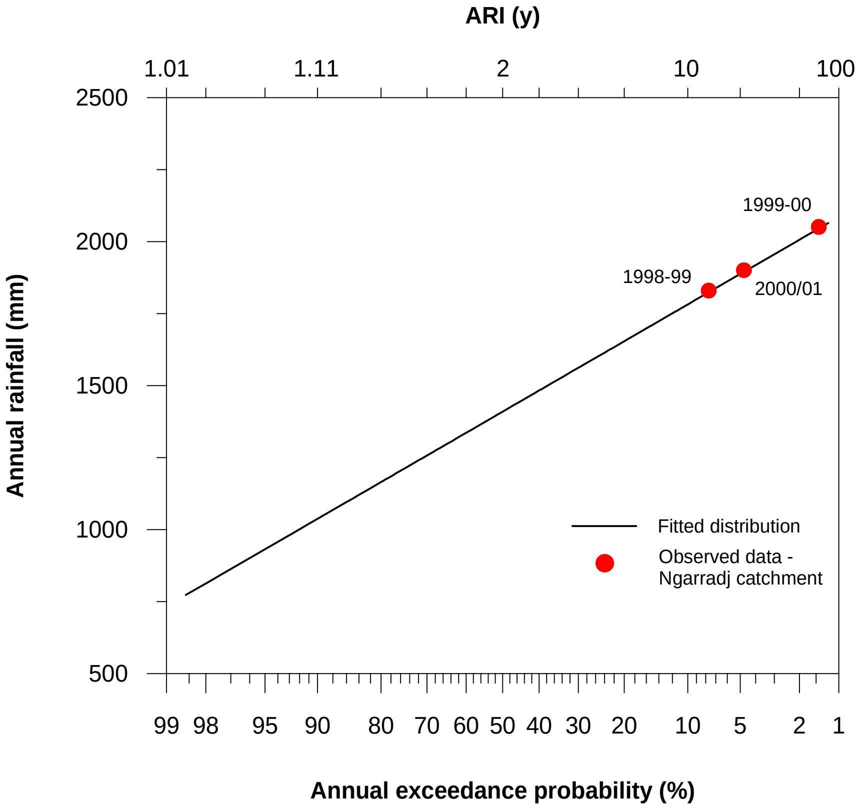

Figure 2.3 Annual rainfall frequency curve for Oenpelli. Three years of rainfall for the Ngarradj catchment (table 2.1) are also shown.

2.2 Runoff data

Stage height (m) at each gauging station was measured at 6 minute intervals by a pressure transducer. Stage data collected at SC, UM and ET were converted to discharge ($m^3 s^{-1}$) using fitted rating tables derived in Moliere et al (2001). The rating tables were derived using velocity-area gaugings taken along a stable cross-section at each gauging station at various times throughout the period of flow (approximately weekly). At 95% confidence limits the fitted rating curves have errors in bankfull discharge values at SC, UM and ET of ±11%, ±14% and ±5% respectively. The accuracy of high flows at most Australian stations is probably not much better than ±25% (Brown 1983, as cited in Pilgrim 1987). The complete hydrograph for each gauging station for the 1998/99, 1999/00 and 2000/01 Wet seasons is shown in Appendix A. On average, flow occurred at each gauging station for approximately 6 months of the year (December–June).

The total runoff for each Wet season at the gauging stations, determined as the area under the hydrograph, is given in table 2.3. 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 2.3. The time that runoff ended was estimated from field observations and is accurate to within 2–3 days (table 2.3).

The average antecedent rainfall, which in this case is defined as the amount of rainfall before the start of streamflow, for the Ngarradj catchment was approximately 430 mm, 280 mm and 250 mm during the 1998/99, 1999/00 and 2000/01 Wet seasons respectively.

Table 2.3 Total rainfall and runoff at each gauging station for the 1998/99, 1999/00 and 2000/01 Wet seasons

Year	Station	Rainfall period	Total rainfall (mm)	Antecedent rainfall (mm)	Runoff period	Total runoff (ML) [Peak discharge (m^3s^{-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]
2000/01	SC	14 Oct – 27 Apr	1947.4	250	29 Nov – 14 Jun	34780.8 [20.6]
	UM		1861.0	250	3 Dec – 14 Jun	17052.2 [13.0]
	ET		1891.4	245	28 Nov – 21 May	8275.2 [8.2]

(1) Data partly provided by Energy Resources of Australia

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

3 Hydrological response

Using the three years of monitoring data described above, an attempt has been made to characterise the hydrological response of streams within the Ngarradj catchment both on a long-term average basis and on an individual storm event basis. The importance of characterising low frequency, high magnitude flood events in developing a stream monitoring sampling program is also briefly examined.

3.1 Diurnal variation in rainfall and runoff

The mean hourly rainfalls measured at the four rain gauges during the three year monitoring period were spatially averaged using the Thiessen Polygon method to determine the diurnal cycle over the Ngarradj catchment (fig 3.1). Figure 3.1 shows that Ngarradj catchment rainfall exhibits a strong diurnal cycle with a peak in the late afternoon, similar to that found over the Darwin region (Li et al 1996, Soman et al 1995). The mean runoff in one hour bins for three years of runoff data collected at the three gauging stations is also shown in figure 3.1.

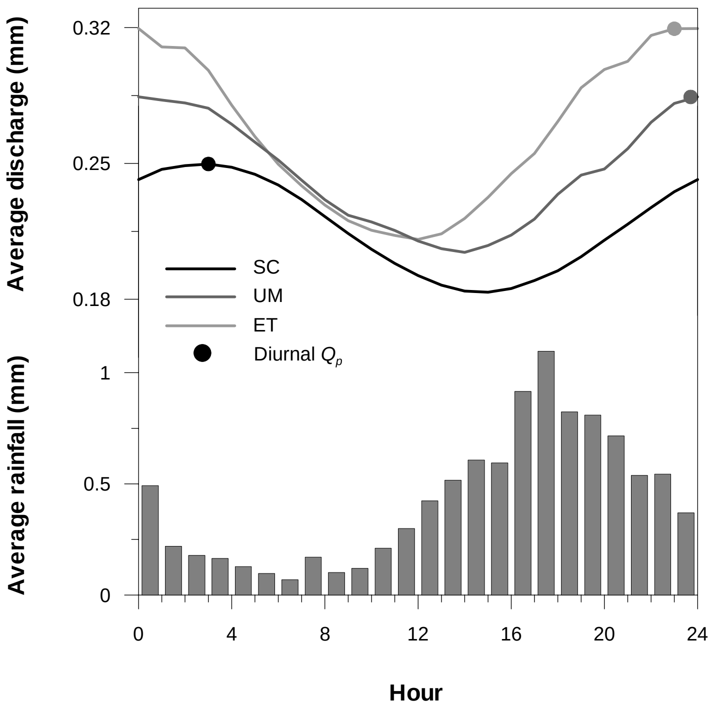

Figure 3.1 Diurnal variation of mean rainfall for the Ngarradj catchment. The diurnal variation in runoff at the three gauging stations is also shown.

The mean hourly runoffs measured at the three gauging stations exhibit a strong diurnal cycle with a peak late in the evening to early in the morning (fig 3.1). The average peak in runoff (Q_p) at SC, UM and ET occurs at approximately 03:00 h, 24:00 h and 23:00 h respectively, corresponding to a 'lag-time' from the peak in rainfall of approximately 9 h, 6 h and 5 h respectively (fig 3.1). The minimum runoff at SC, UM and ET is expected to occur at approximately 15:00 h, 14:00 h and 12:00 h respectively (fig 3.1).

3.2 Runoff response on an event basis

A selection of the largest flood events observed during the three year monitoring period at each gauging station were used to characterise the runoff response to rainfall events on an individual event basis.

In the selection of the flood events a suitable criterion for independence of successive peaks (Hoggan 1997) was applied where two flood peaks were considered to be independent if separated by periods of baseflow. The baseflow at each gauging station, shown in Appendix A, was determined by applying the Lyne and Hollick digital filter (Nathan & McMahon 1990, Grayson et al 1996) to the three years of observed discharge data. For events separated by a period of baseflow it is interpreted that overland flow from the catchment has ceased.

The ten largest flood events, in terms of peak discharge (Q_p), that occurred at each gauging station during the three year monitoring period are shown in table 3.1. The total rainfall, duration and maximum rainfall intensity (over a 60 minute duration) of each rainfall period attributing to the flood peak, are also given in table 3.1. The total rainfall and maximum rainfall intensity for each event (table 3.1) were assumed to occur over the whole Ngarradj catchment and were determined using the Thiessen Polygon method to spatially average the total rainfall and maximum intensity measured at the three gauging stations.

Tabulated intensity-frequency-duration (IFD) data for the Ngarradj catchment region (Bureau of Meteorology pers comm 2000) for a 60 minute duration were used to estimate the average recurrence interval (ARI) for each of the 10 rainfall events (table 3.1).

Table 3.1 The ten largest flood events during the three year monitoring period

Time rainfall commenced	Total rainfall (mm)	Maximum intensity (mm h^{-1}) [ARI (y)]	Rainfall duration (min)	Q_p (SC) ($m^3 s^{-1}$)	Q_p (UM) ($m^3 s^{-1}$)	Q_p (ET) ($m^3 s^{-1}$)
30 Jan 99 22:00	51	51.0 [1.5]	63	20.74	15.00	8.51
11 Mar 99 19:48	66	65.9 [4.3]	54	22.25	14.70	8.39
28 Dec 99 21:42	82	60.6 [3.0]	90	18.14	12.15	7.89
21 Mar 00 19:24	65	65.3 [4.2]	53	17.07	9.93	7.81
22 Feb 01 23:54	55	57.5 [2.4]	48	18.97	12.27	7.20
Short duration mean	64	60.1 [2.9]	61.6	19.43	12.81	7.96
9 Feb 99 17:18	66	25.0 [0.2]	297	20.48	13.41	8.43
9 Jan 01 10:54	87	26.5 [0.3]	410	20.61	12.83	8.21
16 Jan 01 16:36	50	23.1 [0.2]	157	17.95	11.92	7.64
18 Jan 01 19:30	36	28.0 [0.3]	100	19.80	13.05	8.00
13 Feb 01 16:06	47	41.8 [0.8]	110	20.56	12.90	8.03
Long duration mean	57	28.9 [0.3]	214.7	19.88	12.82	8.06

All ten of these flood events occurred between late-December and mid-March (table 3.1). During this period of the Wet season, baseflow was observed to be relatively high and therefore it may be assumed that the rainfall-runoff periods occurred when the Ngarradj catchment was relatively saturated.

The 10 rainfall events occurred between 11:00 h and 24:00 h (table 3.1), with an average start of rainfall time of 18:43 h, which corresponds well to the overall diurnal cycle of rainfall over the Ngarradj catchment (fig 3.1). The average time of Q_p at SC, UM and ET for the 10 events was approximately 00:15 h, 23:30 h and 22:30 h respectively, which also corresponds well to the general trend in mean runoff at each site (fig 3.1).

Data could be sub-divided into two well-defined storm types that contribute to a major flood peak (table 3.1). Flood peaks during the three year monitoring period were attributed to either (1) a short, intense rainfall period, or (2) a relatively constant and less intense rainfall period over a long duration. Total rainfalls and Q_p values of the two storm types, however, were generally similar (table 3.1). Examples of both storm types are shown in figure 3.2. The resultant hydrograph at UM is also shown (fig 3.2).

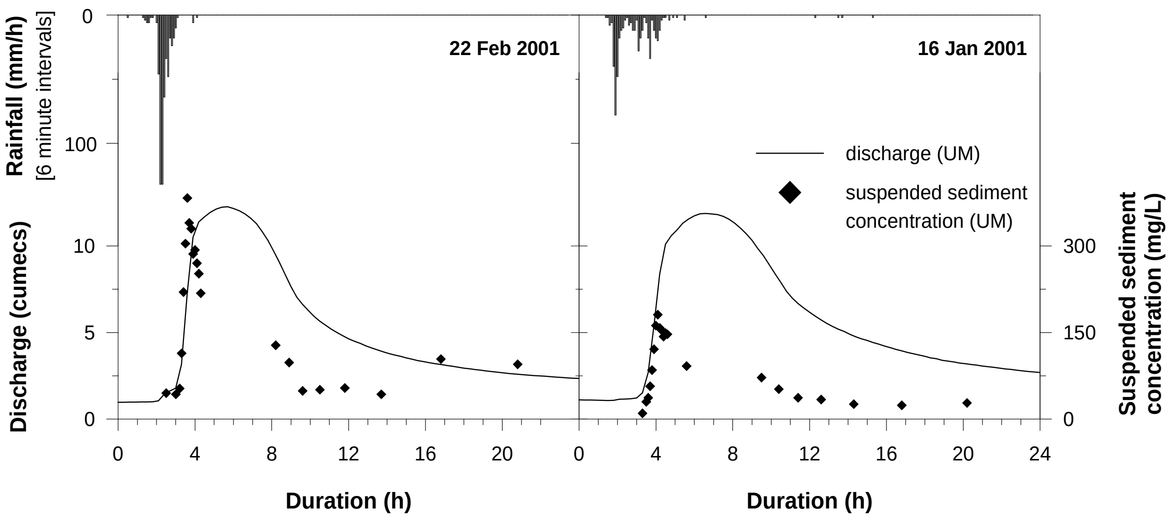

Figure 3.2 An example of the two storm types that contribute to a flood peak — the short, intense rainfall period (Left) and the longer, less intense rainfall period (Right).

Each of the first five flood events listed in table 3.1 were ranked amongst the most intense rainfall periods observed during 1998–2001. The two largest flood peaks at SC and UM were a result of these very short, intense rainfall periods (table 3.1).

3.3 Relationship between lag-time and catchment characteristics

The average lag-times in Q_p of high intensity rainfall events at SC, UM and ET were used to determine a relationship between lag-time and catchment characteristics. The estimation of lag-times for these events is relatively accurate given that for these storm events the (a) rainfall period is short and intense; and (b) resultant peak runoff is only attributable to the intense rainfall period.

A usual definition of lag-time is from the centroid of effective rainfall to Q_p (McMahon pers comm. 2002). However, in this study lag-time is defined as the time taken from the start of rainfall to Q_p. In the Ngarradj catchment region, rainfall during these high intensity events are generally short in duration (ie table 3.1) and more intense during the early stages of the event (ie fig 3.1) and therefore, it is assumed that the difference in lag-times between the two definitions would be minor. However, the application of a relationship between catchment characteristics and lag-times, where lag-time is defined as the time taken from the start of rainfall to Q_p, is relatively simple. For example, if a sampling program was established to collect data during the peak of a runoff event at an ungauged stream in the Ngarradj catchment, and given a predicted lag-time for the ungauged stream pre-determined from catchment characteristics, an estimate for the time Q_p will occur can be obtained almost immediately once intense rainfall commences in the catchment. The application of a relationship between catchment characteristics and lag-times, where lag-time is defined as the time taken from the centroid of effective rainfall to Q_p, is more difficult — by the time the centroid of rainfall has been calculated for an event, depending on the size of the catchment, peak runoff may have already occurred.

During the three year monitoring period there were seven rainfall-runoff events that occurred at all three gauging stations with a spatially averaged rainfall intensity greater than 44.6 mm/hr (over a 60 minute duration), which corresponds to a 1:1 y event at Ngarradj catchment (Bureau of Meteorology pers. comm. 2000). Five of these events contributed to the flood events described in table 3.1. The additional two selected storm events occurred early in the Wet season (25 Dec-98 and 01 Dec-99) and resulted in relatively minor peak discharge events, particularly downstream at SC, because the catchment was relatively dry (resulting in high infiltration capacities).

The average time taken from the start of rainfall to Q_p at SC, UM and ET for the seven rainfall events was approximately 5.2 h, 3.7 h and 3.1 h respectively (table 3.2).

To determine a reliable and statistically significant relationship between lag-time and catchment characteristics, runoff data collected at TN, TC and TS (fig 1.1) during the 1998/99 Wet season (ERA pers. comm. 2001) were included in the analysis. During 1998/99 there were only three storm events with an intensity corresponding to a 1:1 y event at Ngarradj catchment. To establish a reasonable estimate of lag-time for TN, TC and TS, eight rainfall-runoff events that occurred during 1998/99 with an average rainfall intensity greater than 24 mm/hr were selected for analysis. The average time rainfall commenced for the eight intense events was approximately 20:30 h. The average time taken from the start of rainfall to Q_p at TN, TC and TS for the eight events was approximately 46 min, 57 min and 84 min respectively (table 3.2). The average lag-time at SC, UM and ET for these same eight rainfall events during 1998/99 was almost identical to that derived above for the seven most intense events observed during the three year monitoring period (table 3.2).

The mean lag-time recorded at each gauging station was related to several catchment characteristics including catchment area, catchment perimeter, length of the longest catchment flow path, mean catchment slope and mean channel slope. These parameters were derived from a digital elevation model (DEM) of the Ngarradj catchment that was produced on a 5 m grid which has a relative vertical accuracy of ± 0.5 m and relative horizontal accuracy of ± 2 m. Preprocessing of the DEM involved the application of pit-filling and stream-burning algorithms to ensure that the model was both hydrologically and hydrographically correct. The final parameters were derived using the spatial analyst extension of the ESRI ArcView® 3.2 GIS software package and are given in table 3.2.

Table 3.2 Lag-time and catchment characteristics for gauging stations within Ngarradj catchment

Site	Mean lag-time in Q_p (h) [*SD* (h)]	Area (km^2)	Catchment perimeter (km)	Flow length (km)	Mean catchment slope (%)	Mean channel slope (%)
SC	5.2 [0.9]	43.61	62.28	13.71	13.4	8.49
UM	3.7 [0.6]	18.79	45.62	10.97	18.5	10.54
ET	3.1 [0.9]	8.46	29.01	7.87	14.5	8.53
TC	0.95 [0.2]	1.91	9.96	2.72	6.6	2.93
TN	0.76 [0.5]	0.34	4.36	1.67	8.4	5.34
TS	1.4 [0.5]	0.93	5.95	2.27	5.8	1.15

The hydrologic response of a catchment was characterised by examining the geomorphologic structure of a catchment. Rodriguez-Iturbe and Rinaldo (1997) suggested that the time-to-peak is related to stream length, channel density and constant drift velocity. A sensitivity analysis between observed mean lag-times and various catchment characteristics (table 3.2) showed that within the Ngarradj catchment, stream length and mean channel slope were the most significant factors in predicting lag-time at each catchment outlet. The relationship of mean lag-time (t_L) as a function of stream length (L) and mean channel slope (S_C) is given in equation (3.1).

$$t_L = 0.57\, L^{0.983}\, S_C^{-0.187} \qquad (r^2 = 0.97;\ p = 0.006) \qquad (3.1)$$

Figure 3.3 shows the relationship between observed and predicted mean lag-times using equation (3.1) for each of the gauging stations within Ngarradj catchment for an individual storm event.

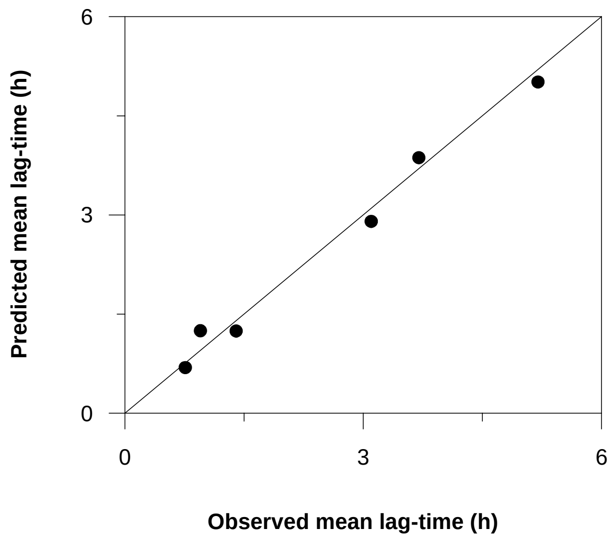

Figure 3.3 Relationship between observed and predicted lag-times (equation (3.1)). The 1:1 line is also shown.

3.4 Implications

The understanding of the diurnal cycle of rainfall over the Ngarradj catchment and the corresponding lag-time for Q_p after a storm event has important implications for stream monitoring sampling within the Ngarradj catchment.

The application of either a fixed time, opportunistic or flow proportional sampling program to the examination of long-term hydrology and sediment transport would give significantly different results. For example, at each ***eriss*** gauging station during the three year monitoring period, suspended sediment concentration, C, data were collected throughout the hydrograph by a stage activated pump sampler and from weekly grab samples. Table 3.3 shows that, in this case, the weekly mid-morning to mid-afternoon grab-sampling regime underestimates both the average and, in particular, the maximum background C in the stream at each gauging station.

Table 3.3 Suspended sediment concentration (C) data from two sampling programs

	1 Stage activated pump sampler	**2. Weekly grab sample**	
Gauging station	**Mean C (mg/L) [maximum C (mg/L)]**	**Mean C (mg/L) [maximum C (mg/L)]**	**Mean time of collection (h) [range of collection times (h)]**
SC	47 [438]	35 [234]	12:30 [8:30–16:00]
UM	63 [567]	41 [262]	10:30 [7:20–15:20]
ET	85 [1346]	35 [95]	11:00 [8:10–15:50]

General diurnal trends and analysis of high magnitude storm events show that peak rainfall and runoff occur in the late afternoon to early morning in the Ngarradj catchment. Five of the ten flood events in table 3.1 had complete C data collected throughout the event hydrograph at each station. Average lag-times in peak C (table 3.4) show that peak C occurs during the rising stage of the hydrograph. Sedigraphs for two flood events at UM showing the peak C occurring during the rising stage of the hydrograph are given in figure 3.2.

These hydrological responses, therefore, need to be considered when establishing a monitoring regime to assess such issues as the impact of the Jabiluka mine on suspended sediment loads in streams within Ngarradj catchment.

Table 3.4 Average lag-times in peak discharge and suspended sediment concentration

Site	**Mean lag-time in Q_p (h) [*SD* (h)]**	**Mean lag-time in peak C (h) [*SD* (h)]**
SC	5.2 [0.9]	3.8 [2.5]
UM	3.7 [0.6]	3.1 [1.6]
ET	3.1 [0.9]	2.4 [1.1]

4 Hydrology modelling

One of the specific objectives of the stream monitoring project at Ngarradj was to calibrate a hydrology model for the long-term 'total catchment' management at Ngarradj. In this chapter, parameters were fitted to the US Army Corps of Engineers' Hydrologic Modelling System (HEC-HMS) using the three years of observed rainfall-runoff data collected at each gauging station. In part, this chapter documents the process of both data input for the HEC-HMS model and parameter derivation to provide instruction for future application of the model to other catchments or streams.

The calibrated model was then used to establish the predicted long-term runoff record at each gauging station within the Ngarradj catchment using a long-term rainfall record (pluvio data) from rain gauges at Jabiru airport and Jabiluka mine. The rainfall station at Oenpelli, which has a longer rainfall record than that at Jabiru or Jabiluka, has no pluvio data available for this type of analysis.

4.1 Background

The US Army Corps of Engineers' Hydrologic Modelling System (HEC-HMS) is a user-friendly software package for simulating rainfall-runoff processes over short and long periods of time. The model is also appropriate at a number of spatial scales, being able to model both large river basin water supply and flood hydrology and small urban or natural catchment runoff. The program features a completely integrated work environment that facilitates simple data management and model optimisation or application. The HEC-HMS model requires three major inputs to simulate rainfall-runoff processes; a basin model, a meteorological model and control specifications. A description of these three major inputs is described below and is based on a more detailed description in the User's Manual (Scharffenberg 2001).

4.1.1 Basin Model

The basin model provides a physical representation of catchments and their associated river systems by connecting hydrologic elements in a dendritic network to simulate runoff processes. The hydrologic elements included in HEC-HMS are: subbasin, reach, reservoir, junction, diversion, source and sink. Each hydrologic element uses a mathematical model to describe the physical process involved in generating or transporting runoff. Subbasins, reaches and junctions are the hydrologic elements used in this study.

A variety of equations can be used within subbasins to describe: (1) precipitation losses; (2) direct runoff; and (3) the return of infiltrated precipitation to the main channel as baseflow. Flow within each reach can also be modelled with a selection of equations. The Green and Ampt infiltration equation, kinematic wave transform and recession baseflow methods are used to model runoff generation and movement in this study. Calibration of the HEC-HMS model involves altering parameters within these equations to fit the predicted hydrograph to an observed hydrograph. The calibration process can be conducted manually or automatically using an optimisation module within HEC-HMS.

Basin models were created within the ArcView® GIS software package by using the HEC-GeoHMS extension (Doan 2000). This add-on program to ArcView® generates background map files, lumped basin models, grid cell parameter files and basin distributed models that can be directly input into HEC-HMS. Furthermore, the HEC-GeoHMS extension allows the user to visualise spatial information, document watershed characteristics, perform spatial analysis and delineate sub-basins and streams.

