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Infrastructure, Planning and Natural Resources

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Frank Harvey
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Acknowledgments

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Abstract

The Murray-Darling Basin is the largest watershed of the south-eastern Australian mainland, draining an area of 1.057 million square kilometres. Over the past decade, rising salinity in surface waters has become a major issue and much attention is being focussed on understanding the mechanisms involved. Using the limited available data, attempts were made to explain the behaviour of EC (electrical conductivity) in four tributary catchments draining into the Murrumbidgee River, one of the major tributaries of the Murray–Darling system.

Discrete electrical conductivity data were examined in the context of the instantaneous flow regimes at the time of sampling. Particular attention was paid to differentiating the EC behaviour for the various parts of the event hydrograph. As well as noting some unique behaviour for each catchment, the investigation observed common empirical relationships that might point to the successful development of regional electrical conductivity parameters.

An analysis of the long-term trends suggested a deceleration in the rate of rise of EC at the four sites. The identification of this non-linear trend in base level EC enables short term forecasting of EC behaviour at each of the sites.

Keywords: electrical conductivity–flow relationships; Murrumbidgee River tributaries; discrete samples; hydrograph characteristics; regional parameters.

1. Introduction

EC (electrical conductivity) is monitored at many stream-gauging stations across the Murray-Darling Basin. The data are of immediate twofold importance. Firstly, EC directly indicates whether the water is suitable for drinking, irrigation or meets the guidelines for the protection of aquatic ecosystems. Secondly, it is used as a means of calculating passing salt loads which are used as an indicator of the state of individual catchments.

Because rising river salinity is such a critical issue in the Murray-Darling Basin, any information pertaining to EC is of immense importance. Jolly *et al*. (1997) identified EC trends that were seasonally and flow-adjusted for 87 gauging stations in the Basin. Williamson *et al*. (1997) noted that 80% of the values of significant rises and falls were in the range +6 to –7 μS/cm per annum. A number of factors, which included surface water hydrology and climate, were listed as contributing to the mobilisation of salt. Follow-up work by Jolly *et al*. (2001) grouped the 87 sites into four regions. They noted that half the sites in 'the southern and eastern dryland region of the basin had significantly rising stream salinity trends.' The four sites used in this study might be expected to exhibit the same rising trend. Jolly *et al.* (2001) also suggested that this rising trend would not persist indefinitely, and that each catchment would eventually achieve a new state of salinity equilibrium.

The wide variability in electrical conductivity at any particular site suggests that complex relationships may be at work. It is likely that these variations can be at least partly explained by the natural hydrological cycle and the impact of vegetation clearing. Changes in methodologies for data collection or laboratory analysis are other possibilities.

EC data have been collected over several decades but, unfortunately, sampling has been infrequent. In contrast, extensive data sets already exist for flow and any link that can be discovered between flow and EC may enable interpolation of the latter. Flow behaviour is readily available and is usually well documented. Often, it is the only long-term data set that can be relied on in detailed salinity investigations.

Any identified electrical conductivity-flow link may enable real-time salinity management decisions to be made based on a real-time knowledge of catchment flow behaviour. There is the potential to provide short-term (monthly) and long-term (yearly) forecasts of EC behaviour for specific catchments. Such forecasting would greatly enhance river management. From a managerial perspective, the capacity to differentiate between typical short-term catchment behaviour and long-term trends is highly desirable. Such differentiation would enable the development of long-term salinity strategies. From an archival perspective, any link would enable the generated EC to be stored in a time series archive such as HYDSYS (1999) in much the same way as flow data. This would enable saltload calculations and EC duration curves, etc., to be generated through the application of various archive tools. In turn, this would enable more accurate estimates of historic saltload.

If relationships can be identified between EC and instantaneous flow, it is likely that salinity behaviour in the Murray-Darling Basin might be more readily understood. Some patterns have already been acknowledged by default; e.g., Williamson *et al*. (1997, p. 11) state 'the assumption is taken that high flows will normally have the low salinity values'.

Several electrical conductivity characteristics that are strongly linked to flow behaviour have been documented over the years. Hem (1989) refers to patterns in EC behaviour, including hysteresis during flow events, and provides a graph of the relationship between daily flow and EC. In discussing the relationship between electrical conductivity and daily flow for the San Francisco River at Clifton (*ibid*., p. 182), the author attributes the wide scatter in the results mainly 'to the failure of the individual samples to represent the average composition of the river for a whole day'. This problem has been minimised in many other studies because of the availability of instantaneous flow.

Gregory and Walling (1973) discuss at great length the relationship between flow and both sediment load and solute concentration. They present a number of illustrations of the relationship between dissolved solids concentrations and discharge, indicating that 'in streams where solute sources and runoff dynamics are complex, different forms of rating relationship may appear, and in certain cases the relationship may be very poorly defined, if not non-existent'. The relationship between total dissolved concentration (C) and streamflow (Q) is usually expressed as the inverse form of a power function:

$$C = aQ^b \tag{1}$$

where a and b are constants and b < 0. 'The inverse character of the relationship is due primarily to a dilution effect' (Gregory and Walling, 1973).

