supervising scientist report **179**

Baseline suspended-sediment, solute, EC and turbidity characteristics for the Ngarradj catchment, Northern Territory, and the impact of mine construction

KG Evans, DR Moliere,
MJ Saynor, WD Erskine
& MG Bellio

Australian Government
Department of the Environment and Heritage
Supervising Scientist

KG Evans – Environmental Research Institute of the Supervising Scientist, GPO Box 461, Darwin NT 0801, Australia

DR Moliere – Environmental Research Institute of the Supervising Scientist, GPO Box 461, Darwin NT 0801, Australia

MJ Saynor – Environmental Research Institute of the Supervising Scientist, GPO Box 461, Darwin NT 0801, Australia

WD Erskine – Centre for Sustainable Use of Coasts and Catchments, School of Applied Science, University of Newcastle, Ourimbah Campus, PO Box 127, Ourimbah NSW 2258 (formerly with the Office of the Supervising Scientist, GPO Box 461, Darwin NT 0801, Australia)

MG Bellio – Environmental Research Institute of the Supervising Scientist, GPO Box 461, Darwin NT 0801, Australia

This report should be cited as follows:

KG Evans, DR Moliere, MJ Saynor, WD Erskine & MG Bellio 2004. *Baseline suspended-sediment, solute, EC and turbidity characteristics for the Ngarradj catchment, Northern Territory, and the impact of mine construction*. Supervising Scientist Report 179, Supervising Scientist, Darwin NT.

The Supervising Scientist is part of the Australian Government Department of the Environment and Heritage.

Supervising Scientist
Department of the Environment and Heritage
GPO Box 461, Darwin NT 0801 Australia

ISSN 1325-1554

ISBN 0 642 24393 X

Printed and bound in Darwin by uniprint NT

Contents

Figures

Tables

Executive summary

A stream gauging network in the Ngarradj catchment, Northern Territory, was established to determine stream baseline conditions to monitor impacts of the Jabiluka mine construction site. Data on stream suspended sediment concentration, electrical conductivity (EC) and turbidity were collected for four wet seasons (1998–2002). The network design enabled the influence of dry season fires on stream suspended sediment concentration to be observed. Water quality trigger values were established using upstream percentiles and a BACIP design using monthly median values. There was very low frequency exceedence of the 99.7th percentile trigger level, however, it cannot be definitively stated that this was due to mine site construction. A late dry season fire occurred contemporaneously with site construction confounding experimental design and elevated sediment loads resulting from the fire may have masked mine site impact. The data set provides good baseline information for future assessment at Jabiluka and demonstrates the need to view measured parameter values on a catchment-wide basis with knowledge of rainfall, discharge and fire distribution.

Acknowledgments

Thank you to Bryan Smith, Gary Fox, Elice Crisp and other ***eriss*** staff who assisted with laboratory and field work in this project. Dr Guy Boggs, Charles Darwin University, and John Lowry, ***eriss***, are thanked for GIS support and assistance with fire mapping. Thank you to Dr Chris Humphrey, ***eriss***, for discussion regarding water quality guidelines and power analysis. Professor Des Walling, University of Exeter, UK, Dr Simon Townsend, Department of Infrastructure, Planning and Environment, Northern Territory, Australia, and Ms Michelle Iles, ***oss***, are thanked for their constructive review of this report.

Baseline suspended-sediment, solute, EC and turbidity characteristics for the Ngarradj catchment, Northern Territory, and the impact of mine construction

KG Evans, DR Moliere, MJ Saynor, WD Erskine & MG Bellio

1 Introduction

In the 1998 dry season, mine construction started on the Jabiluka Mineral Lease located in the Ngarradj catchment, a major right bank tributary of Magela Creek, NT. The Jabiluka Mineral Lease (JML) is adjacent to Kakadu National Park (KNP). The Magela Creek and floodplain are located within KNP, and are listed as Wetlands of International Importance under the Ramsar Convention and recognised under the World Heritage Convention. KNP is one of the largest and most environmentally diverse national parks worldwide and is managed for conservation, tourism and natural and cultural features and values (Kakadu Board of Management & Parks Australia North 1998). Ngarradj has its headwaters on the Arnhem Land Plateau, flows through lowlands within the Jabiluka Mineral Lease, and debouches into the Magela Creek floodplain in KNP (fig 1).

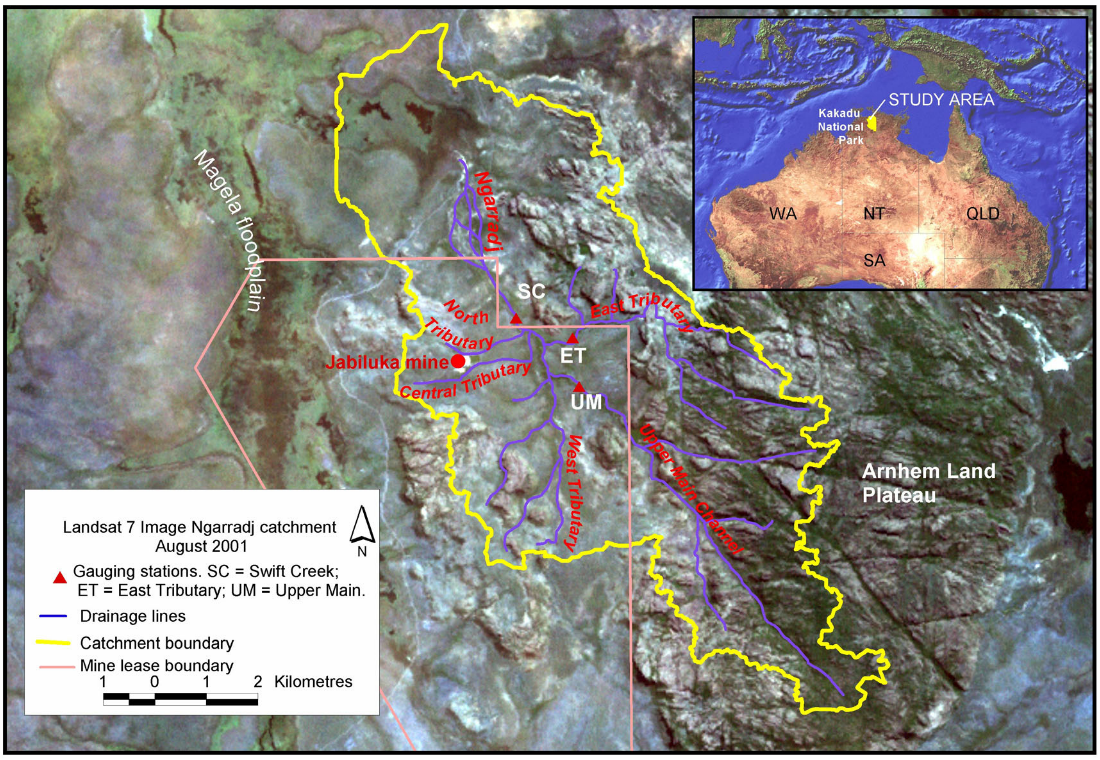


Figure 1 Study site

In the late dry season of 1998 and prior to the 1998–1999 wet season, a stream-monitoring program was implemented in the Ngarradj catchment by the Environmental Research Institute of the Supervising Scientist (***eriss***) (Erskine et al 2001). An important objective of this program was to collect baseline data on sediment movement within the catchment that could be used to develop landform evolution modelling technology (Boggs et al 2001) to assess and proactively manage geomorphic impacts that have the potential to be caused by mining disturbance at Jabiluka and at the nearby ERA Ranger mine. As the project progressed it provided invaluable information to assess environmental impacts through the establishment of water quality trigger values according to the 'Australian and New Zealand Guidelines for Fresh and Marine Water Quality' (ANZECC & ARMCANZ 2000). Previously, stream water chemistry has been characterised for Magela Creek, downstream of Ranger mine (Klessa 2000) and Ngarradj (leGras et al 2001) to establish baseline water quality parameter values. However, these studies did not address suspended sediment concentration.

Data on stream suspended-sediment concentration, electrical conductivity (EC) and turbidity have been collected by ***eriss*** for four wet seasons (1998–2002). This report (1) presents the results of the first four years of stream water quality monitoring in the Ngarradj catchment, (2) determines baseline characteristics of water quality in the catchment and (3) assesses the level of impact on water quality resulting from construction of the mine site.

2 Study site

The region is in the wet dry tropics of the Northern Territory, Australia. High-intensity storms and rain depressions occur between October and April (wet season) with little rain falling during the remainder of the year (dry season). Jabiru Airport, approximately 20 km to the south west of the Jabiluka mine site receives a mean annual rainfall of 1483 mm (σ = 302.5 mm) and Oenpelli, approximately 20 km to the northeast receives a mean annual rainfall of 1397 mm (σ = 284.5 mm) (Bureau of Meteorology 1999).

The Jabiluka uranium ore body is hosted by schist of the Early Proterozoic Cahill Formation and was to be mined as an underground operation. Construction of the mine, completed in the 1998 dry season, included a retention pond, portal and infrastructure such as roads, offices and drainage systems. A small waste rock dump (WRD), comprising Cahill Formation schist and Mamadawerre Formation sandstone[1] and a high-grade mineralised stockpile were also constructed from material removed from the decline. The surface area disturbed as a result of construction was approximately 13.3 ha (McGovern 2003). This construction was located in small sub-catchments to the west of the main Ngarradj channel and it is likely that erosion products from the WRDs will eventually enter Ngarradj (fig 1). The mine has recently been placed in long-term care and maintenance.

The Ngarradj catchment primarily comprises highly weathered Middle Proterozoic Mamadawerre Formation sandstone in the upper reaches, with Tertiary and Quaternary alluvium and colluvium comprising the flood inundated western branch and northern floodplain

---

[1] Previously known as the Kombolgie Formation sandstone and now classified as the Mamadawerre Formation sandstone as a result of a stratigraphic revision (Carson et al 1999).

of the creek. At the mine lease boundary, which crosses the Ngarradj floodplain, more than two thirds of the upstream catchment comprises the sandstone escarpment and its outliers.

The Ngarradj main channel rises in the Mamadawerre Formation sandstone of the Arnhem Land Plateau as a fault-controlled bedrock channel with a meandering sandbed stream in Quaternary sandy lowlands joining the upland channel to a sandy braided reach that forms a black soil backwater flood plain at the confluence with Magela Creek (Erskine et al 2001). There are two major tributaries referred to as East Tributary and West Tributary. East Tributary is the major right bank tributary rising in the Arhnem Land Plateau as a bedrock confined channel and then becomes a meandering sand bed stream in the lowlands. West Tributary is the major left bank tributary rising at the catchment boundary between Ngarradj and 7J Creek to the south. West Tributary is a braided sand bed stream, which joins the main channel at a seasonally inundated backflow billabong. There are three minor left bank tributaries, South, Central and North that drain the mine site catchment. South and Central Tributaries enter Ngarradj through an anabranch that has developed at the confluence of West Tributary and the main channel and rejoins the main channel upstream of the confluence with North Tributary. The discontinuous North Tributary flows directly into Ngarradj.

3 Methods

3.1 Monitoring design

Three river gauging stations were installed in Ngarradj prior to the commencement of the 1998–99 wet season (Saynor et al 2001). Initial aerial photographic and topographic map interpretation was conducted of the catchment to define stream locations and sub-catchment boundaries. Once this was completed intensive ground reconnaissance was conducted based on remotely sensed data interpretation to locate appropriate channel reaches for gauging station installation. The stations were installed as follows (Erskine et al 2001) (fig 1):

- On the main channel upstream of the confluence with West Tributary referred to in this report as UM (Upper Main). Data from the unimpacted catchment upstream of the mine are collected from this site. The UM catchment area was 18.8 km^2.
- On the East Tributary channel upstream of the confluence with the main channel referred to in this report as ET (East Tributary). Data from the unimpacted East Tributary catchment are collected from this site. The ET catchment area was 8.5 km^2.
- On the main channel near the northern lease boundary referred to in this report as SC (Swift Creek). This station is downstream of the mine site and the major and minor tributaries and collects JML data (fig 2). The SC catchment area was 43.6 km^2.

It was not possible to install a station on West Tributary due to the braided nature of the channel. Therefore, the experimental design is that changes in the western part of the catchment where the mine is located should be seen downstream at SC through comparison with the upstream UM and ET data.

The gauging stations comprise a gauge post, stilling well, logger housing, stage-activated automatic pump sampler (APS) with a fixed inlet level, shaft encoder and pressure transducer, rain gauge and gauging wire (Saynor et al 2001). Two APSs were installed at SC in 1998 and one each at ET and UM. A second APS was installed at ET and UM prior to the 2000–01 wet season. Each sampler has the capacity to collect 24 1-litre samples and was set to sample the rising and falling stage of the hydrograph of a discharge event. More samples were collected on the rising stage of the hydrograph than on the recession as it has been shown by several studies in the Kakadu region that suspended sediment concentration often peaks before the hydrograph (Duggan 1991, Moliere et al 2004a) which has been attributed to sediment depletion during runoff events (Walling & Webb 1982, Williams 1989). Sampling intervals during the rising stage of the hydrograph were generally less than 1 h and were often 6 minutes (the minimum sampling interval), particularly during intense storm events when stream stage increased rapidly. The inlet of each APS is purged prior to sampling. The samples were retrieved from the field once each week during the wet season. The second APS at the sites allowed an even sampling coverage at the sites throughout the wet season.

Figure 2 SC gauging station. A second APS is shown located outside the shelter.

3.2 Measured parameters

The samples were generally collected from the APSs once a week. Within the following week after field collection, the water samples were analysed in the laboratory using standard sediment filtering and water chemistry techniques (Eaton et al 1995). Parameters measured were coarse suspended-sediment (>63 μm diameter); fine suspended-sediment (silt+clay) (<63 μm >0.45 μm diameter) and solutes (<0.45 μm diameter); and water quality parameters of turbidity and electrical conductivity (EC). All water samples were analysed first for electrical conductivity and turbidity before being wet sieved through a 0.063 mm sieve to determine the coarse suspended-sediment concentration. The fine suspended-sediment concentration in the remainder of the sample was determined by filtration through a cellulose nitrate filter paper (0.45 μm diameter). The solute concentration was then determined on the filtrate.

Solute concentration data derived from water samples collected during the first two years of the four year monitoring period (1998/99 and 1999/00 wet seasons) were considered unreliable and were not used in the analysis. During these first two years, the preparation procedure for the aluminium foil containers (which the filtrate was poured into for oven-drying) was found to be inadequate. Prior to the third year of sampling, this procedure was refined and the solute concentration data collected during the 2000–01 and 2001–02 wet seasons were considered to be reliable.

3.2.1 Lower limit of detection for fine suspended-sediment concentration

Laboratory techniques can affect the precision and accuracy of contaminant concentration measurements. In earlier studies in the region, using similar filtering techniques, the lower limit of detection (LLD) for suspended solids was found to be 1.2 mg L^{-1} (Cusbert 1990).

In this study the LLD for fine suspended-sediment has been determined as (Westgard 2000):

$$LLD = mean_{blk} + Zs_{blk},$$

where $mean_{blk}$ = the mean contaminant concentration in blank samples of dionised water, Z = 2 and s_{blk} is the standard deviation of blank sample concentrations.

Twelve blank samples of deionised water were filtered and the oven-dried weights of the filter papers, pre- and post-filtering, were determined. The $mean_{blk}$ and s_{blk} were determined and used to derive an LLD of 3 mg L^{-1}.

3.3 Data reduction and analysis

Data were checked and stored in the hydrological data management software package HYDSYS. When entered in to HYDSYS, the data were rounded and stored to 3 decimal places as g L^{-1}. Therefore, values of 0 indicate a data point < 0.0005 g L^{-1} (0.5 mg L^{-1}) as these values would have been rounded to 0 g L^{-1}. In the suspended sediment data it is unlikely that the concentration is 0 mg L^{-1} although the real concentration may be so low it is not detectable. A value of 0.3 mg L^{-1} (the mean of values <0.5 mg L^{-1} rounded up) was substituted for values <0.5 mg L^{-1}, which otherwise were recognised as 0 in HYDSYS, for the purposes of initial data manipulation using log-transformations. Data less then the LLD of 3 mg L^{-1} have not been changed and are included in the analyses as these are real values although their precision is not as good as values ≥3 mg L^{-1}.

Descriptive statistics and frequency distributions of all data for each parameter for each site were determined using MINITAB Release 13. MINITAB uses an Anderson-Darling normality test with a test statistic, $A^2_{0.05} = 2.49$, to determine if the data are normally distributed with 95% confidence. Descriptive statistics were determined for each annual data set and the mean and standard deviation were determined for each monthly data set. Box plots are used to assess the distribution of monthly data.

4 Measured parameter values

4.1 Coarse suspended-sediment

Coarse suspended-sediment is the sand sized (>63 µm diameter), which moves along the stream-bed partly in suspension and by saltation. Full data sets showing the variability of coarse suspended-sediment concentration, [CSS], with rainfall and stream discharge are given in Appendix A. Descriptive statistics and distributions for the full data set for each site are shown in figures 3a to 3c.

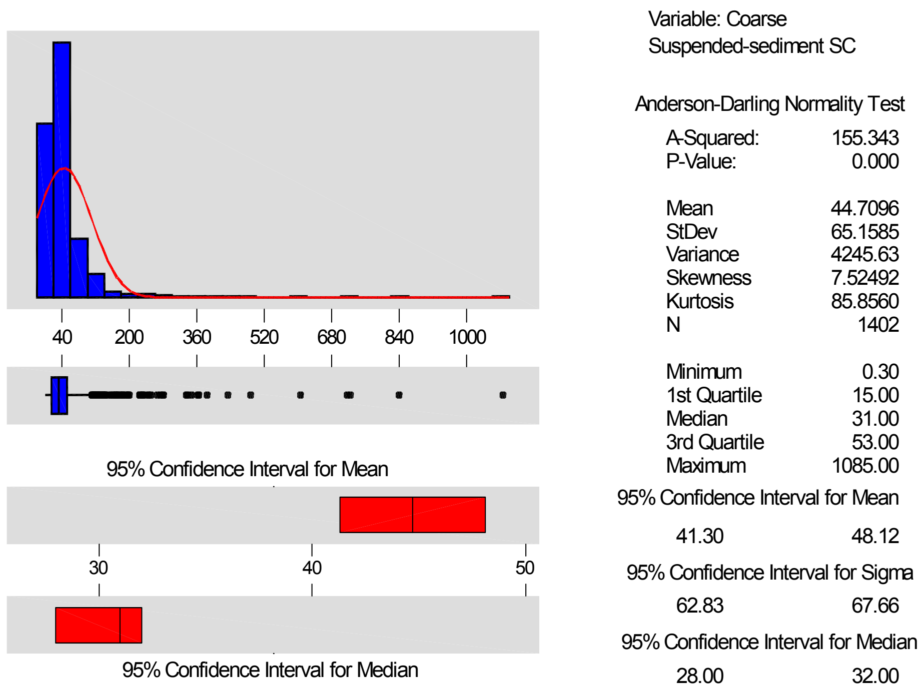


Figure 3a Descriptive statistics and frequency distribution for [CSS] at SC for 1998–2002

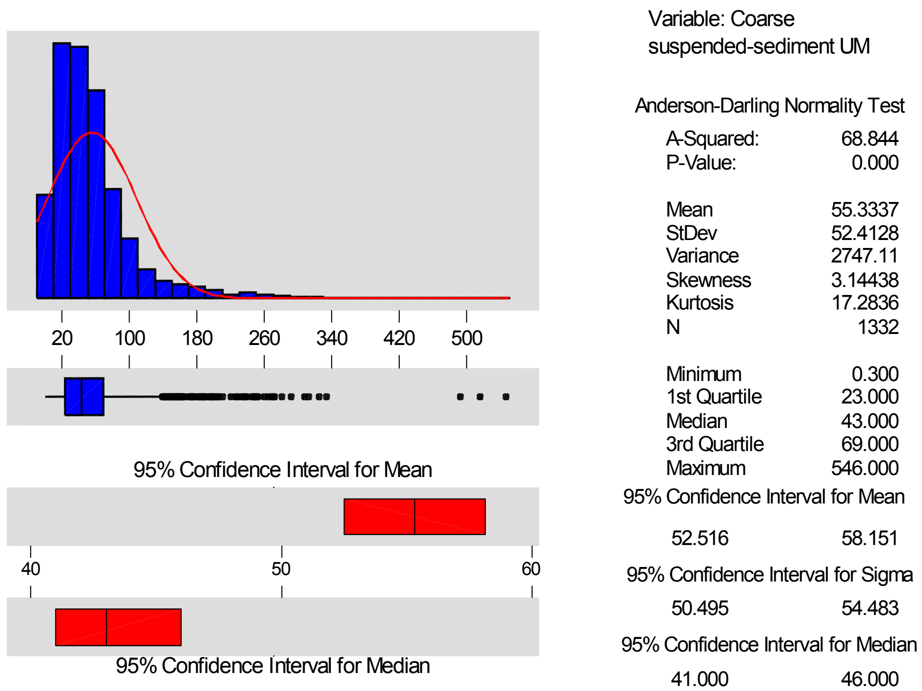


Figure 3b Descriptive statistics and frequency distribution for [CSS] at UM for 1998–2002

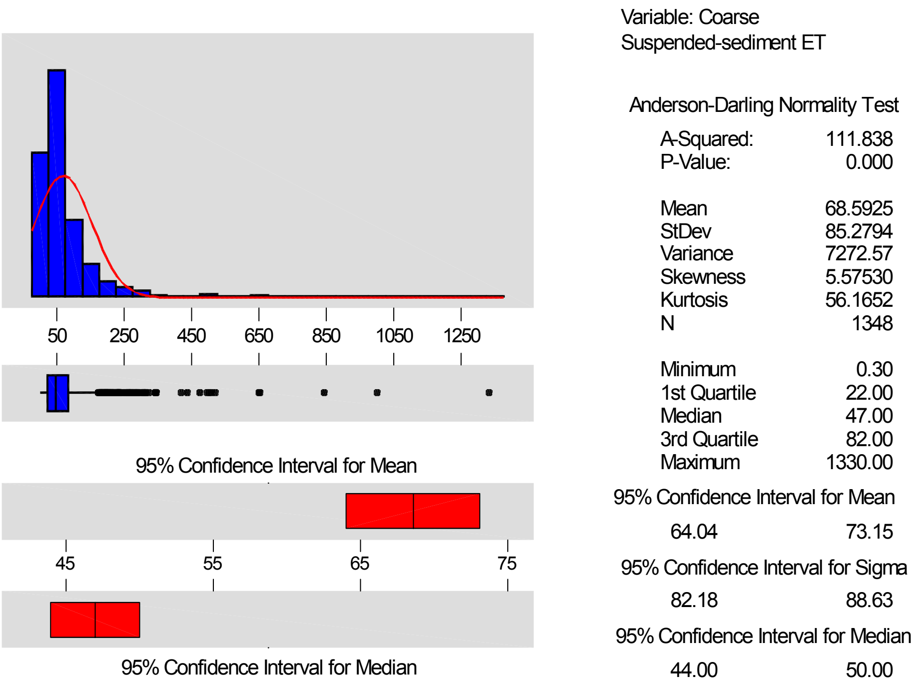


Figure 3c Descriptive statistics and frequency distribution for [CSS] at ET for 1998–2002

The mean coarse suspended-sediment concentration $\overline{[CSS]}$ reduces from the smallest catchment, ET, to the largest, SC, indicating that $\overline{[CSS]}$ is inversely proportional to catchment size. The normal distribution curves based on the descriptive statistics are shown in fig 3, however, the data distributions are positively skewed at all sites with $A^2 > 2.49$ indicating that [CSS] is not normally distributed at any site. The data could not be $\log_{10}$ transformed to achieve a normal distribution based on $A^2_{0.05} = 2.49$ at any site. This analysis shows a number of outliers at each site.

The annual descriptive statistics are presented in table 1. In general, as with the complete data sets (fig 3), the annual mean coarse suspended-sediment concentration, $\overline{[CSS]}_a$, increased from the largest SC catchment to the smallest ET catchment, which conforms with sediment delivery ratio theory (Robinson 1977, Walling 1983). Since monitoring commenced, there has been a yearly increase in $\overline{[CSS]}_a$ at SC resulting in a 276% rise in 2001–02 from 1998–99 levels. Apart from minor variability this magnitude of increase in $\overline{[CSS]}_a$ has not been observed at UM or ET sites where $\overline{[CSS]}_a$ increased by 28% and 15% respectively from 1998–99 to 2001–02.

Monthly statistics are presented in table 2 and figure 4. The mean monthly coarse suspended-sediment concentration $\overline{[CSS]}_m$ ranges are reasonably consistent on a catchment-wide basis from 1998–99 to 2000–01 during the principal flow months of January, February and March. These ranges have elevated and narrowed on a catchment-wide basis at all sites in 2001–02. At SC there is a consistent increase in $\overline{[CSS]}_m$ between years apart from December. For January there was an increase $\overline{[CSS]}_m$ from 1998–2002 of 156% and for February and March at SC an increase from 1998–2002 of 262% and 131% respectively. In April the increase was 150% from 1998–2001. No events were recorded in April in 2001–02. Similar consistent increases have not been observed at UM and ET where $\overline{[CSS]}_m$ is more variable between years.

Table 1 Descriptive statistics for annual coarse suspended-sediment concentration (mg L^{-1})

Site/Year	*n*	$\overline{[CSS]}_a$	σ	S_k	*Median*	*Mode*	*Min*	*Max*	*Flow duration* *Start*	*Finish*
SC 98-99	377	29	32	6.0	23	4	0.3	432	09/12	20/04
SC 99-00	449	36	42	4.0	25	26	0.3	364	22/11	28/04
SC 00-01	399	46	41	1.9	37	11	1	274	28/11	06/04
SC 01-02	177	98	141	4.3	55	38	16	1085	31/12	09/03
UM 98-99	313	57	52	3.2	46	35	0.3	492	14/12	13/04
UM 99-00	411	49	57	3.1	31	12	0.3	515	20/11	26/04
UM 00-01	418	52	45	2.2	41	13	2	333	04/12	09/04
UM 01-02	190	73	54	4.7	59	52	27	546	31/12	11/03
ET 98-99	350	71	65	1.8	56	8	0.3	344	21/12	27/04
ET 99-00	411	73	124	5.3	38	10	0.3	1330	20/11	25/04
ET 00-01	389	55	51	1.7	39	3	1	261	28/11	02/04
ET 01-02	198	82	64	1.9	62	61	4	344	31/12	10/03

n = count; $\overline{[CSS]}_a$ = sample mean (mg L^{-1}); σ = sample standard deviation (mg L^{-1}); S_k = skewness.