4.1.2 Meteorologic Model

The meteorologic model stores the precipitation and evaporation data required to simulate watershed processes. A variety of methods are available within HEC-HMS for distributing measured precipitation data over the study area including; (1) associating a single hyetograph with each subcatchment; (2) inputting user-defined spatial and temporal weights for precipitation data; (3) automatically calculating inverse distance gauge weights; (4) using previously created gridded precipitation data; (5) creating frequency based storm events; (6) using SCS hypothetical storm data; and (7) estimating the precipitation recquired for the standard project flood. However, only one precipitation method can be associated with each meteorologic model. Within this project the user gauge weighting method was used with weights obtained from a Thiessen polygon analysis of gauge location and sub-catchment area.

4.1.3 Control Specifications

The control specifications define the start and end date and time of a simulation run and also the time interval or 'computation step' of the run. If the specified computation step differs from that of the input data (precipitation and/or runoff data), the data will be linearly interpolated to fit the control specifications.

4.2 Data processing

4.2.1 Rainfall-runoff input data

Observed rainfall and runoff data are used to calibrate the hydrology model HEC-HMS. The rainfall and runoff data, for a particular period of time, are stored in a project as a precipitation gauge and a discharge gauge respectively (Scharffenberg 2001). In this study, rainfall-runoff data were imported into HEC-HMS as HEC-Data Storage System (dss) files (as opposed to manually entering the data in HEC-HMS). The importing process is outlined in Scharffenberg (2001).

The rainfall and runoff data collected at each gauging station within Ngarradj catchment from 1998-2001 are stored in the database management system 'HYDSYS'. It was therefore required for the data to be exported from HYDSYS and converted to the .dss file format. The following is a brief description of this conversion process.

Exporting rainfall-runoff data from HYDSYS

Rainfall and runoff data were exported from HYDSYS as a text file. Separate rainfall and runoff files were created for each gauging station for each Wet season (ie SC9899rain.txt — rainfall data collected at SC during the 1998/99 Wet season).

Input into HEC-DSS

A software program, HEC-DSS, was used to convert the .txt file to .dss file format. To use HEC-DSS a header must be included in the text file that describes the data and how it will be stored within the dss file. An example of a typical header inserted into a rainfall text file and a runoff text file for this study follows.

SC9899rain.dss
/ngarradj/Swiftcrk/precip/01OCT1998/1HOUR/GAGE/
mm
per-cum
01OCT1998, 0000

SC9899dis.dss
/ngarradj/Swiftcrk/flow/01OCT1998/1HOUR/GAGE/
cms
inst-val
01OCT1998, 0000

Line 1 of the header is the ouptut .dss file name. Line 2 is the pathname of the data file, and contains six parts (A-F parts) (Scharffenberg 2001): (A) the catchment name; (B) the name of the element within the basin model (in this study, this is the gauging station name); (C) the data descriptor, which in this study is either precip (rainfall) or flow (runoff); (D) the start date; (E) the time interval; and (F) the data type, which in this study is gauging station data (gage).

Lines 3 and 4 are the acceptable measurement units and the data type respectively for dss files (Scharffenberg 2001). In this case, *per-cum* and *inst-val* relate to the total precipitation occurring in each time interval (in mm) and the instantaneous flow at the end of each time interval (in cms) respectively. Line 5 is the start date and time of the gauged data.

The .txt file, including the header, was saved to a HEC-HMS directory. This directory contained both (1) input data files for the HEC-HMS model, and (2) output data files created from the model.

Running HEC-DSS

HEC-DSS was run using the MSDOS program. The following command was run from the directory in which the input text data files were saved (ie c:\hechms) in order to generate the relevant .dss files.

```
>dssts i=sc9899rain.txt o=sc9899rain.out
```

where, 'i' relates to the input text file name and 'o' relates to the output log file name.

This command generated both an .out file, which contained a log of the dss file generaton process for error checking, and a .dss file (which had the same name as that defined in line 1 of the text file header (ie sc9899rain.dss)).

A .dss file was generated for both rainfall and runoff data, for each gauging station (SC, UM and ET) and for each Wet season (1998/99, 1999/00 and 2000/01).

4.2.2 Catchment form data

Data describing the form of a catchment and its associated river network are stored in a basin model in HEC-HMS. A series of lumped basin models depicting increasingly complex representations of the Ngarradj catchment were created using the ArcView extension HEC-GeoHMS (Doan 2000). Calibration of the more complex models was not feasible in this study due to time constraints and therefore a more simplified basin model was used. There were three major steps involved in creating lumped basin models using HEC-GeoHMS: (1) preprocessing the terrain model; (2) processing the study basin; and (3) creating the HMS input file. Each of these 3 steps are described as follows.

Terrain model preprocessing

The process involved in preprocessing the terrain model is illustrated in figure 4.1. A digital elevation model (DEM), which is a rectangular grid of evenly spaced terrain heights, was a required input. The DEM used in this study was captured from 1:25 000 aerial photography and was produced on a 5 m grid with a relative vertical accuracy of ± 0.5 m and relative horizontal accuracy of ± 2 m. Eight additional datasets were derived during the preprocessing of the DEM that collectively describe the drainage patterns of the catchment (fig 4.1). This information was used to perform a preliminary delineation of the streams and subcatchments (Doan 2000).

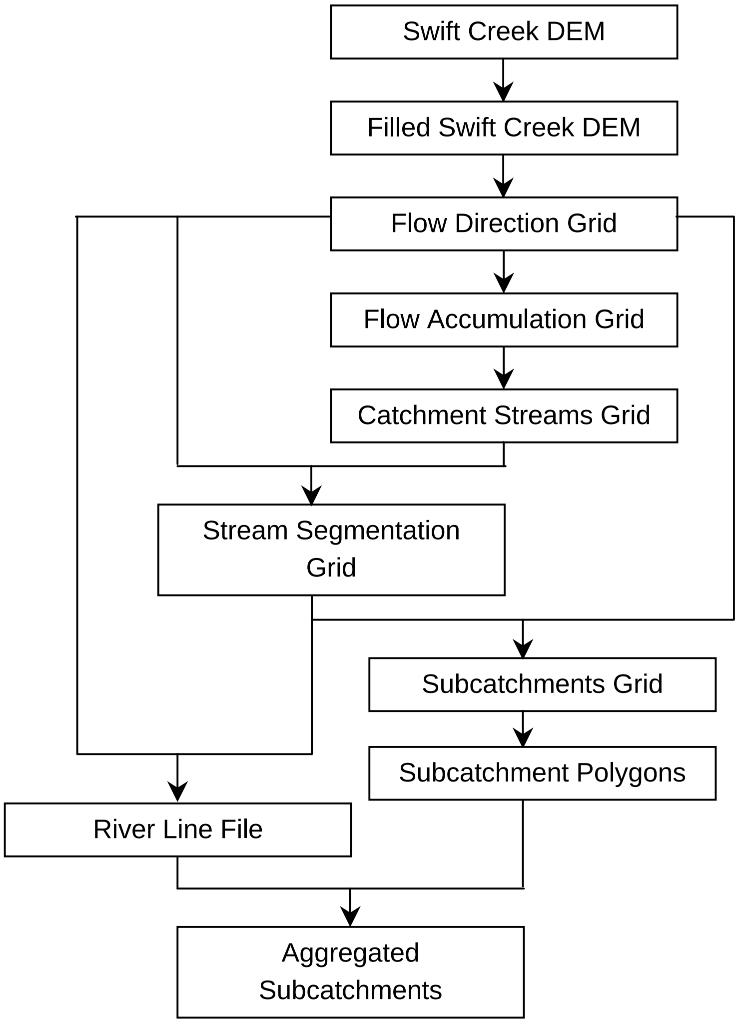

Figure 4.1 Flow chart of the procedures implemented during the preprocessing of terrain data with HEC-GeoHMS

Basin Model Processing

Processing of the basin model involved extracting the preprocessed data based on the delineation of the study catchment and deriving the physical characteristics of streams and subcatchments within the area (fig 4.2). The aggregated subcatchments (fig 4.1), created during the preprocessing of the terrain model, were merged or split, based on the desired complexity of the final model and the location of gauging station information. In this study, the Ngarradj catchment basin model included three subcatchments that corresponded to the location of the three gauging stations SC, UM and ET (fig 4.3 (based on fig 1.1)). Figure 4.3 shows that the total subcatchment defined as TW represents the whole western part of the Ngarradj catchment.

Physical characteristics of the stream network, including stream length and slope, were calculated by HEC-GeoHMS and stored in the attribute file of the river dataset. Physical characteristics of subcatchments, including location of the catchment centroid, longest flow path and flow path from the catchment centroid, were also calculated using HEC-GeoHMS.

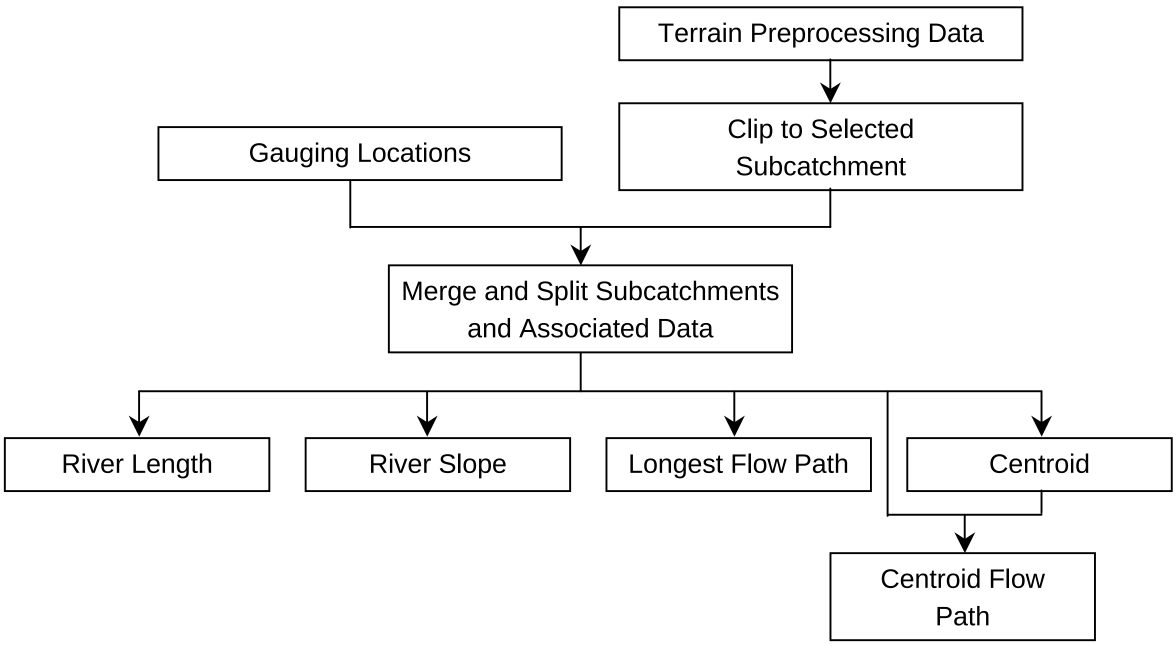

Figure 4.2 Flow chart of the basin processing steps implemented within HEC-GeoHMS

HEC-HMS input files

The final step in the creation of a basin model for HEC-HMS is the production of a lumped-catchment schematic model file and background map file that can be directly read by HEC-HMS (fig 4.4). This involved autonaming the reaches and subcatchments, converting all derived values to HEC-HMS units, checking for errors in the basin and stream connectivity and adding spatial coordinates to the files. These steps were performed using standard functions in HEC-GeoHMS.

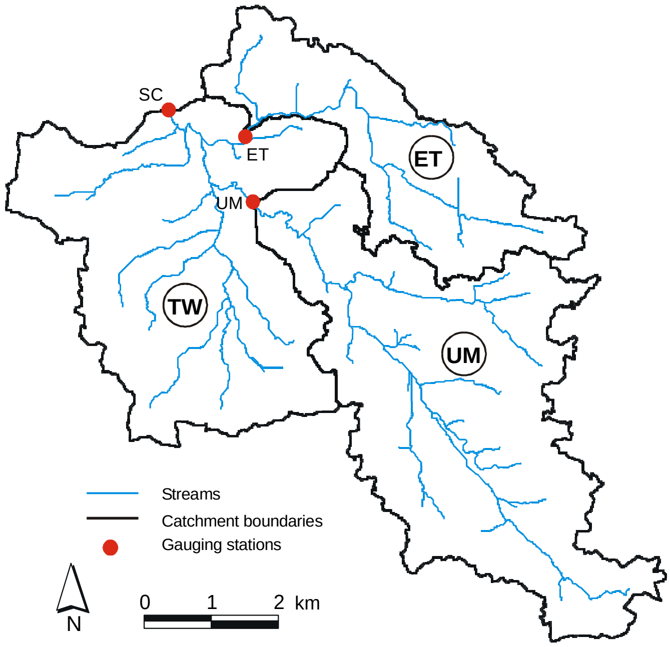

Figure 4.3 Ngarradj catchment basin model used in HEC-HMS

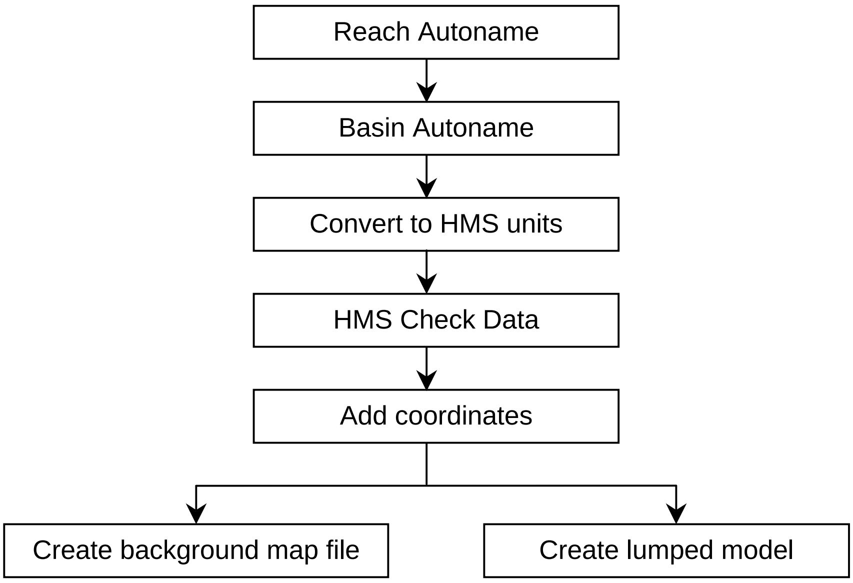

Figure 4.4 Flow chart of the steps involved in the final production of HEC-HMS basin model inputs using HEC-GeoHMS

4.2.3 Predicted runoff data output

For further analysis of the predicted hydrograph in other programs such as HYDSYS, Excel etc, it was necessary to export the data created in HEC-HMS. Predicted runoff data created in HEC-HMS are stored as a particular simulation run within the project file. The predicted runoff data for a simulation run has the same time interval (or computational step) and start and end time as specified in the control specifications. In this study, precipitation and discharge gauge data were input into HEC-HMS for each separate Wet season at a time interval of one hour. The following is a brief description of the process used to export the predicted hydrograph for each simulated Wet season.

The predicted hydrographs were exported from the HEC-HMS project file in a text format using the software program Data Vista v1.0. (This program is run by opening the vista.bat file in the Data Vista program directory stored on the local hard drive.) In Data Vista the project file, which is stored as a .dss file, was opened (session → open → dss file) and the relevant simulation run was selected. The selected simulation run, which contained the predicted hydrograph for a Wet season, was then exported as a .txt file (data → export → text → generic format) and saved in the HEC-HMS directory for analysis.

4.3 Parameter fitting, results and discussion

4.3.1 Parameter fitting procedure

The HEC-HMS model was calibrated for the Ngarradj catchment by manually adjusting specific parameters, computing and inspecting the goodness of fit between the predicted and observed hydrographs. Implementation of this method requires the user to: (1) attach the observed hydrographs to the gauging stations; (2) define the initial catchment and reach parameters; and (3) adjust individual parameters. A full description of these steps can be found in Scharffenberg (2001).

The discharge gauge data input into HEC-HMS in the rainfall-runoff input data section were attached to the UM and ET subbasins and SC junction as observed hydrographs for each year.

The parameters that can be fitted in HEC-HMS depend on the methods used to describe runoff generating and transfer processes within each subbasin and reach. The Green and Ampt infiltration equation, kinematic wave transform and recession baseflow methods were used in this study to model infiltration, direct runoff and the return of infiltrated precipitation to the main channel as baseflow respectively. The kinematic wave was also used to model runoff movement through the channel reaches. The parameters that were fitted to these methods and their value ranges are shown in table 4.1. A number of other fixed parameters were also input in order to calibrate the model (table 4.2). These fixed parameters were derived mainly from the GIS and primarily define the catchment characteristics. Channel width and side-slope (table 4.2) were estimated from cross-sectional surveys taken along the main channels within each sub-catchment (Saynor et al 2002).

The final calibration procedure involved defining initial values for every parameter in each subbasin or reach and running the model. The output hydrograph was compared with the observed hydrograph using three criteria to ensure goodness of fit: (1) annual peak discharge; (2) total annual runoff; and (3) basic shape of the annual hydrograph. The non-fixed parameters were iteratively changed and the model re-run until the observed and predicted hydrographs were most similar based on the defined criteria. The final parameter set, including fitted and fixed parameters, is shown in table 4.2.

Table 4.1 The parameters in HEC-HMS that were fitted for the Ngarradj catchment

Parameter	Minimum constraint	Maximum constraint
Initial loss (mm)	0	500
Vol. Moisture deficit	0.0	1.0
Wet front suction (mm)	0	1000
Hydraulic conductivity (mm/h)	0	250
Imperviousness (%)	0	100
Manning's roughness, n	0.0	1.0
No. of steps	1	100
Initial baseflow	0	100000
Recession constant	0.00001	1.0
Baseflow to Peak ratio	0.0	1.0

In this study, parameter values were intially fitted to one year of rainfall-runoff data (1998/99 Wet season) at each sub-catchment and then further refined using the following two years of rainfall-runoff data (1999/00 and 2000/01 Wet seasons). Parameter values were first fitted to the upstream subcatchments ET and UM. The hydrograph at SC represents the combination of discharge from the UM, ET and TW subcatchments (fig 4.3). To establish a predicted hydrograph at SC that is similar to the observed, parameters were adjusted within the TW subcatchment while keeping the fitted parameters for the ET and UM subcatchments fixed. It was therefore assumed that the predicted hydrograph for TW reflects the actual flow leaving this catchment.

The final parameter set (table 4.2) defines the hydrological response of each catchment. During the parameter fitting process, the HEC-HMS model was found to be more sensitive to some parameters than others. This is reflected in the final parameter set by variability between each catchment within certain parameters. That is, the model was generally found to be less sensitive to parameters that have the same final value for each catchment (ie initial loss (mm), vol. moisture deficit, wet front suct. (mm) and plane roughness - where min. no. of distance steps was not altered and the initial baseflow was known to be 0 for each catchment) whilst different values were solved for conductivity (mm/h), imperviousness, channel roughness, recession constant and threshold Q. The conductivity (mm/h), imperviousness and channel roughness parameters were found to be significant factors in controlling the size and timing of peak discharges, whilst the recession constant and threshold Q affected the width of the individual event hydrographs and discharge during periods of no rainfall. Future studies should investigate and quantify these relationships further.

It should also be noted that an automated procedure for fitting hydrology parameters is also available in HEC-HMS (Scharffenberg 2001). However, in this study, the automated procedure appeared to be less reliable than the manual procedure as both total runoff and in particular, peak discharges, were overpredicted compared with observed data at each gauging station.

Table 4.2 Fitted parameter values for ET, UM and TW. Shaded parameters represent the fixed parameters

Parameter	Subcatchment		
	ET	UM	TW
Loss rate (Green & Ampt)			
Area (km^2)	8.46	18.75	16.28
Initial loss (mm)	140	140	140
Vol. Moisture deficit	0.1	0.1	0.1
Wet front suct. (mm)	20	20	20
Conductivity (mm/h)	79	79	45
Impervious (%)	18	16.5	13
Transform (kinematic wave)			
Planes (left and right)[(1)]			
Length (m)	1000 (800)	1600 (1200)	2500 (1500)
Slope (m/m)	0.2	0.33	0.1
Roughness	0.4	0.4	0.4
% of subbasin area	55 (45)	58 (42)	60 (40)
Min. no. of distance steps	5	5	5
Channels			
Length (m)	6783	9778	6107
Slope (m/m)	0.021	0.05	0.018
Manning's roughness n	0.1	0.13	0.05
Shape	Trapezoid	Trapezoid	Trapezoid
Width (m)	2.5	3.75	2
Side slope (m/m)	0.6	0.6	1
Min. no. of distance steps	2	2	2
Baseflow (recession)			
Initial Q ($m^3 s^{-1}$)	0	0	0
Recession constant	0.58	0.68	0.7
Threshold Q (ratio-to-peak)	0.25	0.2	0.4

(1) Parameter values associated with the second plane, when different to the first, are shown in parenthesis

4.3.2 Results and discussion

The annual predicted hydrographs for each Wet season at each gauging station, shown in Appendix B, are reasonably similar to the observed hydrographs (Appendix B). The total predicted annual volume of discharge and annual peak discharge is similar to that observed (table 4.3). The average annual volume of predicted discharge over the three year monitoring period at each gauging station is also very similar to that observed (table 4.3). However, there are runoff periods observed throughout the Wet season hydrographs that were not well predicted at each of the gauging stations (Appendix B). For example, figure 4.5 shows an intense rainfall-runoff period observed at SC during the 1998/99 Wet season where several of the observed peaks are significantly larger than predicted. The discrepancies in the predicted hydrograph are most likely associated with the limited rainfall gauging network design rather than poor performance by the HEC-HMS model. That is, the HEC-HMS model uses the rainfall data collected from a gauge, or a number of gauges, to predict the runoff at the outlet of a catchment area. The rainfall data at these gauges is extrapolated throughout the whole catchment area using the selected precipitation method. As discussed in section 2.1, the rain gauges used in this study are only located in the wooded lowland areas of the Ngarradj catchment (fig 1.1). Rain gauges were not allowed to be installed on the upper areas of the Ngarradj catchment due to the cultural significance of the Arnhem Land Plateau. Appendix B, and in particular figure 4.5, indicates that there were peaks in the observed hydrograph that occurred as a result of isolated rainfall events in the upper catchment (on the Arnhem Land plateau) that were not recorded at the rain gauges. For example, figure 4.5 shows observed peaks during 3–4 February 1999 where very little rainfall was recorded at the gauges.

Table 4.3 Annual discharge volume and peak discharge

		Total runoff (ML) [Peak discharge (m^3s^{-1})]	
Site	**Year**	**Observed**	**Predicted**
SC	1998/99	33665.3 [22.3]	29818.6 [23.8]
	1999/00	34898.9 [18.1]	40077.5 [20.0]
	2000/01	34780.8 [20.6]	29850.3 [17.0]
	Mean	34448.3	33248.8
UM	1998/99	15665.6 [15.0]	14190.1 [15.7]
	1999/00	17425.8 [12.2]	20164.2 [15.8]
	2000/01	17052.2 [13.0]	14345.4 [11.7]
	Mean	16714.5	16233.2
ET	1998/99	7621.0 [8.5]	7150.0 [9.0]
	1999/00	8531.6 [8.1]	10378.1 [9.7]
	2000/01	8275.2 [8.2]	7220.5 [5.9]
	Mean	8142.6	8249.5

One of the largest observed flood peaks at SC during the three year monitoring period occurred during 30–31 January 1999 (fig 4.5) as a result of very intense rainfall. The predicted runoff during this rainfall was similar to that observed (fig 4.5), indicating that it was likely that the rainfall recorded at the gauges reflected the rainfall over the whole catchment area. In general, the predicted runoff at each site during very intense rainfall was similar to the observed runoff (Appendix B).

The rainfall and runoff for the largest flood event observed at SC, which occurred 11–12 March 1999, is shown in figure 4.6. It shows that the predicted peak discharge and total volume of this flood event is similar to that observed. To accurately predict such large rainfall-runoff events at each gauging station was an important factor in the fitting of parameters to the HEC-HMS model.