Other authors have attempted to fit data to equation (1) with mixed success. Cassie *et al*. (1996) used the power function to produce a relationship between electrical conductivity and flow for a small (54 square kilometres) Canadian stream. They stated that "the concentration-discharge curve can be utilised for monitoring chemical variables over a wide range of flows except for the rising limb of the hydrograph". Olive and Rieger (1987) examined the solute behaviour in five small catchments on the Far South Coast of New South Wales, Australia. They linked concentration to instantaneous discharge and examined baseflow and event-flow separately. Although a relationship was not conclusively developed, a number of characteristics were observed. These included a gradual increase in baseflow solute concentrations between events, and noticeable dilution during runoff events. Similar work has been carried out in various levels of detail to develop suspended sediment ratings (Asselman, 2000; Williams, 1989; Sichingabula, 1998) and bedload ratings (Moog and Whiting, 1998). Asselman (2000) cites a number of authors in a discussion of the significance of regression coefficients in the relationship between suspended sediment and flow.

A number of authors have also sought links between flow and various water quality parameters other than EC. Arheimer *et al*. (1996) investigated the behaviour of nitrate in the context of flow and catchment characteristics. Muroaka and Hirata (1988) observed the general behaviour of a number of water quality parameters (including electrical conductivity) in a small, forested Japanese catchment. Many authors have noted that the relationship between solute concentration and flow often could not be described by a simple power function. For any particular discharge, the rising limb EC might differ by a nominated offset from the EC of the falling limb. When plotted, the flow versus EC relationship forms a loop: this effect is called hysteresis. Evans and Davies (1998) observed hysteresis in the relationships between chemical concentration and discharge. They indicated that the bimodal behaviour offered insights into catchment mechanisms at work in the observed U.S. streams. Cosser (1989), Gregory and Walling (1973), Hem (1989), Olive and Rieger (1987), Moog and Whiting (1998), Muroaka and Hirata (1988), Whitfield and Whitely (1986), and Williams (1989) all acknowledge hysteresis.

Cassie *et al*. (1996) observed higher concentrations on the rising limb of the hydrograph, and attributed this to 'an increase in groundwater discharge, as a result of a rapid rise in hydraulic head along the perimeter of the stream'. They also noted that conductivity alone may provide a useful means for hydrograph separation in streams similar to their study site. The use of electrical conductivity behaviour to separate event and baseflow has been a topic of interest in hydrology for many years. Pilgrim *et al.* (1979) urged caution when applying this concept because the increase in electrical conductivity was more probably due to the time of contact of the event runoff with the soil, rather than a genuine indication of the commencement of the 'old' baseflow. They warned that using EC was likely to considerably overestimate the baseflow component.

The fact that electrical conductivity displays a change in behaviour in the lower part of the hydrograph recession highlights the importance of looking for at least two different relationships when comparing flow and EC data. It also raises questions as to what constitutes baseflow and how it is separated from event flow. Pilgrim (1998) describes three basic techniques for distinguishing baseflow — empirical formulae, semi-logarithmic plots to determine a recession constant, and averaging baseflow recession curves.

It is possible that the behaviour of electrical conductivity is also influenced by hydrograph timing. Gregory and Walling (1973) cite work carried out by Johnson (1943) on sediment load distribution during events. In this study, the salt load was distributed in a predictable way across the rising limb of the discharge hydrograph.

The above papers indicate that it is worthwhile to investigate any relationships that might exist between flow and electrical conductivity as a means of describing the salinity behaviour at a site. An understanding of these relationships would be useful for three reasons. Firstly, it would enable missing EC values to be interpolated during the period of discrete sample records; secondly, it may enable back-dating and so extend the time series record dramatically; thirdly, it might identify flow-driven EC behaviour which can then be incorporated into simulation models.

In striving to achieve the above goals, this paper seeks to ascertain whether a power function — as described by Gregory and Walling (1973), Cassie *et al*. (1996) and Asselman (2000) — can be applied to the available data. In this study, the prospect of developing an empirical relationship between electrical conductivity and flow is diminished by a number of factors: the long time lapses between samples, the large areas of the study catchments — which are likely to encompass multiple processes and result in higher variability — and the long time span of the data sets. However, these weaknesses are typically present in EC data from many sites in the region and it would be of benefit if the study was able to identify a functional relationship applicable to data sets at many of the sites.

Because the catchments are occasionally subjected to prolonged dry periods, it is possible that long baseflow sequences might consistently exhibit EC behaviour that is significantly different from EC behaviour during events. The identification of baseflow sequences is not simple and in determining what defines a baseflow sample the following works were used: Pilgrim *et al.* (1979), Pilgrim (1998), and Nathan and McMahon (1990).

This paper is presented in the following sequence. There is a description of the EC data that was used in the study and a brief discussion of its reliability. An exploratory analysis is described where all of the available data are used. The steps associated with this preliminary work entailed separating the data set into the various hydrograph components and then examining the flow events and the baseflow sequences for consistent EC patterns. A number of characteristics were observed and documented. A more sophisticated statistical analysis was then undertaken, where only some of the data were used. This step analysed the data for trends and any empirical relationships between electrical conductivity and flow. The results were also examined for common regional characteristics.

2. Electrical conductivity data

The growing interest in salinity behaviour in the Murray-Darling basin has focussed attention on catchments that were previously considered of minor importance. This is particularly the case for tributary catchments that are not conduits for the operational network that carries dam releases to the irrigation areas. In New South Wales there are substantial flow records for many tributaries and although the discrete electrical conductivity data collection has spanned decades, the collection methods have been irregular, resulting in a sparse dataset that is difficult to analyse.