SC flowed at a higher $\overline{[CSS]}_a$ than the other two sites in 2001–02 although $\overline{[CSS]}_a$ was elevated at all sites. Based on the experimental design, this indicates that the increased coarse suspended-sediment could be derived from the western section of the catchment where the mine is located. The authors are unaware of any mine-related disturbance in the catchment in the 2001 dry season that would account for the elevation in $\overline{[CSS]}_a$. However, Saynor et al (2002a,b) using scour chains and cross section measurements found that the stream bed at SC had aggraded during the 3 years of monitoring from 1998 to 2001. The same rate of aggradation was not observed at UM and ET. This does not explain the elevated $\overline{[CSS]}_a$ at ET and UM. The main reason for the elevated $\overline{[CSS]}_a$ at each site is due to the first flush storm on 31 Dec 2001. This was a very unusual event – normally the first flush of flow is not a result of such an intense storm. $\overline{[CSS]}_m$ for December is very high at each site (table 2), which has, in turn, elevated the $\overline{[CSS]}_a$. The increase in $\overline{[CSS]}_a$ at SC is greater than the other sites because of the additional fire impact, which occurred late in the 2001 dry season, downstream of UM and ET.

Aggradation of the bed at SC means that the bed would be getting closer to the inlet of the auto-sampler, which would result in an increase in coarse suspended-sediment entering the inlet. During the rising stage of the annual hydrograph in December/January, much of the sand bed is scoured and deposited downstream. Sub-aqueous sand dunes move through the system during the wet with discrete events. As the wet season finishes in March/April the annual hydrograph recedes, depositing sand in the bed to the new aggraded level. Therefore, it is expected that $\overline{[CSS]}_a$ would increase during the later months of March and April and the later years. This is observed in the monthly data (figure 4) and is more obvious in Appendix A – 2000–01 (but not so in the other years).

Table 2 Monthly average and standard deviation for coarse suspended-sediment concentration (mg L^{-1})

Site/Year	Nov			Dec			Jan			Feb			March			April		
	$\overline{[CSS]}_m$	σ	*n*	$\overline{[CSS]}_m$	σ	*n*	$\overline{[CSS]}_m$	σ	*n*	$\overline{[CSS]}_m$	σ	*n*	$\overline{[CSS]}_m$	σ	*n*	$\overline{[CSS]}_m$	σ	*n*
SC 98-99				41	52	81	24	20	139	21	20	38	31	24	111	30	45	8
SC 99-00	11	7	6	31	37	73	26	20	103	40	36	113	36	38	96	54	75	58
SC 00-01	11	6	4	17	23	21	31	37	138	53	37	138	60	45	71	75	44	27
SC 01-02				543[1]	299	10	59	49	25	76	68	114	63	14	28			
UM 98-99				58	24	44	41	46	101	91	64	50	53	33	111	37	12	7
UM 99-00	77	115	37	32	28	81	40	34	89	53	49	73	70	64	97	21	14	34
UM 00-01				11	8	25	49	40	187	63	55	141	53	29	51	45	17	14
UM 01-02				138[1]	83	19	74	74	47	65	29	98	56	15	25			
ET 98-99				54	54	51	88	72	106	77	69	75	61	55	112	7	3	6
ET 99-00	297	369	26	82	91	78	54	82	66	48	45	91	65	45	92	35	29	58
ET 00-01	37	51	12	6	3	30	70	59	189	45	38	92	48	31	56	84	28	10
ET 01-02				149[1]	104	11	22	13	23	88	65	129	77	24	35			

[1] First flush.

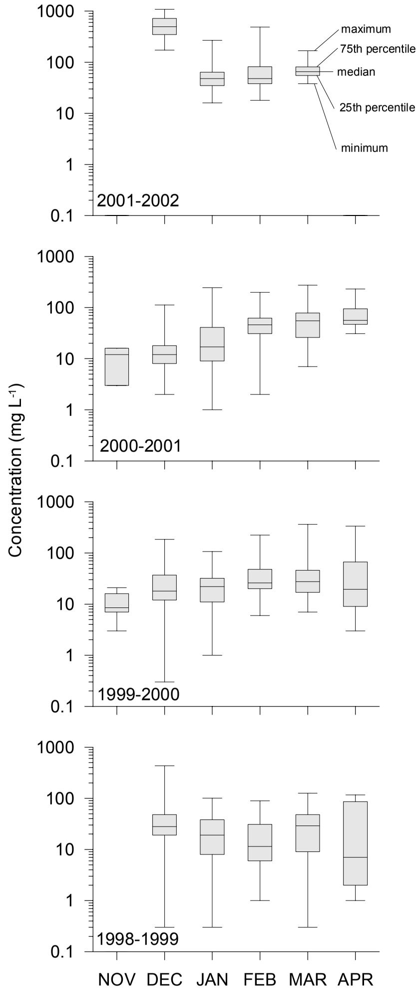


Figure 4a Monthly coarse suspended-sediment distribution in SC

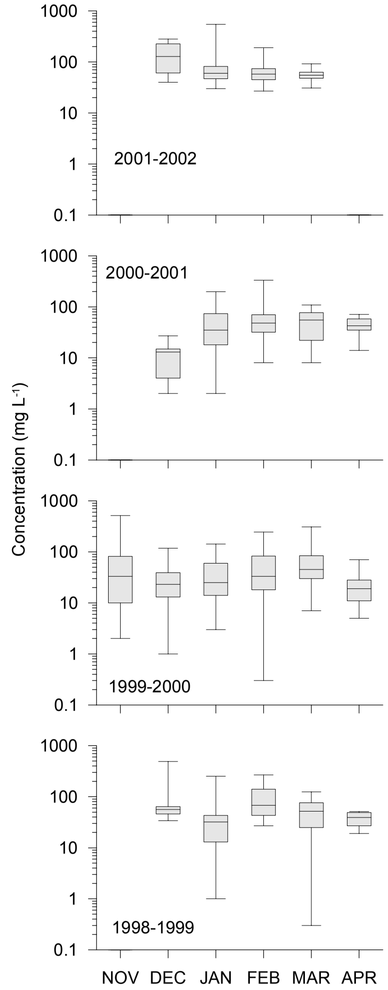


Figure 4b Monthly coarse suspended-sediment distribution in UM

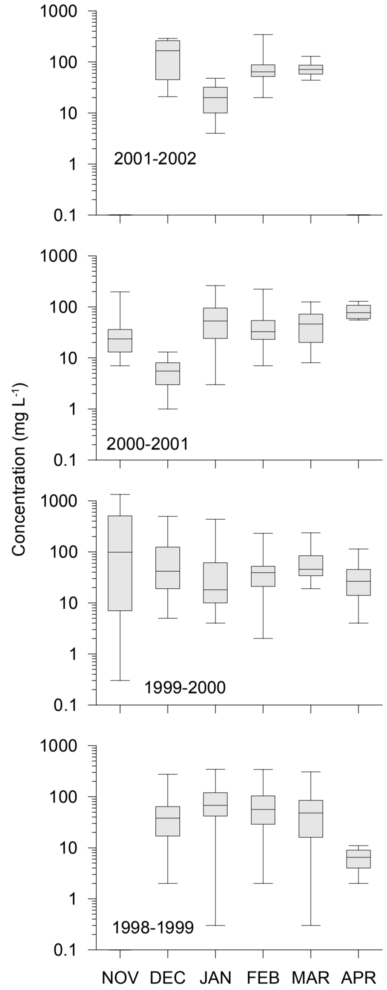


Figure 4c Monthly coarse suspended-sediment distribution in ET

Further work is required to determine the contribution of bedload to the main channel by the left bank mine site Tributary Central and Tributary North to determine if an impact is occurring. Saynor et al (2002a,b) have observed active erosion in Tributary North. Field inspections indicate that a tributary-mouth bar is forming in the main channel at the outlet of Tributary North and further assessment is required to confirm the influence of Tributary North erosion on SC aggradation through comparisons of volume of erosion in Tributary North and deposition at SC. The cause of the aggradation at SC may be a shift upstream in the locus of deposition resulting from larger than average wet seasons during the monitoring period causing stressed back flow relationships at the confluence of Ngarradj and Magela Creek. The location of the inlet to the sampler needs to be reassessed on an annual basis dependent on aggradation rate.

4.2 Fine suspended-sediment

Fine suspended-sediment is the silt + clay fraction (<63 μm >0.45 μm diameter), which is an important indicator of stream health because it is associated with contaminant transport, increases in turbidity and adverse affects on aquatic ecosystems (Walling & Webb 1985, Neal et al 1999, Pentz & Kostaschuk 1999, Bonta 2000). Full data sets showing the variability of fine suspended-sediment concentration, [FSS], with rainfall and stream discharge are given in Appendix B. Descriptive statistics and distributions for the full data set for each site are shown in figures 5a to 5c. At SC, 446 samples, at UM, 371 samples, and at ET, 339 samples were ≤ LLD of 3 mg L^{-1}. These were 31.8%, 28.1% and 25.3% of the total samples collected at SC, UM and ET respectively. The mean fine suspended-sediment concentration, $\overline{[\mathrm{FSS}]}$, reduces from the smallest catchment, ET, to the largest, SC, indicating that $\overline{[\mathrm{FSS}]}$ is inversely proportional to catchment size. But $\overline{[\mathrm{FSS}]}$ at SC and UM are very similar being 10.3 (σ = 16.1) mg L^{-1} and 10.4 (σ = 11.8) mg L^{-1} respectively. The normal distribution curves based on the descriptive statistics are shown in figure 5, however, the data distributions are positively skewed at all sites and $A^2 > 2.49$ indicating that [FSS] is not normally distributed at any site. The data could not be $\log_{10}$ transformed to achieve a normal distribution based on $A^2_{0.05} = 2.49$ at any site. This analysis shows a number of outliers at each site.

The annual descriptive statistics are presented in table 3. In general, annual mean fine suspended-sediment concentration, $\overline{[\mathrm{FSS}]}_a$, increased from the largest catchment (SC) to the smallest catchment (ET), which conforms to sediment delivery ratio theory (Robinson 1977, Walling 1983). At SC, $\overline{[\mathrm{FSS}]}_a$ decreased by 56% from 16 mg L^{-1} to 7 mg L^{-1} from 1998–99 to 1999–2000 and remained constant from 1999–2000 to 2000–01 and then increased by a similar percentage from 2000–01 to 2001–02. At UM, $\overline{[\mathrm{FSS}]}_a$ remained relatively constant from 1998–2002 with a 22% increase from 1998–99 to 1999–00, which is only 2 mg L^{-1}. Concentration at ET remained constant for the first two seasons and decreased by 65% from 1999–2000 to 2000–01. At ET the concentration increased from 2000–01 to 2001–02 but only by 5 mg L^{-1}. Annual $\overline{[\mathrm{FSS}]}_a$ at SC in 1999–2000 and 2000–01 is less than UM and ET although ET $\overline{[\mathrm{FSS}]}_a$ had decreased in 2000–01.

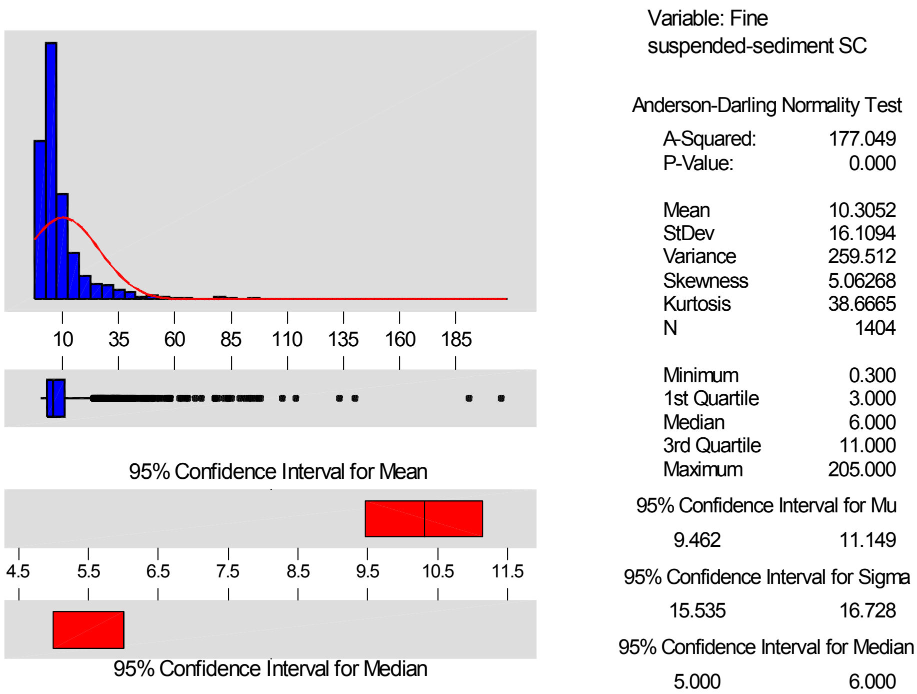


Figure 5a Descriptive statistics and frequency distribution for [FSS] at SC for 1998–2002

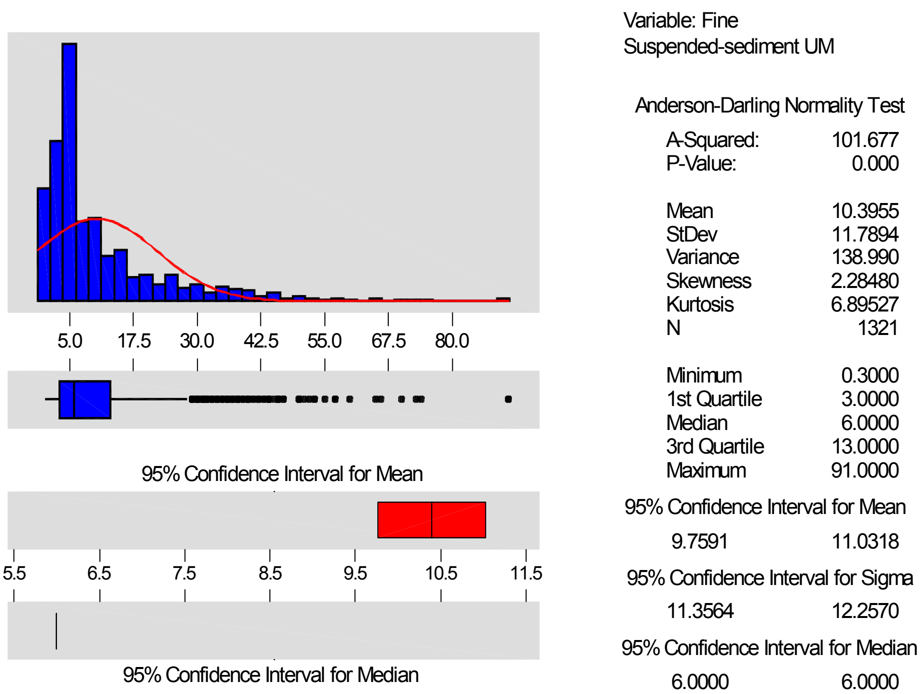


Figure 5b Descriptive statistics and frequency distribution for [FSS] at UM for 1998–2002

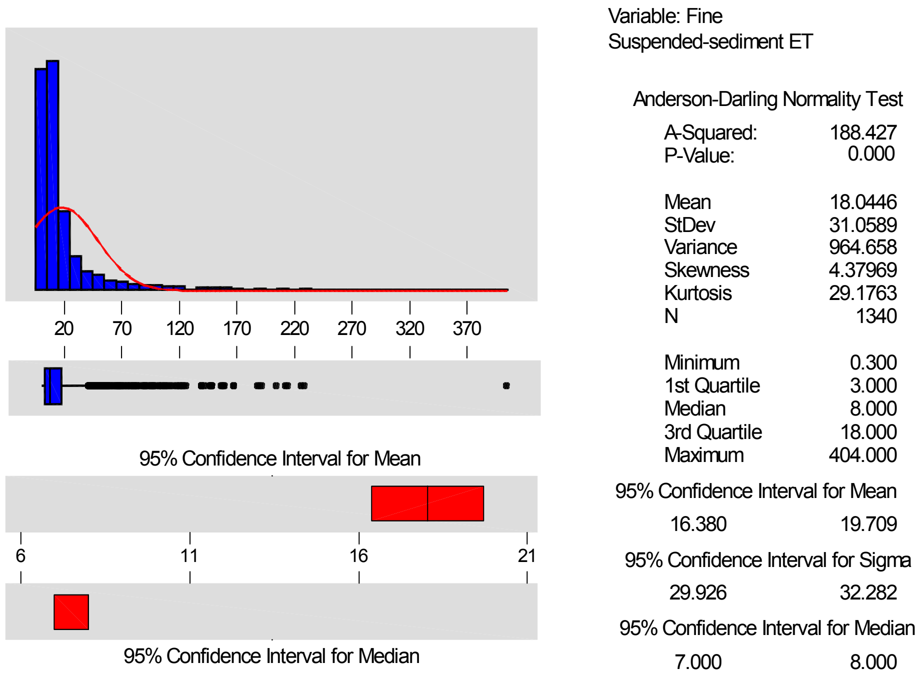


Figure 5c Descriptive statistics and frequency distribution for [FSS] at ET for 1998–2002

Table 3 Descriptive statistics for annual fine suspended-sediment concentration (mg L^{-1})

Site/Year	Untransformed								Flow duration	
	n	$\overline{[FSS]}_a$	σ	S_k	Median	Mode	Min	Max	Start (dd:mm)	Finish (dd:mm
SC 98-99	374	16	20	2.3	8	6	0.3	108	9/12	20/04
SC 99-00	451	7	9	3.1	5	2	0.3	69	22/11	28/04
SC 00-01	402	7	6	2.4	4	3	0.3	44	28/11	06/04
SC 01-02	177	15	29	4.4	7	4	0.3	205	31/12	09/03
UM 98-99	299	9	10	2.2	6	2	0.3	65	14/12	08/04
UM 99-00	411	11	10	1?	6	2	0.3	52	20/11	26/04
UM 00-01	421	11	13	2.5	6	3	1	91	04/12	09/04
UM 01-02	190	11	13	2.5	6	6	0.3	74	31/12	11/03
ET 98-99	343	26	39	4.3	12	4	0.3	404	21/12	27/04
ET 99-00	410	23	34	2.8	10	4	0.3	226	20/11	25/04
ET 00-01	389	8	11	3.7	4	3	1	88	28/11	02/04
ET 01-02	198	13	28	5.3	6	2	0.3	228	31/12	10/03

n = count; $\overline{[FSS]}_m$ = sample mean (mg L^{-1}); σ = sample standard deviation (mg L^{-1}); S_k = skewness.

Monthly statistics are presented in table 4 and figure 6. After the first flush where concentrations are generally elevated, monthly mean fine suspended-sediment concentration, $\overline{[FSS]}_m$, at SC reached a relatively constant level of about 7 mg L^{-1} by January 2000 and 2001, February 1999 and March 2002. These are considered to be pre-disturbance baseline levels at the downstream SC site. There was a first-flush elevation of concentration in

December 2001 and January of 2002. $\overline{[FSS]}_m$ reduced to about 4 mg L^{-1} in April in all years. In 1998–99 $\overline{[FSS]}_m$ at SC was elevated to 28 mg L^{-1} and 16 mg L^{-1} in December and January respectively but $\overline{[FSS]}_m$ was returning to baseline levels by February/March. First-flush $\overline{[FSS]}_m$ at SC in 2001–02 were 105 mg L^{-1} and 16 mg L^{-1} in December and January respectively. The event recorded in December 2001 at SC started on 31/12/01 and continued to 01/01/02 (Appendix B). At UM, $\overline{[FSS]}_m$, is reasonably consistent between years during the monitoring seasons, although slightly less in December, January and February (fig 6). There is first-flush evidence at UM in December 2001 where $\overline{[FSS]}_m$ is 39 mg L^{-1}. This is much less than that recorded at SC for the same period. There is little consistency in $\overline{[FSS]}_m$ at ET between years and months although 1998–99 follows similar trends as 2000–01 but at an elevated level (fig 4).

The $\overline{[FSS]}_m$ levels at UM and SC are reasonably consistent during the monitoring years during the principal flow months of January, February and March apart from January 1998–99 and 2001–02 at SC. The highest $\overline{[FSS]}_m$ at SC during the monitoring period was the December 2001 first flush. At ET, $\overline{[FSS]}_m$ is quite variable between years but displays a general trend of gradually declining from January toward the end of the wet season. The highest $\overline{[FSS]}_m$ at ET was in January 1999.

At SC, $[FSS]$ for 1999–2000 and 2000–01 have very similar distribution. The elevated $\overline{[FSS]}_a$ at SC in 1998–99 and 2001–02 and $\overline{[FSS]}_m$ values at SC in December 1998 and 2001 and January 1999 and 2002 were not observed at UM or ET. The source appears to be the western part of the catchment where two major impacts occurred during the 1998 dry season prior to monitoring. These were the construction of the mine and an extremely hot fire that burnt most of the western catchment (fig 7) in the late dry season. A fire also occurred in the 2001 dry season (fig 7). There was no further mine disturbance but a very intense storm early in the season resulted in high concentrations in the first flush. Both fires had little impact on UM or ET. The Kakadu lowlands are highly vulnerable to construction and mining disturbance (Duggan 1988). There have been a number of studies, which found that significant increases in erosion occur post-fire, which would subsequently result in elevated stream sediment concentrations (Atkinson 1984, Zierholz et al 1995, Evans et al 1999, Townsend & Douglas 2000). The effects of fire do not appear to affect the descriptive statistic determined using all data (fig 5). Based on these data it is difficult to separate the effects of mine construction and fire, however, the longer-term data indicate no apparent continuous elevation of [FSS] that might be due to mine construction.

Fine suspended-sediment concentrations at UM and SC appear to have similar responses to natural catchment conditions, but ET concentrations appear to change independently.

Table 4 Monthly average and standard deviation for fine suspended-sediment concentration (mg L^{-1})

Site/Year	*Nov*			*Dec*			*Jan*			*Feb*			*March*			*April*		
	$\overline{[FSS]}_m$	σ	*n*	$\overline{[FSS]}_m$	σ	*n*	$\overline{[FSS]}_m$	σ	*n*	$\overline{[FSS]}_m$	σ	*n*	$\overline{[FSS]}_m$	σ	*n*	$\overline{[FSS]}_m$	σ	*n*
SC 98-99				28	23	81	16	22	137	8	9	38	10	10	110	4	2	8
SC 99-00	1.4	0.7	6	11	12	77	7	7	102	7	8	111	7	10	96	4	3	59
SC 00-01	9	5	4	3	1	21	8	7	139	7	7	139	5	3	72	5	4	27
SC 01-02				105	62	10	16	13	25	10	14	102	5	3	40			
UM 98-99				8	10	43	7	9	93	10	11	50	10	10	107	6	6	6
UM 99-00	10	13	37	12	10	81	12	12	89	13	12	73	8	7	97	6	4	34
UM 00-01				4	2	25	13	13	187	12	16	144	8	7	51	4	2	14
UM 01-02				39	19	19	12	10	47	6	5	99	3	3	25			
ET 98-99				28	40	52	41	59	101	19	19	74	16	15	110	5	4	6
ET 99-00	7	6	26	29	37	77	13	16	66	26	35	91	33	47	92	17	19	58
ET 00-01	8	5	13	4	2	30	10	14	189	7	6	91	7	8	56	3	1	10
ET 01-02				12	7	11	7	4	23	17	34	129	6	6	35			