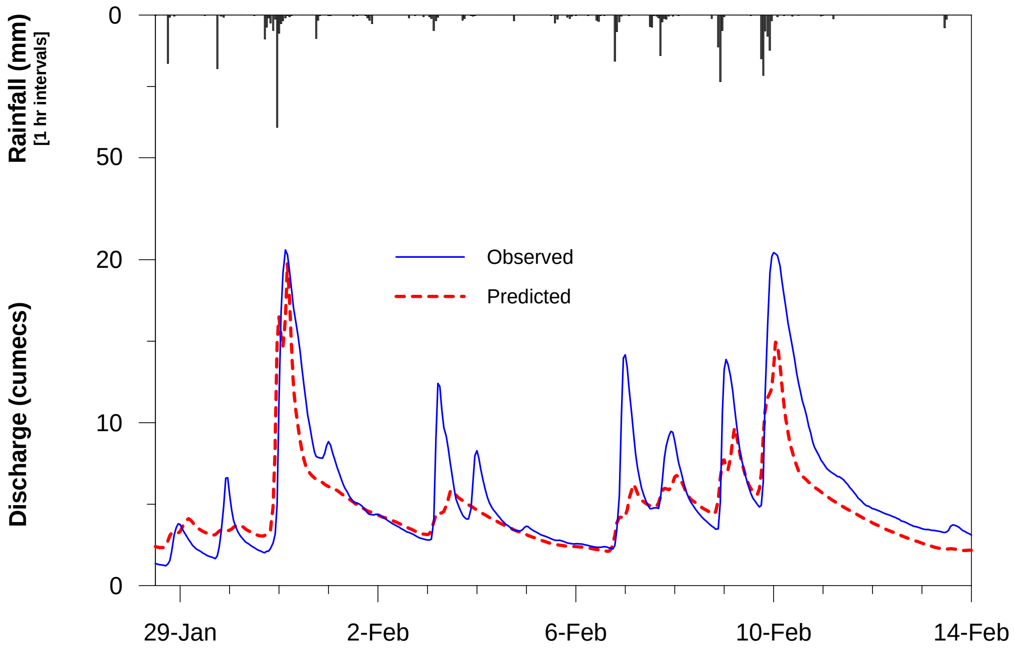

Figure 4.5 Rainfall and both observed and predicted runoff during an intense rainfall-runoff period at SC during the 1998/99 Wet season

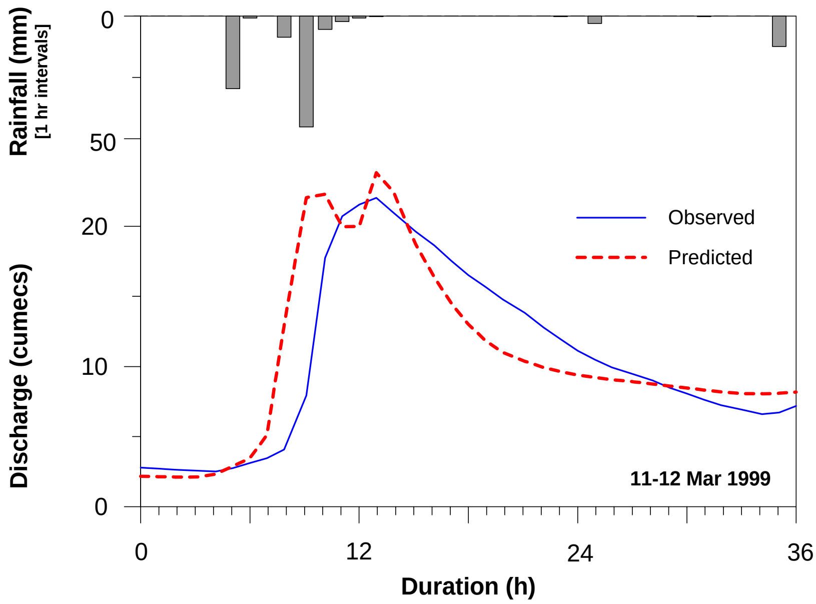

Figure 4.6 Rainfall and both observed and predicted runoff for the largest recorded flood event at SC over the three year monitoring period

4.4 Assessment

4.4.1 2001–02 Wet season

At the completion of the parameter fitting process, rainfall-runoff data for the 2001/02 Wet season at SC, UM and ET became available. This record was used to test the parameterised hydrology model against an observed annual runoff record. The rainfall data for the 2001/02 Wet season at Ngarradj (at a one hour time interval) was input into the HEC-HMS model and, using the parameter values fitted to the Ngarradj catchment using 1998–2001 data (table 4.2), a hydrograph for each gauging station was predicted (fig 4.7).

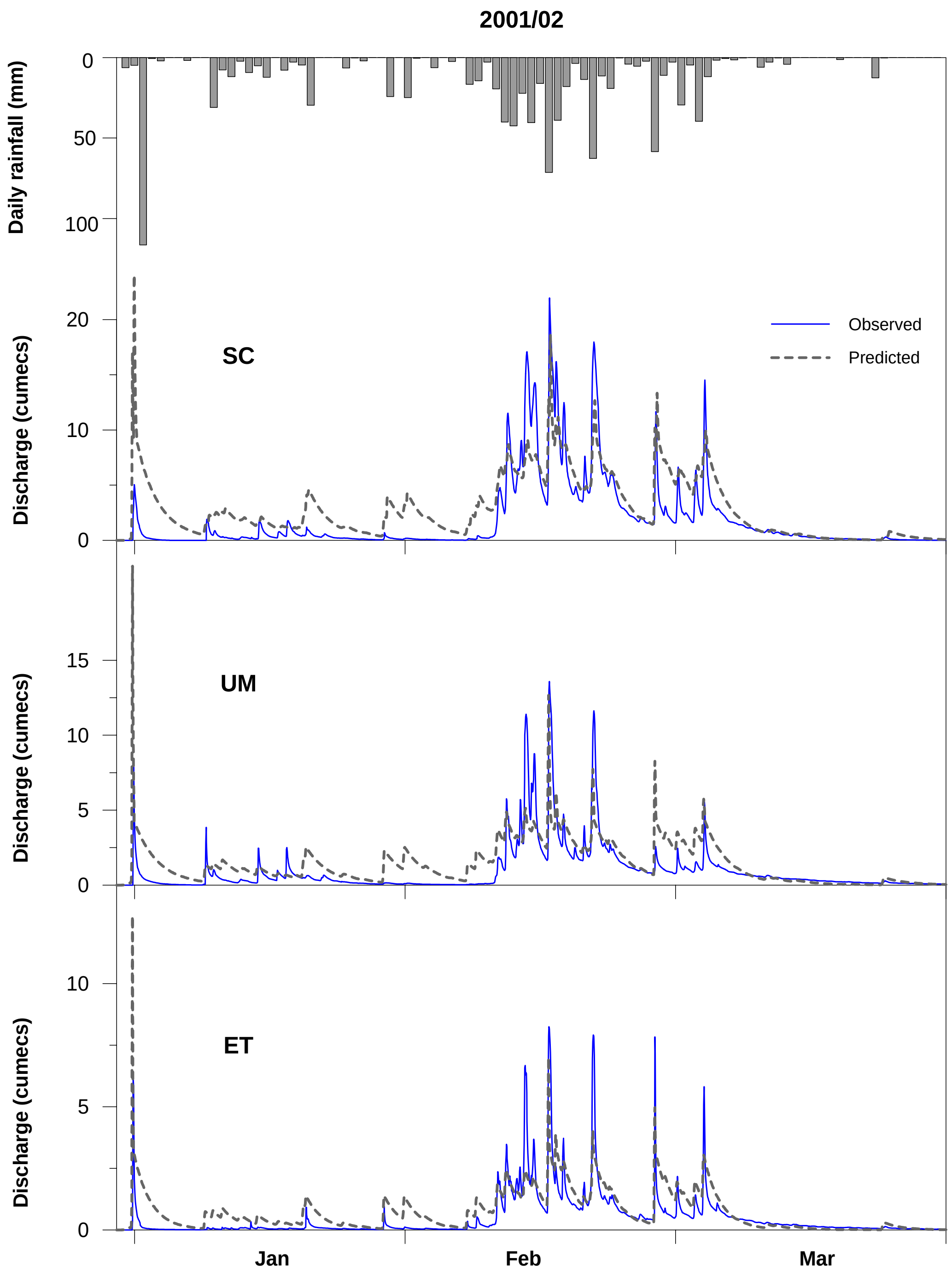

Figure 4.7 Daily rainfall (at the SC gauge) and both observed and predicted runoff during the 2001/02 Wet season at each gauging station

Figure 4.7 shows that the hydrology model overpredicted runoff at each gauging station during the storm event that occurred on 31 December 2001. As a result, the predicted annual volume of runoff at each gauging station is higher than that observed for the 2001/02 Wet season by 50–62% (table 4.4).

Table 4.4 Annual discharge volume and peak discharge for the 2001/02 Wet season

	Total runoff (ML) [Peak discharge (m^3 s^{-1})]	
Site	**Observed**	**Predicted**
SC	14382 [22.0]	23321 [24.1]
UM	7595 [13.6]	11878 [21.3]
ET	3959 [8.3]	5971 [12.7]

The rainfall-runoff event on 31 December 2001 was the most intense rainfall event over a two hour duration recorded during the four year monitoring period at Ngarradj (table 4.5). According to IFD curves for the Ngarradj region, this was equivalent to a greater than 1 in 100 y event at the Jabiluka mine site and a greater than 1 in 15 y event at the gauging stations (table 4.5). The next highest rainfall intensity over any duration observed at Ngarradj during the four year period was equivalent to a less than 1 in 5 y event. It also contributed to the highest daily rainfall figure observed over the four year monitoring period (fig 4.7).

Table 4.5 Rainfall data for the event on 31 December 2001

Site	Total event rainfall (mm)	Maximum rainfall intensity over a 2 h duration (mm h^{-1}) [ARI (y)]
SC	114.4	52.5 [20]
UM	No data	–
ET	112.0	51.1 [15]
Jabiluka mine*	187.5	87.4 [>100]

* Data supplied by ERA

Therefore, the predicted peak discharges for this event, which correspond to the predicted annual maximum flood peak at each gauging station (table 4.4), seem to be reasonable. However, the observed flood peak at each gauging station as a result of this very intense rainfall event was unexpectedly small, and therefore was significantly overpredicted by the model (fig 4.7). Two possible explanations for the relatively small observed flood peak during this intense rainfall event are:

1. Both the total rainfall and the maximum rainfall intensity over a two hour duration for this event recorded at each rain gauge (table 4.5) indicate that the storm centre may have been over the western part of Ngarradj catchment (fig 1.1). This indicates that rainfall over the eastern part of the catchment, particularly on the upper reaches of the ET and UM sub-catchments, may have been less than that recorded on both the western part of the catchment (Jabiluka mine rain gauge) and on the floodplain (SC and ET rain gauge).
2. This storm resulted in the first flush of runoff at Ngarradj, and therefore it may be assumed that this event occurred when the catchment was relatively dry and infiltration rates were high. The model had been calibrated to a wetted-up catchment resulting in predicted low infiltration rates and high discharge.

As a result of the overprediction of runoff for this storm event, figure 4.7 indicates that perhaps baseflow for the remainder of the Wet season, particularly during January 2002, was also overpredicted.

The assessment of the parameterised HEC-HMS model using rainfall data collected during 2001/02 has shown that significant modelled runoff that occurs at the beginning of streamflow, such as that predicted as a result of the storm event on 31 December 2001 (fig 4.7), should be examined before being accepted. Rainfall-runoff data collected from streams within the region, including Ngarradj gauging stations (1998–2001) (Appendix A) and Magela Creek station GS8210009 (1971–2001) (ERA pers comm 2001), show that initial flow is generally relatively minor compared to much larger flood events that occur later in the Wet season (February–March), when the catchment area can almost certainly be assumed to be saturated and baseflow relatively high. In this case, for reasons outlined above, the predicted hydrograph for the initial flush of flow at each gauging station in the Ngarradj catchment for the 2001/02 Wet season should be omitted.

The parameterised model was reassessed using the 2001/02 Wet season data with the storm event on 31 December 2001 removed from the rainfall record. The predicted annual volume of runoff and maximum annual peak discharge at each gauging station for the 2001/02 Wet season (with the event on 31 December 2001 omitted from the rainfall record) is reasonably similar to that observed (7-18% underprediction) (table 4.6). The predicted hydrograph for each gauging station is shown in figure 4.8.

Table 4.6 Annual discharge volume and peak discharge for the 2001/02 Wet season (event on 31 December omitted)

	Total runoff (ML) [Peak discharge (m^3 s^{-1})]	
Site	**Observed**	**Predicted**
SC	14168 [22.0]	13160 [14.4]
UM	7307 [13.6]	5979 [11.5]
ET	3831 [8.2]	3196 [6.7]

Figure 4.8 shows that the model underpredicts some of the major runoff events during the 2001/02 Wet season, particularly during most of the intense rainfall-runoff period observed at each gauging station during February 2002. Similar to that observed during the previous three Wet seasons at Ngarradj (Appendix B), the peaks in the observed hydrograph during February 2002 probably occurred as a result of intense rainfall events in the upper catchment that were not recorded at the rain gauges (or at a much lower intensity). For example, the annual observed maximum flood at each gauging station occurred on 15 February 2002 (fig 4.8) and was the second highest peak discharge observed at the SC gauging station during the four year monitoring period. However, the maximum rainfall intensity over the various durations on 15 February 2002 was only relatively minor (maximum rainfall intensity over the various durations corresponded to a storm with an ARI significantly smaller than 1:1 y).

Therefore, as discussed above in section 4.3.2, it is more likely that the descrepancies between the predicted and observed hydrograph for the 2001/02 Wet season are a result of the restricted rain gauge network rather than poor calibration of the HEC-HMS model. The rain gauge network needs to be expanded into the upper catchment as a priority to refine the parameterised model. It is also important to interpret the model results based on an understanding of the system ie. a knowledge that the catchment does need to wet-up to enable accurate predictions as very infrequent, large, early Wet season rainfall events on a dry catchment can result in significant over-prediction of runoff. The parameterised HEC-HMS model may be considered valid and reliable for the Ngarradj catchment area for most Wet season conditions.

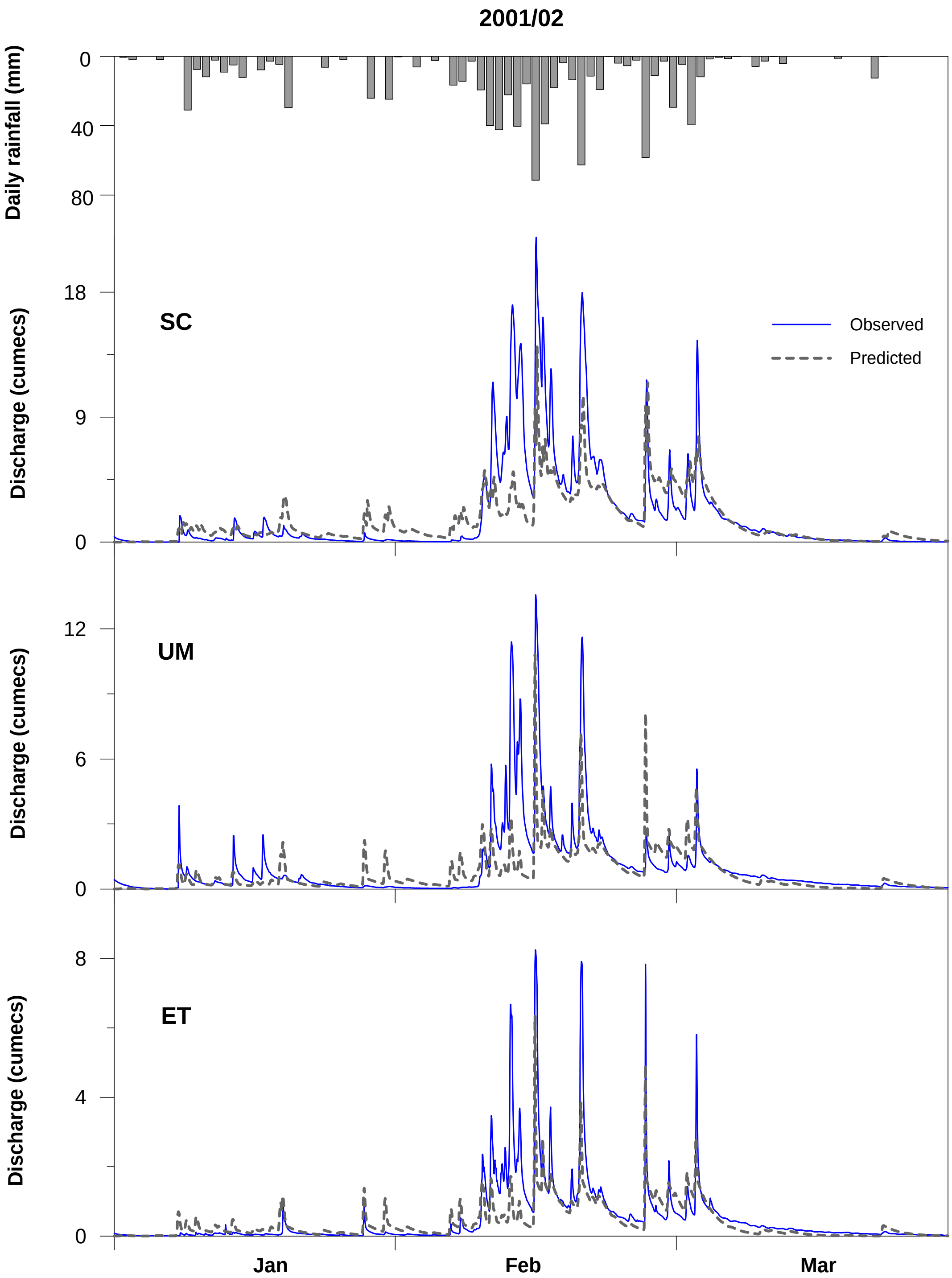

Figure 4.8 Daily rainfall (at the SC gauge) and both observed and predicted runoff during the 2001/02 Wet season at each gauging station (with the event on 31 December 2001 omitted)

4.4.2 January 1998 flood event

Stage data were collected at SC during the 1997/98 Wet season by Energy Resources of Australia (ERA) for most of the period of flow. No stage data were collected at the other gauging stations during this Wet season, and rainfall data were only collected at the Jabiluka mine site (fig 1.1).

At the end of January 1998, a high magnitude flood event associated with rainfall generated from a rain depression over the Northern Territory (tropical cyclone 'Les') was observed at the SC gauging station. The rainfall-runoff record for this event was used to test the parameterised hydrology model against an observed low frequency, high magnitude flood event. Stage data collected by ERA were converted to discharge using fitted rating tables derived in Moliere et al (2001).

The hydrograph at SC for the January 1998 flood is shown in figure 4.9. It shows that the predicted hydrograph for this event, using the Jabiluka mine site rainfall data as input into the parametersised HEC-HMS model, is reasonably similar to that observed. This result suggests that the HEC-HMS model may be considered reliable for estimating peak discharges of large flood events within the Ngarradj catchment. This is particularly important for using the model to derive a flood frequency curve from a predicted runoff record (see Section 4.5.2).

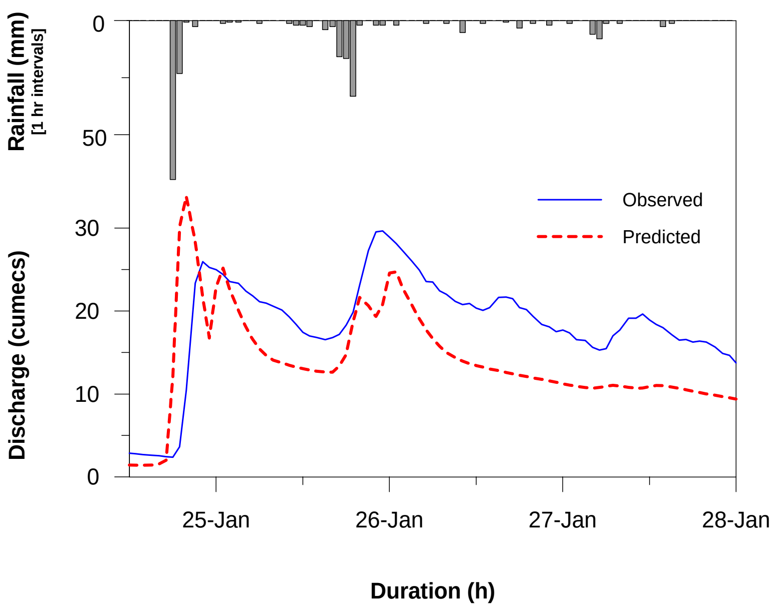

Figure 4.9 Rainfall and both observed and predicted runoff for the January 1998 flood event at SC

4.5 Application

To provide a better understanding of the baseline hydrological characteristics and long-term trends of the Ngarradj catchment the parameters were used to (1) establish a long-term runoff record for each gauging station, and (2) derive a flood frequency curve for each station. Both the long-term runoff record and the flood frequency curves have important applications for sediment transport analysis and flood risk assessment in the Ngarradj catchment.

4.5.1 Long-term runoff

The long-term rainfall record, as described in table 4.7, was input into the HEC-HMS model and, using the parameters derived above (table 4.2), a long-term runoff record for each gauging station was established. It was assumed that the rainfall record at Jabiru (1972-1994) and Jabiluka (1994-1998) was representative of the rainfall that occurred over the whole Ngarradj catchment area for the corresponding period of record.

Table 4.7 A description of the rainfall data used as input into HEC-HMS

Location	Period of record	Data type	Source of data
Jabiru airport	Jan 1972 – Dec 1989[(1)]	Half-hourly data	Bureau of Meteorology
Jabiru airport	Oct 1990 – June 1994	Pluvio data	ERA
Jabiluka mine site	June 1994 – June 1998	10 minute interval data	ERA

(1) Incomplete record — six years of data were missing

The total annual runoff and annual peak discharge at each gauging station for each Wet season of rainfall data is shown in table 4.8. Only the Wet seasons with complete rainfall data (no missing data) were used to predict the annual hydrograph for each station in HEC-HMS. It was also assumed that 250 mm of antecedent rainfall occurred each Wet season at each site. In other words, the first 250 mm of the rainfall record for each Wet season was not input into the HEC-HMS model. The antecedent rainfall figure of 250 mm was considered to be a conservative estimate for each Wet season, as it was the least amount of observed rainfall before runoff commenced during the three year monitoring period (1998–2001) (table 2.3).

During the 1983/84 and 1985/86 Wet seasons, half-hourly interval rainfall data were missing between September and December. Rainfall data were collected from 1 January for the remainder of the Wet season. From daily rainfall records (Bureau of Meteorology 1999), the total rainfall during September-December for the 1983/84 and 1985/86 Wet seasons was 282 mm and 364 mm respectively. This was assumed to be the antecedent rainfall for these two Wet seasons and, therefore, runoff was assumed to commence on 1 January.

The total runoff observed at SC, UM and ET during the three year monitoring period (table 4.3) are all above average (table 4.8), which reflects the above average annual rainfall figures recorded at the Ngarradj catchment (table 2.1).

The 1979/80 Wet season was predicted to have had the greatest total annual runoff at all three gauging stations. Although the total annual rainfall during the 1979/80 Wet season was not the largest on record (table 4.8), one extraordinary flood event occurred on 4 February 1980 which influenced the total annual runoff value. This particular event is discussed in section 4.5.3.

4.5.2 Flood frequency analysis

A log Pearson III distribution was fitted for the predicted annual peak discharges for each gauging station. The following is a brief description of the method used for fitting and plotting a log Pearson III distribution to the annual peak discharge data based on Pilgrim (1987).

- The annual peak discharges for each Wet season for the period of record (table 4.8) were ranked in order of magnitude. The mean (M), standard deviation (S) and skewness (g) of the logarithms of the annual peak discharges for each gauging station were calculated (figs 4.10, 4.11 and 4.12).
- Peak discharges for a range of annual exceedance probabilities (AEPs) were calculated using equation (4.1) (Pilgrim 1987):

  $$Ry = M + Ky\,S \qquad (4.1)$$

  where, Ry = the logarithm of peak discharge having an AEP of 1 in y years; Ky = frequency factor found from tables in Pilgrim (1987) for the required AEP.

The fitted frequency curves for each gauging station are shown in figures 4.10, 4.11 and 4.12 respectively. A summary of the AEPs and the corresponding peak discharges for each station are shown in table 4.9.

- The plotting positions ($PP(m)$) of each annual peak discharge value (table 4.9) for each station were calculated as a percentage using equation (4.2) and plotted on figures 4.10, 4.11 and 4.12.

$$PP(m) = (m - 0.4)/(N + 0.2) \times 100 \qquad (4.2)$$

where, N is the number of years of record (20); m is the rank of the annual peak discharge value.

Table 4.8 Total rainfall, runoff and annual peak discharges predicted for SC, UM and ET.