The four catchments used in this study (Figure 1) are located on the south-west slopes of New South Wales. They are part of the Murrumbidgee River system, between Burrinjuck Dam and the regional centre of Wagga Wagga. Compared with most of the studies cited earlier, the catchment areas are quite substantial (Table 1) and are more likely to exhibit complex behaviour. This factor, coupled with the sporadic nature of the data collection, has made the necessary analysis a challenge.

Prior to 1991, grab samples were collected during routine visits by hydrographers at approximately 6 weekly intervals, usually at the same time as flow gaugings were measured. The visits usually involved downloading data or chart changes. Non-grab samples (in the form of auto and rising stage sampling) were usually collected intensively over short time spans during the course of a hydrologic event. There were usually several sequences of non-grab samples in a time series that might span 30 years. An example, typical of the four sites, is shown in Figure 2.

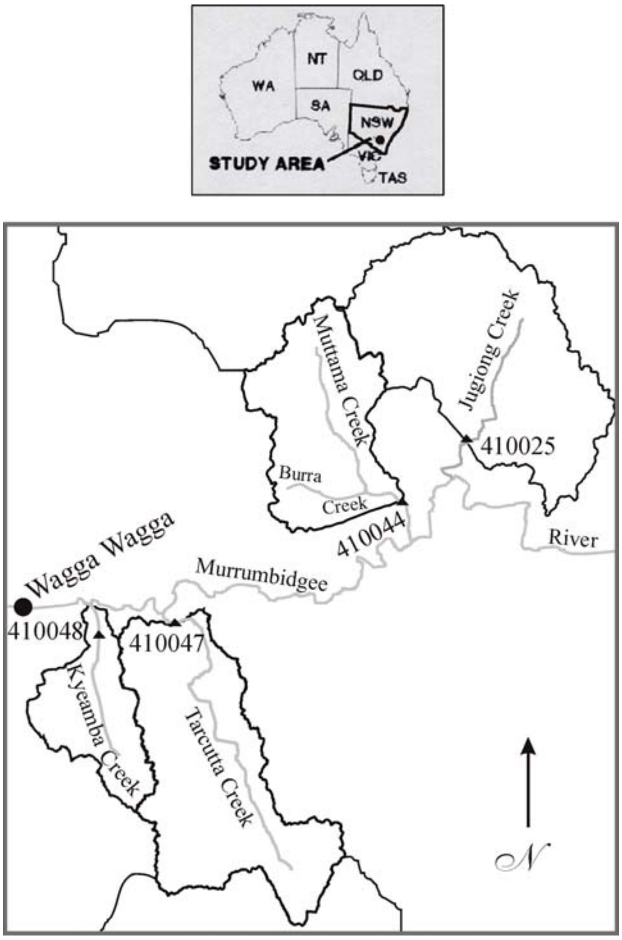

Figure 1. Location of the four test sites

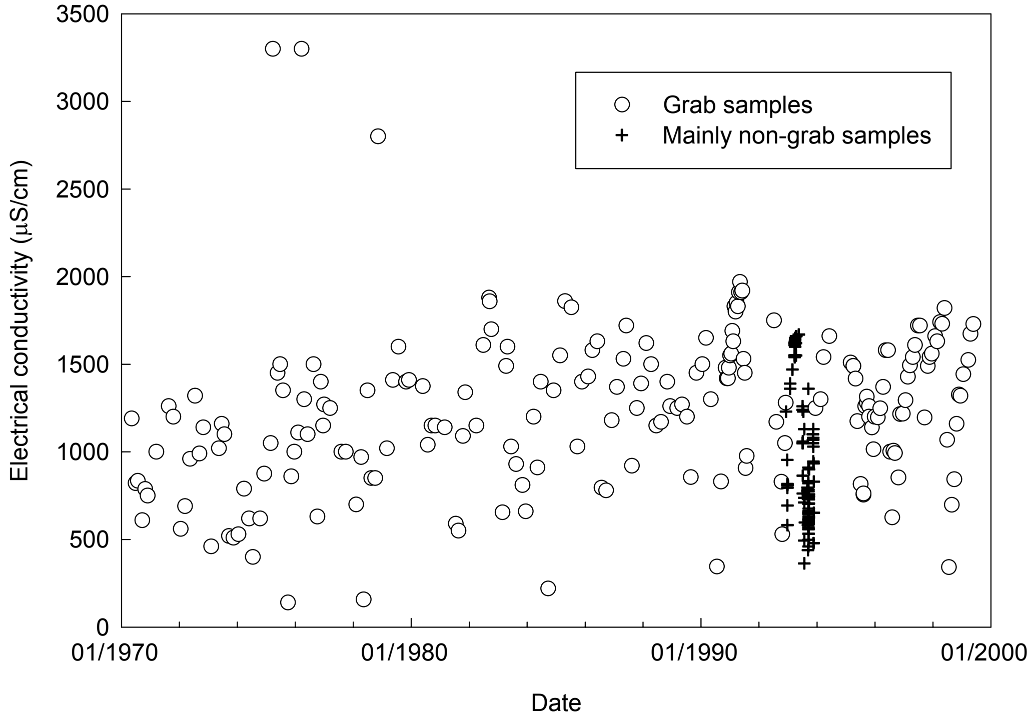

Figure 2. Typical time series distribution of EC (µS/cm) for Jugiong Creek (410025)

The collection of data from 1992 to 1993 was intensive and involved three techniques including rising stage sampling (RSS), automatic sampling at specified times and grab sampling. After 1993, the sampling interval was approximately monthly (Table 1).