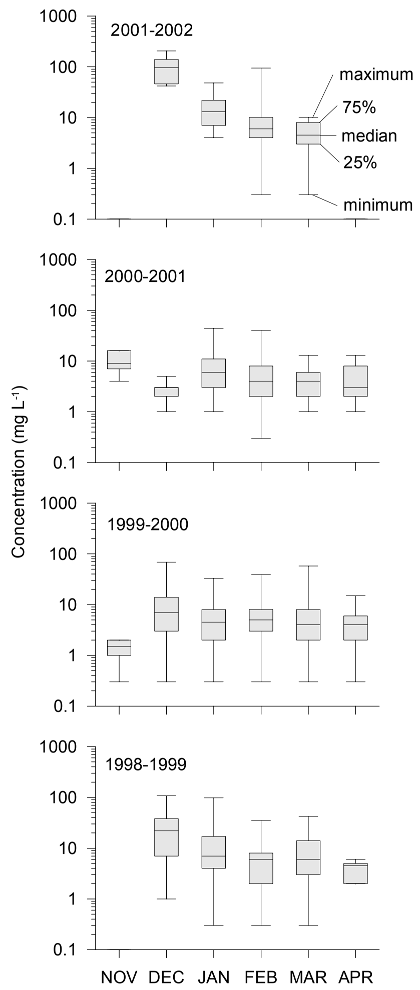


Figure 6a Monthly fine suspended-sediment distribution in SC

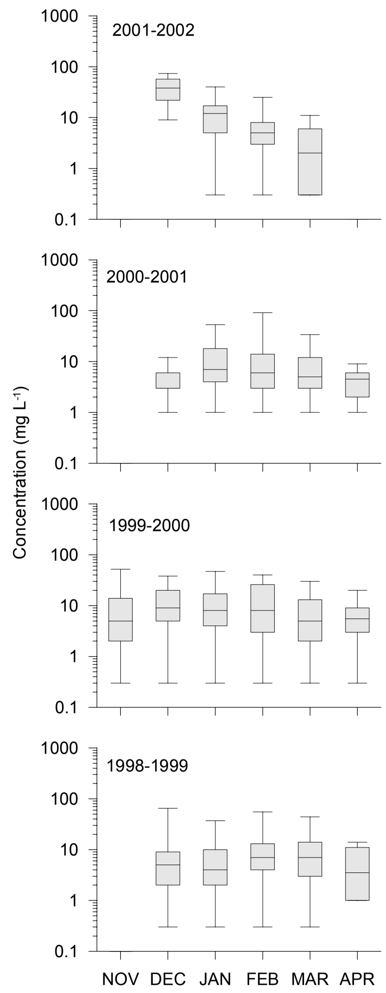


Figure 6b Monthly fine suspended-sediment distribution in UM

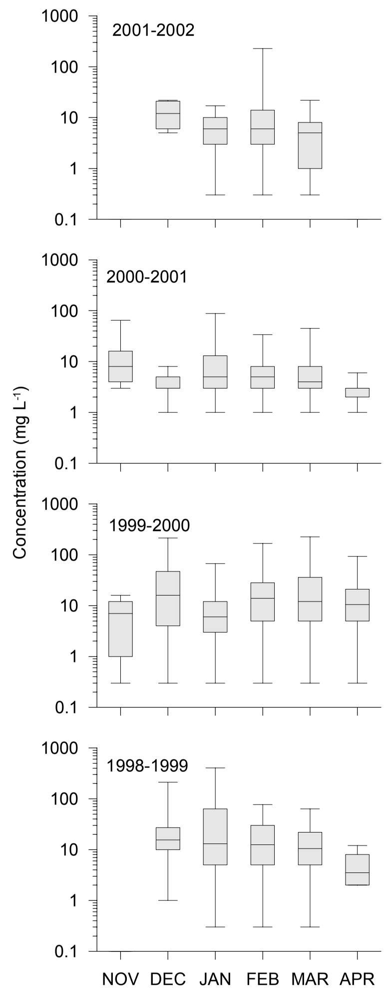


Figure 6c Monthly fine suspended-sediment distribution in ET

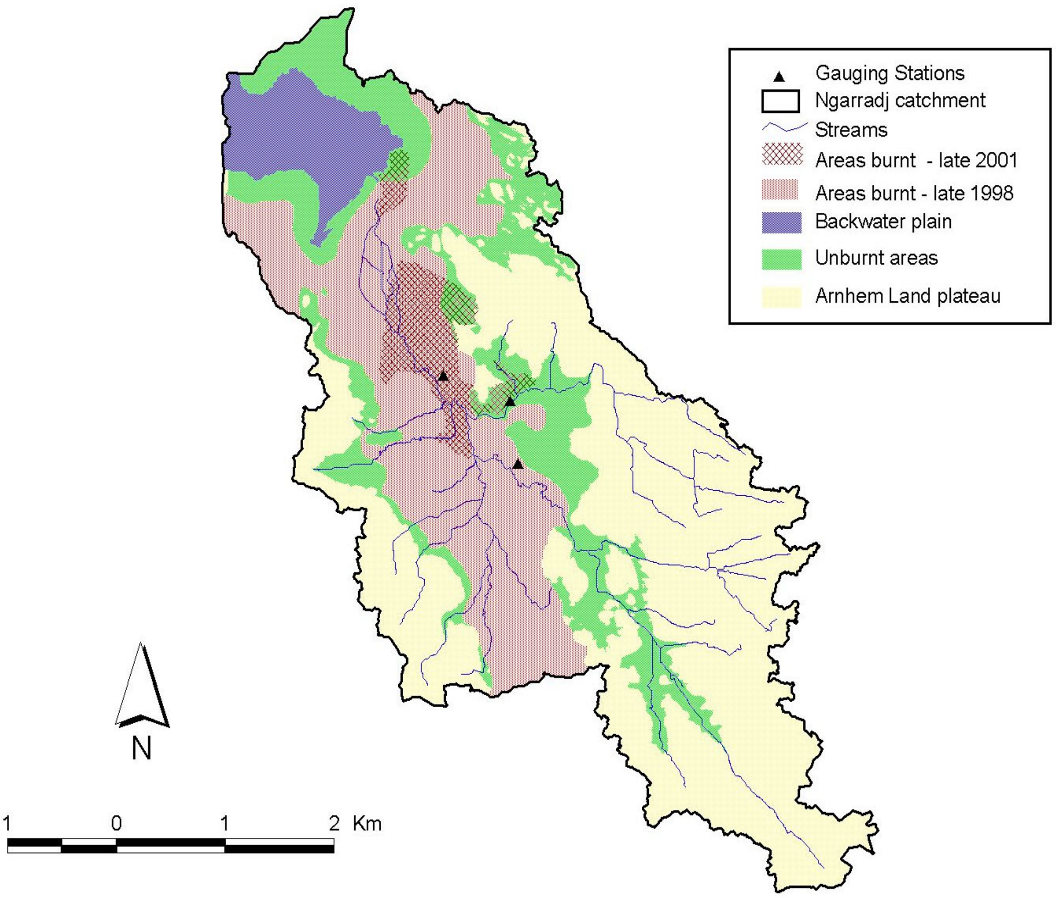


Figure 7 Fire distribution in the dry season 1998 and the dry season 2001

4.3 Solutes

This fraction is the dissolved material <0.45 µm. Full data sets showing the variability of solute concentration, [sol], with rainfall and stream discharge are given in Appendix C. Descriptive statistics and distributions for the full data set for each site are shown in figures 8a to 8c. The mean solute concentration, $\overline{[\text{sol}]}$, 23.4 (σ = 11.9) mg L^{-1} is highest at SC (fig 8a), slightly higher than $\overline{[\text{sol}]}$ at ET and UM which are very similar at 19.5 (σ = 11.2) mg L^{-1} and 20.0 (σ = 11.7) mg L^{-1} respectively. The frequency distribution curves, mean and standard deviation are shown in figure 8, however, the data distributions are positively skewed at all sites with $A^2 > 2.49$ indicating that [sol] is not normally distributed at any site. The data could not be $\log_{10}$ transformed to achieve a normal distribution based on $A^2_{0.05} = 2.49$ at any site. This analysis shows a number of outliers at each site.

The annual descriptive statistics are presented in table 5. There were no data for 1998–99 and 1999–00. There is little change in mean annual solute concentration $\overline{[\text{sol}]}_a$ from 2000–01 to 2001–02 on a catchment-wide basis. For both years $\overline{[\text{sol}]}_a$ at SC is about 6% higher than UM and ET and the fire during 2001 seemed to have little effect on SC [sol].

Table 5 Descriptive statistics for annual solute concentration (mg L^{-1})

Site/Year	*n*	$\overline{[sol]}_a$	σ	S_k	*Median*	*Mode*	*Min*	*Max*
SC 98-99	No data							
SC 99-00	No data							
SC 00-01	351	24	13	1.7	22	22	0.3	97
SC 01-02	173	23	9	1.2	22	24	7	63
UM 98-99	No data							
UM 99-00	No data							
UM 00-01	319	20	13	0.9	18	17	0.3	74
UM 01-02	189	20	9	1.4	20	20	1	80
ET 98-99	No data							
ET 99-00	No data							
ET 00-01	267	19	13	1.2	17	18	0.3	76
ET 01-02	196	20	8	0.8	19	16	2	58

n = count; $\overline{[sol]}_a$ = sample mean (mg L^{-1}); σ = sample standard deviation (mg L^{-1}); S_k = skewness.

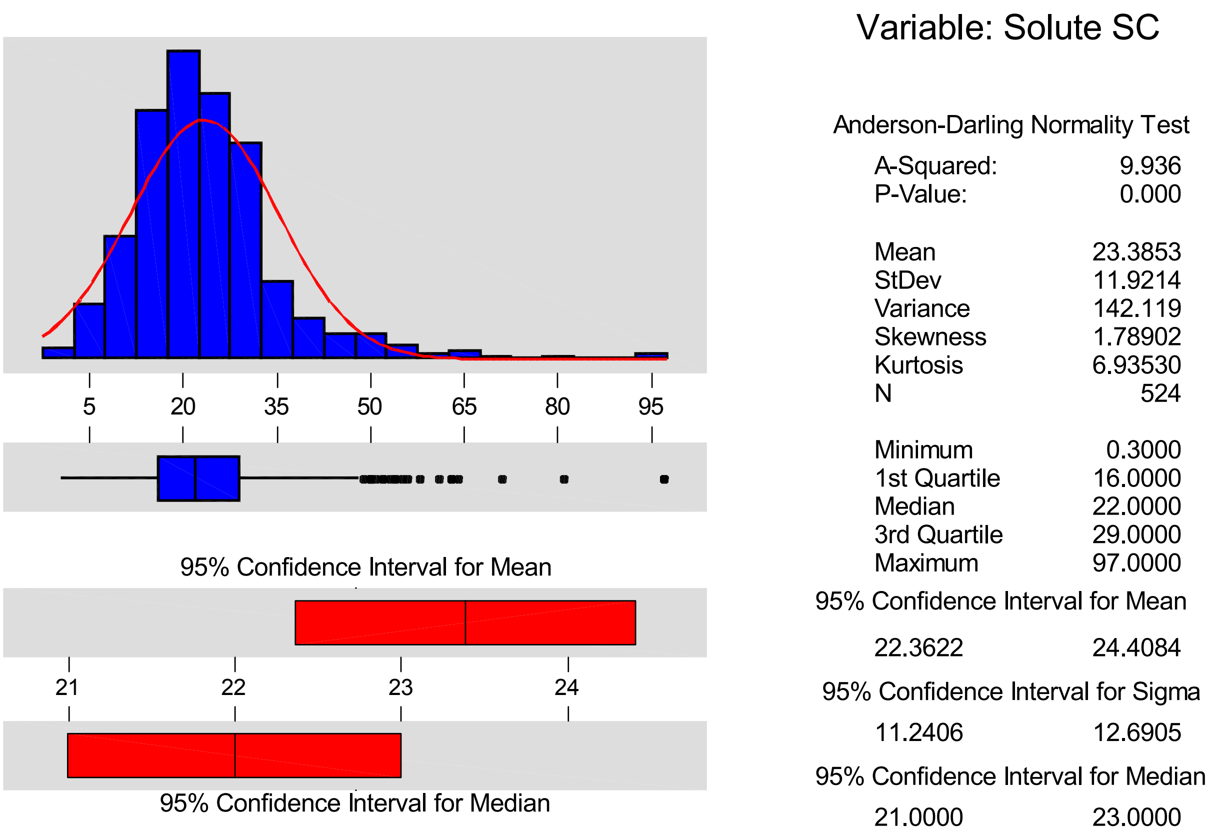


Figure 8a Descriptive statistics and frequency distribution for [sol] (mg L^{-1}) at SC for 1998–2002

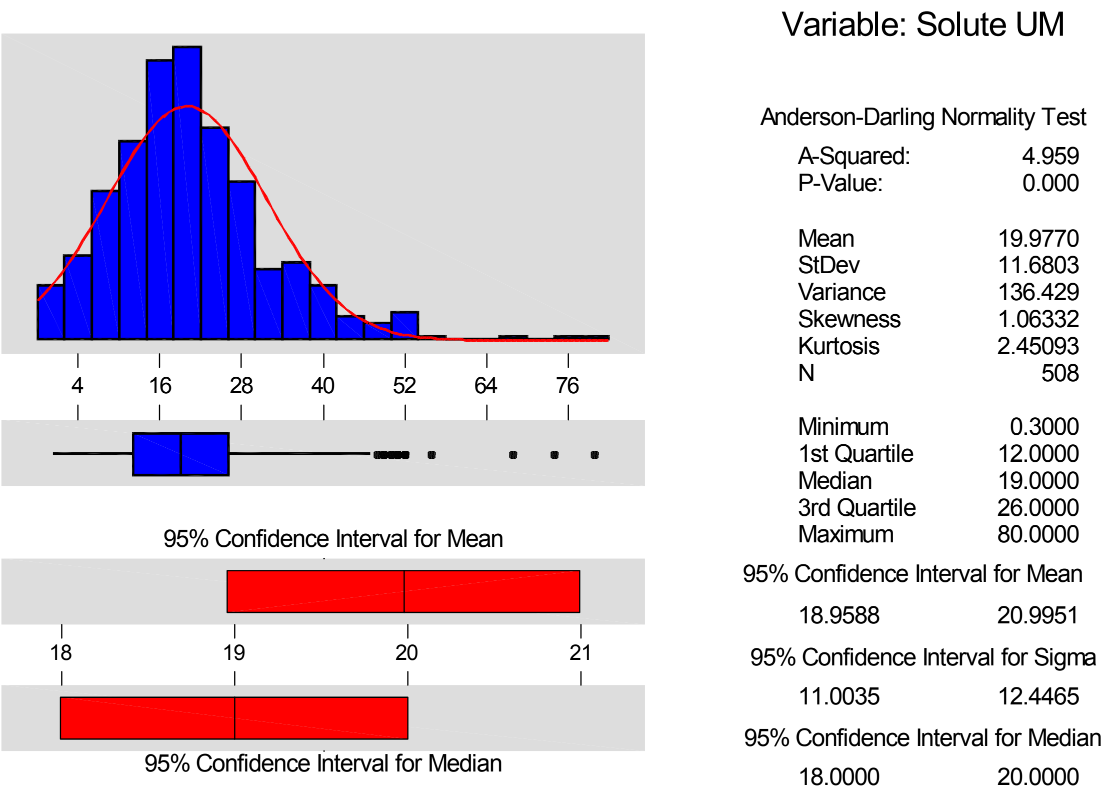


Figure 8b Descriptive statistics and frequency distribution for [sol] (mg L^{-1}) at UM for 1998–2002

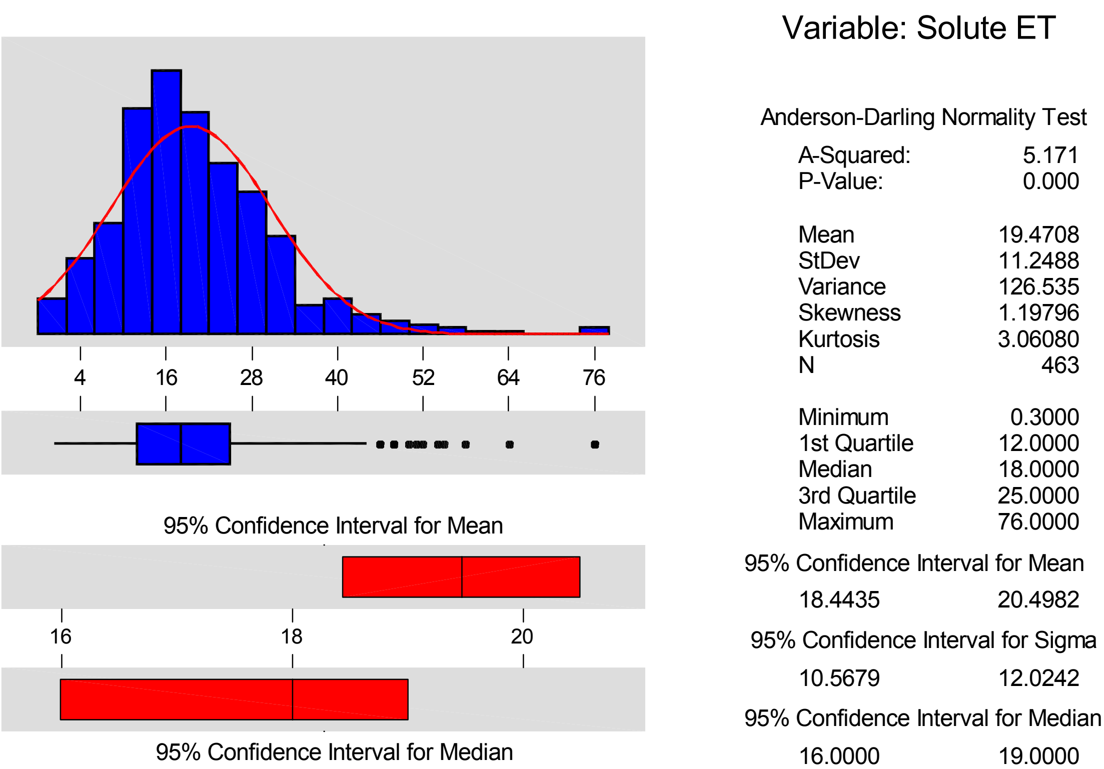
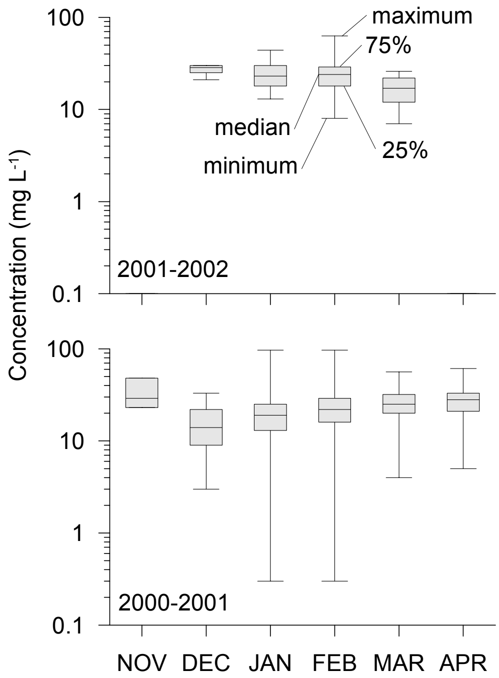
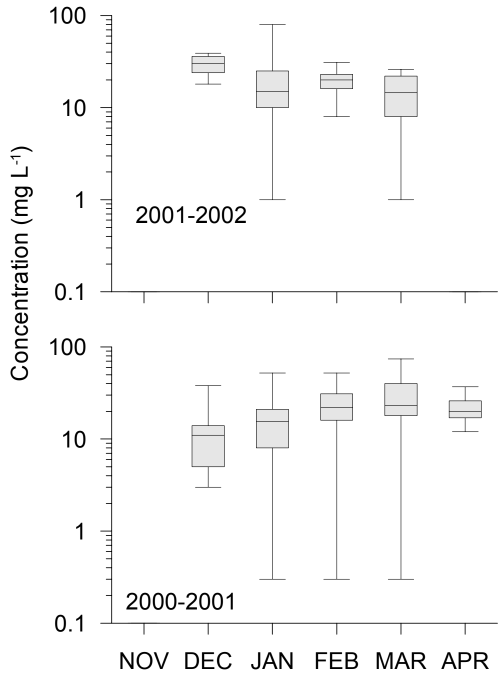


Figure 8c Descriptive statistics and frequency distribution for [sol] (mg L^{-1}) at ET for 1998–2002

Monthly statistics are presented in table 6 and figure 9. At SC in 2000–01, monthly mean concentration $\overline{[\mathrm{sol}]}_{\mathrm{m}}$ exhibits a slight rise during the wet season from a decrease after the initial first-flush in November 2000. There is a slight decrease toward the end of the wet season during 2001–02. Generally, there is a catchment-wide response in $\overline{[\mathrm{sol}]}_{\mathrm{m}}$ to natural catchment conditions.

It is likely that in a larger catchment, such as SC, there is more opportunity for runoff to pick up more soluble material. The concentrations reported here are very low and it is not considered that the level of concentration is transport-limited allowing more material to go into solution as runoff travels through the catchment.





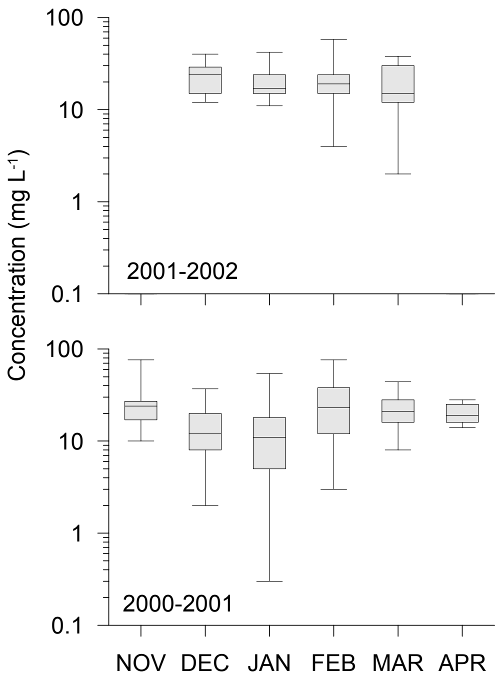


Figure 9a (top left) Monthly [solute] distribution in SC

Figure 9b (top right) Monthly [solute] distribution in UM

Figure 9c (left) Monthly [solute] distribution in ET

Table 6 Monthly average and standard deviation for suspended solute concentration (mg L^{-1})

Site/Year	*Nov*			*Dec*			*Jan*			*Feb*			*March*			*April*		
	$\overline{[sol]}_m$	σ	*n*	$\overline{[sol]}_m$	σ	*n*	$\overline{[sol]}_m$	σ	*n*	$\overline{[sol]}_m$	σ	*n*	$\overline{[sol]}_m$	σ	*n*	$\overline{[sol]}_m$	σ	*n*
SC 98-99	No data																	
SC 99-00	No data																	
SC 00-01	32	11	4	15	8	21	20	12	88	25	15	139	26	10	72	28	11	27
SC 01-02				27	3	10	24	8	25	24	9	98	17	5	40			
UM 98-99	No data																	
UM 99-00	No data																	
UM 00-01				11	7	25	17	12	124	23	11	105	27	17	51	22	7	14
UM 01-02				30	6	19	18	13	47	20	6	99	15	7	24			
ET 98-99	No data																	
ET 99-00	No data																	
ET 00-01	27	17	13	14	8	30	13	11	94	26	16	64	22	9	56	20	5	10
ET 01-02				23	9	11	20	8	23	20	8	127	19	10	35			

4.4 Electrical Conductivity (EC)

Full data sets showing the variability of EC with rainfall and stream discharge are given in Appendix D. Descriptive statistics and distributions for the full data set for each site are shown in figures 10a to 10c. The mean EC, 12.1 ($\sigma = 2.9$) µS cm^{-1}, is highest at UM (fig 10b), while SC (fig 10a) and ET (fig 10c) are similar at 11.0 ($\sigma = 3.1$) µS cm^{-1} and 10.7 ($\sigma = 3.8$) µS cm^{-1} respectively. The normal distribution curves based on the descriptive statistics are shown in figure 10, however, the data distributions are positively skewed. At all sites $A^2 > 2.49$ indicating that EC is not normally distributed at any site. The data could not be $\log_{10}$ transformed to achieve a normal distribution based on $A^2_{0.05} = 2.49$ at any site. This analysis shows a number of outliers at each site. In nearby Magela Creek, baseline Ranger pre-mining data for EC are log-normally distributed with a median of 16 µS cm^{-1} and a mean of 18 µS cm^{-1} (Klessa 2000) but these were not event-based data.

The annual descriptive statistics for EC are presented in table 7. On a catchment-wide basis mean annual EC (μ_{EC}) is lower in 1999–2000 and 2000–01 than 1998–99 and 2001–02. At SC and ET, μ_{EC} is very similar and at the upstream UM site, μ_{EC} is slightly higher than the other sites. All annual data are positively skewed (table 7).

Monthly statistics are presented in table 8 and figure 11. At all three sites there is a trend of declining monthly average EC (μ_{ECm}) during the wet season after initial first-flush effects, which is typical of the region (Iles & leGras pers comm 2003, www.deh.gov.au/ssd/monitoring/index.html). The high conductivity during the early period of flow in the catchment is due to flushing of the soil profile and resuspending of creek bed sediments. After the first flush effects the conductivity decreases steadily throughout the wet season (fig 11) and then begins to increase again towards the end of the wet season as a result of groundwater intrusion (Iles & leGras pers comm 2003).

There appears to be no significant fire effect at SC. At the upstream site UM, μ_{ECm} is consistently slightly higher than the ET and SC sites. Monthly range is also similar with some slight scatter but not on a consistent monthly basis (fig 11).

Finally, the event-based trends in conductivity (shown in Appendix D) are not observed within the solute concentration data (Appendix C). It is difficult to determine whether this is due to the fact that (1) there is not a strong correlation between solute concentration and conductivity data for the Ngarradj catchment, or (2) the filtering technique for the direct measurement of solute concentration is not suitable for the Ngarradj catchment conditions (ie stream solutes are too low – the filtering technique cannot reliably measure the small changes in stream salt concentration that a conductivity meter can detect).

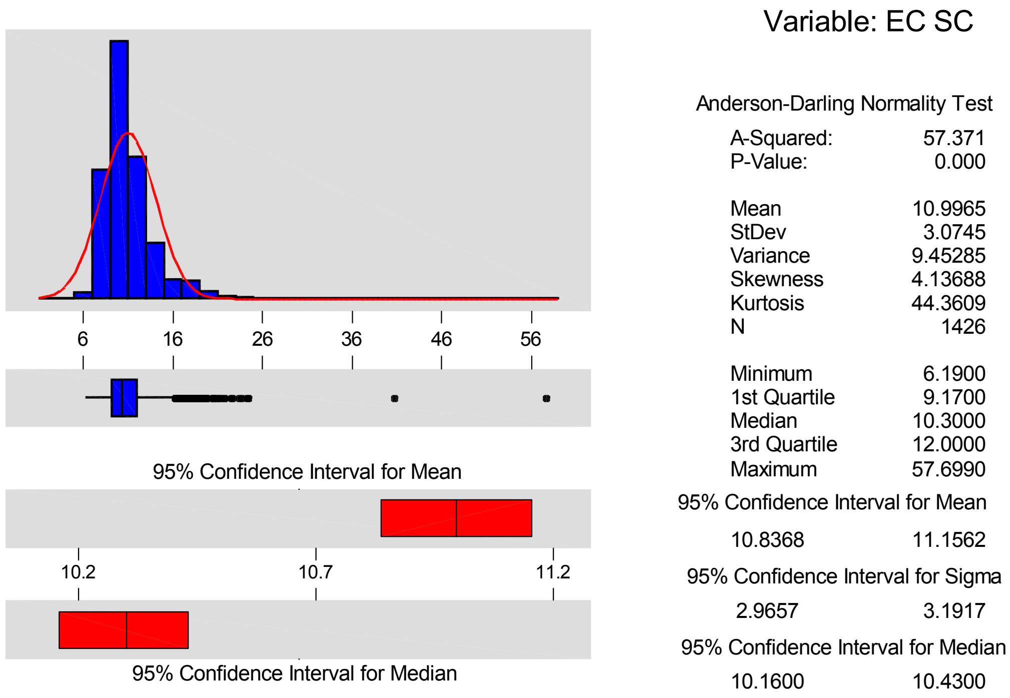


Figure 10a Descriptive statistics and frequency distribution for EC (µS cm^{-1}) at SC for 1998–2002

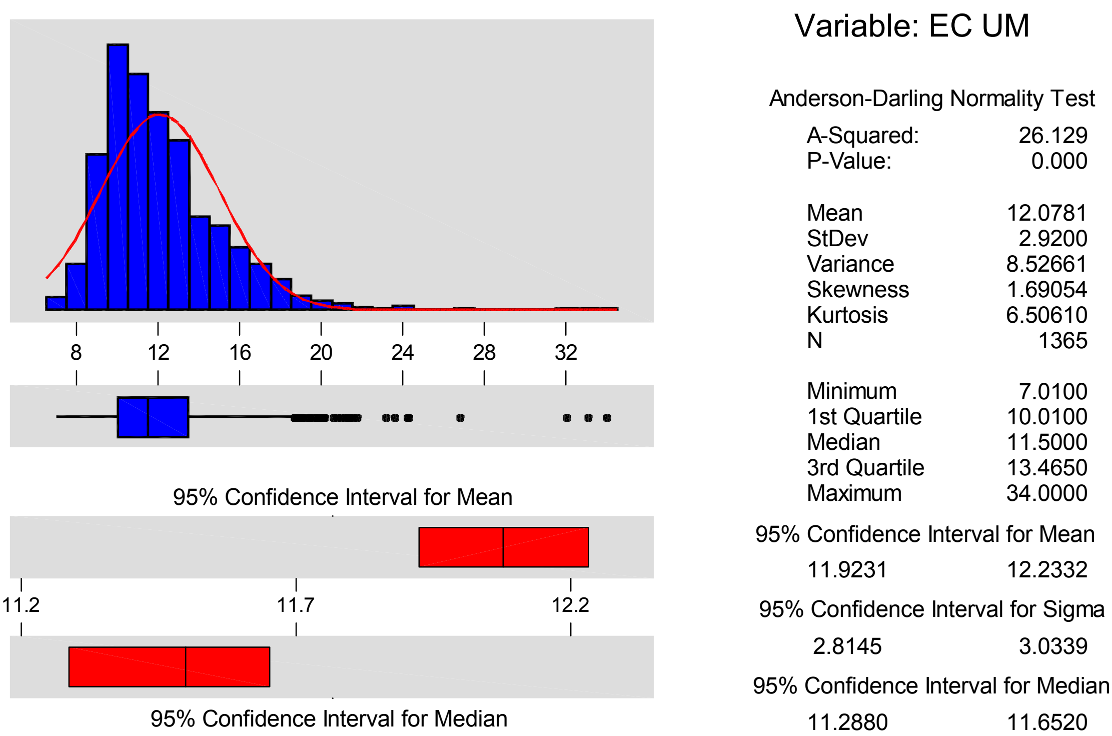


Figure 10b Descriptive statistics and frequency distribution for EC (µS cm^{-1}) at UM for 1998–2002