		Tot runoff (ML) [peak Q ($m^3 s^{-1}$)]		
Year	**Annual rainfall (mm)**	**SC**	**UM**	**ET**
1972/73	1438	25543 [59.0]	9951 [25.5]	5050 [14.0]
1973/74	1479	16079 [7.6]	7576 [5.8]	4146 [3.6]
1974/75	1536	27560 [31.5]	11350 [14.1]	5641 [8.0]
1977/78	1419	23376 [13.9]	10917 [9.9]	5961 [5.9]
1978/79	1449	19879 [10.1]	9595 [8.3]	5309 [4.9]
1979/80	1809	37990 [72.6]	18466 [40.9]	8616 [20.3]
1983/84	1671(1)	20769 [15.3]	9810 [10.0]	5184 [5.3]
1985/86	1222(1)	12202 [8.5]	5796 [5.5]	3030 [3.0]
1986/87	1293	16107 [13.9]	7772 [11.6]	4267 [6.6]
1987/88	898	11728 [9.5]	5862 [7.4]	3014 [4.6]
1988/89	1388	18870 [10.3]	9188 [7.9]	5041 [4.8]
1990/91	1373	24282 [19.0]	12320 [15.3]	6421 [9.9]
1991/92	985	12219 [12.8]	6030 [9.9]	3082 [6.0]
1992/93	1184	18522 [29.2]	9008 [19.8]	4087 [10.3]
1993/94	1467	19098 [11.2]	8828 [7.6]	4863 [4.5]
1994/95	1895	29928 [19.6]	13406 [14.1]	7289 [7.8]
1995/96	1292	23536 [27.0]	10290 [13.4]	5341 [7.7]
1996/97	1764	19313 [11.3]	8497 [6.7]	4720 [4.0]
1997/98	1676	34105 [33.8]	15137 [18.1]	7727 [10.3]
1998/99	1826	29819 [23.8]	14190 [15.7]	7150 [9.0]
1999/00	2047	40078 [20.0]	20164 [15.8]	10378 [9.7]
2000/01	1897	29850 [17.0]	14345 [11.7]	7221 [5.9]
Average annual flow (ML)		23221	10841	5615

(1) Bureau of Meteorology (1999)

Figures 4.10, 4.11 and 4.12 show that the frequency curves give a good fit to the estimated data over the whole range of values. All of the data points fit within the 5% and 95% confidence limits (figs 4.10, 4.11 and 4.12).

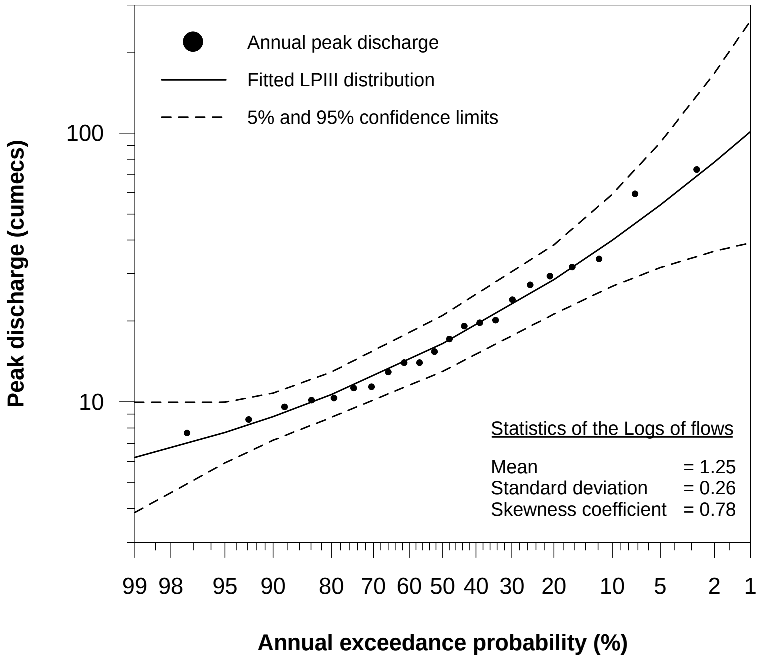

Figure 4.10 Frequency curve of annual peak discharge, SC

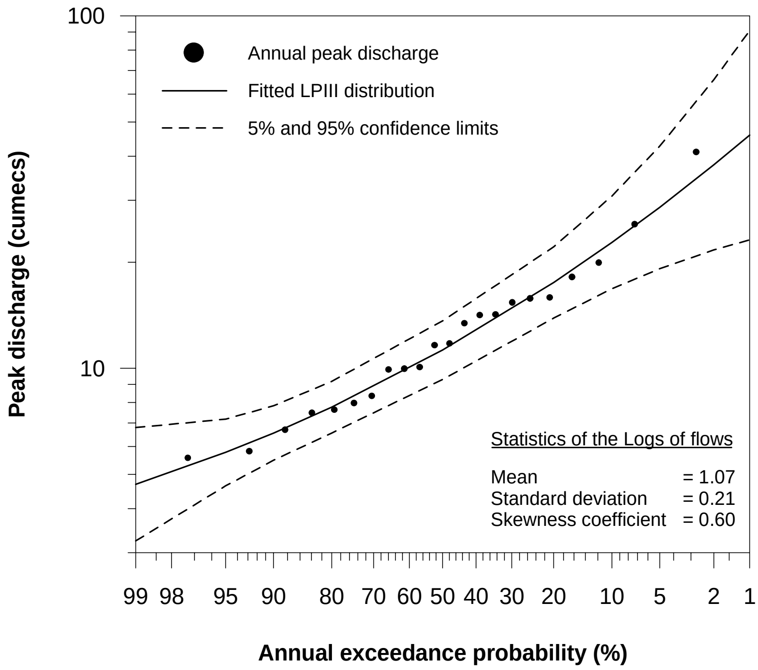

Figure 4.11 Frequency curve of annual peak discharge, UM

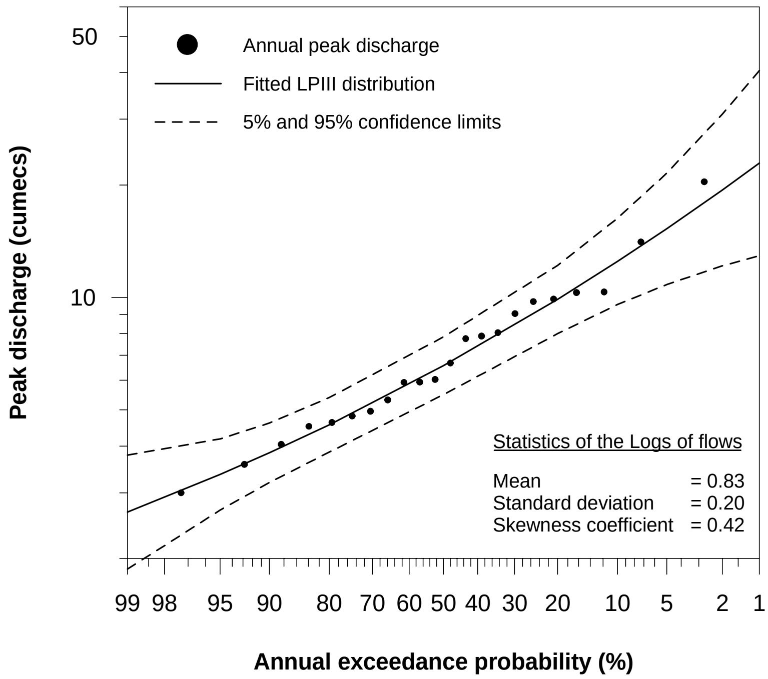

Figure 4.12 Frequency curve of annual peak discharge, ET

Table 4.9 Summary of the fitted flood frequency distribution for each gauging station

		Peak discharge ($m^3 s^{-1}$)		
ARI (y)	**AEP (%)**	**SC**	**UM**	**ET**
2	50	16.48	11.26	6.56
5	20	28.53	17.53	9.88
10	10	39.88	22.74	12.48
20	5	53.97	28.62	15.26
50	2	77.81	37.74	19.38
100	1	101.1	45.85	22.87

Using figures 4.10, 4.11 and 4.12, the ARIs of each of the observed annual maximum peak discharges for the three year monitoring period (1998–2001) at SC, UM and ET were estimated (table 4.10). Table 4.10 shows that the maximum peak discharges observed for the three year period, compared to that predicted for previous years, have been relatively minor (table 4.8).

The maximum rainfall intensities of these flood events (over a one hour duration) are all equivalent to a less than 1:5 y rainfall event (table 3.1), which reflects the ARIs of each observed annual maximum peak discharge at each gauging station (table 4.10).

Table 4.10 ARIs for annual maximum peak discharges observed at SC, UM and ET

	Annual peak discharge ($m^3 s^{-1}$) [ARI (y)]		
Year	**SC**	**UM**	**ET**
1998/99	22.3 [3.1]	15.0 [3.4]	8.5 [3.3]
1999/00	18.1 [2.3]	12.2 [2.3]	8.1 [3.0]
2000/01	20.6 [2.7]	13.0 [2.6]	8.2 [3.1]

4.5.3 Selected flood events

A selection of the four largest flood events predicted from 1972 to 2001 at each gauging station (table 4.11) was used to characterise the type of rainfall event that generates a major flood event within the Ngarradj catchment.

For each flood event the corresponding ARI for peak discharge is also shown (table 4.11). The total rainfall, duration and maximum rainfall intensity, over several durations, of each rainfall period contributing to the flood peak are also given in table 4.11. Tabulated intensity-frequency-duration (IFD) data for the Ngarradj catchment region for these durations (Bureau of Meteorology pers comm 2000) were used to estimate the average recurrence interval (ARI) for each of the rainfall events (table 4.11).

The peak discharge for the flood event in February 1980 had an average ARI of approximately 1:55 y at all three gauging stations. The peak discharge for the event in March 1973 had an average ARI of approximately 1:18 y at all three gauging stations, and the remaining two events had an average ARI of approximately 1:6 y at all three stations. As expected, the peak discharge of these large flood events have an ARI that is similar to the average ARI of the rainfall intensities across the various durations of the attributing rainfall period (table 4.11).

Table 4.11 also shows that, except for the two largest flood events (February 1980 and March 1973), the majority of the annual maximum peak discharges were all either approximately equal to, or less than, 1:6 y events. The exceptionally high peak discharges predicted for the February 1980 and March 1973 events can be attributed directly to the severe rainfall periods recorded at Jabiru airport (table 4.11). These two events are discussed below.

February 1980

The most severe storm ever recorded in the Kakadu region was at Jabiru airport on 4 February 1980. The storm had a duration of 16 hours with a total rainfall of 303 mm (Water Division 1982) and featured a very intense rainfall period of 240 mm in 5 hours (table 4.11). The ARI of the rainfall intensity during this storm was greater than that for a 1:100 y rainfall event for the Jabiluka region over a 3 h, 6 h (table 4.11) and 24 h (Bureau of Meteorology pers. comm. 2000) duration. Assuming this rainfall event occurred at Ngarradj, the predicted peak discharge at each gauging station in response to this storm is significantly higher than that observed during the three year monitoring period (1998–2001) (tables 4.10 and 4.11). Figure 4.13 shows the predicted hydrograph at SC for this event and the scale of the peak flow compared to that observed during the three year monitoring period.

During the storm in February 1980, a flood hydrograph was recorded at Gulungul Creek, which is also a tributary of Magela Creek. The catchment size of Gulungul Creek (46 km^2) is similar to that at SC (43.6 km^2) and therefore the flood hydrograph for an intense storm such as that on February 1980 should be a good analogue for the flow response at SC (Johnston & Prendergast 1999). The observed peak discharge for this event at Gulungul Creek was approximately 420 $m^3 s^{-1}$ (Johnston & Prendergast 1999). The predicted peak discharge at SC of 72.6 $m^3 s^{-1}$ is much less than that recorded at Gulungul Creek. To determine whether the predicted discharge at SC, and therefore UM and ET, is actually an underprediction by the HEC-HMS model, or if the Gulungul Creek is not a suitable analogue for the Ngarradj catchment, requires further investigation which is beyond the scope of this study. However, this comparison does highlight the need for more years of rainfall and streamflow data to be collected at Ngarradj catchment to determine how well the model and the current parameters predict large flood events (>1:10 y event).

Table 4.11 Four largest flood events at each gauging station from 1972. Approximate ARIs for peak discharge and maximum rainfall intensity are also shown.

				Intense rainfall period		Duration				
						30 min	60 min	120 min	180 min	360 min
Date	**SC – Peak Q ($m^3 s^{-1}$) [ARI (y)]**	**UM – Peak Q ($m^3 s^{-1}$) [ARI (y)]**	**ET – Peak Q ($m^3 s^{-1}$) [ARI (y)]**	**Rainfall (mm)**	**Duration (h)**	**Max. Intensity ($mm h^{-1}$) [ARI (y)]**	**Max. Intensity ($mm h^{-1}$) [ARI (y)]**	**Max. Intensity ($mm h^{-1}$) [ARI (y)]**	**Max. Intensity ($mm h^{-1}$) [ARI (y)]**	**Max. Intensity ($mm h^{-1}$) [ARI (y)]**
Feb 1980	72.6 [41.7]	40.9 [66.7]	20.3 [58.8]	240	5	57.6 [0.5]	57.6 [2]	56.0 [30]	51.3 [>100]	41.9 [>100]
Mar 1973[(1)]	59.0 [25.0]	25.5 [13.7]	14.0 [14.5]	118	2.5	86.2 [2]	74.4 [8]	50.7 [15]	41.6 [35]	21.5 [17]
				90	1.5	83.4 [2]	78.9 [11]	46.7 [10]	32.0 [7]	16.2 [3]
Jan 1998	33.8 [6.9]	18.1 [5.4]	10.3 [5.6]	86	1.4	112.8 [10]	77.0 [10]	46.5 [10]	31.2 [5]	16.0 [3]
Jan 1993	29.2 [5.3]	19.8 [6.8]	10.3 [5.6]	104	3	101.2 [5]	63.8 [4]	36.3 [3]	34.5 [10]	19.9 [10]

(1) This peak discharge was attributed to two successive rainfall events which occurred within a 24 h period. The peak discharge occurred during the second rainfall event.

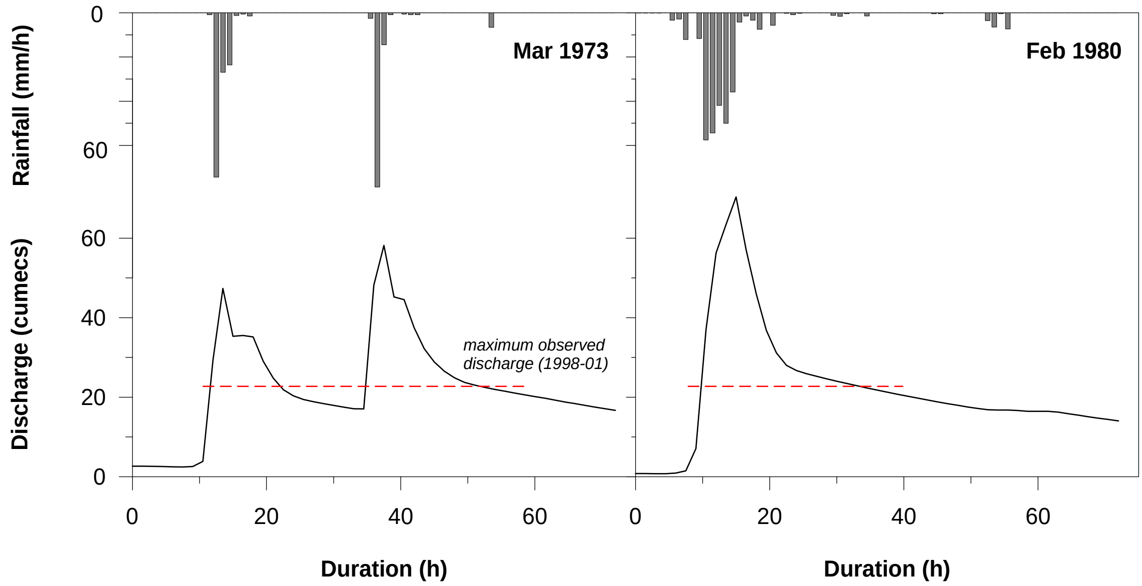

Figure 4.13 The rainfall and predicted hydrograph for the two largest flood events at SC. The maximum discharge observed during 1998–2001 is indicated by a dashed line.

March 1973

The rainfall period on 9 and 10 March 1973 was exceptional in that there were two successive, and very intense, storms that occurred within 24 hours of each other (table 4.11). The ARIs of the rainfall intensities during both the first and second rainfall periods were greater than 1:10 y over several durations (table 4.11). The maximum rainfall intensities of the two storms over a one hour duration (table 4.11) were both considerably larger than that observed during the most intense rainfall-runoff periods during the three year monitoring period (1998–2001) (table 3.1).

Figure 4.13 shows the predicted hydrograph at SC as a result of the two successive, and very intense, storm events. The predicted peak discharge of the resultant flood in response to these two storms occurred during the second rainfall period (fig 4.13) and, similar to the February 1980 event, was significantly higher at each gauging station than that observed during the three year monitoring period (1998–2001) (tables 4.10 and 4.11).

4.6 Conclusions

The HEC-HMS model has been calibrated for the Ngarradj catchment in the Northern Territory of Australia. Calibration of the model was conducted using a basin model generated by the ArcView extension HEC-GeoHMS and three years of observed rainfall/runoff data. Within the Ngarradj catchment the model was found to be most sensitive to the parameters describing conductivity (mm/h), imperviousness, plane roughness, recession constant and threshold Q.

Rainfall-runoff data collected during the 2001/02 Wet season were used to test the parameterised hydrology model against an observed annual runoff record. Comparison of the predicted hydrograph with the observed hydrograph found that the model predicted annual runoff volume reasonably well but underpredicted some storm events, including the annual maximum peak discharge. This is attributed to rainfall in the upper catchment that was not recorded at the gauging stations rather than errors within the model. This is a significant issue that emphasises the need for a well distributed gauging network in rainfall-runoff modelling.

Runoff data collected at SC during late-January 1998 by ERA were used to test the parameterised HEC-HMS model against an observed low frequency, high magnitude flood event. Comparison of the predicted hydrograph with the observed hydrograph for this event found that the model may be considered reliable for estimating peak discharges of large flood events within the Ngarradj catchment.

The calibrated model has been run using 15 y of rainfall data collected at Jabiru airport and 4 y at Jabiluka Mine to generate a 22 y runoff record (including the three years of observed runoff data (1998–2001)). When compared with this long-term record, the three years of observed runoff (1998/99, 1999/00 and 2000/01) were found to be above average. This corresponds with previous analysis of the rainfall. Flood frequency analysis of these data indicate that during the 22 year period there were 2 very large events (ARIs of approximately 1:55 y and 1:18 y), whilst the rest had ARIs of less than 1:6 y. Further analysis of the large events show that they were associated with the largest recorded storm event in Kakadu and two consecutive large rainfall events respectively. However, it is important that future work determines how well the model and the current parameters predict very large flood events (>1:10 y event) as they have high significance in the assessment of risk and geomorphological change.

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Appendix A

Observed hydrographs and daily rainfall

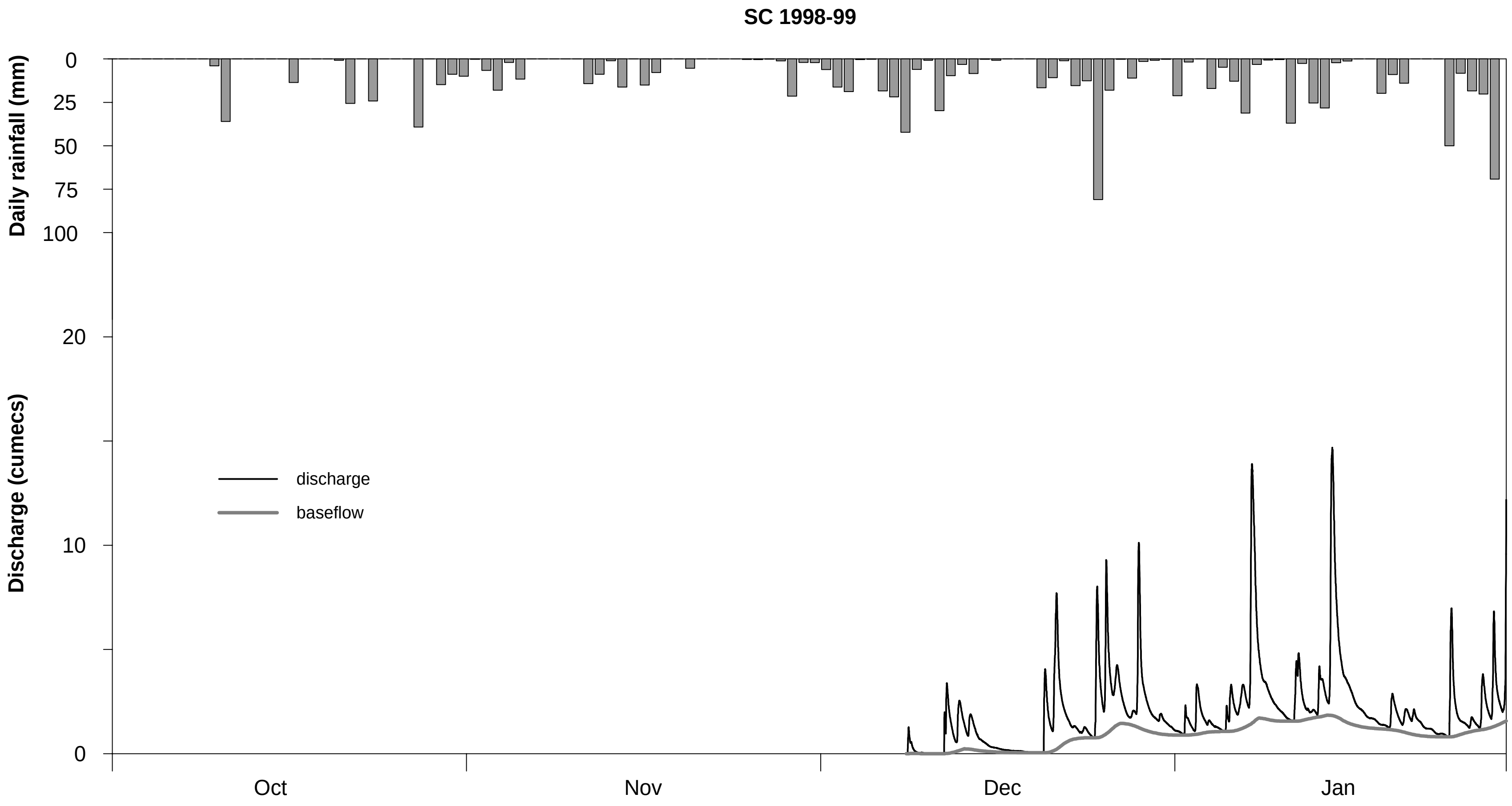

Figure A.1 Daily rainfall and the hydrograph for SC during the 1998/99 Wet season. The baseflow is also shown.

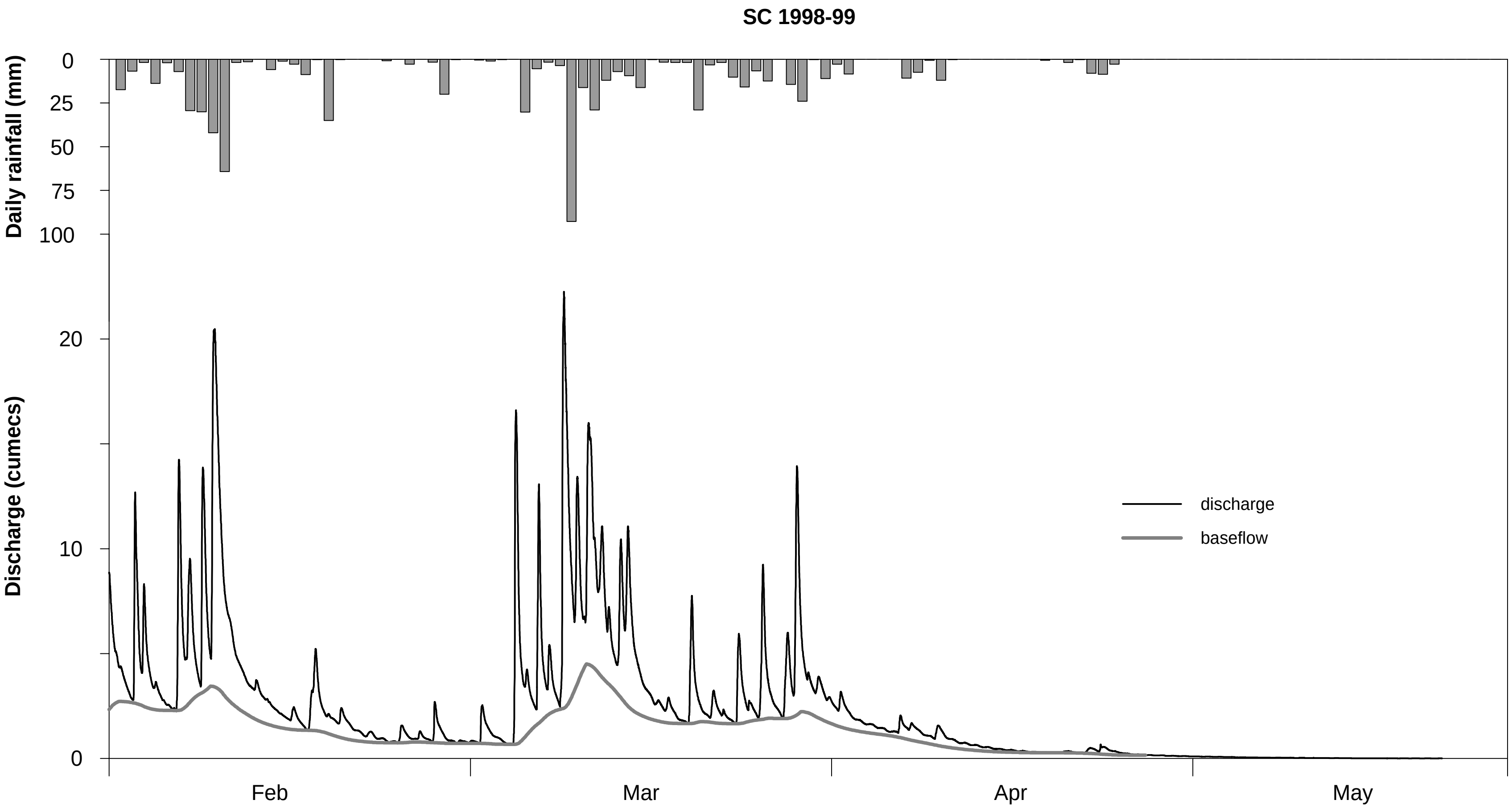

Figure A.1 (continued) Daily rainfall and the hydrograph for SC during the 1998/99 Wet season. The baseflow is also shown.