Table 1. Selected characteristics of electrical conductivity (µS/cm) samples and sample catchments of the Murrumbidgee River

R, rising stage sampling technique; A, automatic sampling equipment used

	Station name			
	Jugiong Creek at Jugiong	Muttama Creek at Coolac	Tarcutta Creek at Old Borambola	Kyeamba Creek at Ladysmith
Station No.	410025	410044	410047	410048
Catchment area (Km^2)	2120	1025	1660	530
EC range (µS/cm)	140 – 3 300	208 – 2 160	52 – 783	90 – 1 720
No. samples to 1991	138 (start 5/1970)	133 (start 7/1976)	164 (start 11/1967)	106 (start 4/1970)
No. samples 1992 -93	102 (35xR, 52xA)	103 (47xR, 47xA)	152 (58xR, 81xA)	21 (20xR)
No. samples 1994-99	58	60	55	7 (6xR)
Total Number samples	298 (35xR, 52xA)	296 (47xR, 47xA)	371 (58xR, 81xA)	134 (26xR)

The quality of data is dependent on the effectiveness of collection, delivery and laboratory analysis procedures; its accuracy could have a significant impact on the results. The earlier part of the record is of unknown quality. In the absence of evidence to the contrary, it was considered that all the grab sample data were reliable. Inquiries indicate that adequate protocols existed for the collection and analysis of the grab samples from the late 1970s onwards. These took the form of frequent checks of the electrical conductivity meters, using standard solutions prepared at laboratories.

The archived RSS data had to be reworked to ensure that the sample had been linked to the correct date and time. This step was necessary in order to attribute the correct flow value to the EC value. The RSS method of sample collection is generally considered of doubtful reliability. In the past, samples that were known to be erroneous were not placed on the archive. However, there is still some concern about the RSS data that were archived. Bowling *et al*. (1993) list two problems with the RSS technique — ongoing exchange of water after submersion of the sampling bottles, and the water quality of the surface samples not being representative of the water body passing the sampling station.

The RSS sequences were not included in the statistical analyses of long-term data but were used to develop relationships between electrical conductivity and high flows. Samples that had been deployed for more than one event, or had undergone long periods of submersion were considered to be unreliable and were not included in analyses.

3. Statistical methods

Statistical analyses of electrical conductivity-flow relationships were based on grab samples, since electrical conductivities measured on rising stage samples were considered unreliable (see Bowling *et al*., 1993). Furthermore, samples from autosamplers and rising stage samplers were collected over very short time scales when different hydrological processes were likely to be operating and the electrical conductivities of these samples were serially correlated.

Associations between pairs of variables were established using Spearman's rank correlation (Conover, 1980) because it is a robust method for detecting monotonically increasing or decreasing trends.

Analysis of covariance was used to compare two linearly related variables among multiple groups (Snedecor and Cochran, 1989). The technique allows the slopes and intercepts of different regression relationships to be compared.

Locally weighted regression smoothing or Lowess (Cleveland, 1993), a robust, data-based technique, was used for exploring patterns in the data. Relationships between electrical conductivity and flows were examined using Ordinary Least Squares regression (Montgomery and Peck, 1992) or by fitting semiparametric models (Hastie and Tibshirani, 1990). Semiparametric regression models are an extension of OLS regression models whereby nonparametric smoothing functions are included to model nonlinear relationships between the response variable and explanatory variables. Smoothing functions are particularly suitable for modelling nuisance variables (i.e. variables that are of secondary importance in the analysis) such as temporal trends in EC. Here, cubic smoothing splines with a smoothing parameter equivalent to 3 degrees of freedom were fitted to time. The degrees of freedom determine the level of smoothing of the trend term.

Approximate F-tests can be used to compare two Generalized Additive Models and to compare the linear and nonlinear components of the additive terms (Hastie and Tibshirani, 1990). The p-values for these F-distributions are only approximate and hence some caution was used when interpreting the p-values.

Several electrical conductivity records were associated with discharges of zero ML/d for Kyeamba Creek. When applying a logarithmic transformation to a flow sequence that includes zeroes it is usual to add a small number (usually one) to all flows. However, this would have influenced the values of some of the regression parameters so the zeroes were replaced by a small increment (0.01 ML/d) and all other flow values were unaltered.

The smoothing function for time can be partitioned into linear and nonlinear components of trend. The linear component of the trends in electrical conductivity were converted from logarithms to the original scale, expressed as percentage change in EC per annum, via the relation $\{\exp(b) - 1\}*100$ where b is the regression coefficient for the linear component of trend. The percentage trend can also be expressed as an annual trend in electrical conductivity units by multiplying the percentage trend by the mean conductivity for the period of record. The values of the spline trend at given intervals can be used to estimate trends over portions of the record.