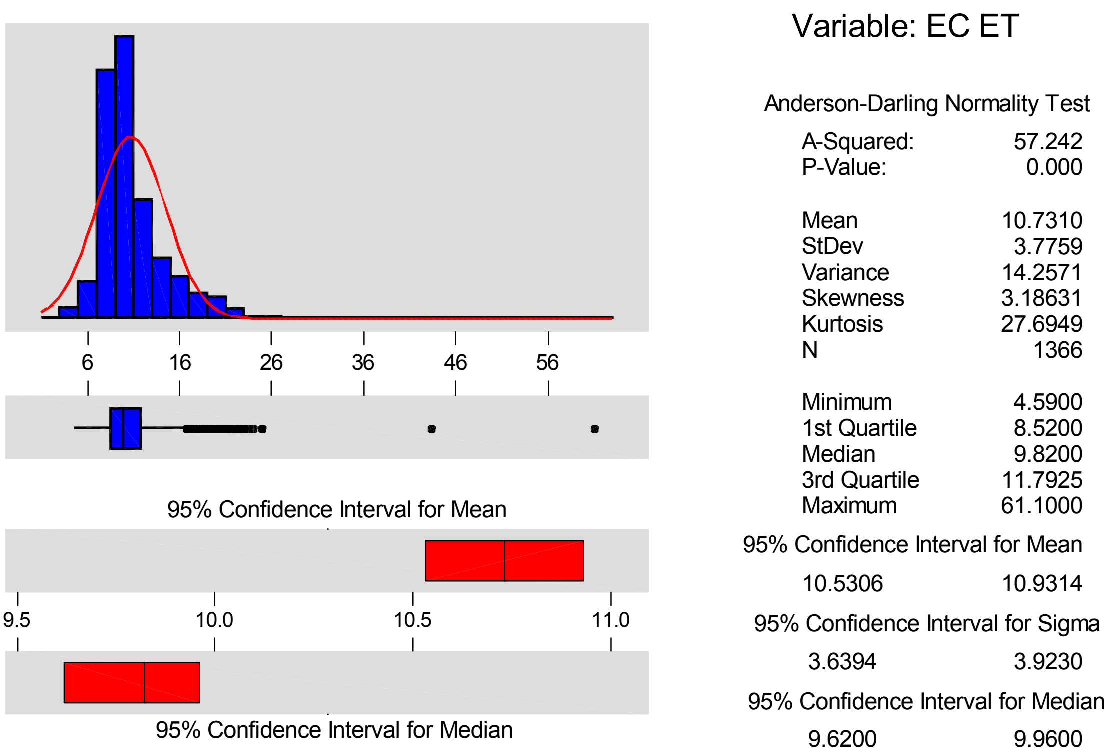


Figure 10c Descriptive statistics and frequency distribution for EC (µS cm^{-1}) at ET for 1998–2002

Table 7 Descriptive statistics for annual EC (µS cm^{-1})

Site/Year	*n*	μ_{EC}	σ	S_k	*Median*	*Mode*	*Min*	*Max*
SC 98-99	359	11.9	2.9	1.4	11.5	11.6	7.0	23.7
SC 99-00	488	10.6	2.3	1.5	10.1	9.3	6.2	20.6
SC 00-01	401	9.9	2.1	2.3	9.5	9.5	6.4	24.5
SC 01-02	176	12.5	4.0	2.6	11.4	8.6	7.1	40.7
UM 98-99	342	12.6	3.8	1.7	12.2	12.6	7.1	34.0
UM 99-00	412	11.8	2.4	1.3	11.3	11.2	8.1	21.7
UM 00-01	421	11.0	2.0	2.3	10.7	11.1	7.0	26.8
UM 01-02	190	14.1	2.7	0.5	13.2	13.2	9.0	21.3
ET 98-99	365	10.7	3.2	1.6	10.0	9.0	5.3	25.0
ET 99-00	413	10.1	3.5	1.4	9.1	8.0	4.6	23.0
ET 00-01	390	10.6	4.1	6.8	9.7	9.6	6.3	61.1
ET 01-02	198	12.4	4.2	0.4	11.8	20.1	4.8	24.0

n = count; μ_{EC} = sample mean (µS cm^{-1}); σ = sample standard deviation (mg L^{-1}); S_k = skewness.

Table 8 Monthly average and standard deviation for EC ($\mu S\ cm^{-1}$)

Site/Year	*Nov*			*Dec*			*Jan*			*Feb*			*March*			*April*		
	μ_{ECm}	σ	*n*	μ_{ECm}	σ	*n*	μ_{ECm}	σ	*n*	μ_{ECm}	σ	*n*	μ_{ECm}	σ	*n*	μ_{ECm}	σ	*n*
SC 98-99				15.0	3.5	81	12.1	1.6	142	10.7	1.2	40	9.5	1.2	86	9.3	2.4	10
SC 99-00	19.2	1.4	6	12.9	2.4	111	10.9	1.1	103	9.6	1.0	113	8.8	1.3	96	9.7	0.9	59
SC 00-01	26.3	21.0	4	15.5	2.5	21	10.7	1.4	139	8.5	0.8	139	9.6	0.6	72	8.6	0.7	27
SC 01-02				11.6	1.9	10	19.4	4.9	25	12.0	2.4	102	9.6	0.8	40			
UM 98-99				17.6	3.8	57	14.0	1.7	101	10.7	3.1	66	10.0	2.0	111	9.5	1.9	7
UM 99-00	15.2	3.4	37	14.1	1.5	80	11.7	1.7	89	10.9	1.0	73	9.8	0.8	99	10.6	0.7	34
UM 00-01				14.5	1.4	25	11.7	2.1	187	9.7	0.9	144	10.8	0.7	51	10.7	0.7	14
UM 01-02				13.5	0.7	19	17.6	1.9	47	13.5	1.6	98	10.3	0.7	25			
ET 98-99				14.9	4.4	62	10.8	2.0	109	8.7	1.5	75	9.8	1.9	113	8.5	1.6	6
ET 99-00	18.1	3.3	26	12.6	3.5	79	10.7	1.6	67	8.9	1.4	91	7.2	1.4	92	8.5	1.0	58
ET 00-01	18.6	13.2	13	17.2	2.5	30	10.3	2.9	189	8.9	1.0	92	9.7	0.7	56	8.7	0.5	10
ET 01-02				14.8	1.9	11	19.6	2.5	23	11.8	3.4	129	8.9	1.3	35			

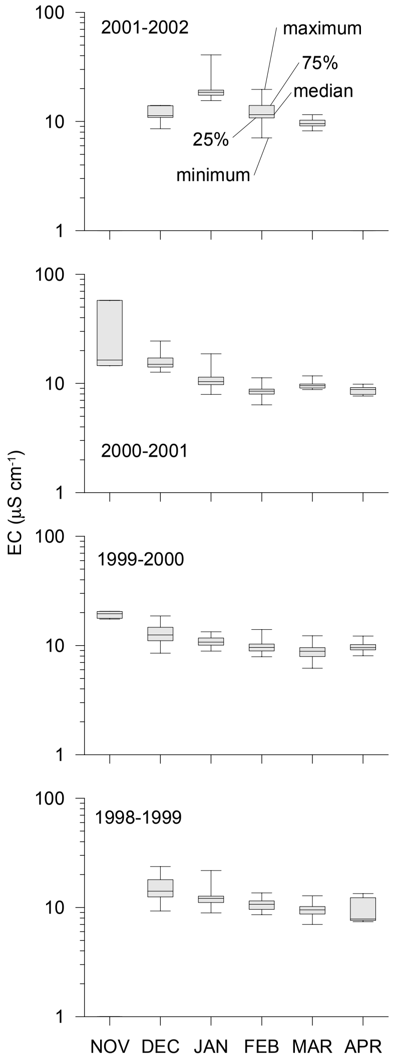


Figure 11a Monthly EC distribution in SC

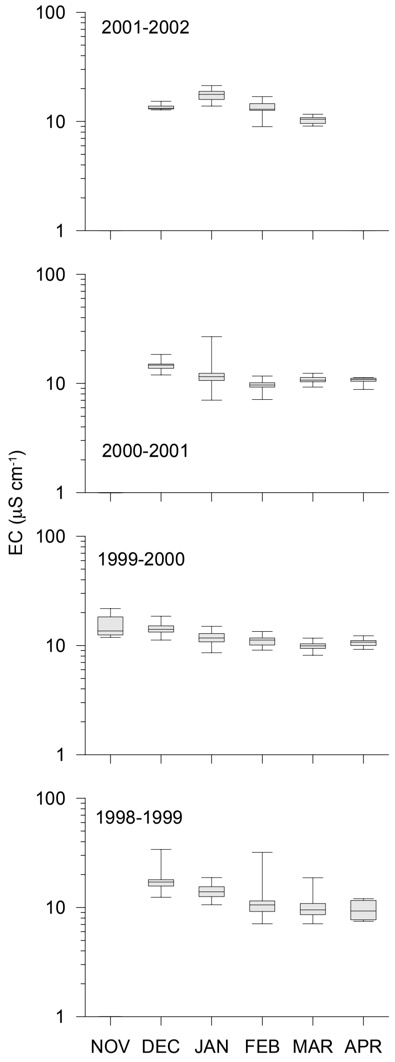


Figure 11b Monthly EC distribution in UM

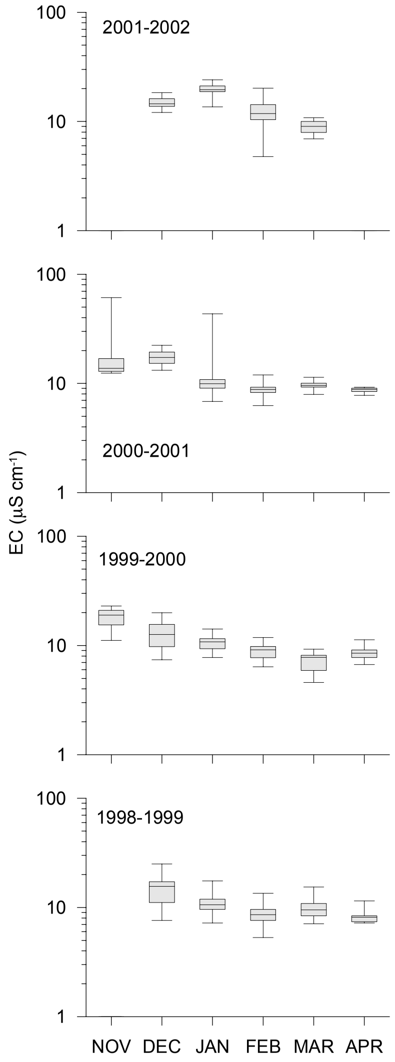


Figure 11c Monthly EC distribution in ET

4.5 Turbidity

Full data sets showing the variability of laboratory-measured turbidity (NTU) with rainfall and stream discharge are given in Appendix E. Descriptive statistics and distributions for the full data set for each site are shown in figures 12a to 12c.

The mean turbidity at SC and UM are very similar being 8.9 (σ = 13.2) NTU and 8.3 (σ = 8.3) NTU respectively. Turbidity at ET is higher being 14.1 (σ = 20.8) NTU. The normal distribution curves based on the mean and standard deviation are shown in figure 12, however, the data distributions are positively skewed at all sites and $A^2 > 2.49$ indicating that turbidity is not normally distributed at any site. Apart from ET, the data could not be $\log_{10}$ transformed to achieve a normal distribution based on $A^2_{0.05} = 2.49$ at any site. This analysis shows a number of outliers at each site. Non-event related data for the period 1997 to 2000 from SC give a mean turbidity of 2.1 (σ = 0.8) NTU and upstream mean turbidity as 1.4 (σ = 2.1) NTU (leGras et al 2001).

The annual descriptive statistics for turbidity are presented in table 9. Average annual NTU (μ_{NTU}) distributions and trends are very similar to average annual fine suspended-sediment distributions and trends (Section 4.2).

Monthly statistics are presented in table 10 and figure 13. Again, average monthly NTU (μ_{NTUm}) distributions and trends are similar to μ_{mm} (Section 4.2).

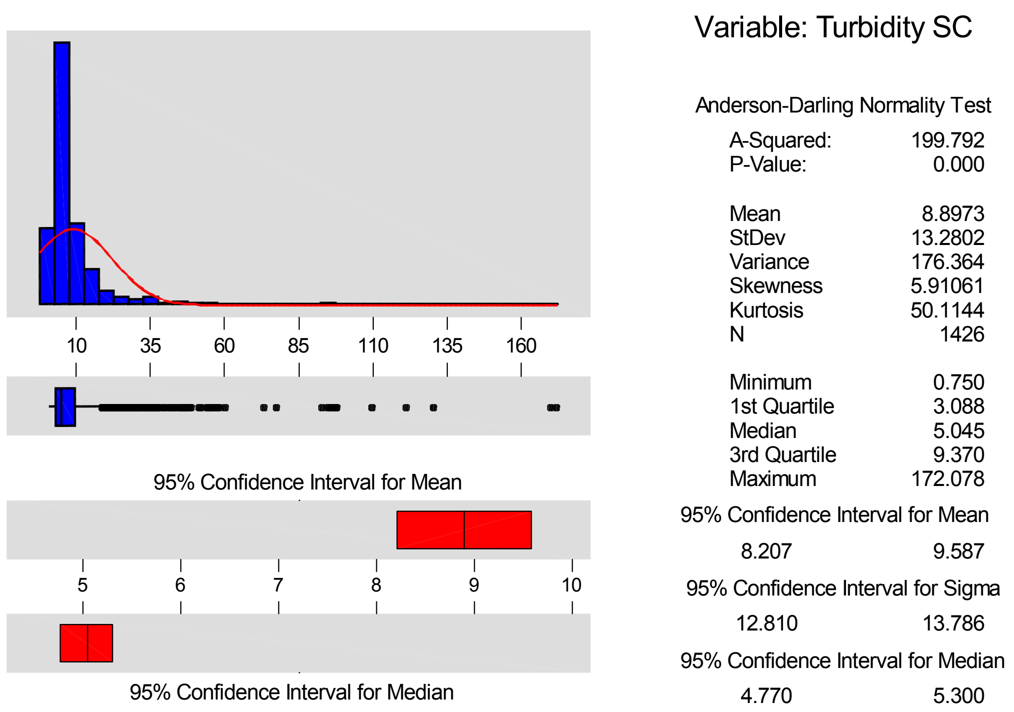
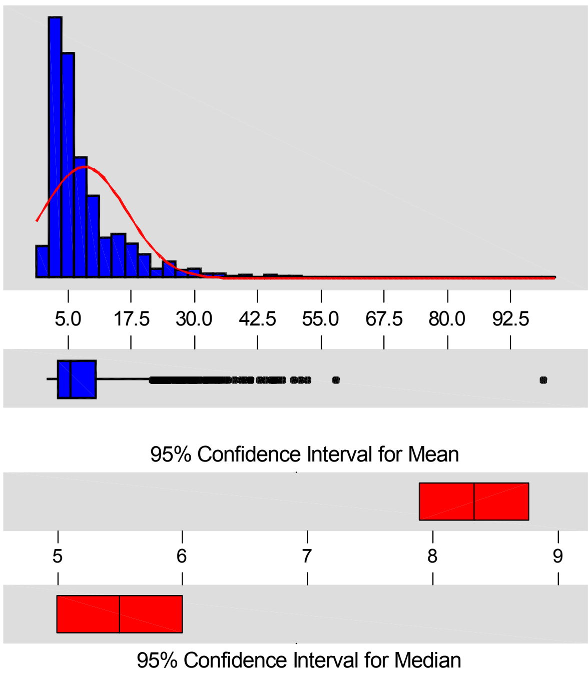


Figure 12a Descriptive statistics and frequency distribution for turbidity (NTU) at SC for 1998–2002



Variable: Turbidity UM

Anderson-Darling Normality Test

A-Squared:	96.405
P-Value:	0.000
Mean	8.32980
StDev	8.27250
Variance	68.4342
Skewness	2.92758
Kurtosis	15.5701
N	1366
Minimum	0.7300
1st Quartile	3.0000
Median	5.5000
3rd Quartile	10.4350
Maximum	99.0000

95% Confidence Interval for Mean

7.8907 8.7689

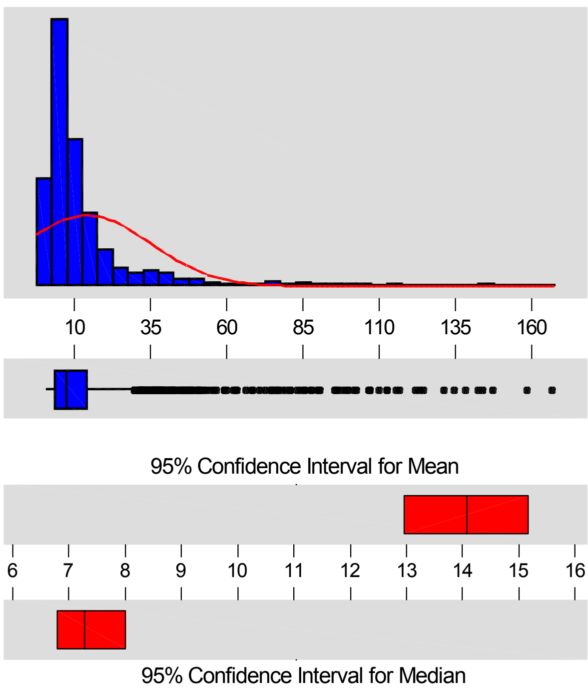
95% Confidence Interval for Sigma

7.9735 8.5950

95% Confidence Interval for Median

5.0000 6.0000

Figure 12b Descriptive statistics and frequency distribution for turbidity (NTU) at UM for 1998–2002



Variable: Turbidity ET

Anderson-Darling Normality Test

A-Squared:	178.597
P-Value:	0.000
Mean	14.0699
StDev	20.7530
Variance	430.687
Skewness	3.58387
Kurtosis	15.2994
N	1367
Minimum	0.500
1st Quartile	3.660
Median	7.280
3rd Quartile	14.060
Maximum	166.602

95% Confidence Interval for Mean

12.969 15.171

95% Confidence Interval for Sigma

20.003 21.562

95% Confidence Interval for Median

6.800 8.000

Figure 12c Descriptive statistics and frequency distribution for turbidity (NTU) at ET for 1998–2002

Table 9 Descriptive statistics for annual turbidity (NTU)

Site/Year	*n*	μ_{NTU}	σ	S_k	*Median*	*Mode*	*Min*	*Max*
SC 98-99	359	13	18	3.0	6	4	1	122
SC 99-00	488	7	6	2.8	4	5	1	47
SC 00-01	401	7	6	2.8	5	3	1	46
SC01-02	177	12	23	5.4	6	6	2	172
UM 98-99	342	8	10	3.9	5	2	1	99
UM 99-00	413	8	7	1.8	6	1	1	51
UM 00-01	421	8	8	2.4	6	2	1	48
UM 01-02	190	8	9	2.6	4	3	1	52
ET 98-99	365	18	26	2.9	9	4	1	167
ET 99-00	414	18	24	2.9	10	11	1	158
ET 00-01	390	8	9	3.9	6	2	1	76
ET 01-02	198	10	16	4.8	6	3	1	122

n = count; μ_{NTU} = sample mean (NTU); σ = sample standard deviation (NTU); S_k = skewness.

There are statistically significant correlations between [FSS] and turbidity at all sites (fig 14). While the relationships for ET and UM are similar, the relationship at SC is different from the two upstream sites. It is not possible to determine the cause without significant research. However, more recent studies (Moliere et al 2004b), using site-calibrated *in situ* turbidity probes, show significant relationships with little variation between sites. This leads to conjecture that residence time in the automatic samplers may have resulted in errors in laboratory-derived turbidity measurements.

Table 10 Monthly average and standard deviation for turbidity (NTU)

Site/Year	*Nov*			*Dec*			*Jan*			*Feb*			*March*			*April*		
	μ_{NTUm}	σ	*n*	μ_{NTUm}	σ	*n*	μ_{NTUm}	σ	*n*	μ_{NTUm}	σ	*n*	μ_{NTUm}	σ	*n*	μ_{NTUm}	σ	*n*
SC 98-99				21	15	81	15	23	142	9	12	40	4	3	86	3	1	10
SC 99-00	2	1	6	9	9	11	6	5	103	6	6	113	6	6	96	5	4	59
SC 00-01	5	3	4	2	1	21	7	7	139	7	7	139	6	4	72	8	5	27
SC 01-02				83	57	10	10	7	25	7	7	102	7	3	40			
UM 98-99				13	17	57	6	6	101	7	7	66	9	8	111	3	2	7
UM 99-00	9	10	37	9	6	81	10	8	89	9	7	73	7	6	99	6	3	34
UM 00-01				2	1	25	9	9	187	9	8	144	7	5	51	6	2	14
UM 01-02				30	13	19	9	6	47	5	3	98	4	2	25			
ET 98-99				21	32	62	26	35	109	11	12	75	14	14	113	2	1	6
ET 99-00	3	3	26	19	22	80	10	11	67	20	24	91	25	34	92	17	17	58
ET 00-01	7	9	13	2	1	30	10	12	189	7	4	92	8	6	56	8	3	10
ET 01-02				11	6	11	7	4	23	12	20	129	7	4	35			

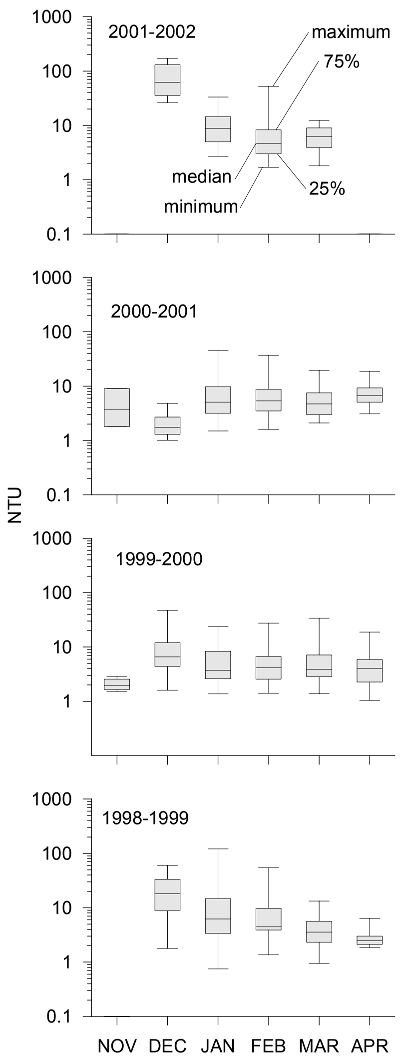


Figure 13a Monthly turbidity distribution in SC

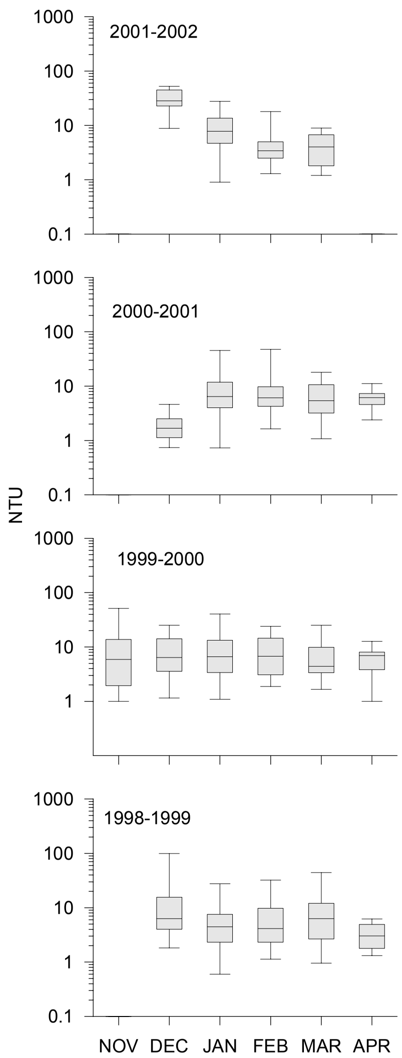


Figure 13b Monthly turbidity distribution in UM

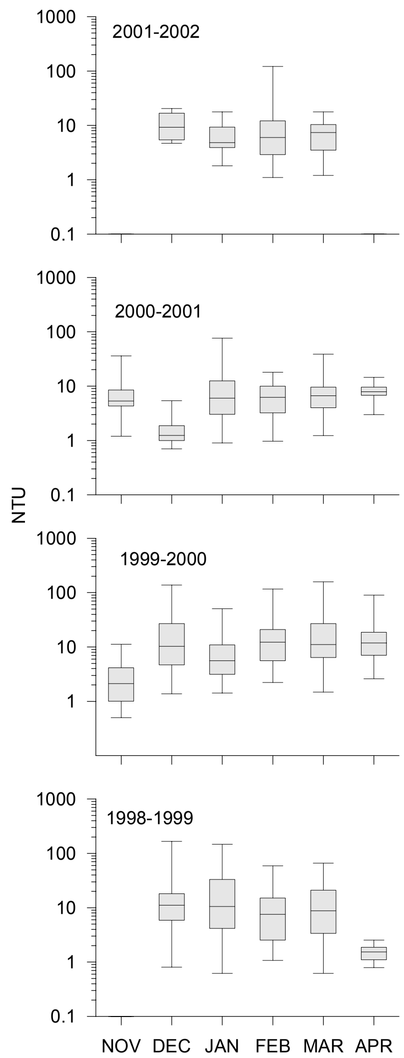


Figure 13c Monthly turbidity distribution in ET

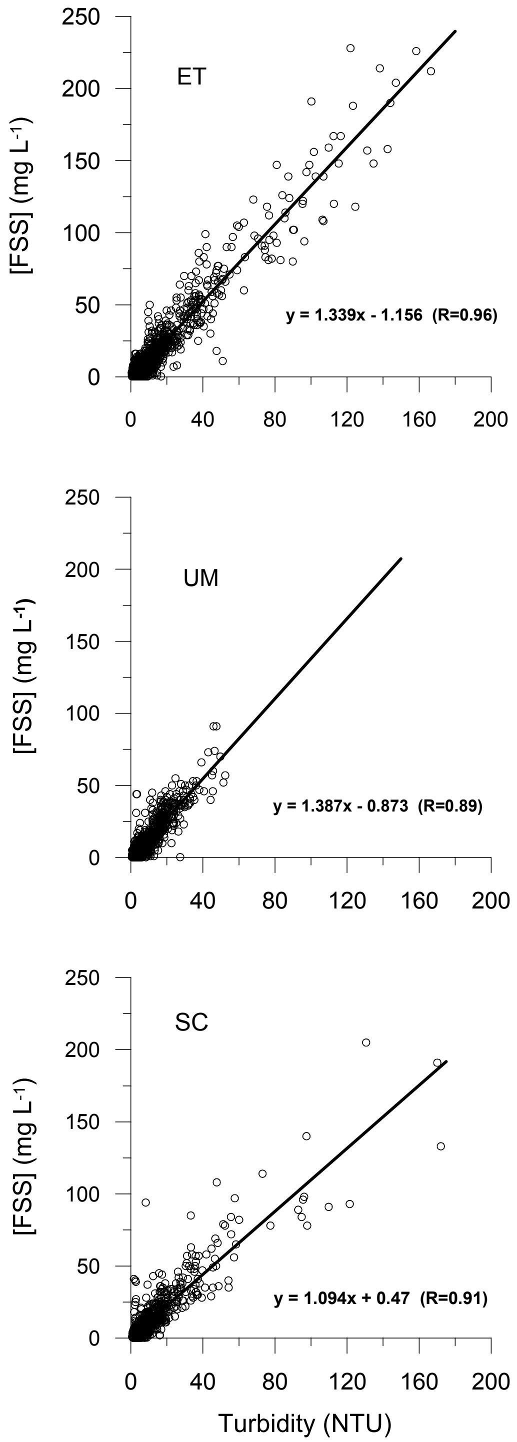


Figure 14 Variation of [FSS] with turbidity at all sites

5 Water quality trigger values to assess impact

Water quality guidelines for the parameters discussed in this report have not been established for the Ngarradj catchment using event-based data. In accordance with The Australian and New Zealand water quality guidelines (WQG) (ANZECC & ARMCANZ 2000) the aim of this section is to determine numerical concentrations or contaminant levels, which will trigger a management response should the measured parameter exceed that value. Two methods are used. The first method is comparison of the downstream SC site parameter values with limits derived from data from the upstream UM site. The second method is a Before-After-Control-Impact, paired difference design (BACIP) where the upstream site UM is before impact in a spatial sense and the downstream site SC is after impact in a spatial sense. Comparison is also made between ET and SC as the upstream and downstream site respectively. In both cases the ET site can be used to confirm whether an observed elevated measurement at SC not observed at UM is (1) from the mine-site catchment or (2) from ET and therefore a natural occurrence. If elevated values are not observed at ET it is assumed that the source is from the mine-site catchment and investigations are required to identify the source.