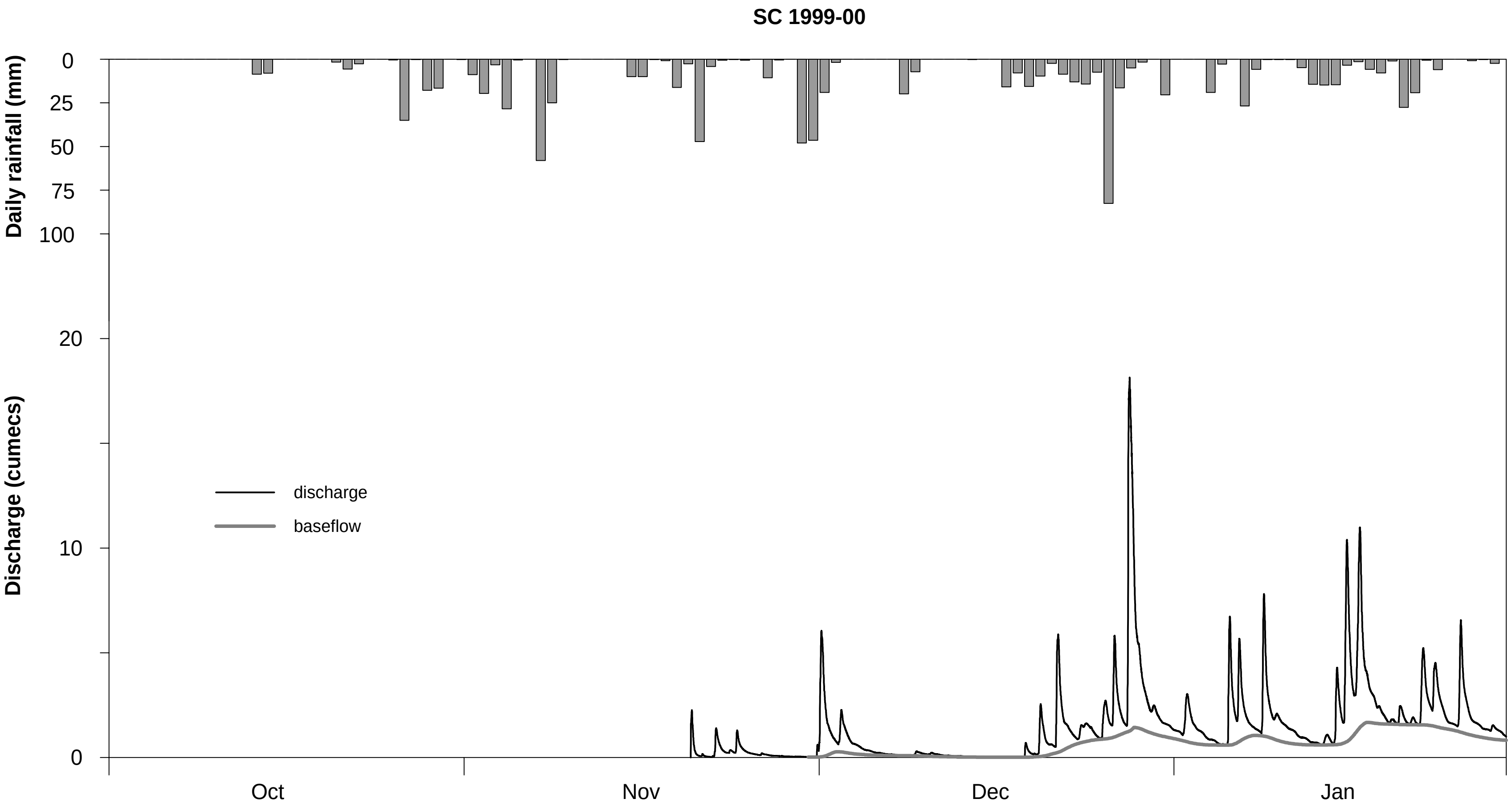

Figure A.2 Daily rainfall and the hydrograph for SC during the 1999/00 Wet season. The baseflow is also shown.

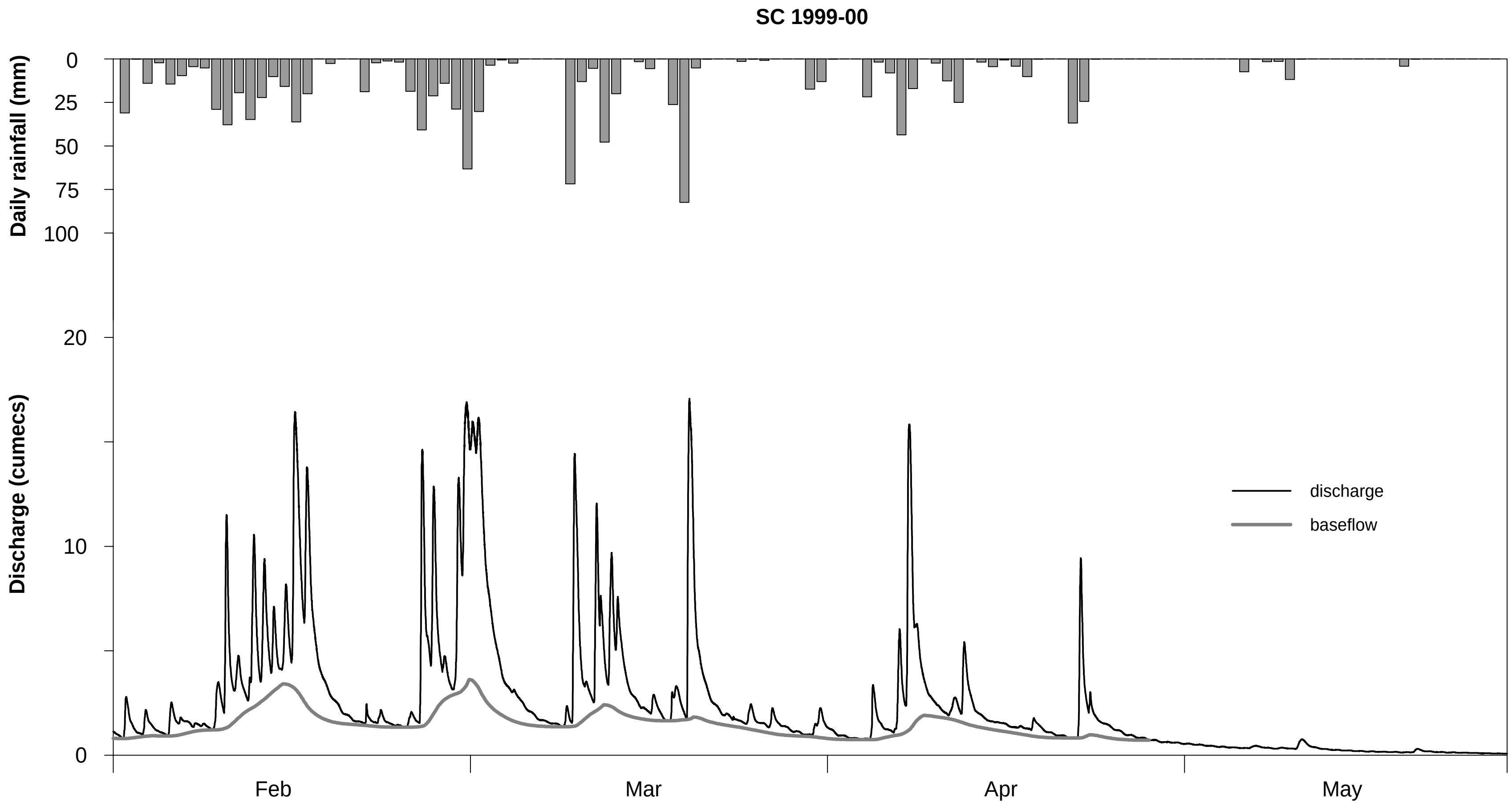

Figure A.2 (continued) Daily rainfall and the hydrograph for SC during the 1999/00 Wet season. The baseflow is also shown.

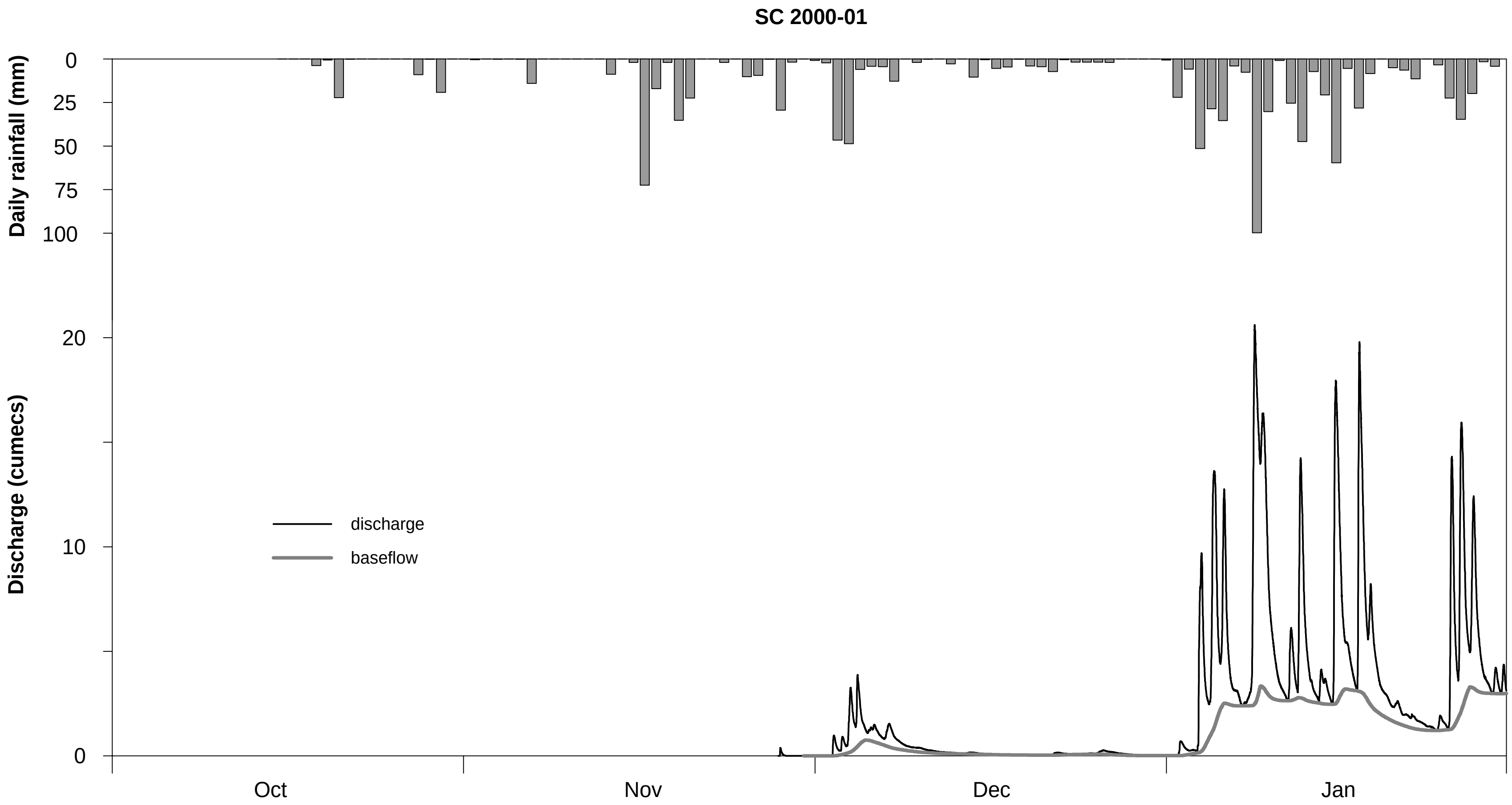

Figure A.3 Daily rainfall and the hydrograph for SC during the 2000/01 Wet season. The baseflow is also shown.

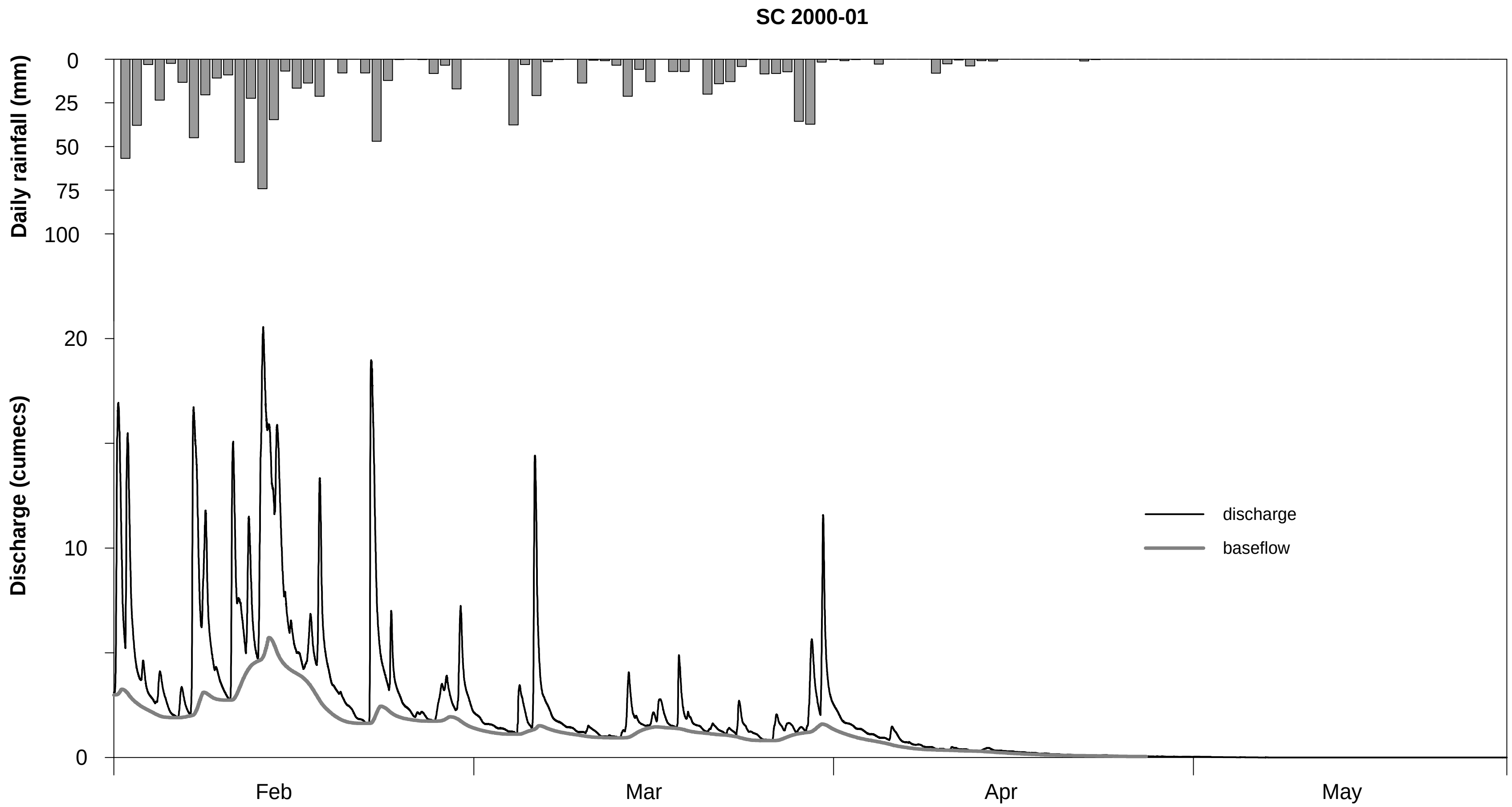

Figure A.3 (continued) Daily rainfall and the hydrograph for SC during the 2000/01 Wet season. The baseflow is also shown.

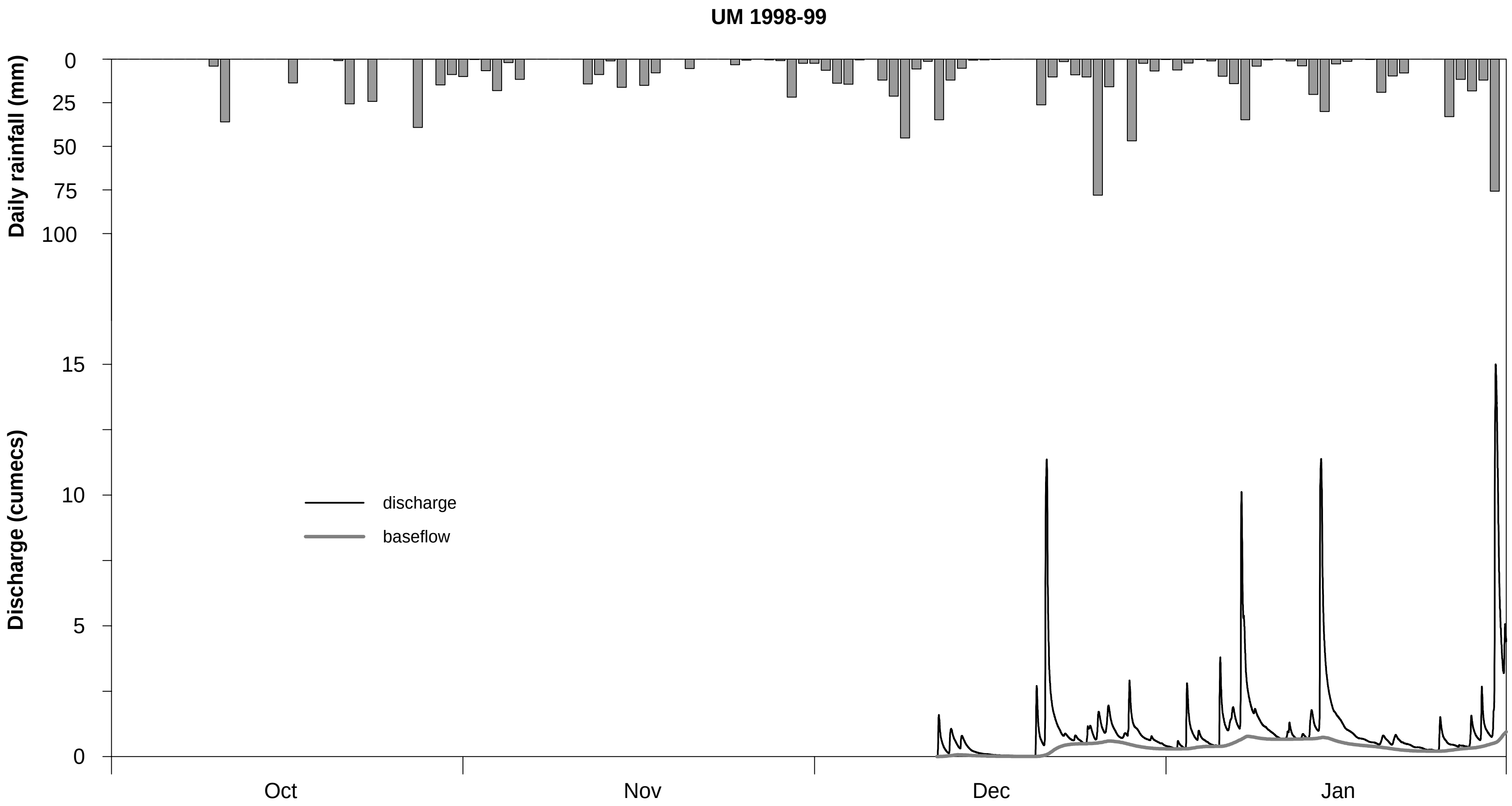

Figure A.4 Daily rainfall and the hydrograph for UM during the 1998/99 Wet season. The baseflow is also shown.

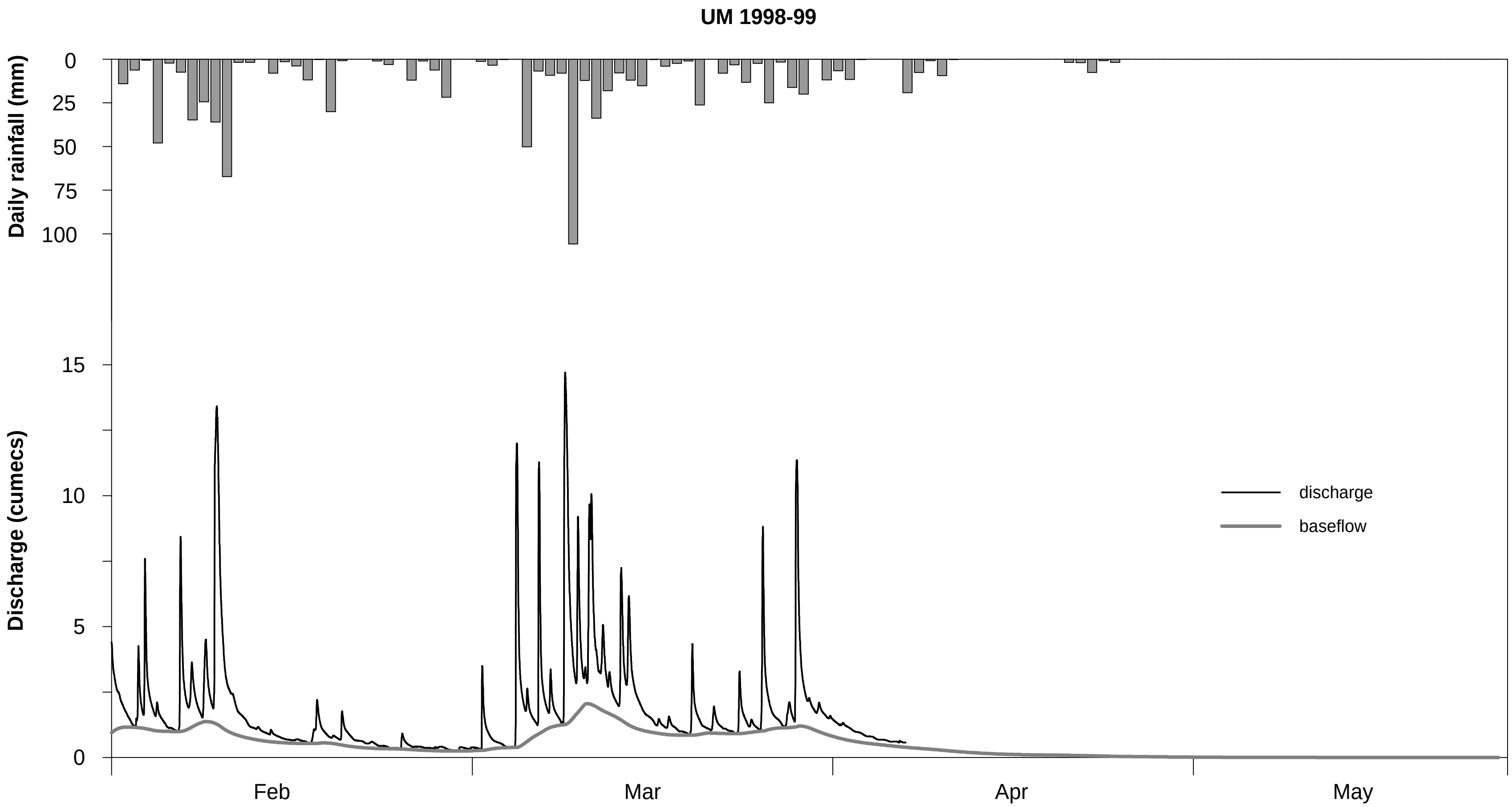

Figure A.4 (continued) Daily rainfall and the hydrograph for UM during the 1998/99 Wet season. The baseflow is also shown.