Regression diagnostics were applied to check the adequacy of individual regression models for describing the data (Kleinbaum *et al*. 1988). These included normal scores plots of the residuals from each model, plots of residuals versus fitted values from the model, and plots of residuals and fitted values against explanatory variables.

4. Exploratory analysis

Exploratory plots were undertaken using all of the available EC data (Figure 3). Separate Graphs were produced to describe baseflow sequences and event behaviour, both of which are described later in this Section. The regression and temporal trend analyses are described in Section 5.

4.1. Some preliminary patterns.

All the data were used in a natural log-log plot of electrical conductivity versus instantaneous flow (Figure 3). Some noticeable characteristics were observed for the four stations: the magnitudes of electrical conductivity were comparatively small for large flows and the electrical conductivity values during low flows were generally much larger when compared with the EC for high flows.

The data exhibited a large amount of scatter (Figure 3). EC values were influenced by long-term trends, complex responses to catchment processes during hydrologic events, and possible biases inherent in the sampling technique. Data from RSS and auto-samples resulted in clusters of points in the top right-hand portions of the scatterplots, and was not regarded as 'first flush' (Section 4.4).

The data from grab samples (Figure 3) indicated varying degrees of curvature in the EC versus flow relationship. The curvature suggested that, for some stations, the power function (equation 1)

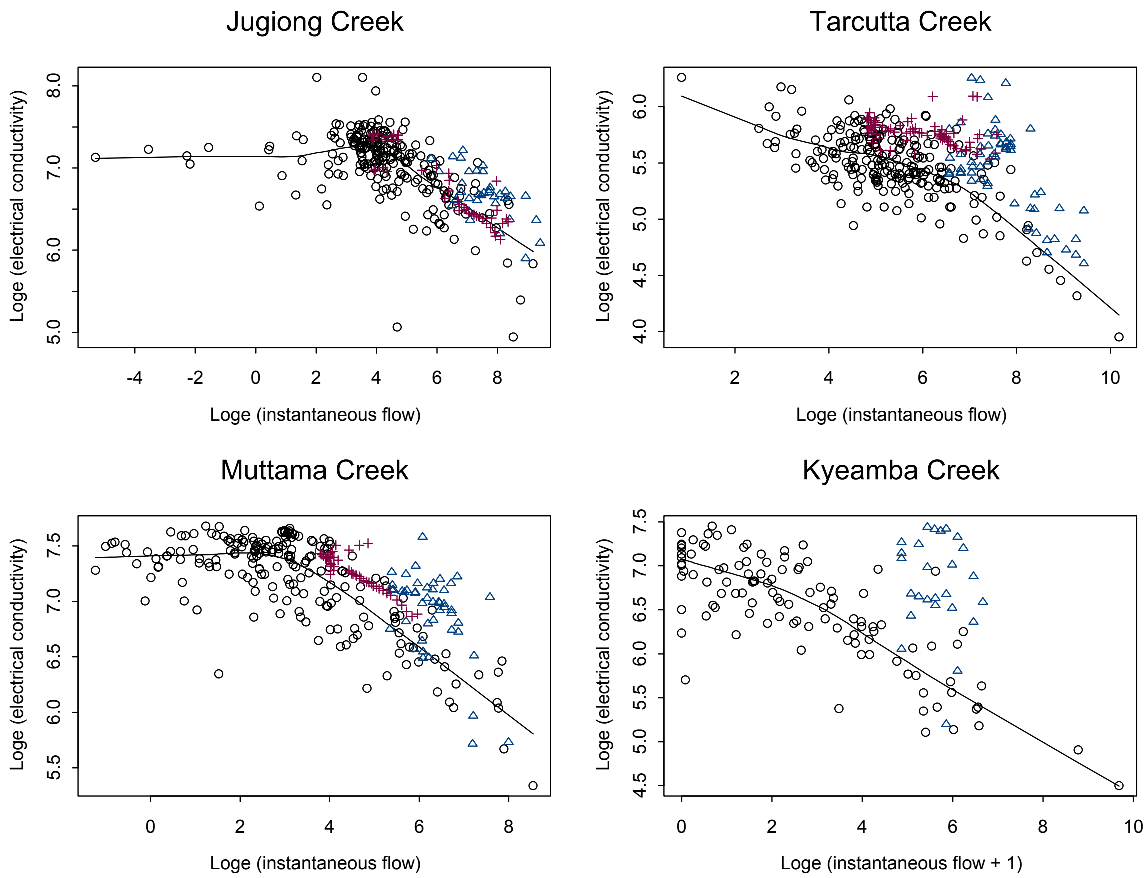

Figure 3. Plots of $\log_e$ EC (µS/cm) versus $\log_e$ instantaneous flow (ML/d) using all available data. A smoothed Lowess curve has been fitted to the grab sample data and illustrates the dual nature of the relationship between EC and flow. Triangles represent rising stage samples and crosses indicate autosampler samples.

might not be the most suitable choice. In these cases, the data were truncated and power functions were fitted to the segments of the data above the threshold flows. The threshold flows were 20 ML/day for Jugiong Creek, 15 ML/day for Muttama Creek and 5 ML/day for Kyeamba Creek.

When the grab sample data were split into decades, it was noted that the electrical conductivity appeared to be increasing throughout the record (Figure 4), and this trend explained a significant proportion of the variability in the data (Table 2). Analysis of covariance showed that the intercepts and slopes of the EC versus discharge relationship for each decade were highly significantly different from zero but the interaction between these terms was not significant.