5.1 Upstream limits

The WQG recommend a trigger value of the 80th percentile of parameter values of a suitable reference. In this case the reference site of the downstream site, SC, is the upstream site UM. This means that, values measured at SC should be ≤ 80th percentile at UM. The Supervising Scientist Division, in discussion with stakeholders, is establishing hierarchical trigger values for the Alligator Rivers Region including Ngarradj. These values are, 80th, 95th and 99.7th percentiles representing different levels of interventions by supervising authorities and the mining company. The levels that trigger intervention are still under discussion.

The trigger values for SC have been determined using the complete data set from four years monitoring. The data are summarised in table 11. The trigger values are given in table 12 and are plotted on the SC data presented in Appendices A–E. The Appendices show that a number of SC data points are above the trigger values. This is due to event related variability. The percentage of time the SC is above the trigger values for the measured parameters are given in table 13.

At SC, [CSS], [FSS] and turbidity are higher than the 80 percentile at UM less than 20% of the time (table 13). This indicates that with respect to sediment, SC flows at a lower concentration than UM. This concurs with sediment delivery theory, which suggests that for similar disturbance conditions, larger area catchments generally have lower concentrations than smaller area catchments. SC is at concentrations higher than the UM 99.7th percentile concentration >0.3% of the time. These relatively infrequent concentrations are probably due to the first flush and fire-effected spikes observed at SC and not UM. This is confirmed in Appendices A, B and E where sediment and turbidity spikes are seen to exceed the 99.7th percentile only during the fire-affected years of 1998–1999 and 2001–2002 during events early in the season.

The need to assess high parameter values at SC relative to both UM and ET to determine mine impact is displayed in figure 15 that shows an extract of [FSS] data from 1998–99. High event-related [FSS] are observed at SC but not UM during two events – (1) 26 December 1998 and (2) 26 January 1999. However, the data (shaded regions fig 15) show elevated [FSS] at ET indicating that this tributary is the source of elevated [FSS] and therefore it is unlikely the source is from that part of the catchment where the mine is located.

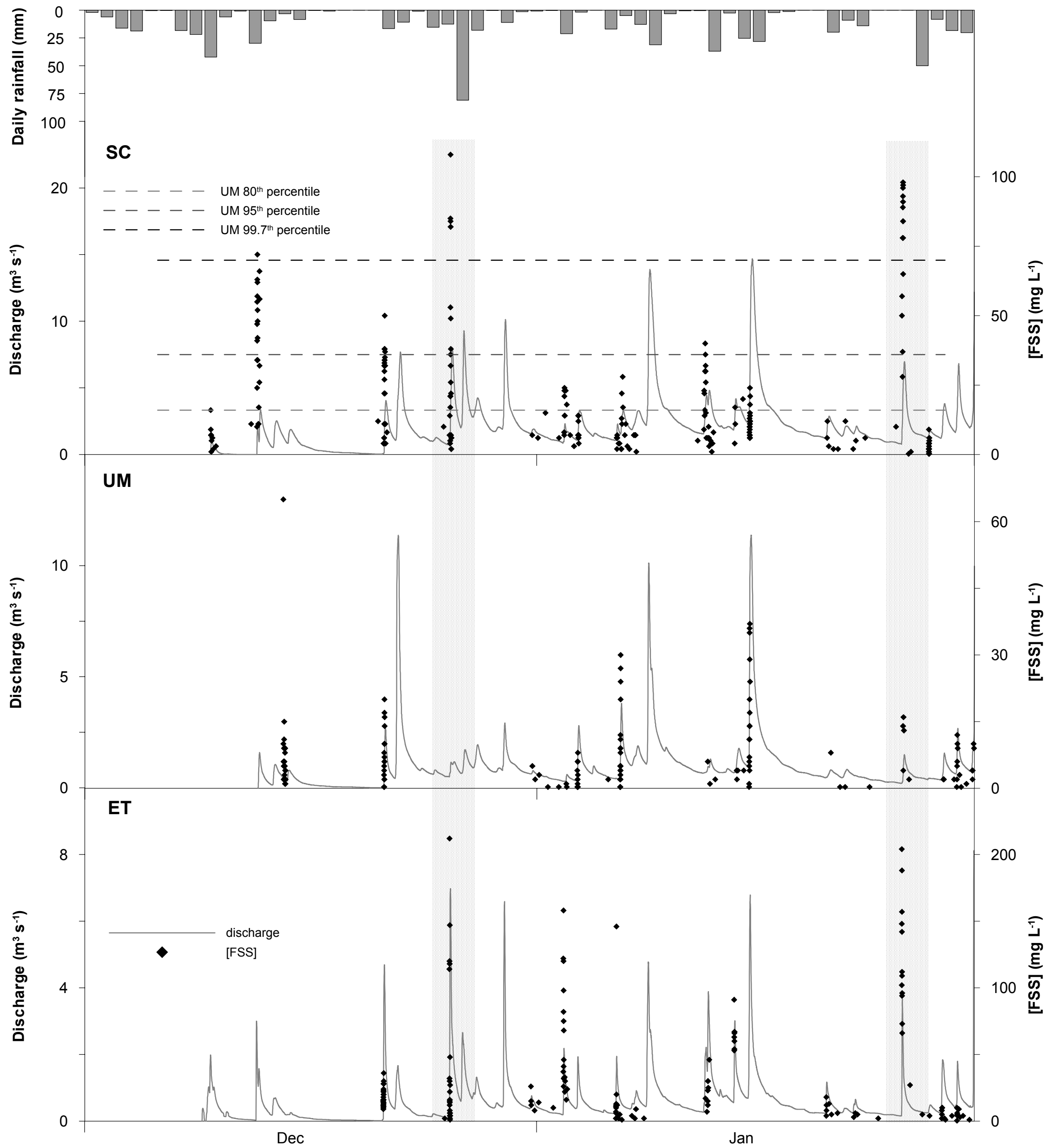


Figure 15 Extract of [FSS] data shows elevated concentrations on 26 December 1998 and 26 January 1999 (shaded regions) at SC and ET but not at UM

Table 11 Mean, median and range for SC, UM and ET gauging station data

	SC				UM				ET			
Parameter	**mean**	**median**	**maximum**	**minimum**	**mean**	**median**	**maximum**	**minimum**	**mean**	**median**	**maximum**	**minimum**
[CSS] (mg L^{-1})	45	31	1085	0.3	55	43	546	0.3	69	47	1330	0.3
[FSS] (mg L^{-1})	10	6	205	0.3	10	6	91	0.3	18	8	404	0.3
[sol] (mg L^{-1})	23	22	97	0.3	20	19	80	0.3	19	18	76	0.3
EC (μS cm^{-1})	11	10	58	6	12	12	34	7	11	9	61	5
Turbidity (NTU)	9	5	172	0.8	8	6	99	0.7	14	7	167	0.5
Flow (m^3 s^{-1})	5.25	4.38	21.7	0.01	3.04	2.01	12.9	0.001	2.01	1.35	8.11	0.003

Table 12 Trigger values for the downstream SC site derived using the upstream UM reference site

Percentile	Coarse suspended-sediment (mg L^{-1})	Fine suspended-sediment (mg L^{-1})	Solutes (mg L^{-1})	EC (μS cm^{-1})	Turbidity (NTU)
80	78	16	28	14.1	12
95	151	36	41	17.4	24
99.7	325	70	71	24.3	49

Table 13 Percentage of SC data points exceeding trigger values given in table 14

	Percentage data points above trigger value (%)				
Trigger percentile	**Coarse suspended-sediment**	**Fine suspended-sediment**	**Solutes**	**EC**	**Turbidity**
80	12	15.8	29.3	11.3	17.9
95	3.3	5	6.5	4.2	6.6
99.7	0.9	1.6	0.6	0.3	1.7

5.2 BACIP

This assessment uses a BACIP design (Stewart-Oaten et al 1986, 1992, Humphrey et al 1995) where UM and SC and ET and SC are treated as two sets of paired sites and the comparison of differences is used to assess impact.

The time period chosen for comparison was one calendar month. The parameter used to assess impact was the monthly median ($\tilde{\mu}$) parameter value at UM, ET and SC because distributions were generally skewed (ANZECC & ARMCANZ 2000, table 6.9a). The monthly medians of two distributions at UM and SC and ET and SC were compared, ie $\tilde{\mu}$ of all samples collected in a month.

The test parameter used was the inference about the difference after (downstream) and before (upstream) impact i.e. the difference between the monthly median concentration at SC and UM ($\theta_{SC} - \theta_{UM}$) and SC and ET ($\theta_{SC} - \theta_{ET}$) (ANZECC & ARMCANZ 2000, table 6.9b). Outliers, which were considered to be those points outside two standard deviations from the mean of the $\theta_{SC} - \theta_{UM}$ and $\theta_{SC} - \theta_{ET}$ populations were removed and power analysis was conducted to determine the probability of Type I and II errors occurring for the number of samples available in this study. There were 18 monthly data points available for $\tilde{\mu}$. The WQGs recommend that assessment be based on the 24 most recent data values, however, power analysis indicate the probability of Type I and II error occurring for the number of samples available in this study i.e. for an effect size of one standard deviation from the mean the probability of a Type II (β) error with alpha of 0.05 is 0.20 with a power of 80% (table 14).

Analysis indicated that the distribution of the populations of $\theta_{SC} - \theta_{UM}$ and $\theta_{SC} - \theta_{ET}$ are normal therefore, trigger values were set as +1σ, +2σ and +3σ (σ = standard deviation) respectively (Supervising Scientist 2002). Figures 16 to 20 shows the temporal variation in monthly median for UM and SC and $\theta_{SC} - \theta_{UM}$ and monthly median for ET and SC and $\theta_{SC} - \theta_{ET}$ for [CSS], [FSS], [sol], EC and turbidity respectively. The trigger values are also plotted. Outliers usually result from first flush, fire-impacted events at the start of the 1998–1999 wet season and the 2001–2002 wet season. $\theta_{SC} - \theta_{UM}$ and $\theta_{SC} - \theta_{ET}$ occasionally exceeds +1σ but rarely exceed +2σ. Values exceeding +2σ are infrequent and irregular and probably result from rainfall and hydrograph variation as expected in this variable natural system. In general, both ET and UM are elevated when SC is elevated, resulting in median differences that are within guidelines. The exception to this is [FSS] in December 1998 where $\tilde{\mu}$ for [FSS] at SC is considerably elevated compared to UM. At ET, $\tilde{\mu}$ for [FSS] is also elevated for December 1998 but unfortunately there are no early-December data at ET. Assessment of $\tilde{\mu}$ for the sites indicates a possible elevation due to the mine since SC is high relative to ET and UM. However, due to the effect of fire on SC for 1998-99 and the lack of data for early-December at ET, it cannot be definitively stated that mine disturbance has resulted in elevated $\tilde{\mu}$ at SC. This indicates the importance of the continuous data and both UM and ET to provide a good understanding of the system for impact assessment.

Table 14 Power of sample sizes for an effect of one standard deviation

Estimate of						
n	10	15	17	22	28	32
α	0.05	0.05	0.05	0.05	0.05	0.05
β	0.45	0.25	0.2	0.1	0.05	0.025
Power(%)	55	75	80	90	95	98

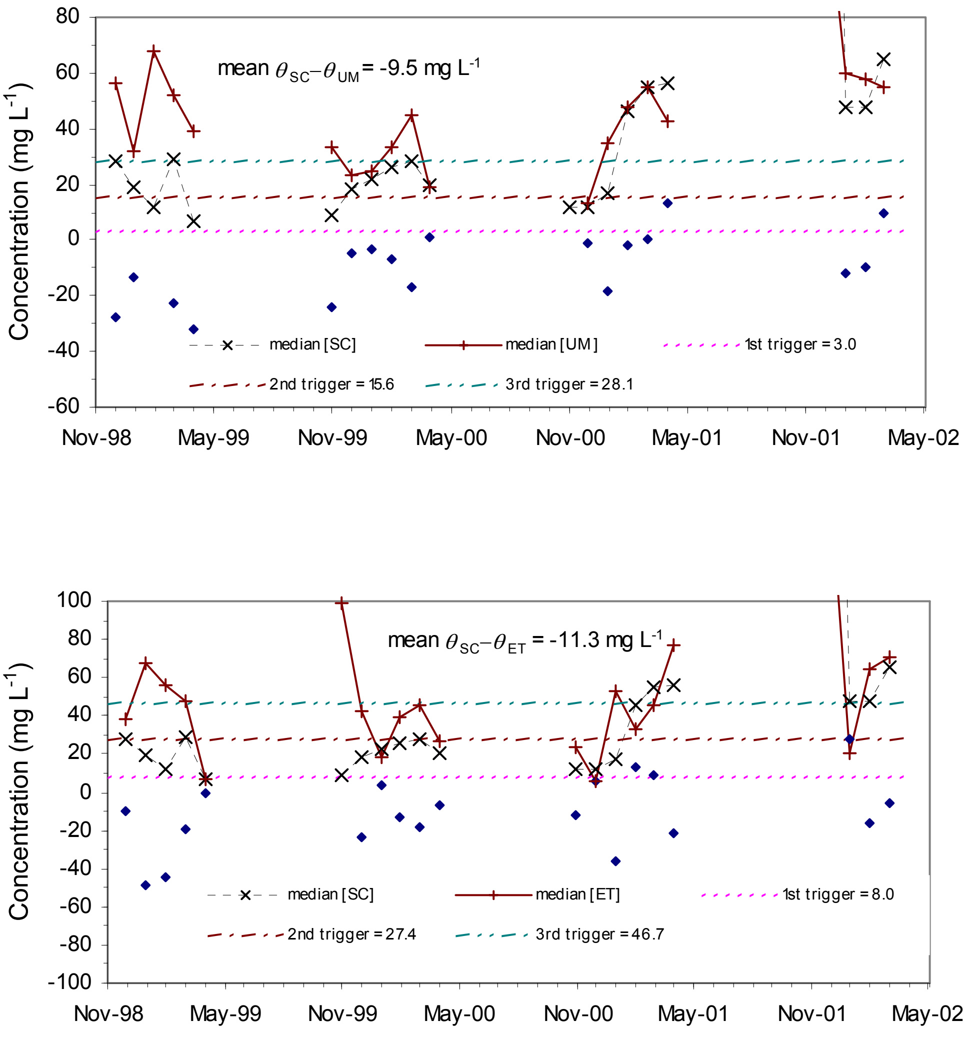
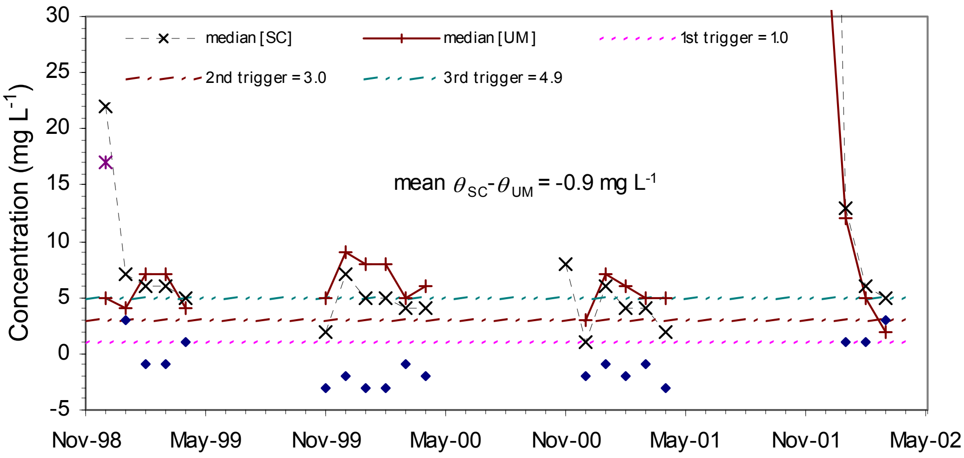


Figure 16 Temporal variation of $\theta_{SC} - \theta_{UM}$ (♦) (top) and $\theta_{SC} - \theta_{ET}$ (♦) (bottom) for [CSS] and 1st, 2nd and 3rd trigger values. Monthly median values are also shown.



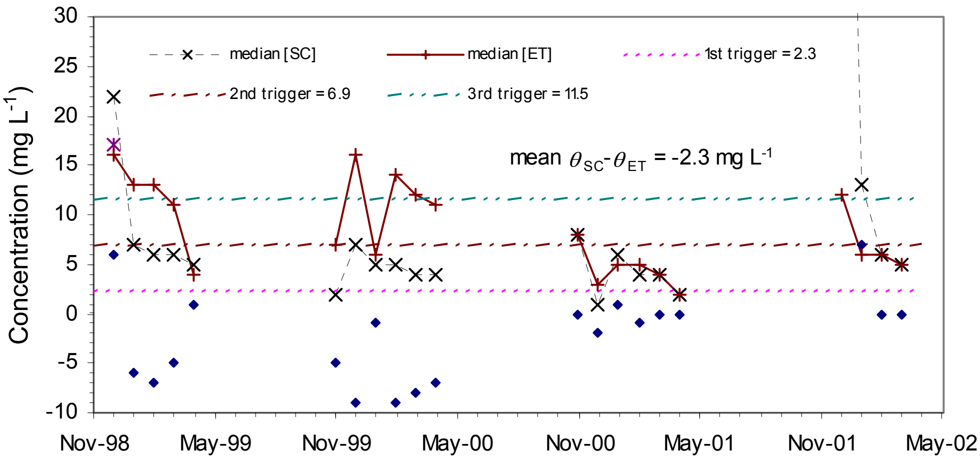
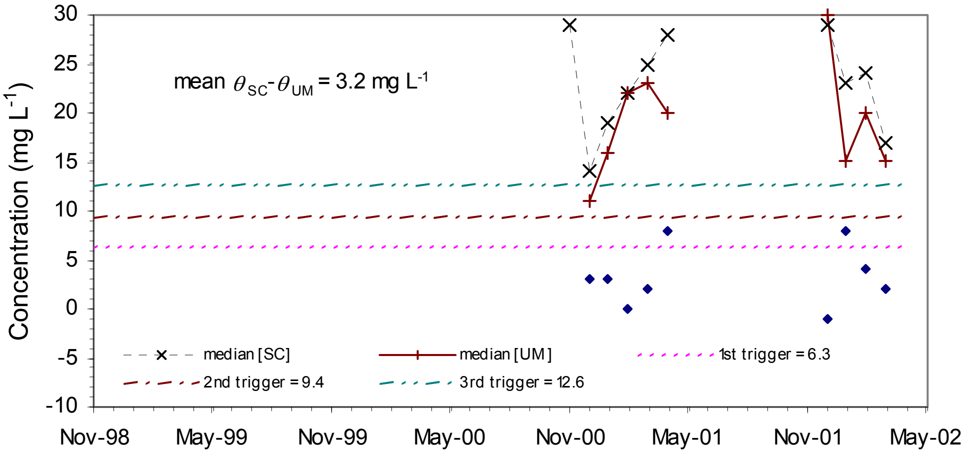


Figure 17 Temporal variation of $\theta_{SC} - \theta_{UM}$ (♦) (top) and $\theta_{SC} - \theta_{ET}$ (♦) (bottom) for [FSS] and 1st, 2nd and 3rd trigger values. Monthly median values are also shown.



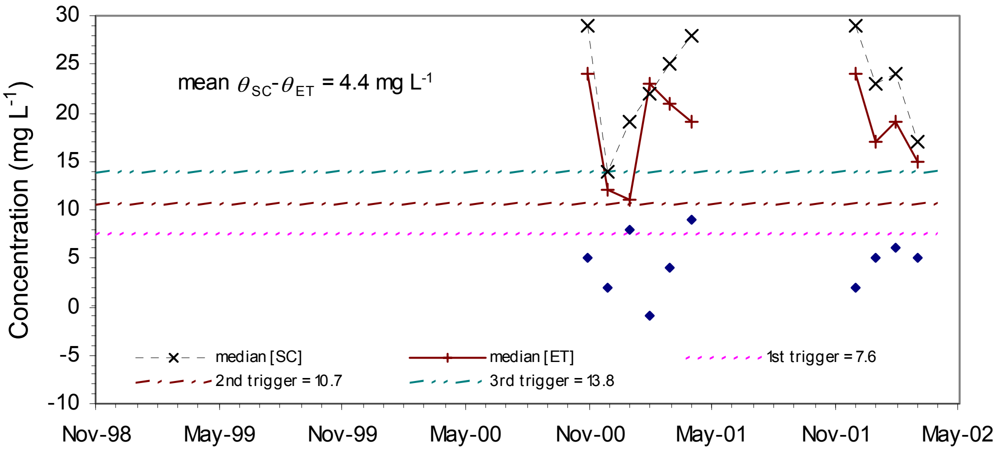


Figure 18 Temporal variation of $\theta_{SC} - \theta_{UM}$ (♦) (top) and $\theta_{SC} - \theta_{ET}$ (♦) (bottom) for [sol] and 1st, 2nd and 3rd trigger values. Monthly median values are also shown.

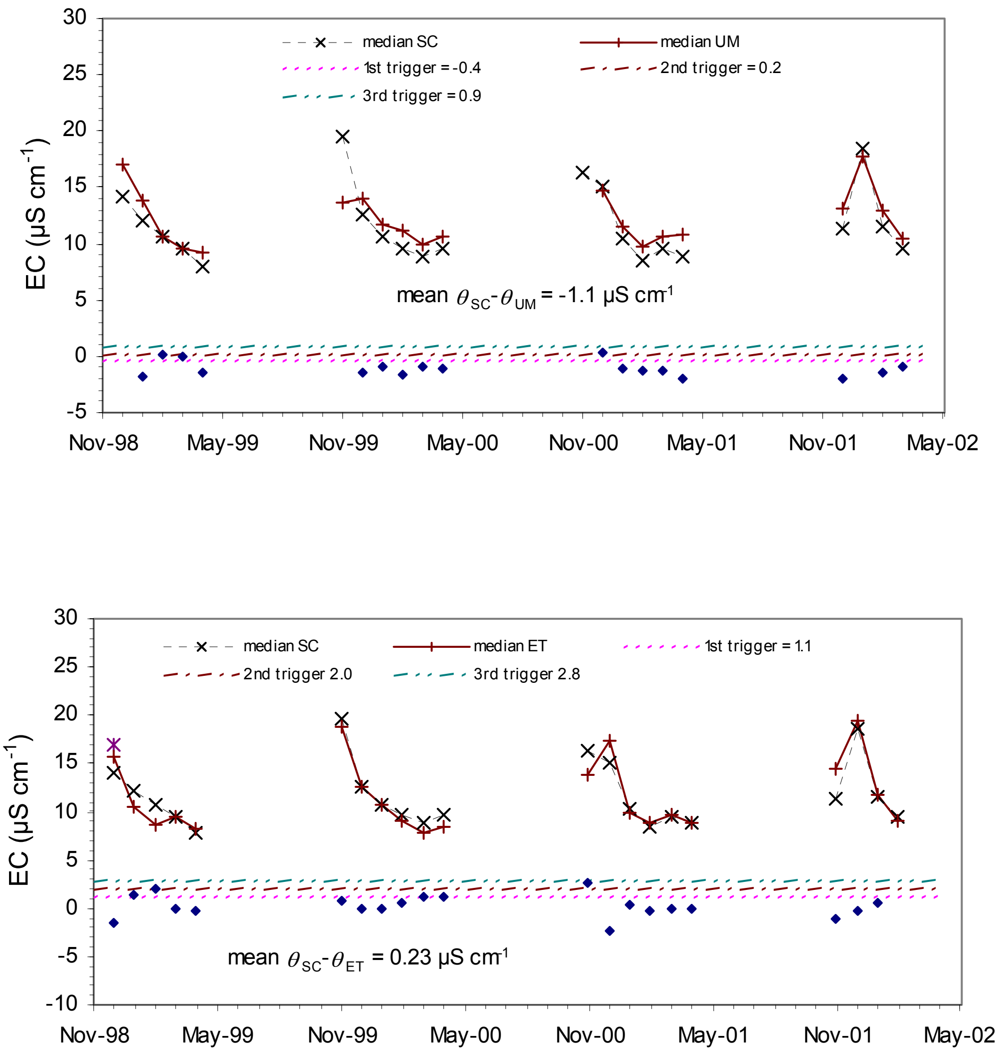


Figure 19 Temporal variation of $\theta_{SC} - \theta_{UM}$ (♦) (top) and $\theta_{SC} - \theta_{ET}$ (♦) (bottom) for EC and 1st, 2nd and 3rd trigger values. Monthly median values are also shown.