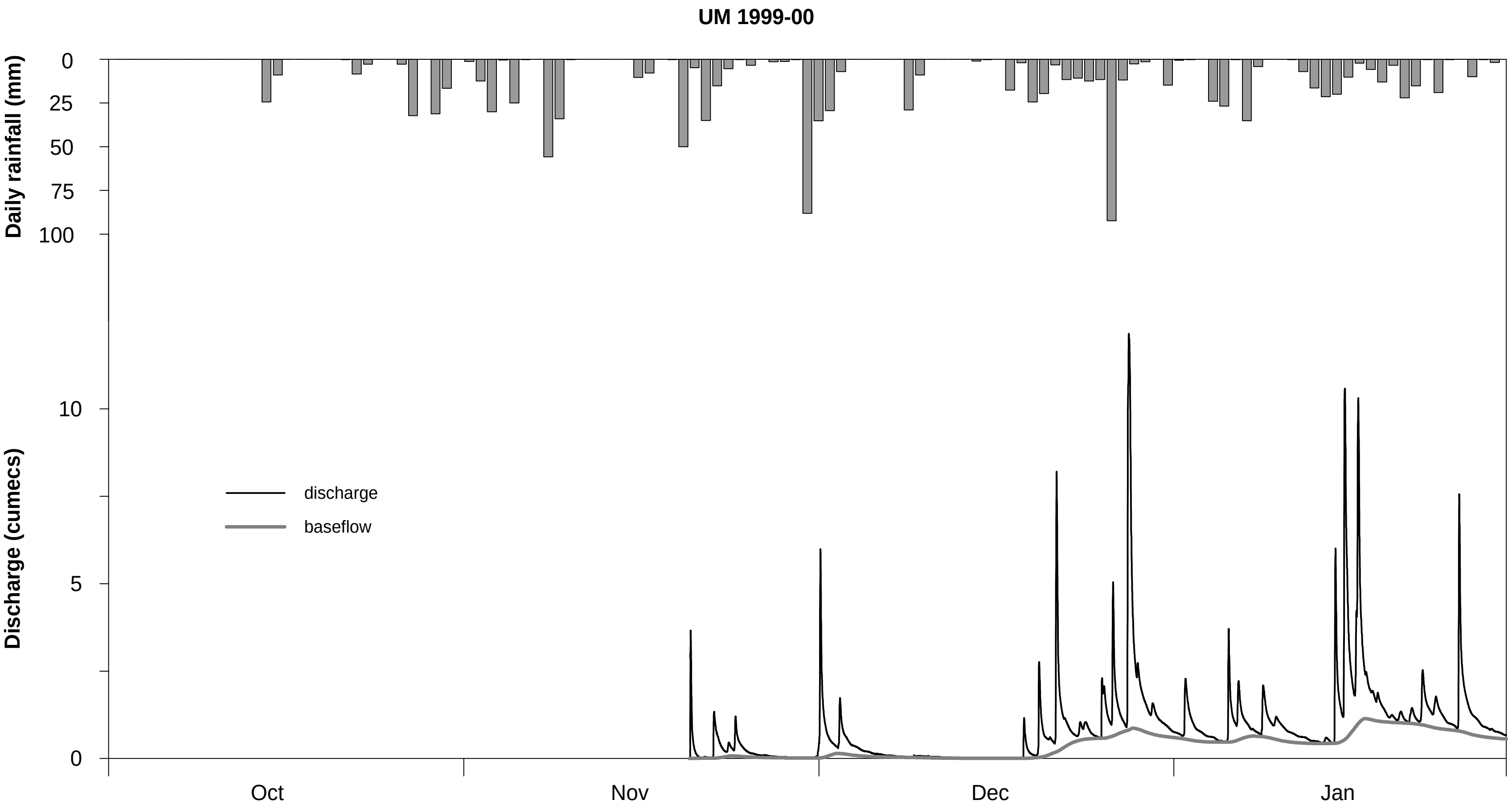

Figure A.5 Daily rainfall and the hydrograph for UM during the 1999/00 Wet season. The baseflow is also shown.

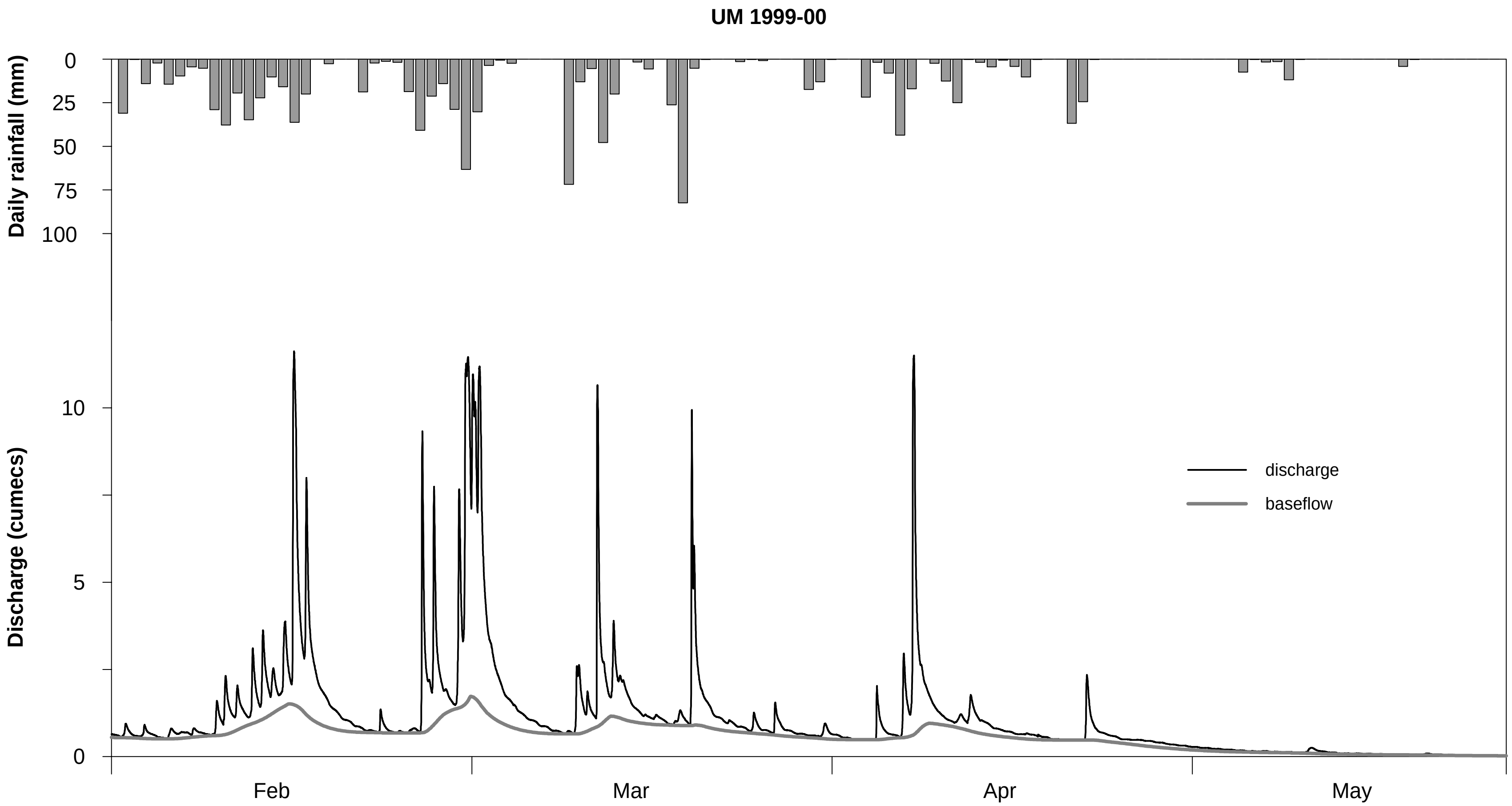

Figure A.5 (continued) Daily rainfall and the hydrograph for UM during the 1999/00 Wet season. The baseflow is also shown.

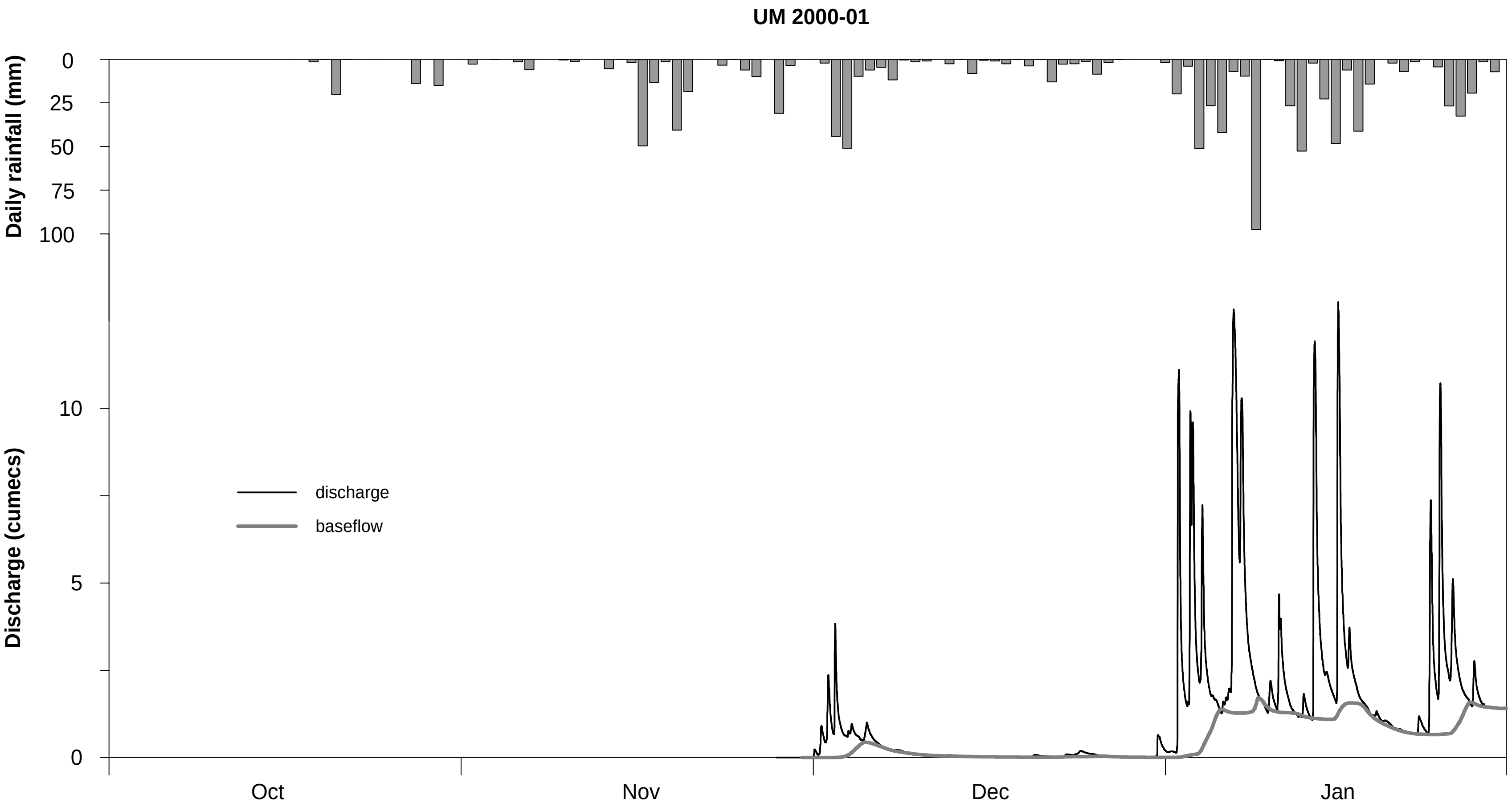

Figure A.6 Daily rainfall and the hydrograph for UM during the 2000/01 Wet season. The baseflow is also shown.

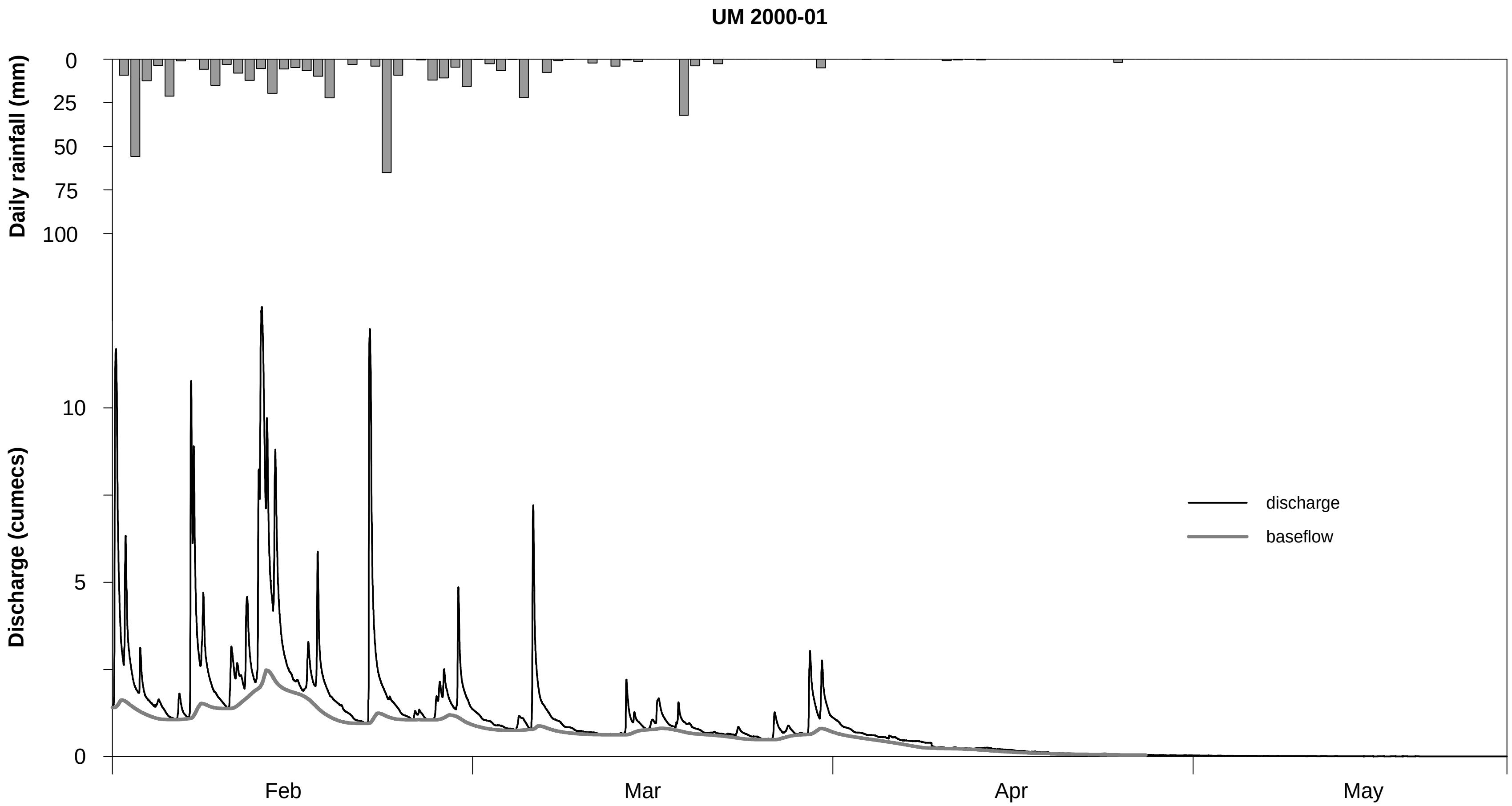

Figure A.6 (continued) Daily rainfall and the hydrograph for UM during the 2000/01 Wet season. The baseflow is also shown.

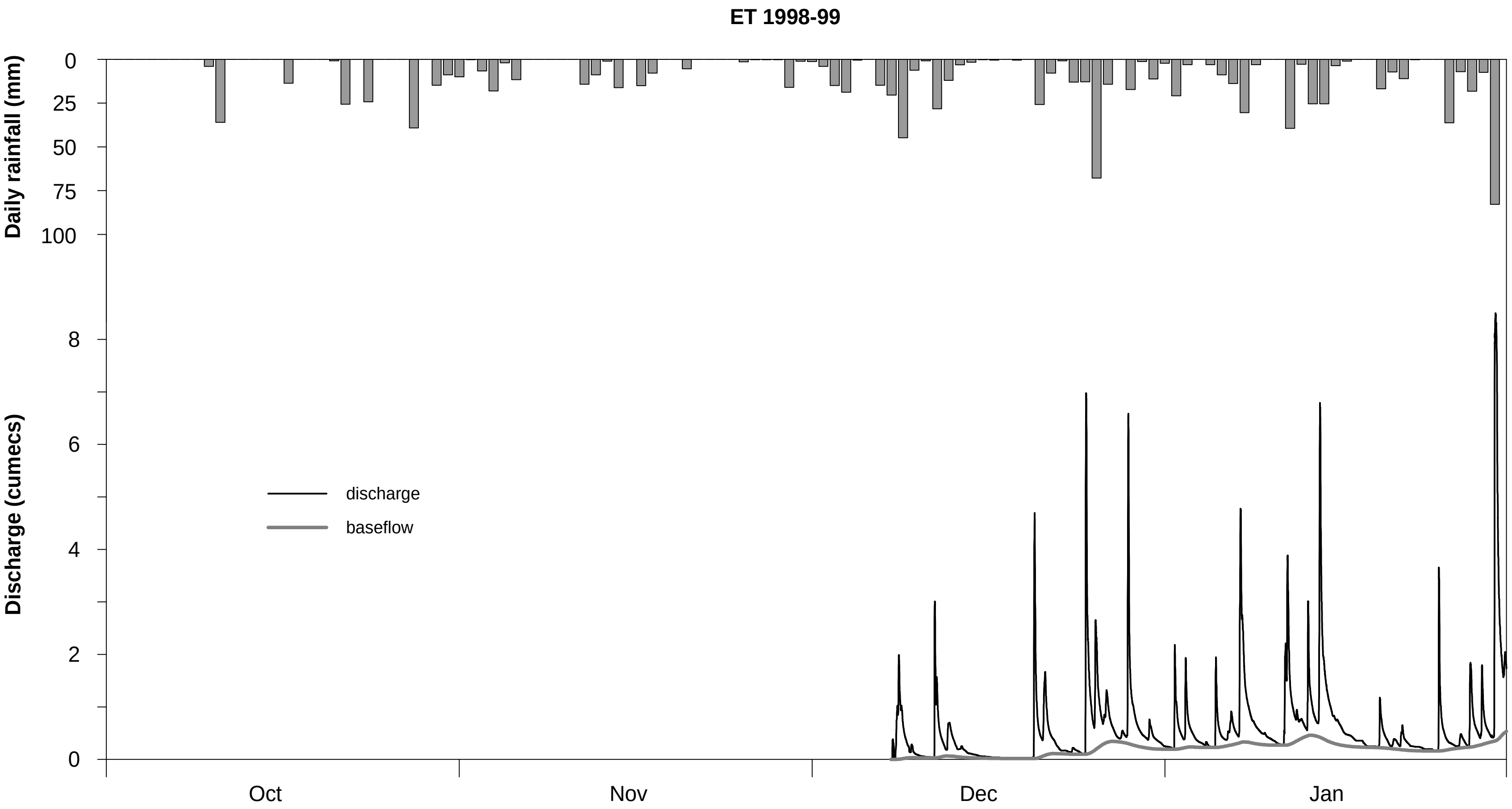

Figure A.7 Daily rainfall and the hydrograph for ET during the 1998/99 Wet season. The baseflow is also shown.

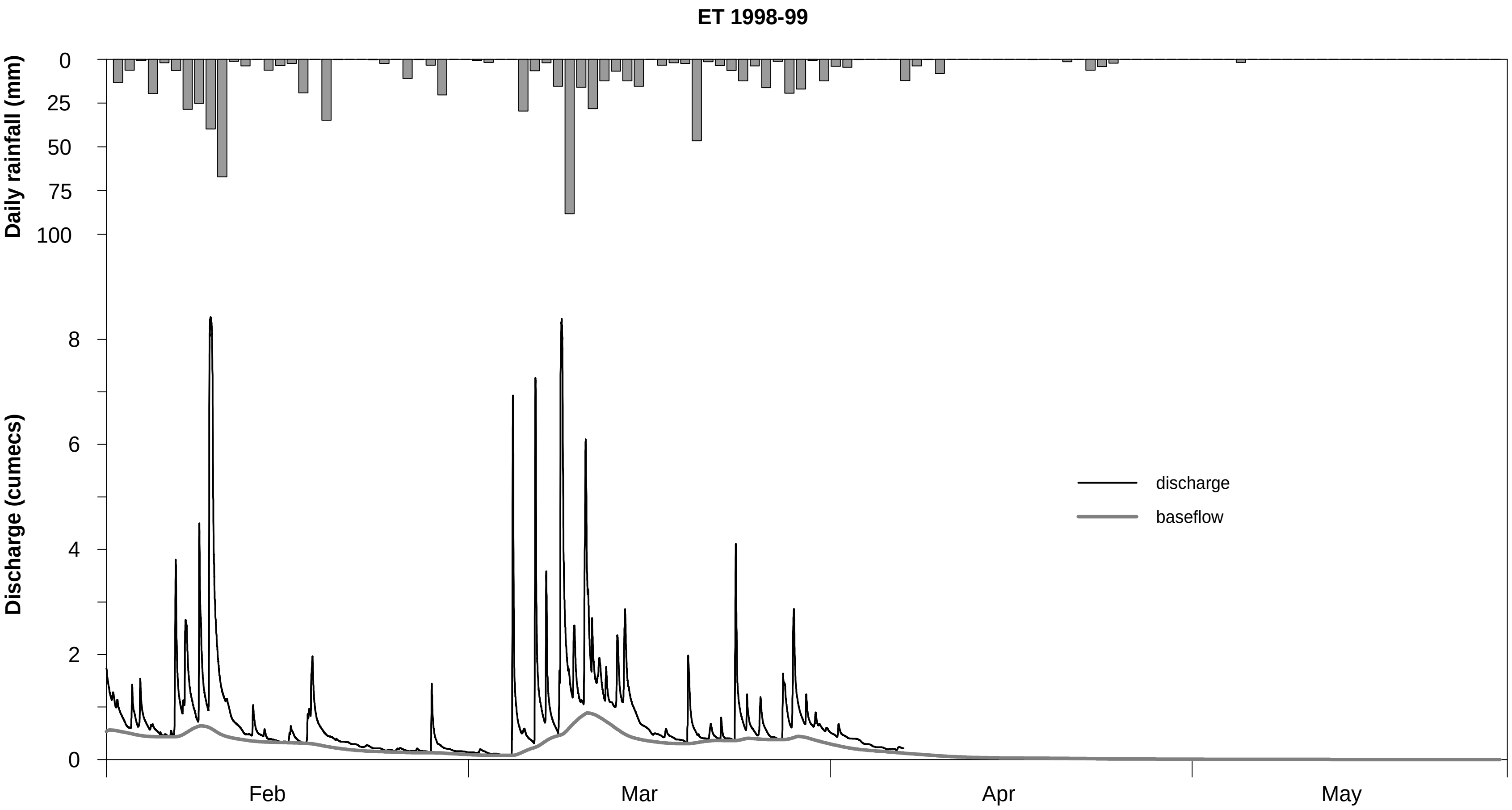

Figure A.7 (continued) Daily rainfall and the hydrograph for ET during the 1998/99 Wet season. The baseflow is also shown.