It was considered that some the variability could be explained by the source of the flow. The data were split using basic hydrograph analysis techniques.

Table 2. Summary of analysis of covariance comparing the log EC (µS/cm) versus log flow (ML/d) relationship between three decades

Source of variation	Degrees of freedom	Sum of squares	Mean square	F value	Pr (F)
Decade	2	2.721	1.361	35.6	< 0.001
Linear contrast	1	0.535	0.535	14.0	<0.001
Quadratic contrast	1	2.186	2.186	57.2	<0.001
Log (instflow)	1	16.549	16.55	433.0	< 0.001
Decade x log(instflow)	2	0.181	0.091	2.37	0.10
Residual error	173	6.613	0.038		

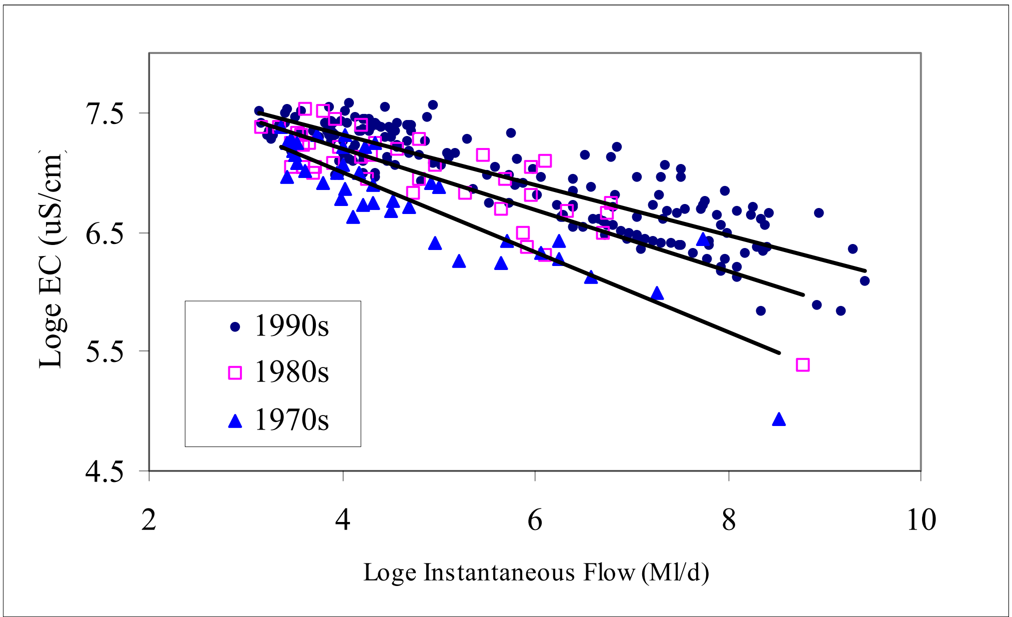

Figure 4. Plots of log$_e$ EC (µS/cm) versus instantaneous flow (ML/d) over three decades for Jugiong Creek (410025). Data are for discharges greater than 20 ML/d (Log $_e$ value= 3.0) . Regression lines have been fitted for each decade.

4.2. Identifying hydrograph components

The samples were grouped according to their position on the hydrograph. These categories were ‘baseflow’, 'rising limb', 'falling limb' and 'crest'. The ‘baseflow’ was separated from the event flow, because it was anticipated that EC behaviour in the two phases might be different (Pilgrim *et al.* 1979, Cassie *et al.* 1996). The event data were split into 'rising' and 'falling' limb because of the possibility of hysteresis.

A quick means of identifying the hydrograph components made use of the hydrograph slope ($\Delta i / \Delta t$) = (i_2-i_1) / (t_1-t_2), which represents the change in consecutive instantaneous discharge values (i_x) for a specified time interval. The rate of change of discharge slope ($\Delta^2 i / \Delta t^2$) was also used. The sign of the second term indicated whether the hydrograph curvature was concave (+) or convex (-). This additional information enabled samples near the peak to be distinguished from the baseflow data.

An hourly interval was used to calculate hydrograph slope. This interval was too coarse on the rising limb of the hydrograph, and the work associated with the RSS was repeated using a 15-minute interval.

It was also necessary to check if the $\Delta i / \Delta t$ and $\Delta^2 i / \Delta t^2$ values at the time of sampling were typical of the slopes for adjoining hours. In some instances, particularly for the earlier record, some smoothing of the slope values was necessary because sampling often occurred at the same time as the join between two separate blocks of flow data. In the past, some adjustments were made when the data were edited and this sometimes produced an artificial counter-trend in what otherwise was a general rise or fall in the hydrograph.

4.3. Baseflow separation

Pilgrim (1998) describes a number of methods for identifying the hydrograph recession curve behaviour and therefore identifying the likely point of baseflow separation. Two of these methods were used. Firstly, discharge (log scale) was plotted against time (linear scale) using the Department of Land and Water Conservation's archiving system, HYDSYS (1999). In theory, the recession plots as three straight lines representing surface runoff, interflow and groundwater. The straight line representing the groundwater component was visually estimated for a number of events at each site. It is referred to as 'baseflow' in this study.