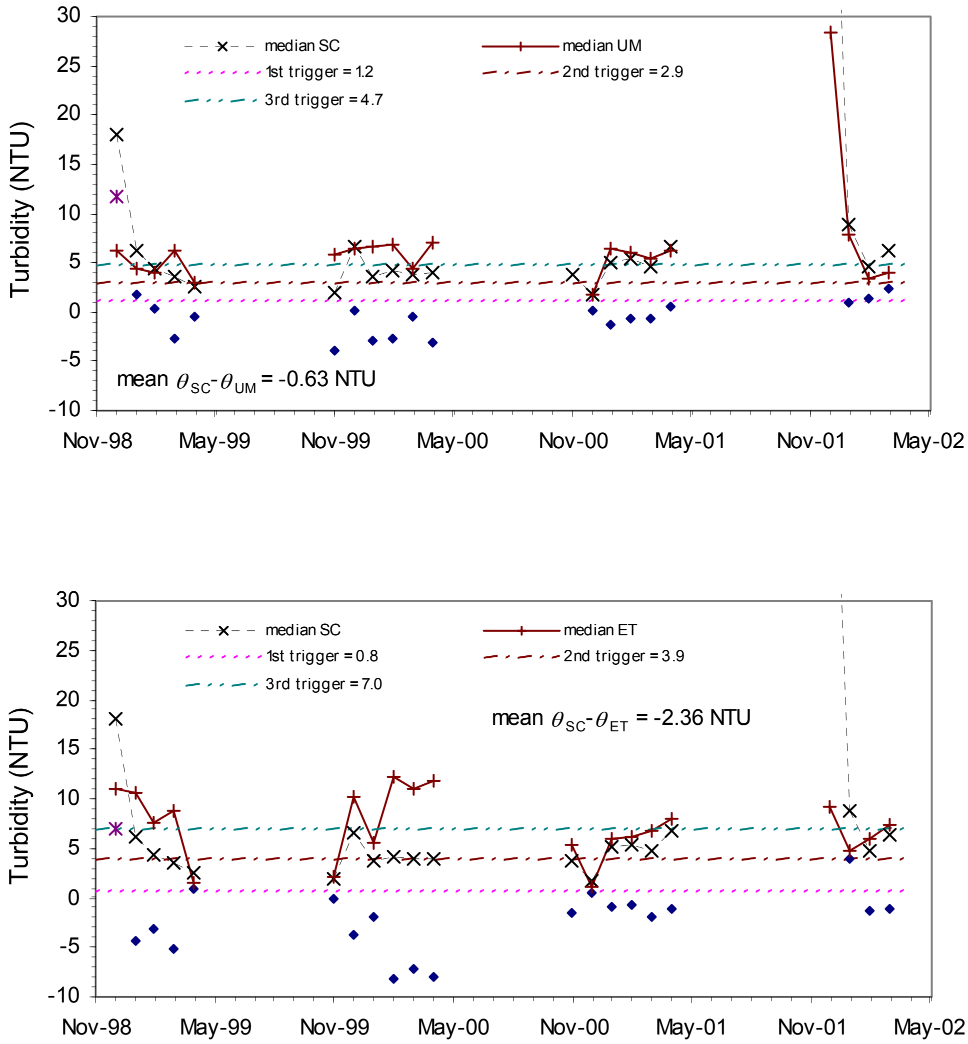


Figure 20 Temporal variation of $\theta_{SC} - \theta_{UM}$ (♦) (top) and $\theta_{SC} - \theta_{ET}$ (♦) (bottom) for turbidity and 1st, 2nd and 3rd trigger values. Monthly median values are also shown.

6 Conclusions

The fours years of monitoring have provided a high-frequency, high-quality data set. The system has high natural variability dependent on rainfall events and subsequent discharge and dry season fires. None of the measured parameter populations could be normalised. There are some similarities between parameter populations between SC and UM but ET displays different population distributions. ET is an important sampling point to confirm whether elevated levels as SC come from upstream or the mine site catchment.

In general, parameter values are elevated at the commencement of the wet season until about February. This is caused by first-flush removal of surface material detached during the dry season by agents such as fire, bioturbation (including anthropogenic activity), wind erosion and surface dessication.

Water quality trigger values at SC were derived using UM percentiles and the before-after-control-impact, paired site design. Both analyses showed no apparent long-term elevation of the measured parameters above WQG derived limits in the wet season immediately after mine construction in 1998 or during the remainder of the study period. However, the impacts of dry season fires confounded experimental design and made it difficult to assess impact in 1998–99 immediately following mine construction.

The data set provides good baseline information for future assessment at Jabiluka and demonstrates the need to view measured parameter values on a catchment-wide basis with knowledge of rainfall, discharge and fire distribution.

7 References

ANZECC & ARMCANZ 2000. *Australian and New Zealand guidelines for fresh and marine water quality*. National Water Quality Management Strategy Paper No 4, Australian and New Zealand Environment and Conservation Council & Agriculture and Resource Management Council of Australia and New Zealand, Canberra.

Atkinson G 1984. Erosion damage following bushfires. *Journal of Soil Conservation of NSW* 40, 4–9.

Boggs GS, Devonport CC, Evans KG, Saynor MJ & Moliere DR 2001. *Development of a GIS based approach to mining risk assessment*. Supervising Scientist Report 159, Supervising Scientist, Darwin.

Bonta JV 2000. Impact of coal surface mining and reclamation on suspended sediment in three Ohio watersheds. *Journal of American Water Resources Associations* 36(4), 869–887.

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

Carson LJ, Haines PW, Brakel A, Pietsch BA & Ferenczi PA 1999. 1:250000 Geological Map Series Explanatory Notes Milingimbi SD 53-2. Department of Mines and Energy, Northern Territory Geological Survey and Australian Geological Survey Organisation, Darwin.

Cusbert PJ 1990. Investigation of methods for the determination of suspended soils in water. Internal report 5, Supervising Scientist for the Alligator Rivers Region, Canberra. Unpublished paper.

Duggan K 1988. Mining and erosion in the Alligator Rivers Region of northern Australia. PhD thesis, Macquarie University, Sydney.

Duggan K 1991. Mining and erosion in the Alligator Rivers Region of Northern Australia. Open file record 81, Supervising Scientist for the Alligator Rivers Region, Canberra. Unpublished paper.

Eaton AD, Clesceri LS & Greenberg AE (eds) 1995. *Standard methods for the examination of water and wastewater*. American Public Health Association, Washington, DC 20005.

Erskine WD, Saynor MJ, Evans KG & Boggs GS 2001. *Geomorphic research to determine the off-site impacts of the Jabiluka Mine on Swift (Ngarradj) Creek, Northern Territory*. Supervising Scientist Report 158, Supervising Scientist, Darwin.

Evans KG, Saynor MJ & Willgoose GR 1999. Changes in hydrology, sediment loss and micro-topography of a vegetated mine waste rock dump impacted by fire. *Land Degradation and Development* 10, 507–522.

Humphrey CL, Faith DP & Dostine PL 1995. Baseline requirements for assessment of mining impact using biological monitoring. *Australian Journal of Ecology* 20, 150–166.

Kakadu Board of Management & Parks Australia 1998. *Kakadu National Park Plan of Management*. Australian Government Publishing Service, Canberra.

Klessa DA 2000. *The chemistry of Magela Creek: A baseline for assessing change downstream of Ranger*. Supervising Scientist Report 151, Supervising Scientist, Darwin.

leGras C, Moliere D & Norton D 2001. Chemical characteristics of stream waters in the Jabiluka region: Second interim report. Internal Report 364, Supervising Scientist, Darwin. Unpublished paper.

McGovern E 2003. Appendix 8A to Jabiluka MMP. Amended Jabiluka project plan of rehabilitation #7, January 2003. Energy Resources of Australia, Darwin.

Moliere DR, Evans KG, Saynor MJ & Erskine WD 2004a. Estimation of suspended sediment loads in a seasonal stream in the wet-dry tropics, Northern Territory, Australia. *Hydrological Processes* 18, 531–544.

Moliere DR, Saynor MJ & Evans KG 2004b. Suspended sediment concentration-turbidity relationships for Ngarradj – a seasonal stream in the wet-dry tropics. *Australian Journal of Water Resources* (in review).

Neal C, Jarvie HP & Oguchi T 1999. Acid-available particulate trace metals associated with suspended sediment in the Humber rivers: a regional assessment. *Hydrological Processes* 13, 1117–1136.

Pentz SB & Kostaschuk RA 1999. Effect of placer mining on suspended sediment in reaches of sensitive fish habitat. *Environmental Geology* 37(1–2), 78–89.

Robinson AR 1977. Relationship between soil erosion and sediment delivery. *International Association of Hydrological Sciences* 122, 159–167.

Saynor MJ, Dawson JC, Smith BL, Crisp E & Moliere DR 2001. Installation, maintenance and running of gauging stations in the Swift (Ngarradj) Creek catchment, Northern Territory. Internal Report 384, Supervising Scientist, Darwin. Unpublished paper.

Saynor MJ, Erskine WD, Smith BL, Fox GJ & Evans KG 2002a. Cross sectional data and a preliminary assessment of channel changes in the Swift Creek (Ngarradj) catchment between 1998 and 2001. Internal Report 385, Supervising Scientist, Darwin. Unpublished paper.

Saynor MJ, Erskine WD, Smith BL, Fox GJ & Evans KG 2002b. Scour and fill in the Swift Creek (Ngarradj) catchment: Results of scour chains for the 1998/1999, 1999/2000 and 2000/2001 Wet seasons. Internal Report 388, Supervising Scientist, Darwin. Unpublished paper.

Stewart-Oaten A, Murdoch WW & Parker KR 1986. Environmental impact assessment: ‘Pseudoreplication’ in time? *Ecology* 67, 929–940.

Stewart-Oaten A, Bence, JR & Osenberg CW 1992. Assessing effects of unreplicated perturbations: No simple solutions. *Ecology* 73, 1396–1404.

Supervising Scientist 2002. Supervising Scientist Monitoring Program: Instigating an environmental monitoring program to protect aquatic ecosystems and humans from possible mining impacts in the ARR. www.deh.gov.au/ssd/monitoring/background.html

Townsend SA & Douglas MM 2000. Effect of three fire regimes on stream water quality, water yield and export coefficients in a tropical savanna (northern Australia). *Journal of Hydrology* 229, 118–137.

Walling DE 1983. The sediment delivery problem. *Journal of Hydrology* 65, 209–237.

Walling DE & Webb 1982. Sediment availability and the prediction of storm-period sediment yields. In *Recent developments in the explanation and prediction of erosion and sediment yield*. Proceedings Exeter Symposium, July 1982, IAHS Publication 137, 327–337.

Walling DE & Webb BW 1985. Estimating the discharge of contaminants to coastal waters by rivers: some cautionary comments. *Marine Pollution Bulletin* 16(12), 488–492.

Westgard JO 2000. Method validation – the detection limit experiment. http://www.westgard.com/lesson29.htm

Williams GP 1989. Sediment concentration versus water discharge during single hydrologic events in rivers. *Journal of Hydrology* 111, 89–106.

Zierholz C, Hairsine P & Booker F 1995. Runoff and soil erosion in bushland following the Sydney bushfires. *Australian Journal of Soil & Water Conservation* 8, 28–37.

Appendix A
Coarse suspended-sediment concentration data

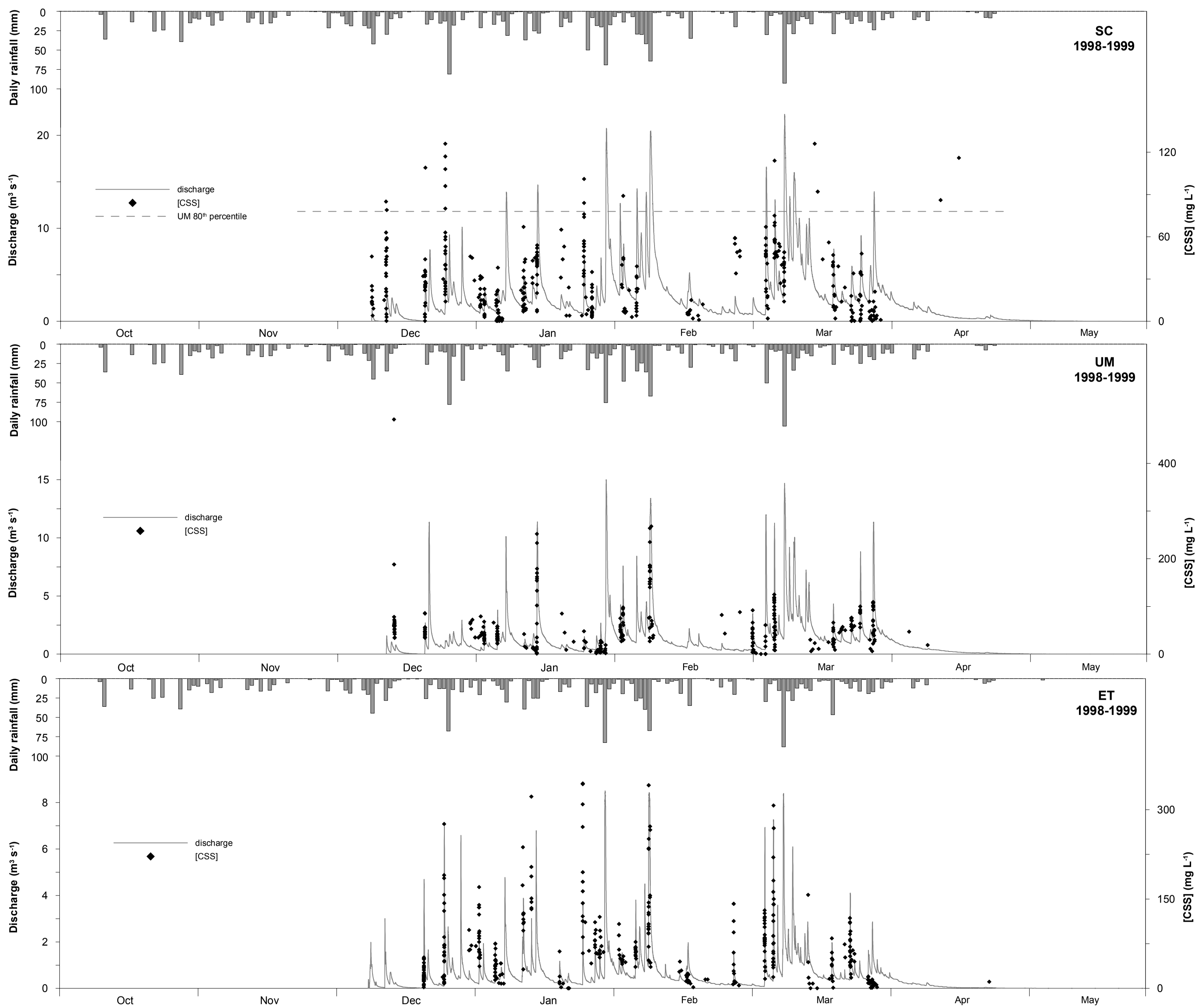


Figure A.1 Daily rainfall, hydrograph and coarse suspended-sediment concentration ([CSS]) during 1998–99

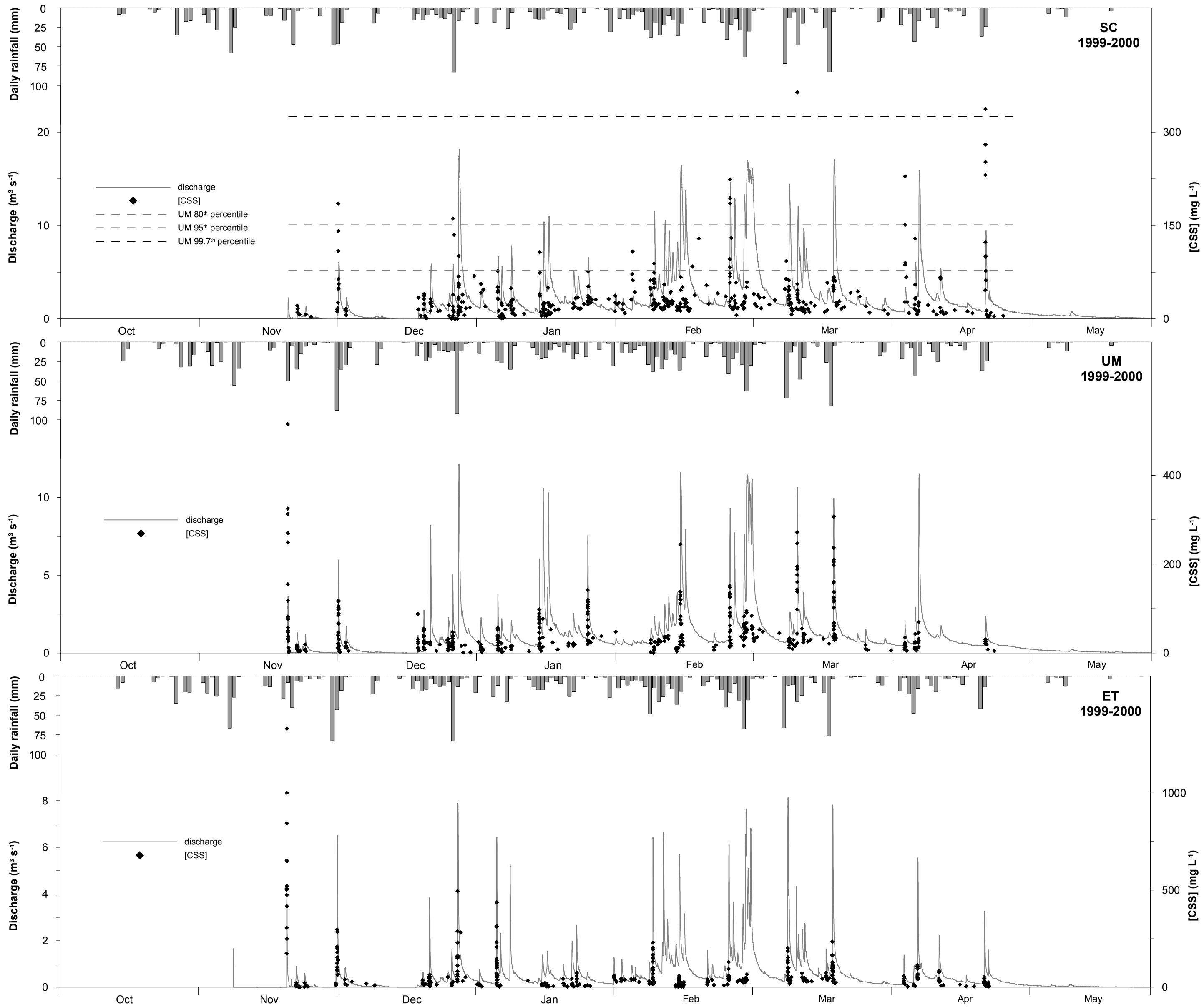


Figure A.2 Daily rainfall, hydrograph and coarse suspended-sediment concentration ([CSS]) during 1999–2000

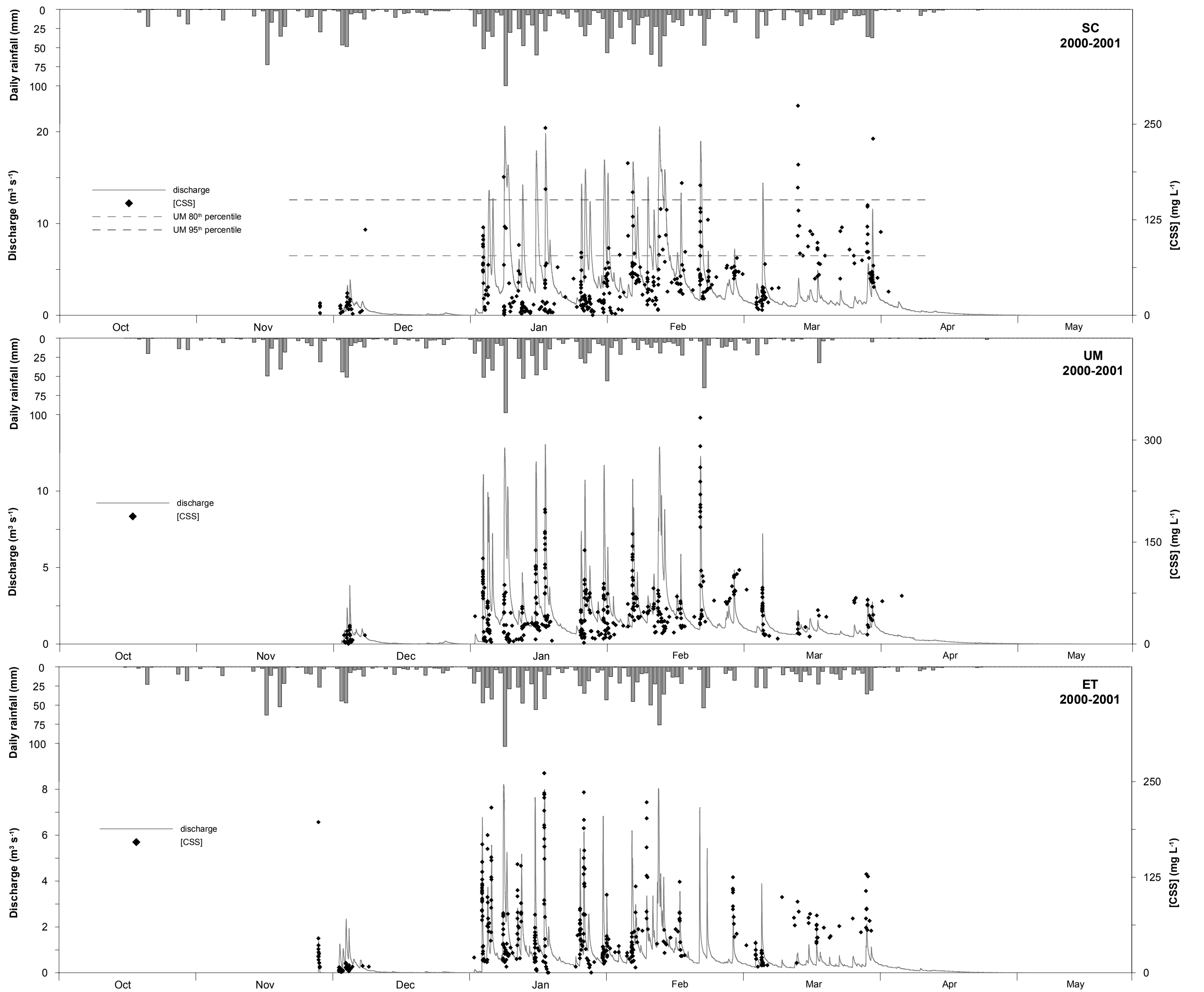


Figure A.3 Daily rainfall, hydrograph and coarse suspended-sediment concentration ([CSS]) during 2000–01

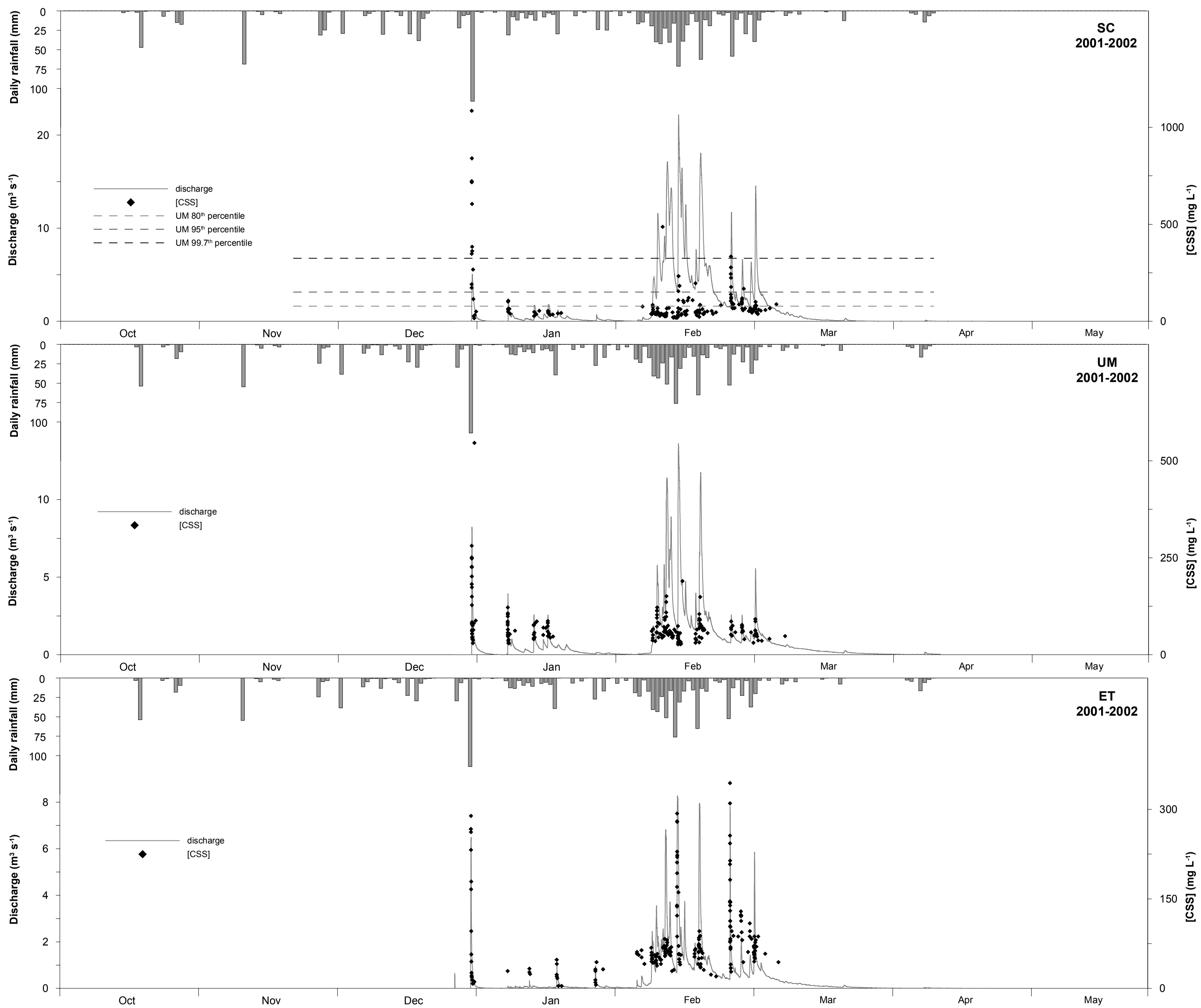


Figure A.4 Daily rainfall, hydrograph and coarse suspended sediment concentration ([CSS]) during 2001–02