ET 1999-00

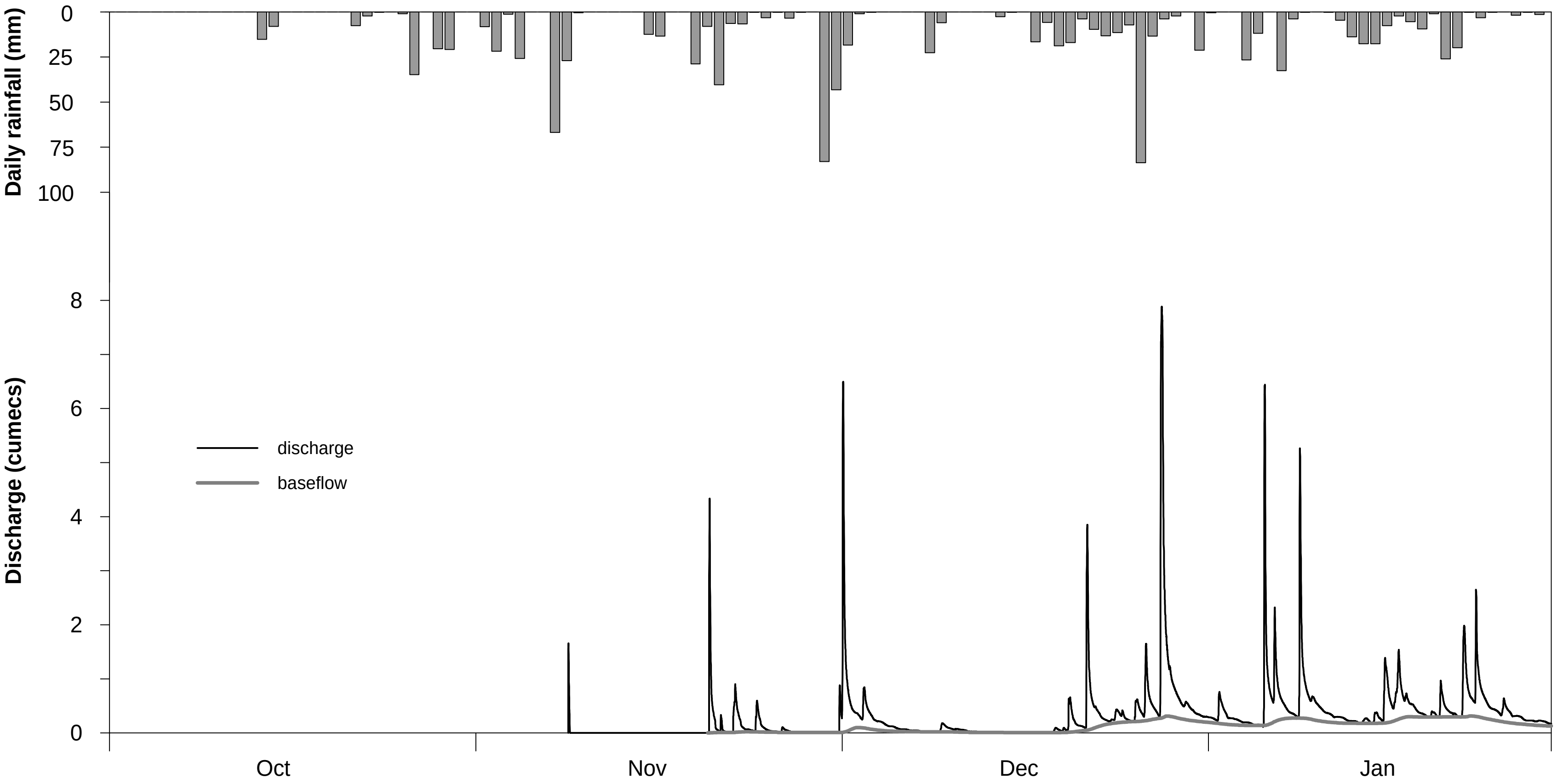

Figure A.8 Daily rainfall and the hydrograph for ET during the 1999/00 Wet season. The baseflow is also shown.

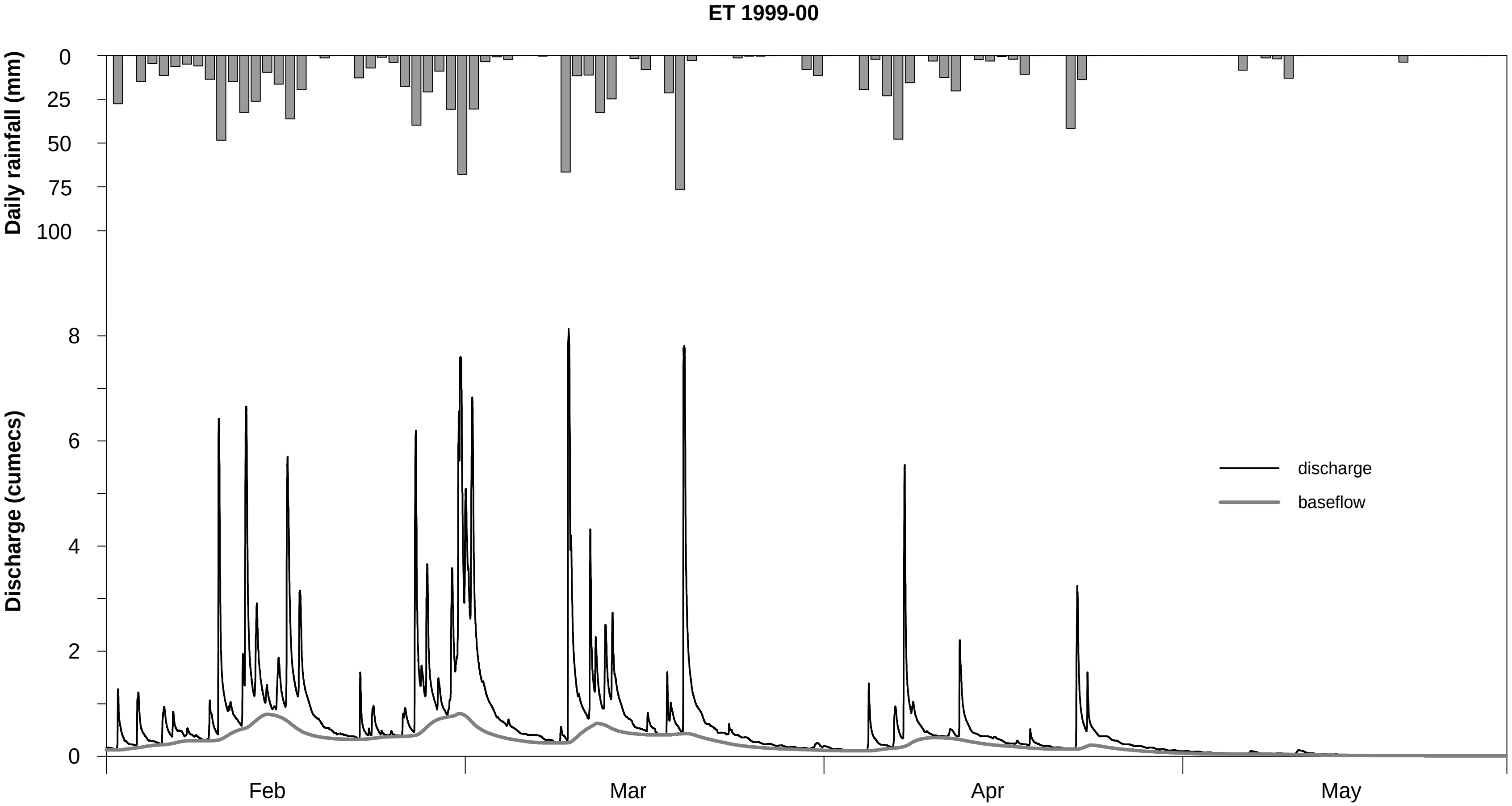

Figure A.8 (continued) Daily rainfall and the hydrograph for ET during the 1999/00 Wet season. The baseflow is also shown.

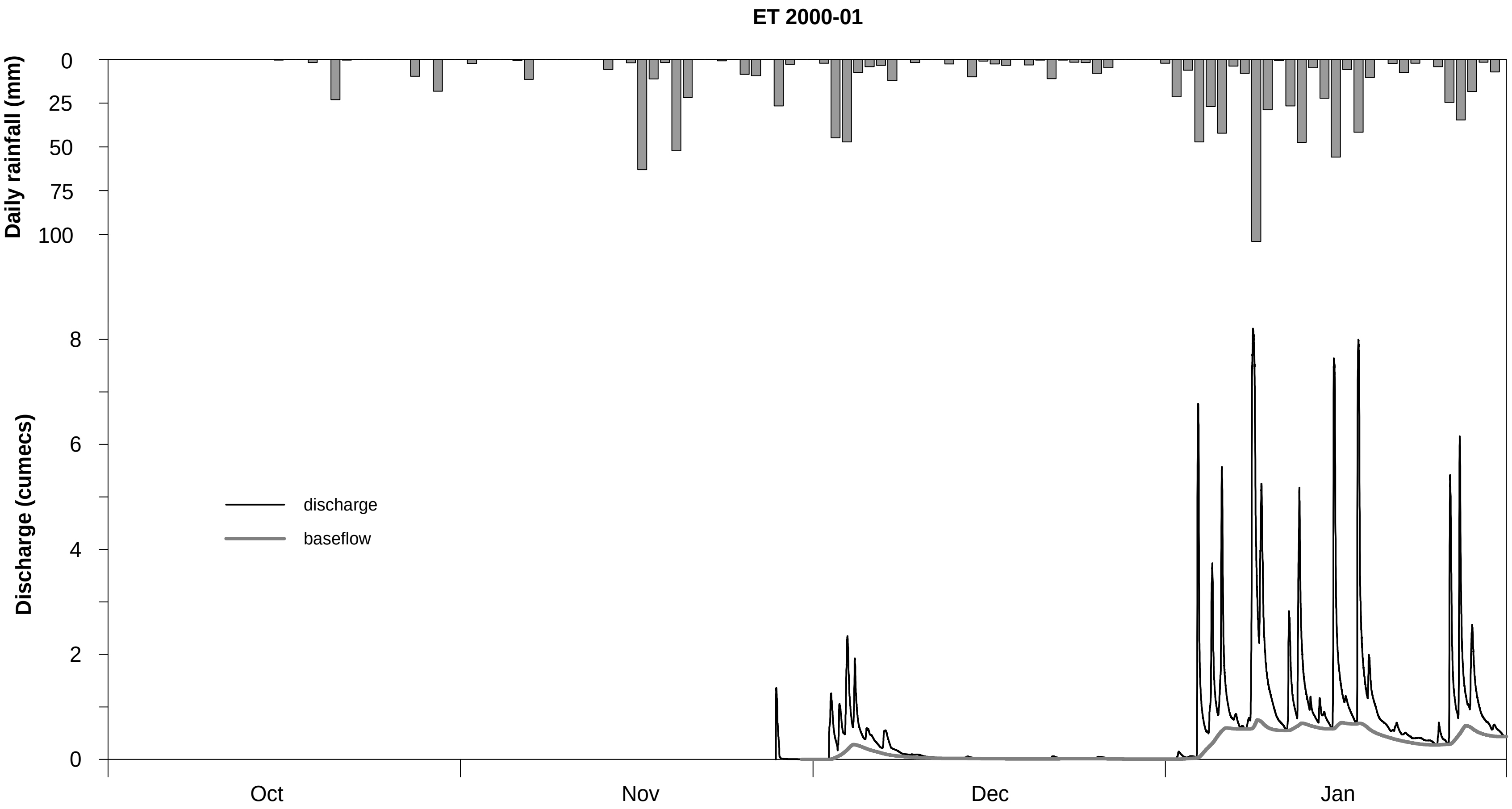

Figure A.9 Daily rainfall and the hydrograph for ET during the 2000/01 Wet season. The baseflow is also shown.

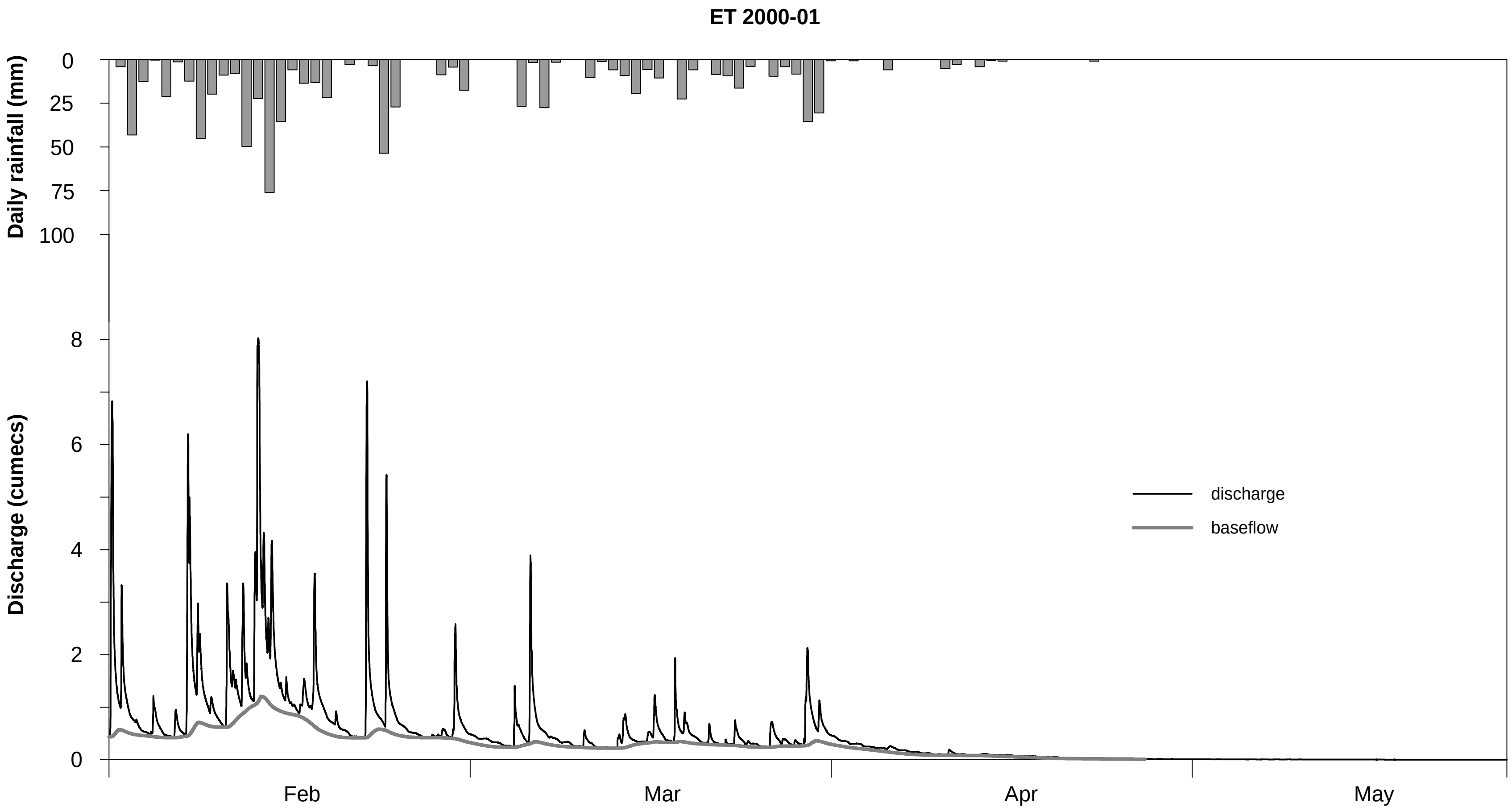

Figure A.9 (continued) Daily rainfall and the hydrograph for ET during the 2000/01 Wet season. The baseflow is also shown.

Appendix B

Observed and predicted hydrographs

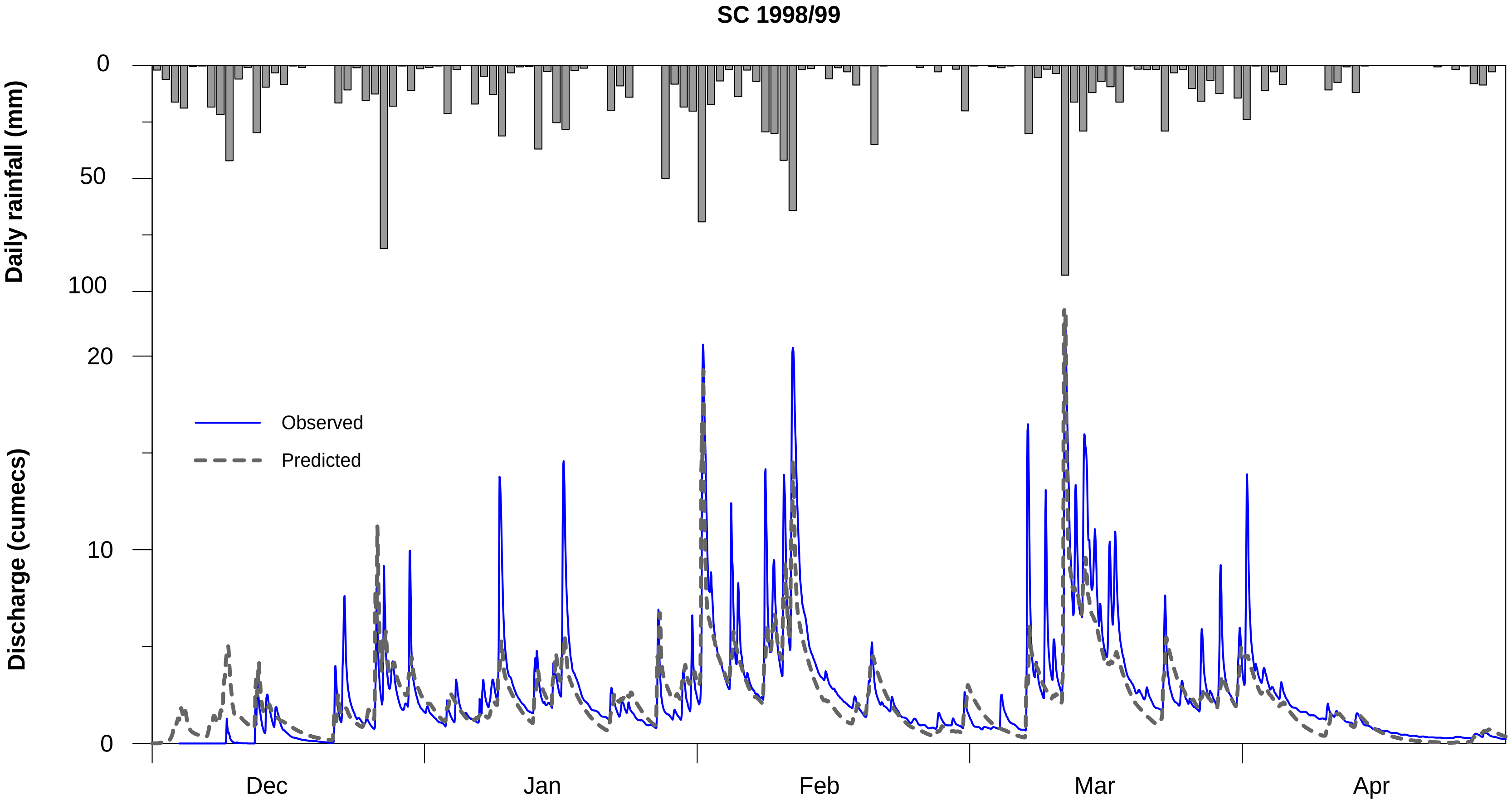

Figure B.1 Observed and predicted hydrographs at SC using parameters fitted in HEC-HMS (table 4.2).

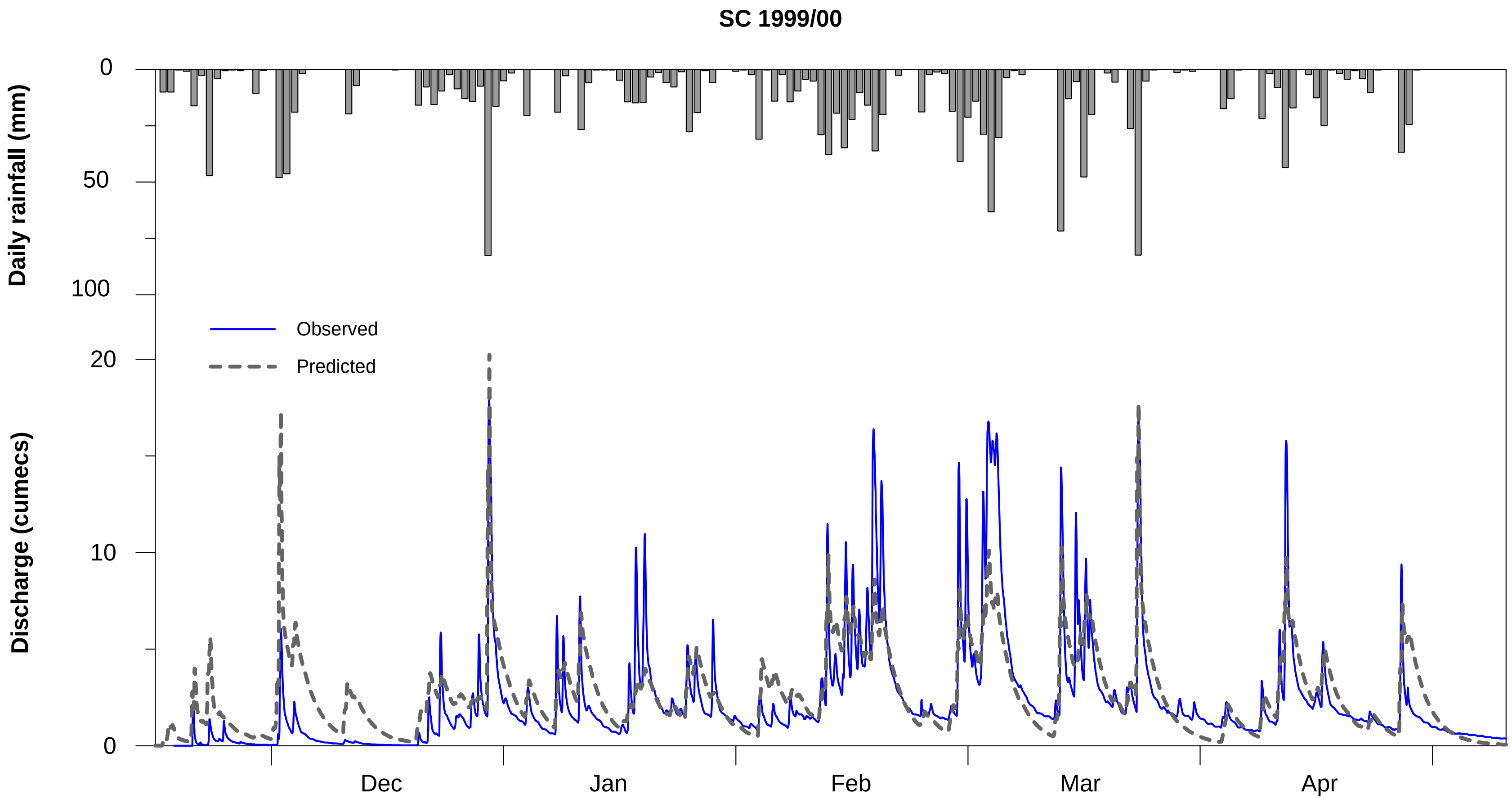

Figure B.1 (continued) Observed and predicted hydrographs at SC using parameters fitted in HEC-HMS (table 4.2).

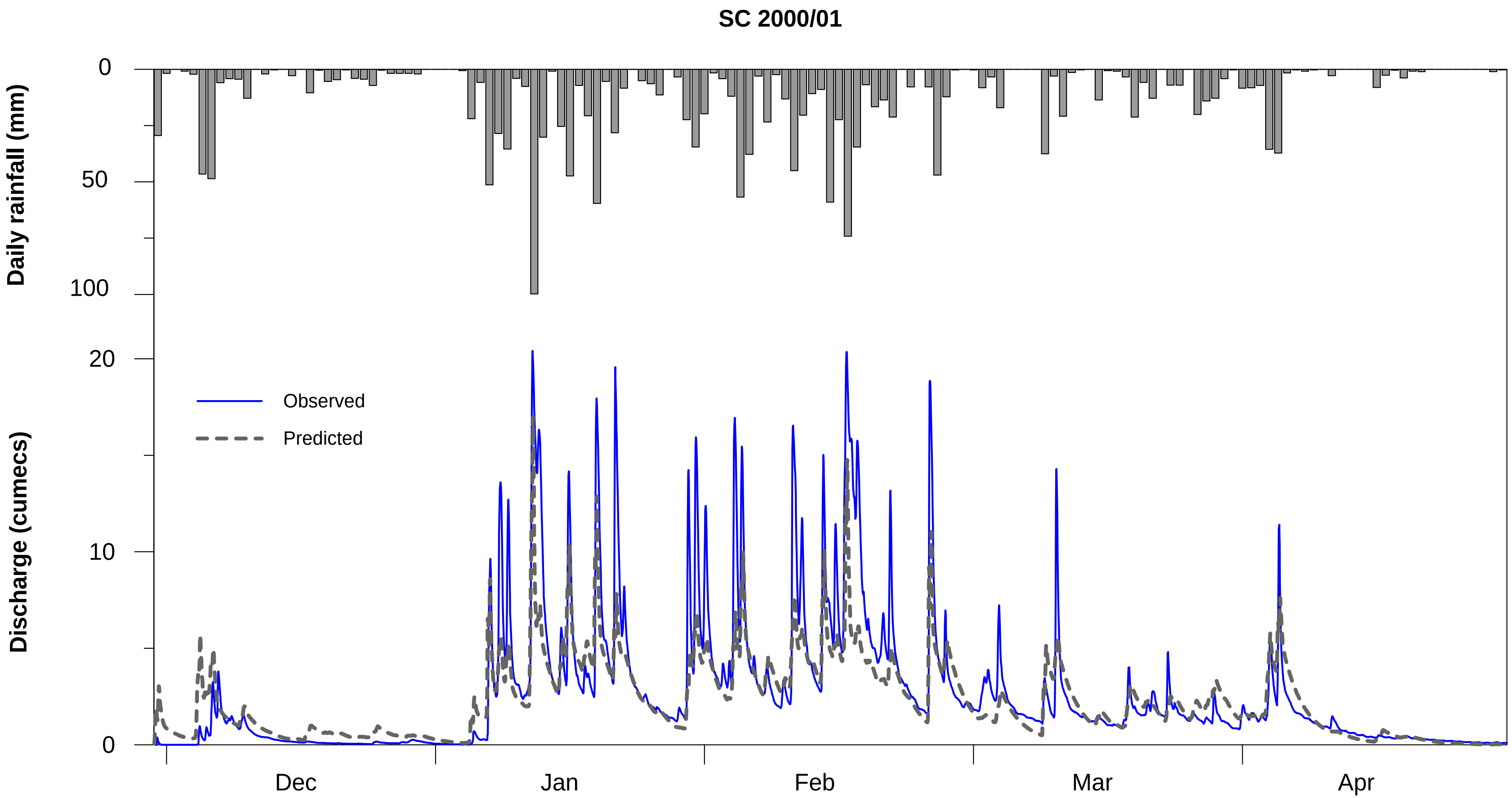

Figure B.1 (continued) Observed and predicted hydrographs at SC using parameters fitted in HEC-HMS (table 4.2).