Secondly, once the recession component was identified, the natural slope of the groundwater component was then calculated for each event. An overall value was then adopted, which then became the slope representation of baseflow. This provided a starting point for the investigation. The process was not applied to the Kyeamba Creek site (number 410048) owing to insufficient data. The various characteristics used to define the hydrograph components are shown in Table 3. After the baseflow data were removed, the remaining (event) data, excluding interflow, were examined.

Table 3. Flow characteristics of hydrograph components
$\Delta i/\Delta t$, slope of hydrograph component and represents hourly change in instantaneous flow (ML/d)
$\Delta^2 i / \Delta t^2$, rate of change in slope (ML/d)

	Station name			
	Jugiong Creek at Jugiong	Muttama Creek at Coolac	Tarcutta Creek at Old Borambola	Kyeamba Creek at Ladysmith
Baseflow	$7.0 > \Delta i/\Delta t > -3.0$	$2.5 > \Delta i/\Delta t > -1.3$	$5.1 > \Delta i/\Delta t > -2.51$	
Interflow	$-3.0 > \Delta i/\Delta t > -10.0$	$-1.3 > \Delta i/\Delta t > -4.0$	$-2.51 > \Delta i/\Delta t > -10$	
Falling limb (Event)	$-10 > \Delta i/\Delta t$	$-4 > \Delta i/\Delta t$	$-10 > \Delta i/\Delta t$	
Rising limb (Event)	$\Delta i/\Delta t > 7.0$	$\Delta i/\Delta t > +2.5$	$\Delta i/\Delta t > 5.1$	
Crest total	$\Delta^2 i/\Delta t^2 < -12.0$	$\Delta^2 i/\Delta t^2 < -12.0$	$\Delta^2 i/\Delta t^2 < -5.0$	
Runoff between samples (mm)	< 1.5 mm	< 0.5 mm		< 2.5 mm
Runoff rate (mm/28 days)	< 1.5 mm	< 0.4 mm	< 2.0 mm	< 1.0 mm

4.4. Electrical conductivity samples during flow events

The EC data associated with flow events were investigated for the following characteristics: (*i*) anomalous values of EC associated with the rising limb as per Cassie *et al*. (1996); (*ii*) the range of EC values observed during flow events compared with the EC range observed during baseflow and (*iii*) hysteresis.

Although the largest EC values were generally associated with low flows, this was not always the case. EC spikes were observed during medium flows for three of the stations when all the data were used. This behaviour was catchment specific and seemed to be linked to flow characteristics. It is discussed in Section 6.3, and is the subject of an ongoing field investigation.

4.4.1. Tarcutta at Old Borambola (station number 410047)

Several characteristics were evident from the event data:

(i) At this site, the highest electrical conductivity occurred during surface runoff events. This behaviour was unusual when compared with the other three sites, for which the event EC generally did not exceed baseflow EC. The high values appeared as a 'hump' generally located in the flow range 500 to 3 000 ML/d. When eleven rising stage and auto-sampling sequences were observed more closely, the bulge was found to incorporate a number of EC 'spikes'. These were associated — mainly, but not exclusively — with the rising hydrograph. The validity of these spikes is discussed in Section 6.3.

(ii) The hump coincided with an apparent change in slope in the relationship between electrical conductivity and flow, accentuated by several very high flows in the early 70s and 80s (Figure 3, Log_e range 6.5 to 8.5). An attempt was made to estimate the slope 'b' of the power function (1) for higher flows. The step involved separating the high flow data points from the remainder of the data set, and was complicated by two factors. Firstly, there was a pronounced rise in EC over time (Figure 4). Secondly, there were seldom sufficient data to allow a fit to be attempted with any confidence. An approximate estimate has been made using eight falling limb data points from seven events in the 1970s (Figure 5). This was a period when the relationship between electrical conductivity and flow appears to have been relatively stable. The observed value of –0.37 for 'b' is likely to be an underestimate. However, it is useful as a preliminary attempt.

(iii) Cassie *et al*. (1996) indicated that the power function was a good description of the EC versus flow relation for all cases except the rising limb. In keeping with this reservation, a number of EC spikes were observed, mainly on the rising limb. EC values were plotted against the hourly hydrograph slope (Figure 6). Small slopes are an indication of baseflow, small events, or an early part of the hydrograph at the start of large events. 28 samples recorded EC greater than 360 μS/cm at this site. All but 3 occurred after June 1990. Of the remainder, 17 occurred when the hydrograph was comparatively flat indicating baseflow. However, the slopes of the remaining 8 signified that high salinity was occurring after the commencement of a runoff event.