Appendix B
Fine suspended-sediment concentration data

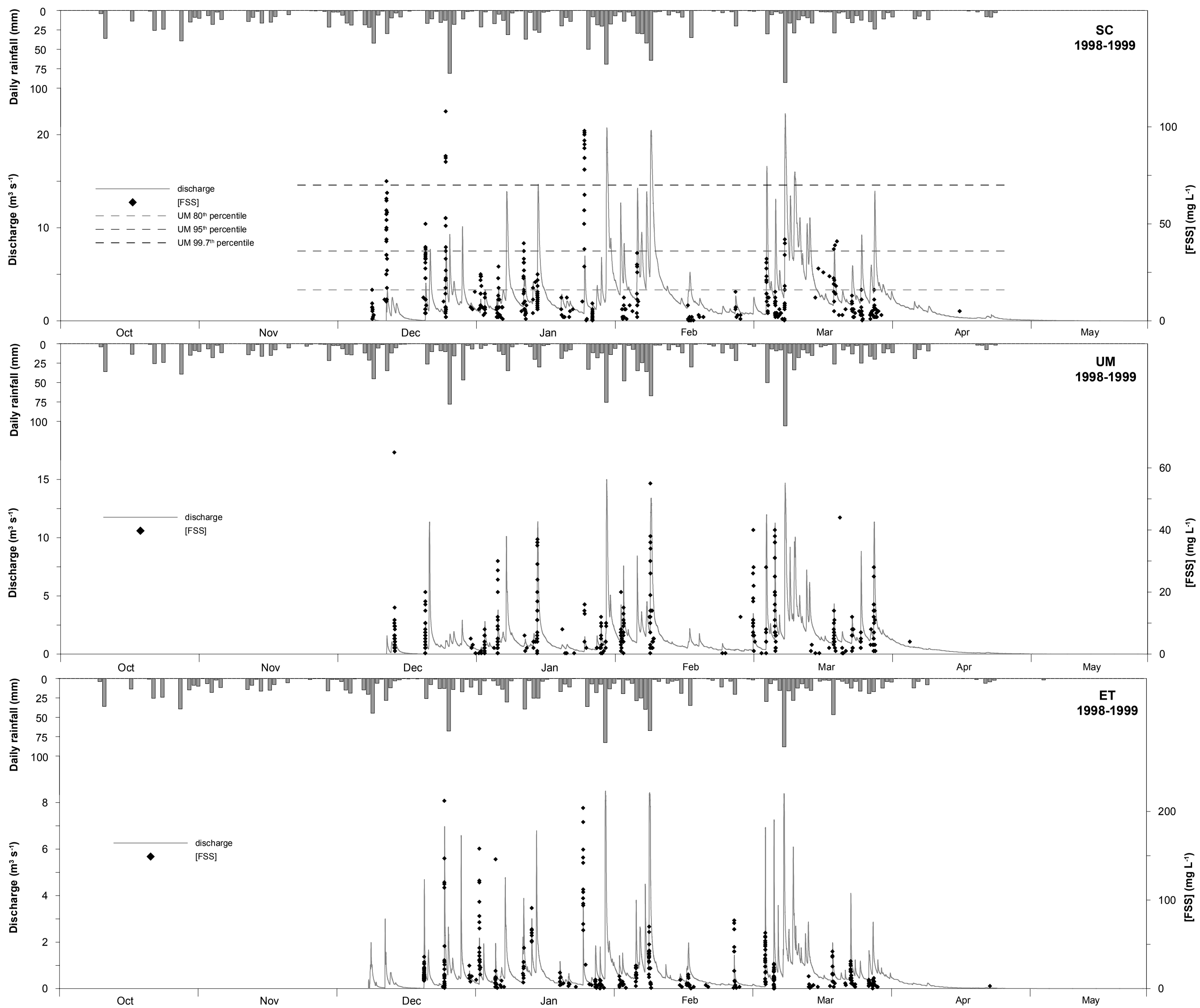


Figure B.1 Daily rainfall, hydrograph and fine suspended-sediment concentration ([FSS]) during 1998–99

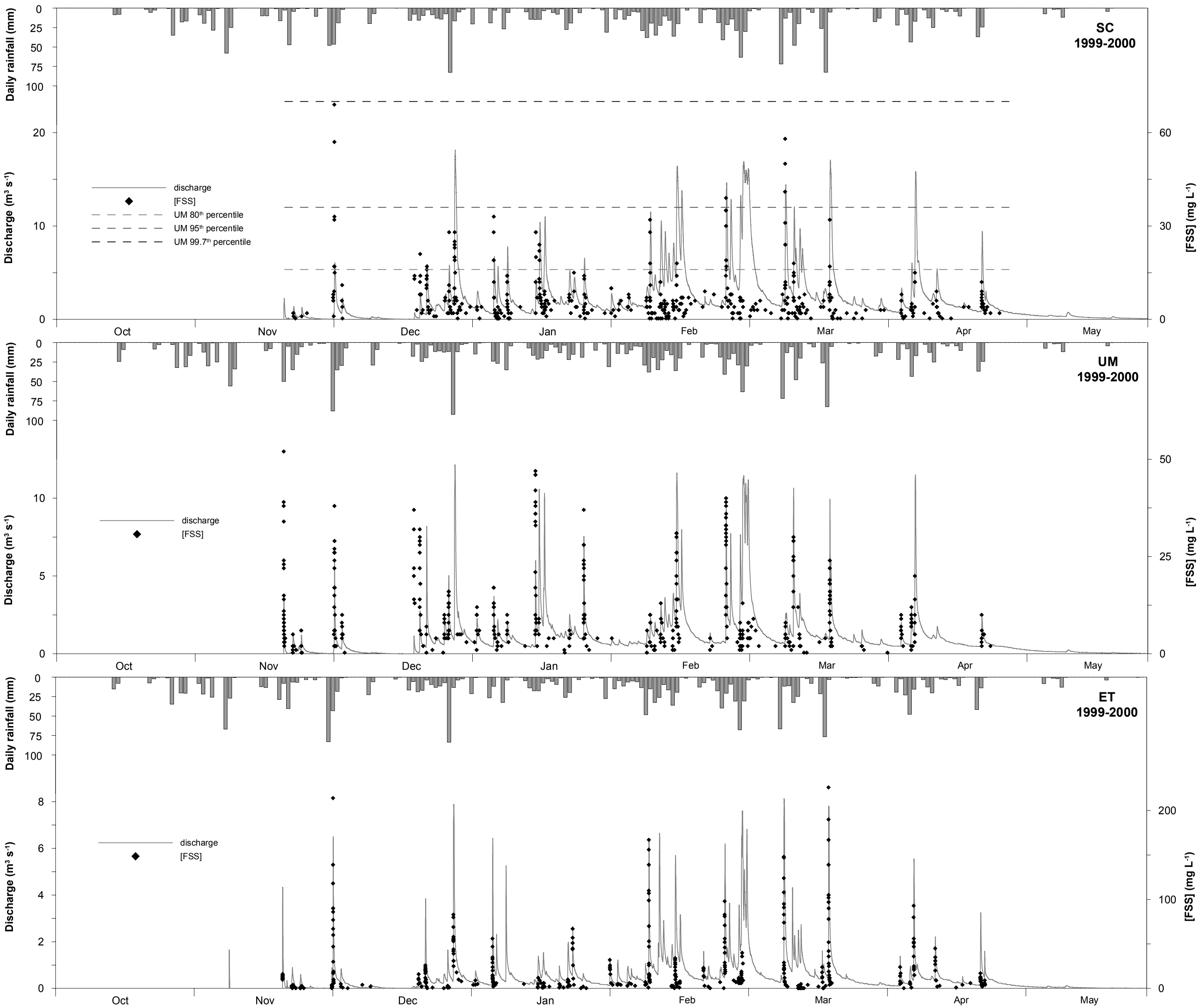


Figure B.2 Daily rainfall, hydrograph and fine suspended-sediment concentration ([FSS]) during 1999–2000

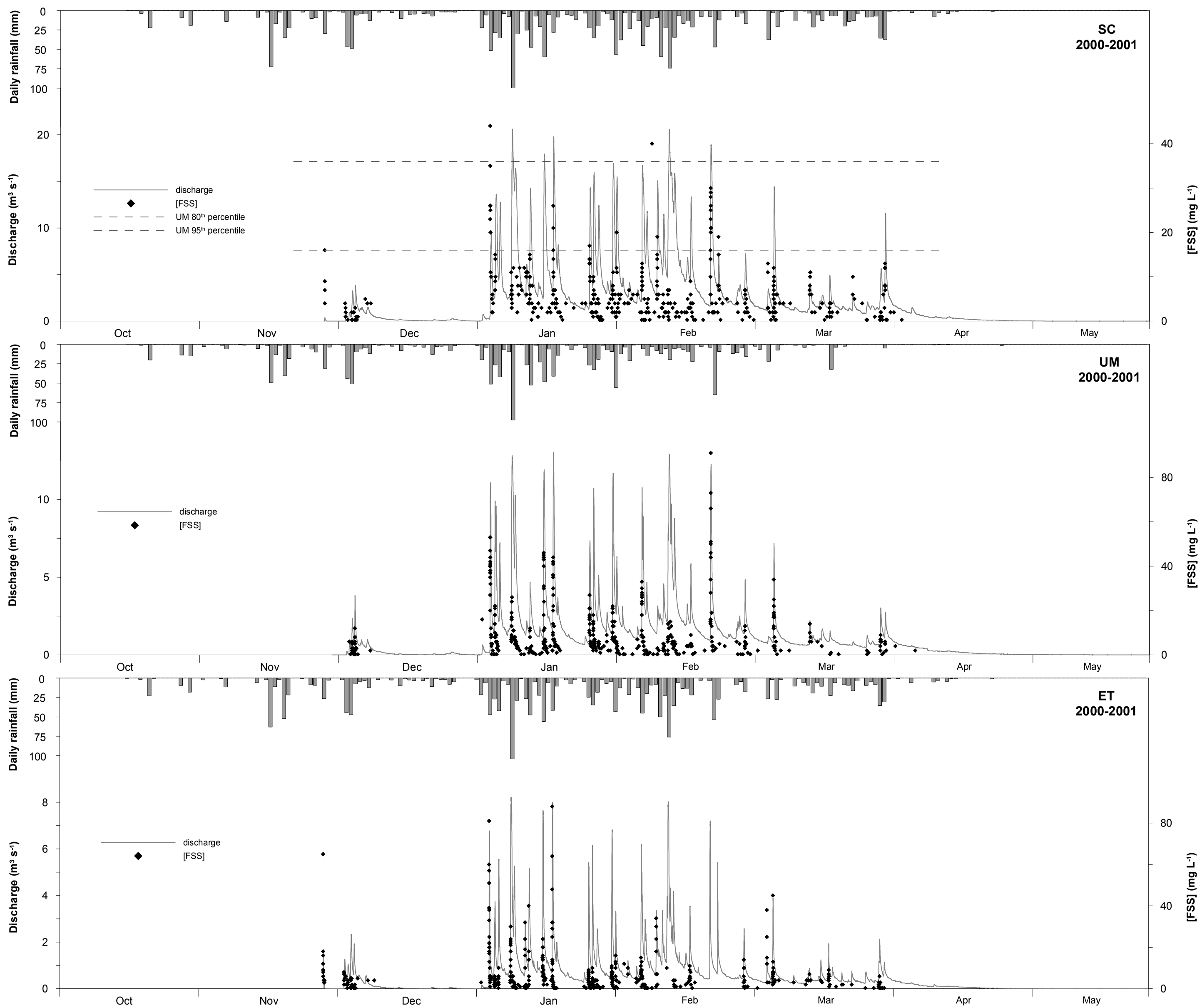


Figure B.3 Daily rainfall, hydrograph and fine suspended-sediment concentration ([FSS]) during 2000–01

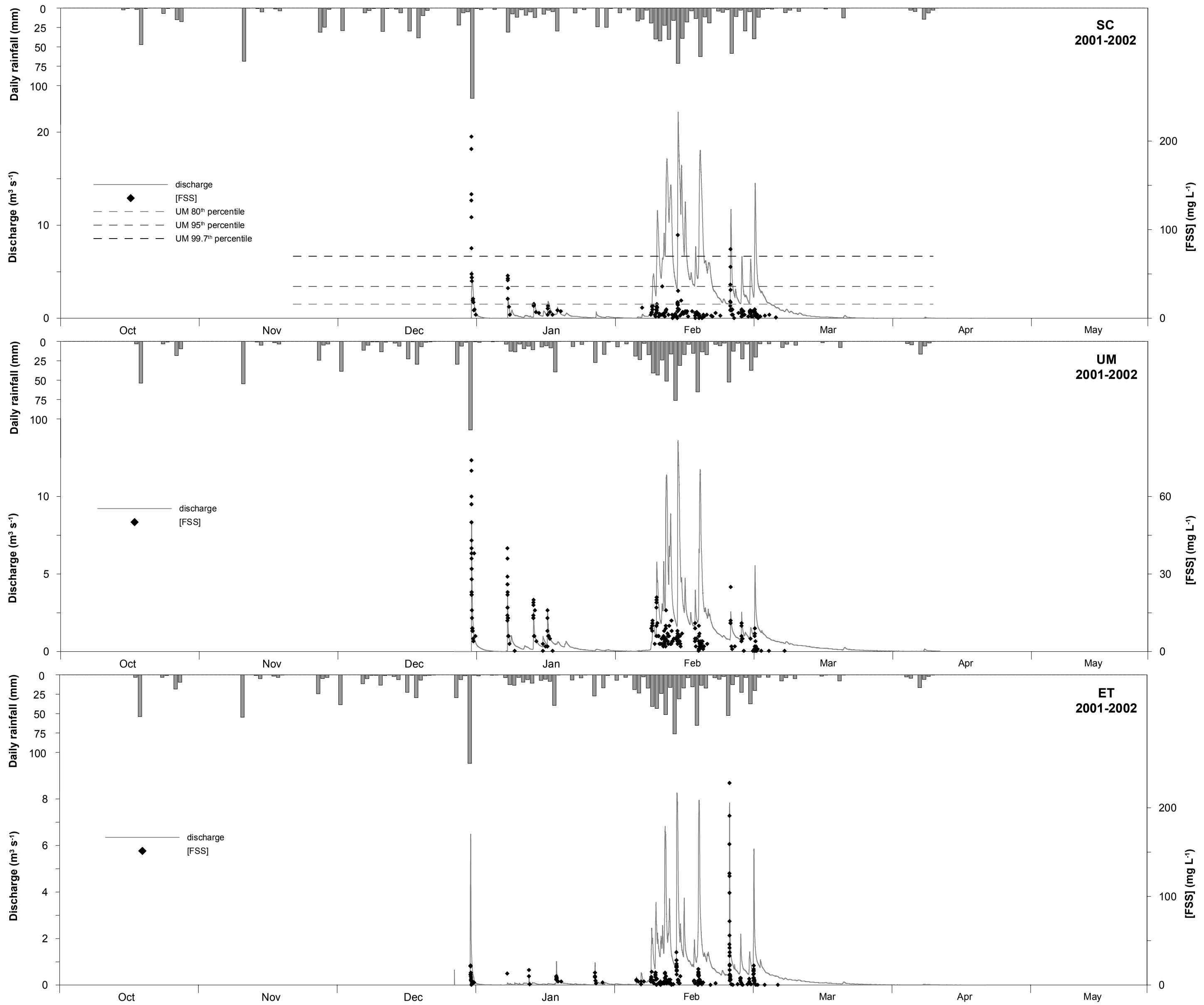


Figure B.4 Daily rainfall, hydrograph and fine suspended-sediment concentration ([FSS]) during 2001–02

Appendix C
Solute concentration data

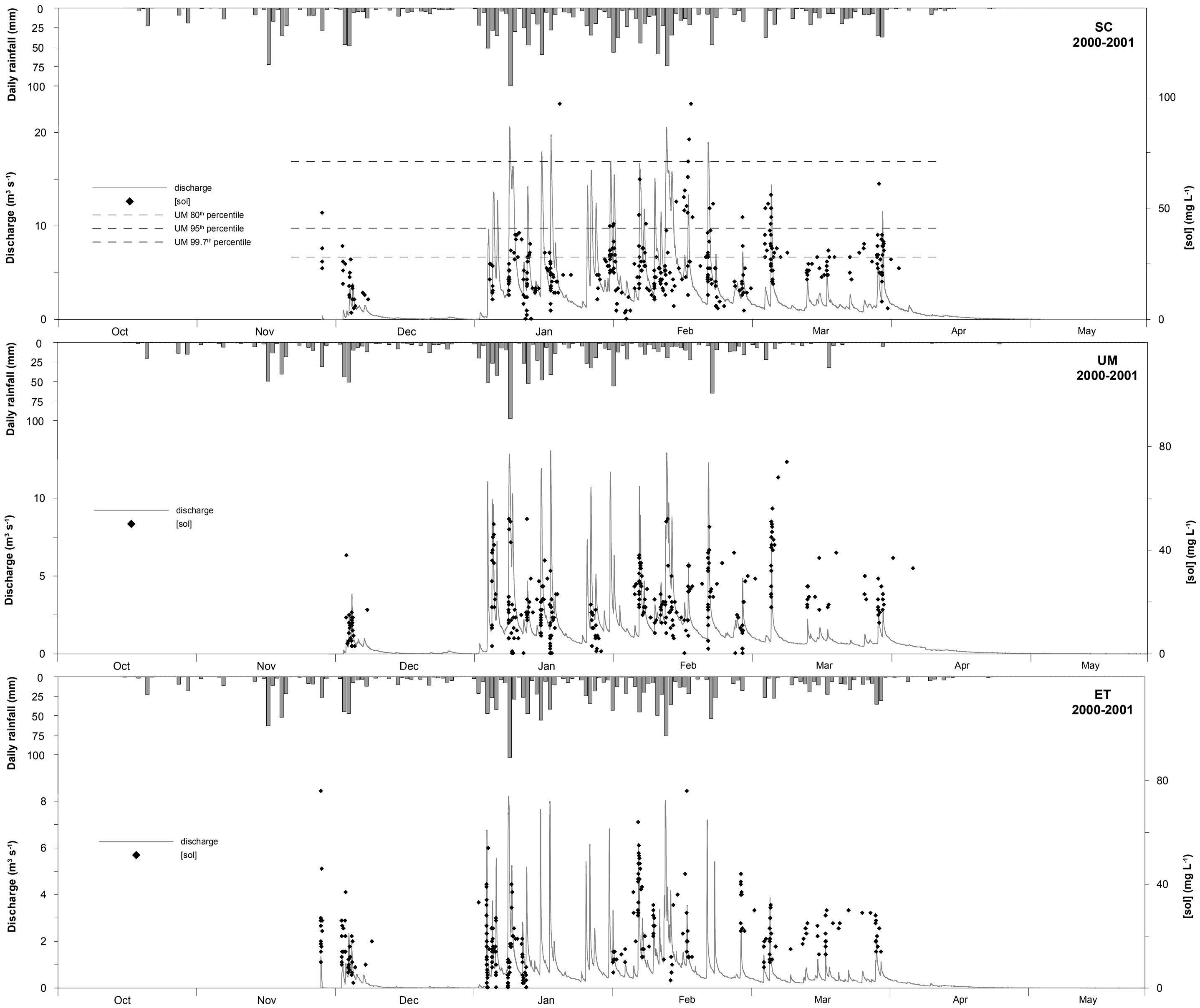


Figure C.1 Daily rainfall, hydrograph and solute concentration ([sol]) during 2000–01

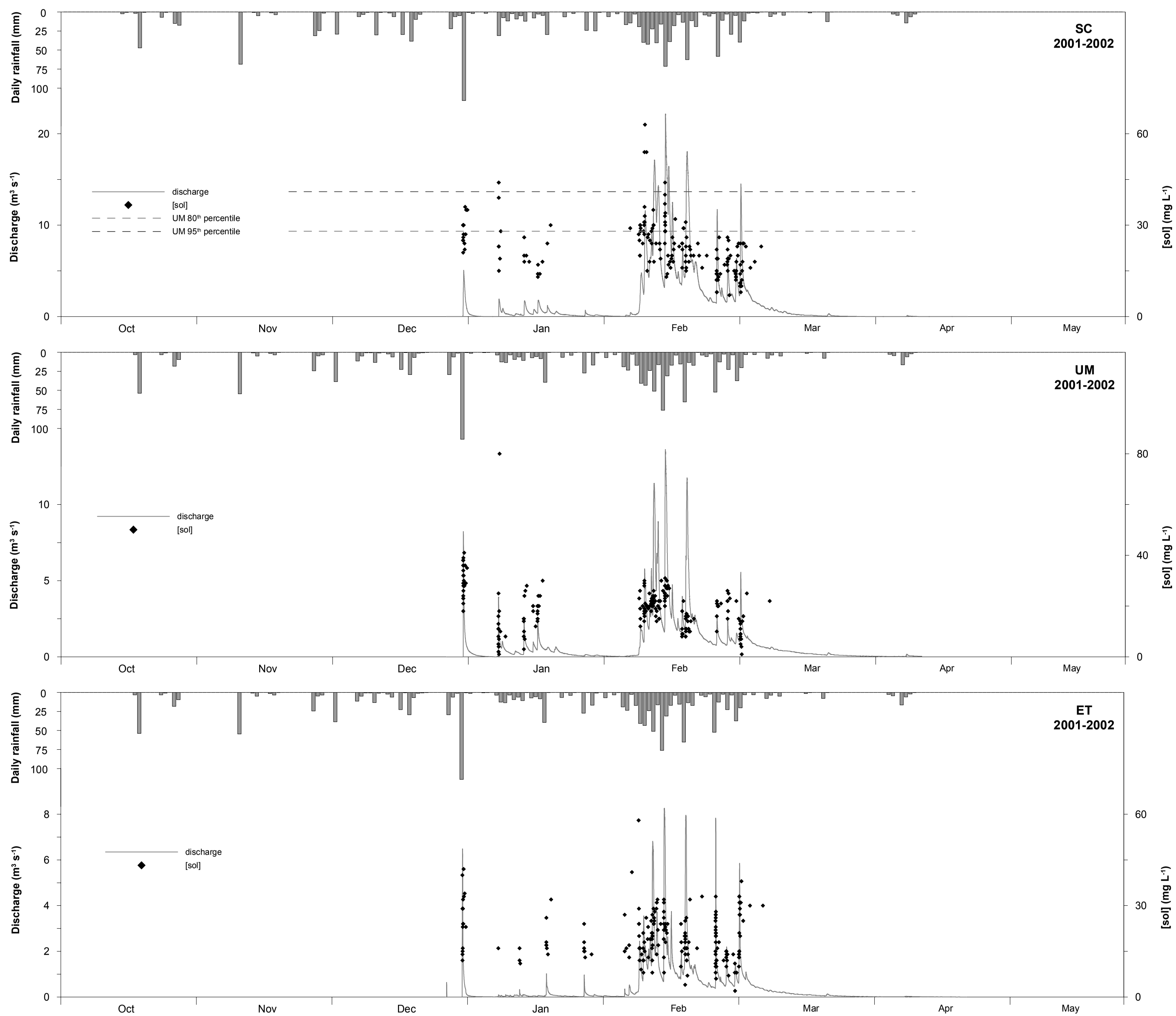


Figure C.2 Daily rainfall, hydrograph and solute concentration ([sol]) during 2001–02

Appendix D
Electrical conductivity data

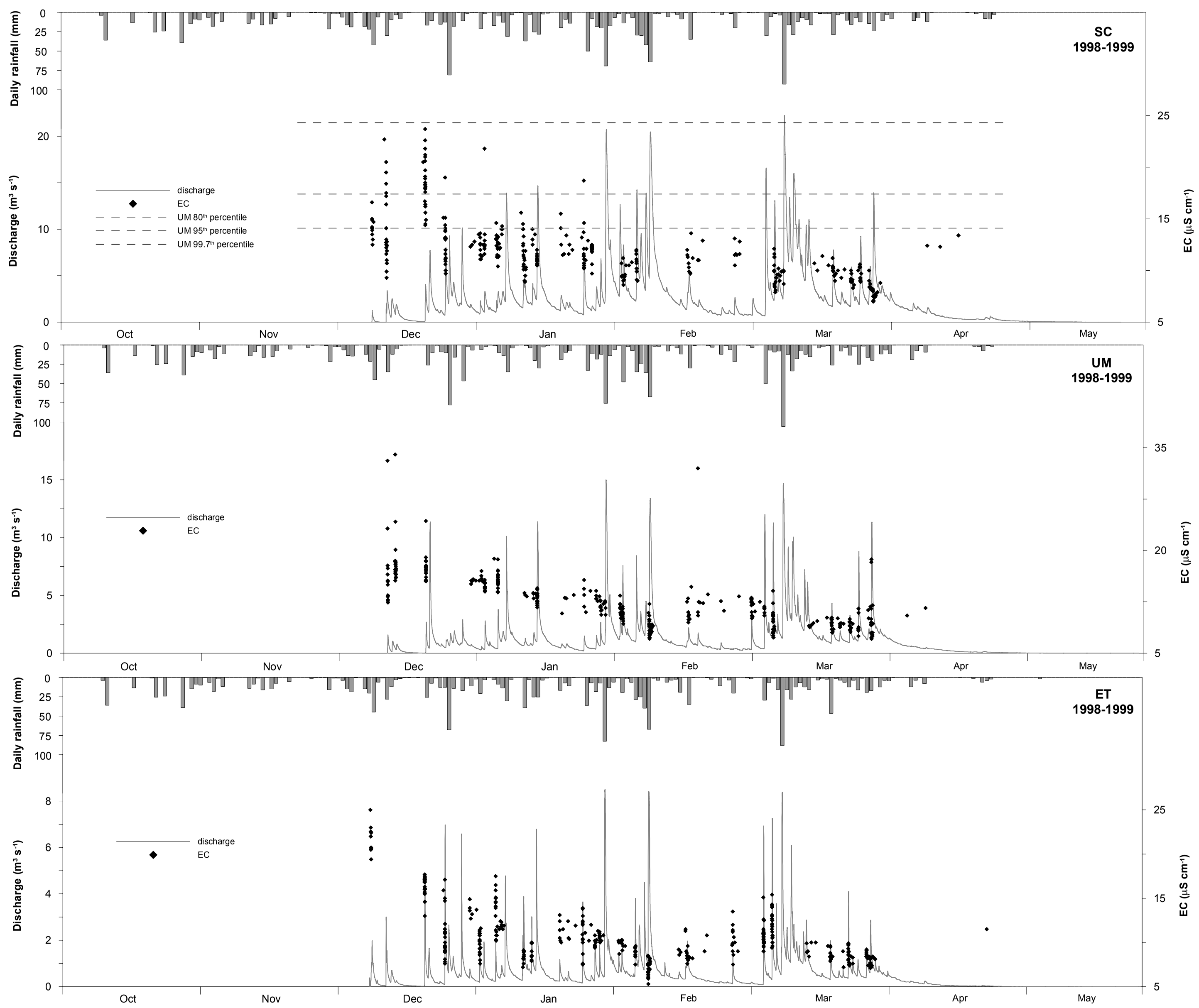


Figure D.1 Daily rainfall, hydrograph and electrical conductivity (EC) during 1998–99