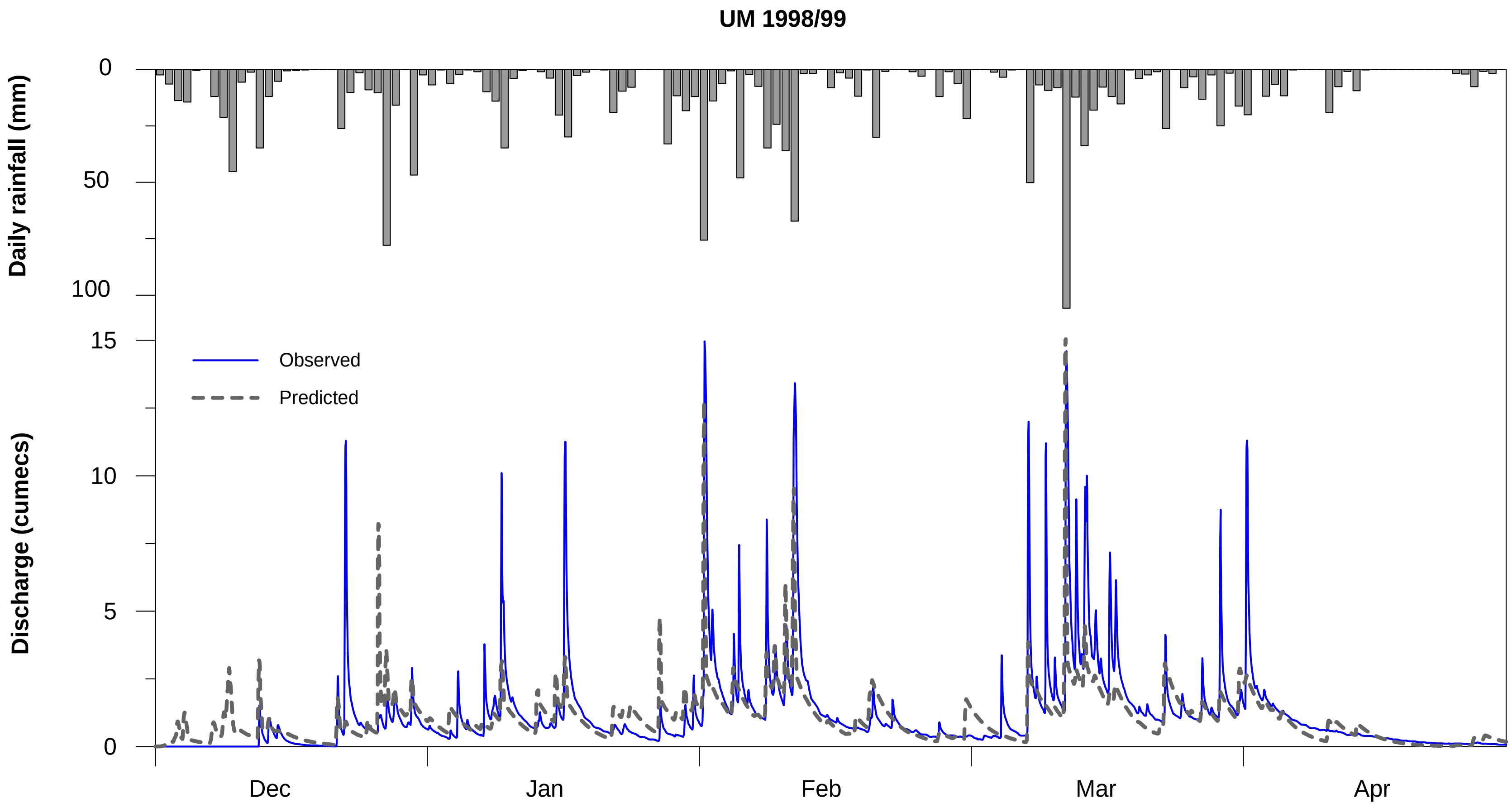

Figure B.2 Observed and predicted hydrographs at UM using parameters fitted in HEC-HMS (table 4.2).

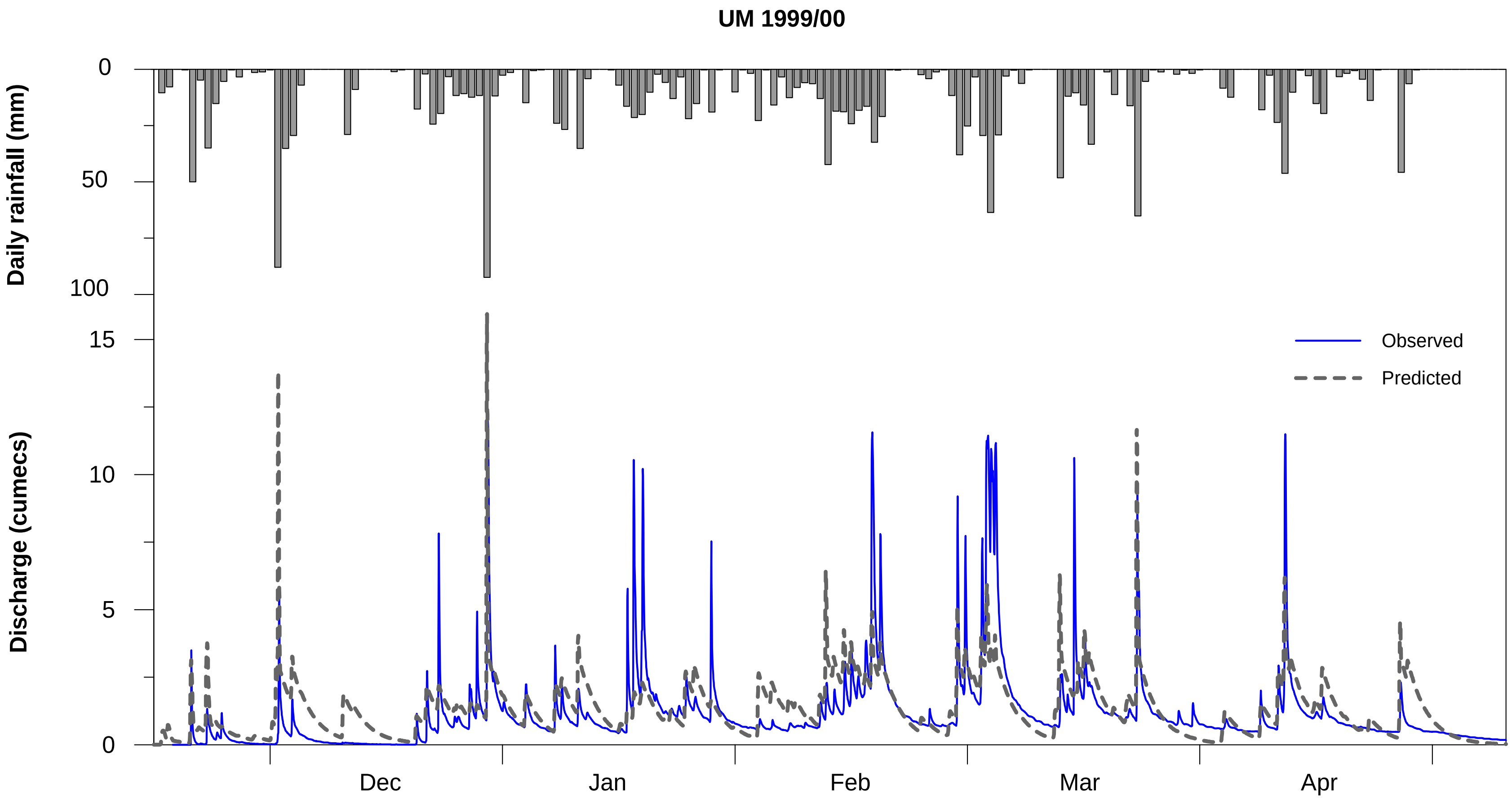

Figure B.2 (continued) Observed and predicted hydrographs at UM using parameters fitted in HEC-HMS (table 4.2).

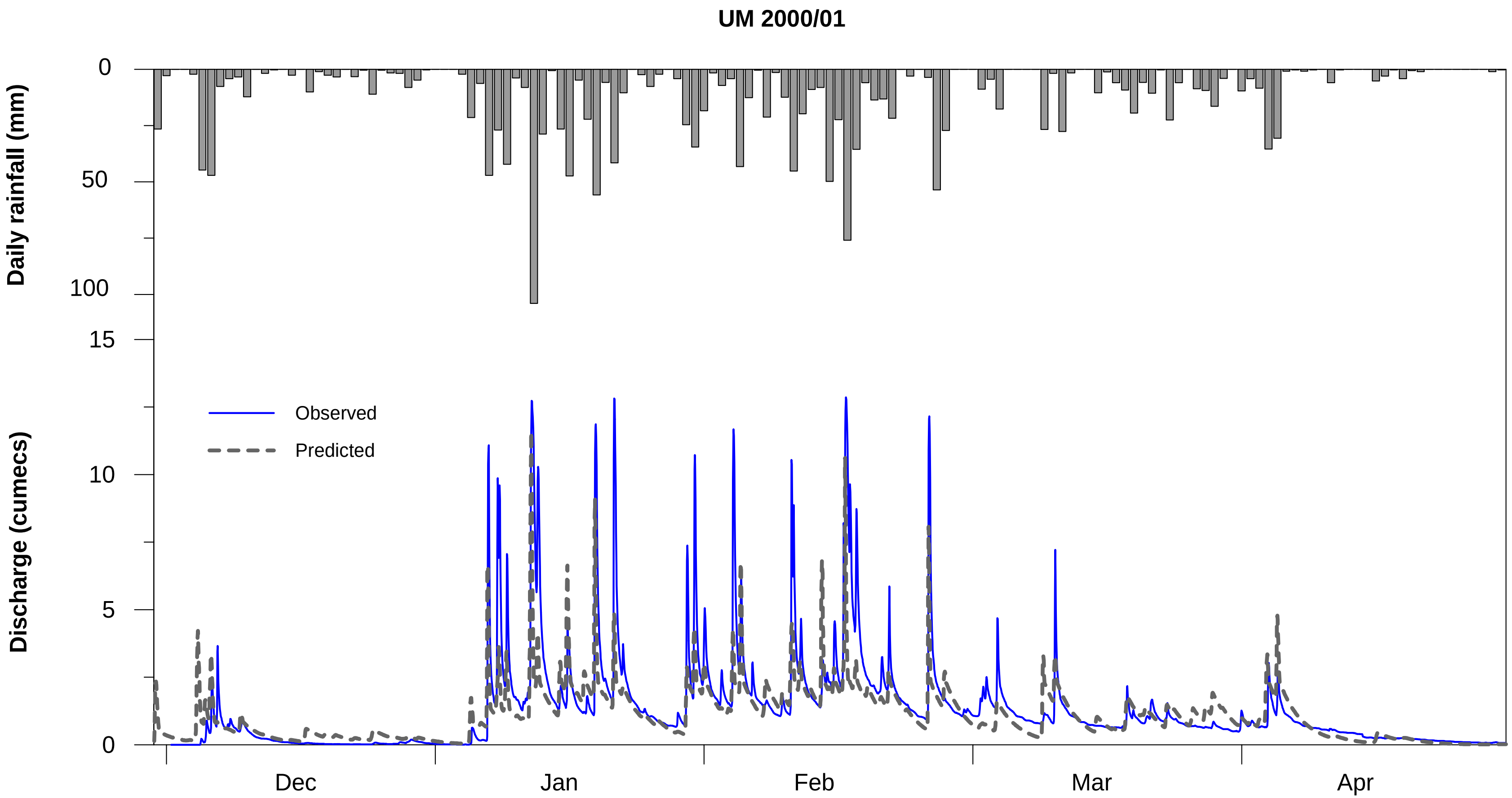

Figure B.2 (continued) Observed and predicted hydrographs at UM using parameters fitted in HEC-HMS (table 4.2).

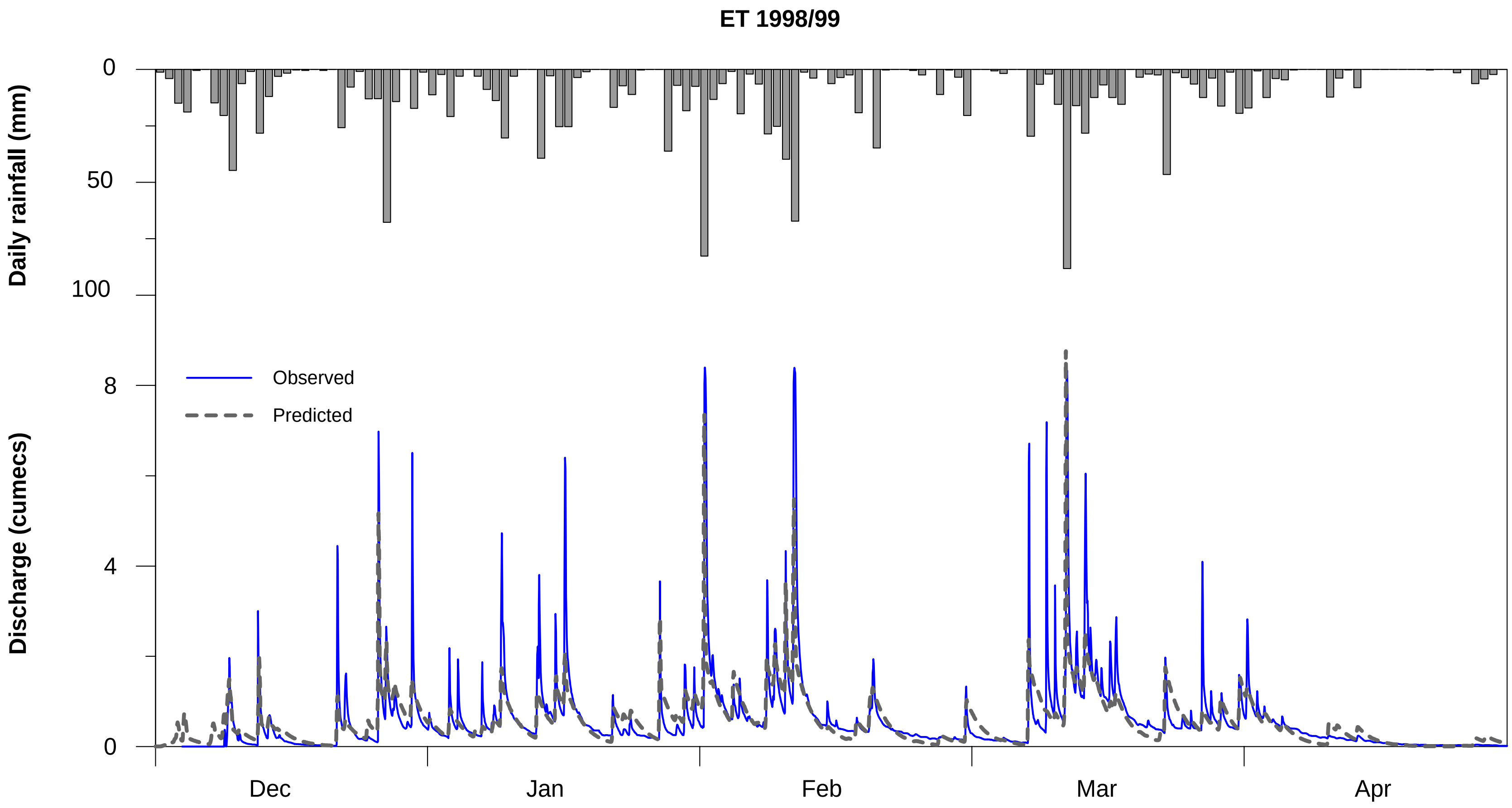

Figure B.3 Observed and predicted hydrographs at ET using parameters fitted in HEC-HMS (table 4.2).

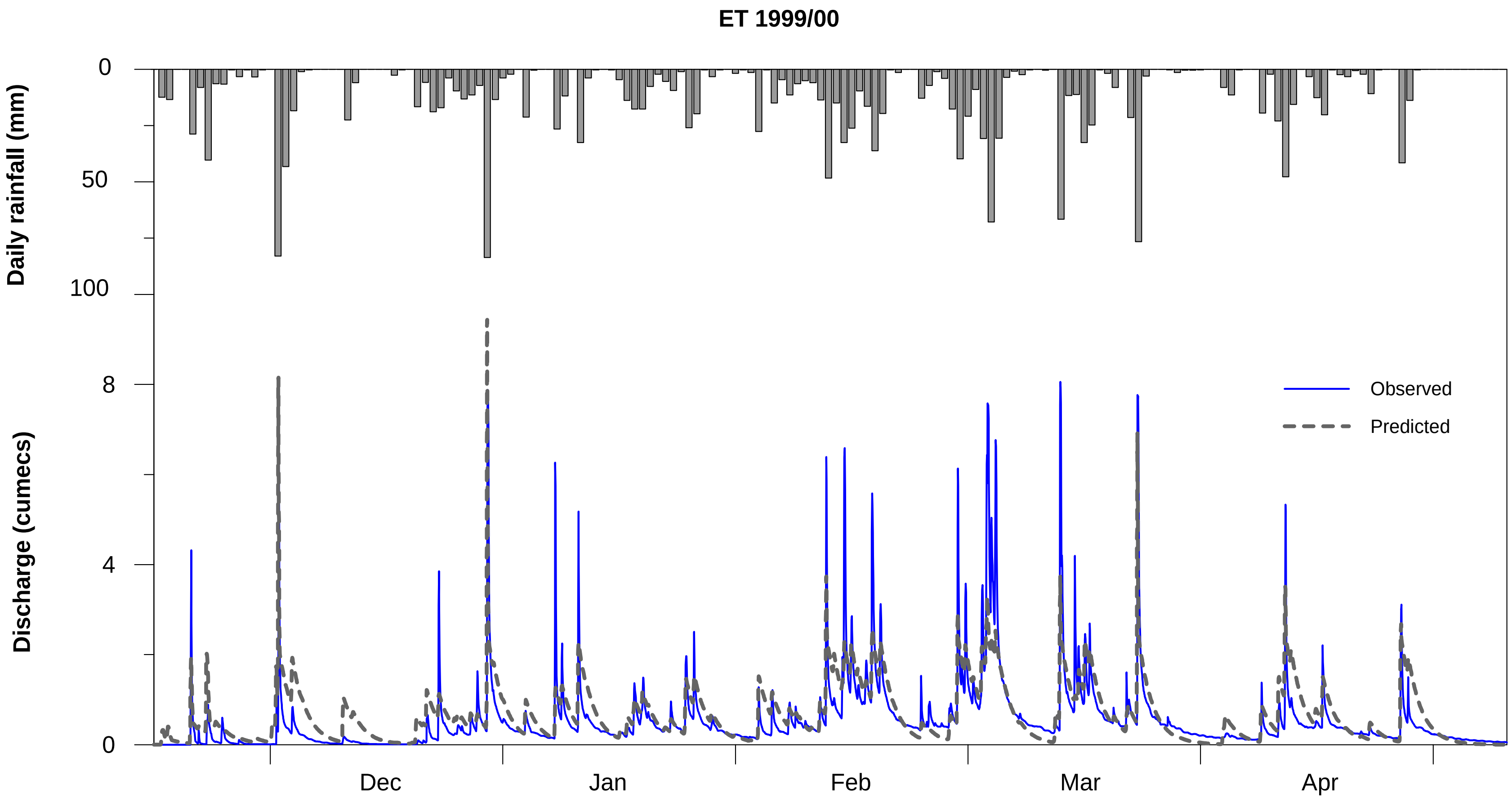

Figure B.3 (continued) Observed and predicted hydrographs at ET using parameters fitted in HEC-HMS (table 4.2).

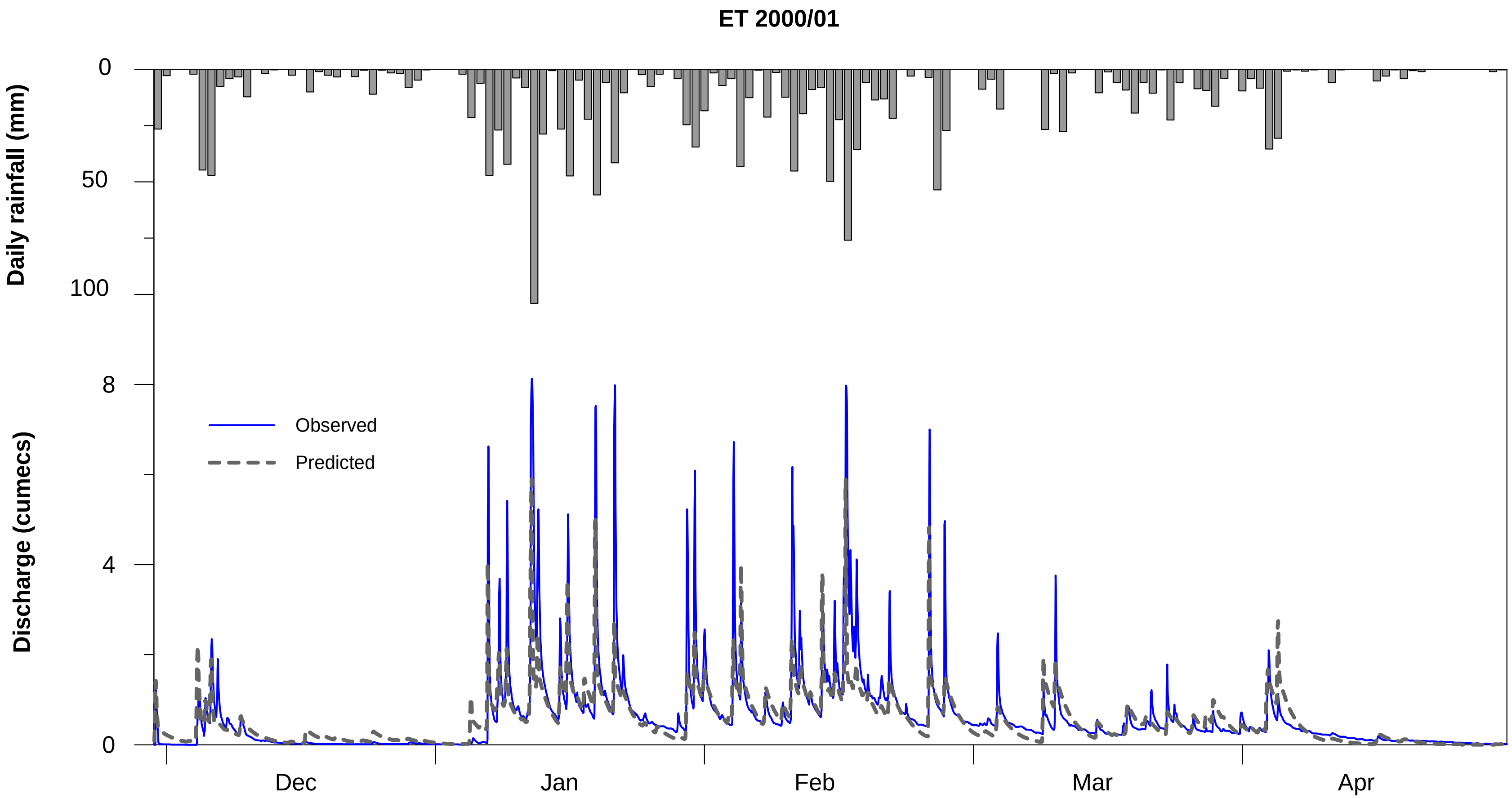

Figure B.3 (continued) Observed and predicted hydrographs at ET using parameters fitted in HEC-HMS (table 4.2)