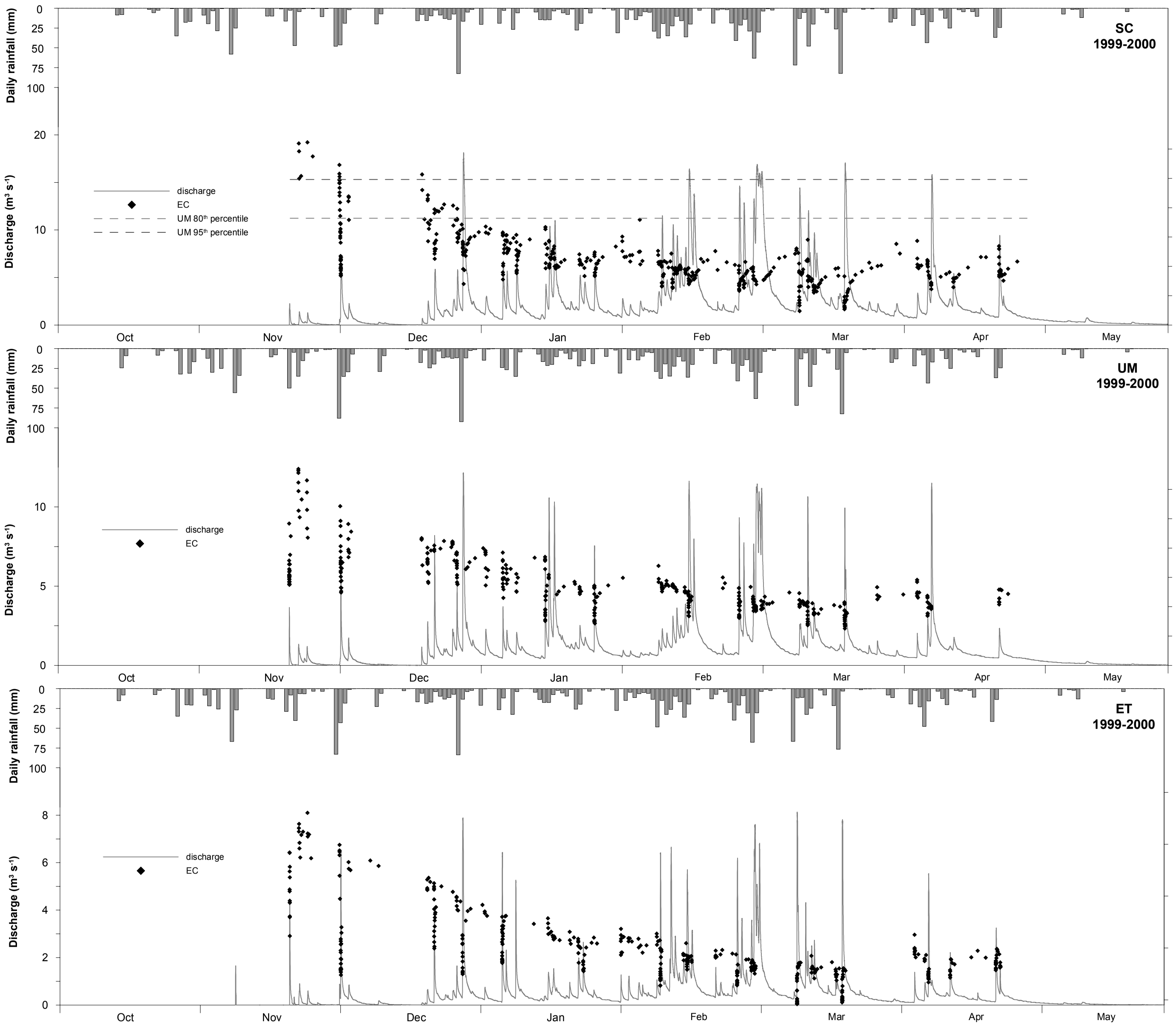


Figure D.2 Daily rainfall, hydrograph and electrical conductivity (EC) during 1999–2000

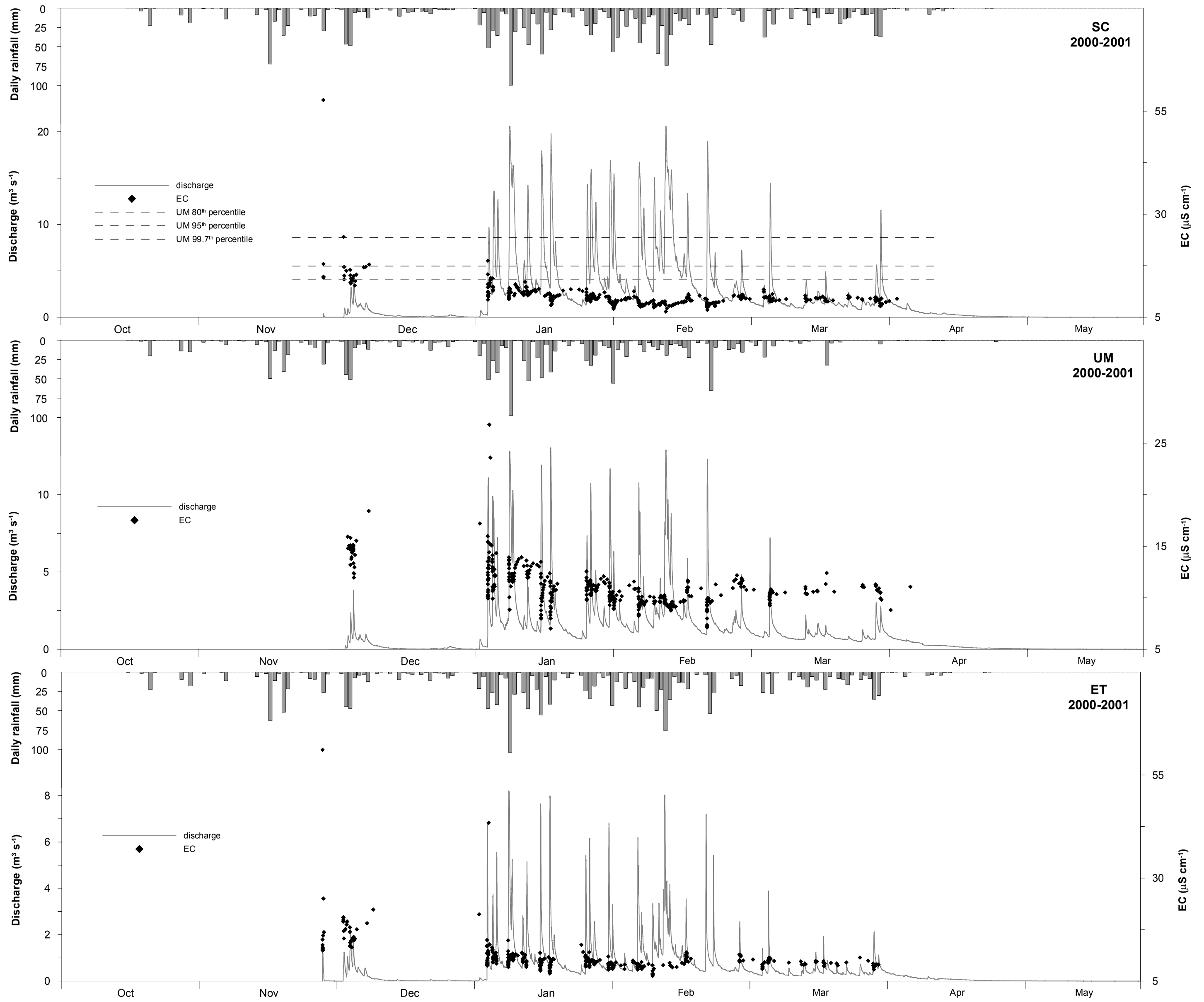


Figure D.3 Daily rainfall, hydrograph and electrical conductivity (EC) during 2000–01

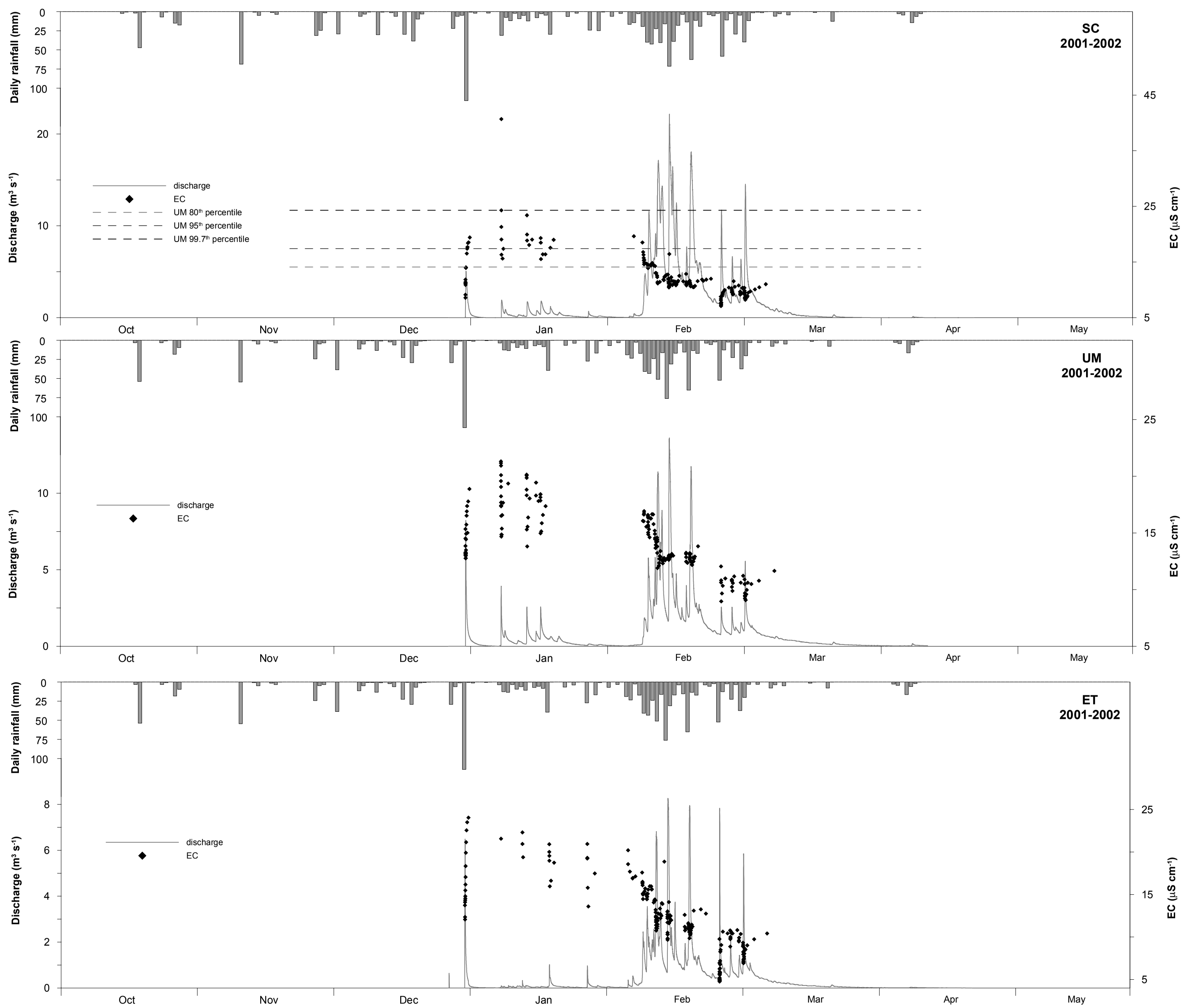


Figure D.4 Daily rainfall, hydrograph and electrical conductivity (EC) during 2001–02

Appendix E
Turbidity data

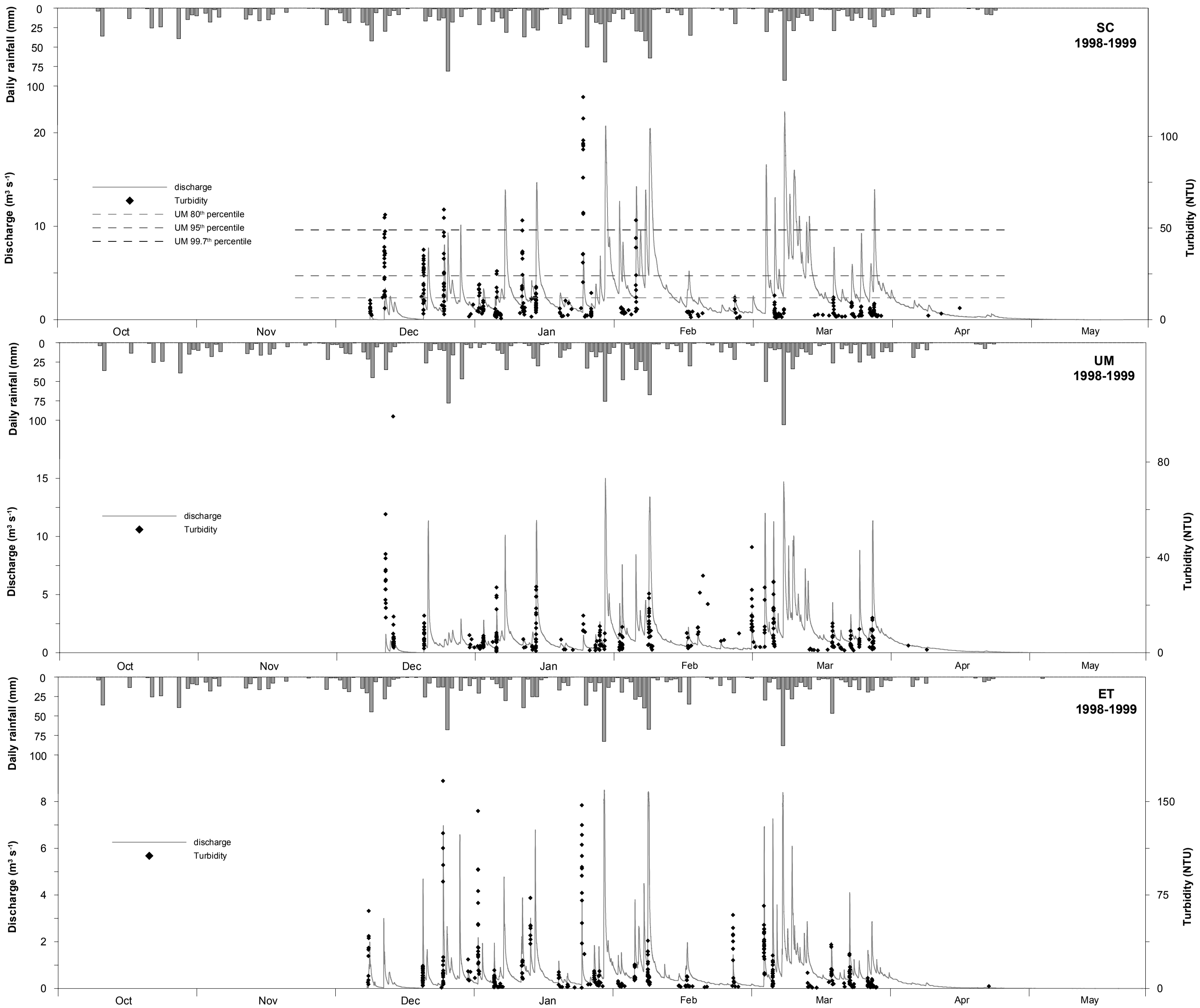


Figure E.1 Daily rainfall, hydrograph and turbidity during 1998–99

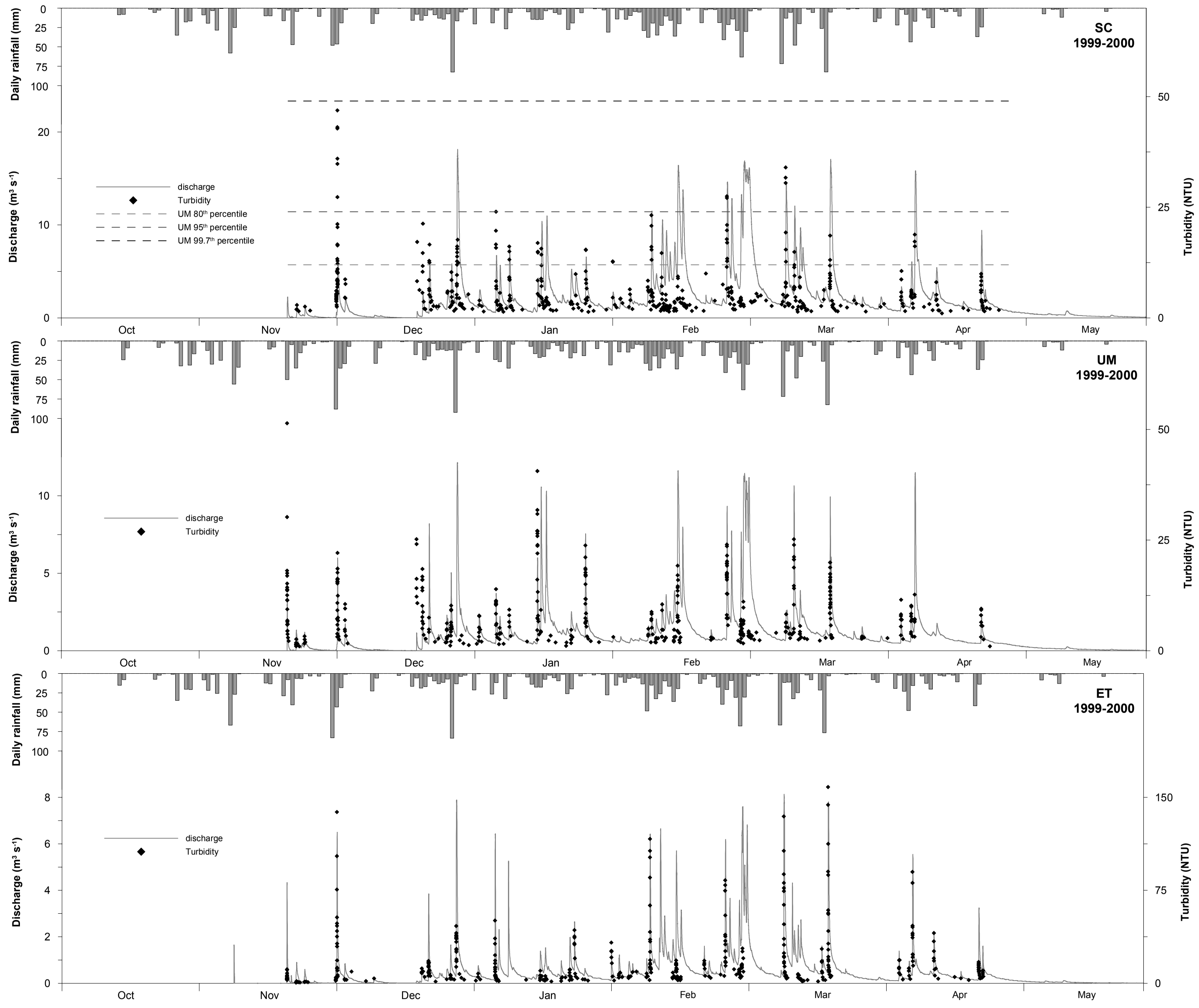


Figure E.2 Daily rainfall, hydrograph and turbidity 1999–2000

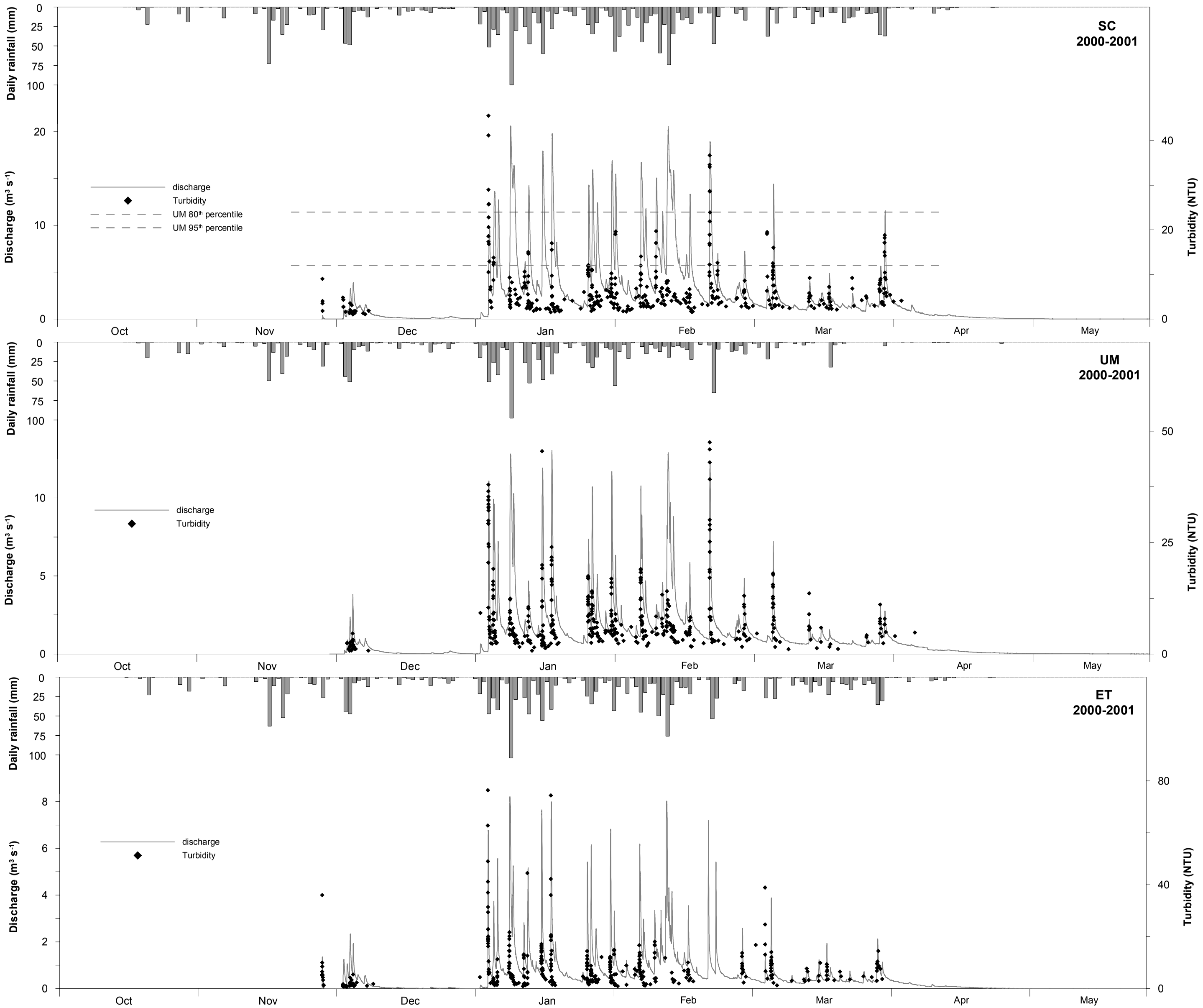


Figure E.3 Daily rainfall, hydrograph and turbidity during 2000–01

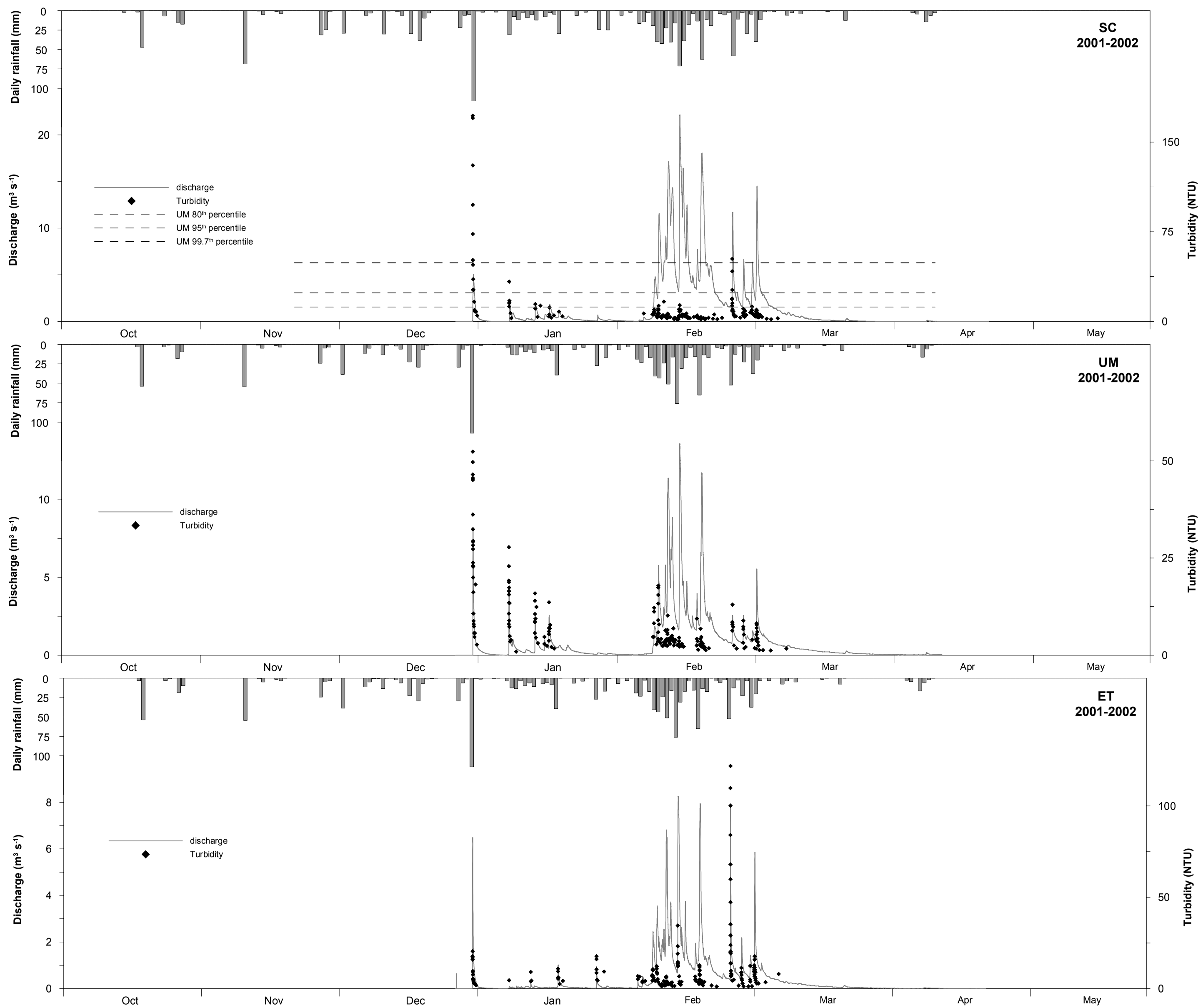


Figure E.4 Daily rainfall, hydrograph and turbidity during 2001–02