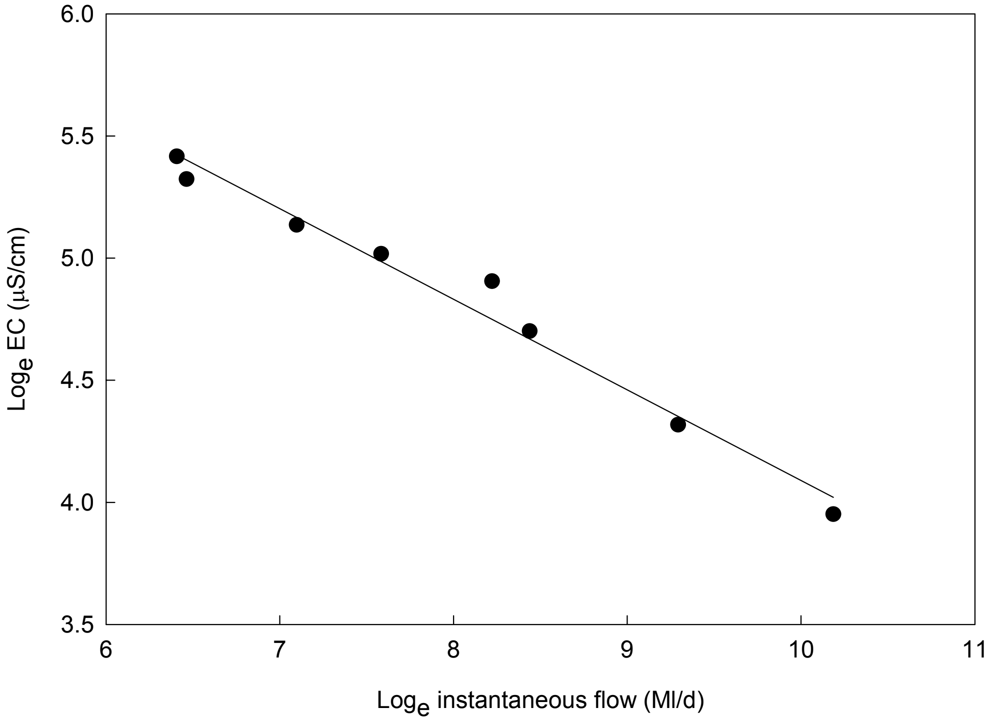

Figure 5. Relationship between log$_e$ EC (μS/cm) and log$_e$ instantaneous flow (ML/d) for the falling limb. Samples from Tarcutta Creek during the period 1970-79 and flows > 600 ML/d.

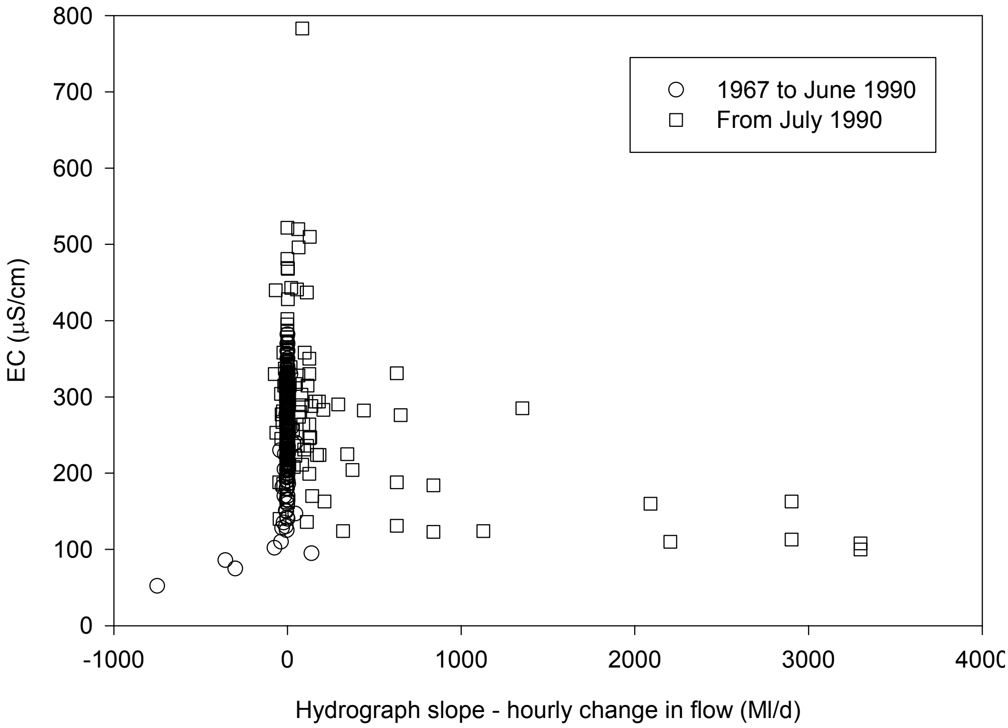

Figure 6. Plot indicating the location of high EC (μS/cm) values in relation to the steepness of the hydrograph for Tarcutta Creek. The smaller slopes indicate either baseflow, or the early part of a larger event.

4.4.2. Muttama Creek at Coolac (station number 410044)

In late 1992 and during 1993, five rising stage sample sequences were monitored for separate events (Figure 7). Two noteworthy characteristics were observed:

(i) Four of the five events registered a substantial negative EC spike early on the rising limb of the hydrograph, at about 500 ML/d. In each case, the spike indicated that the EC had temporarily dropped by 500 μS/cm

(ii) In two cases (November 1992 and May 1993), the events were twin-peaked, and the last sample in the sequence was taken from the second (higher) peak. In both cases, the EC of the second peak was much higher than the first peak.

It is possible that the spikes are an artefact of the collection technique, but in view of the repeated occurrences, and their association with particular flow regimes, there is the likelihood of pronounced non-homogeneity in salinity. That is, at least two parts of the catchment are delivering markedly different concentrations of EC, with one having a predominate influence for a short time only.

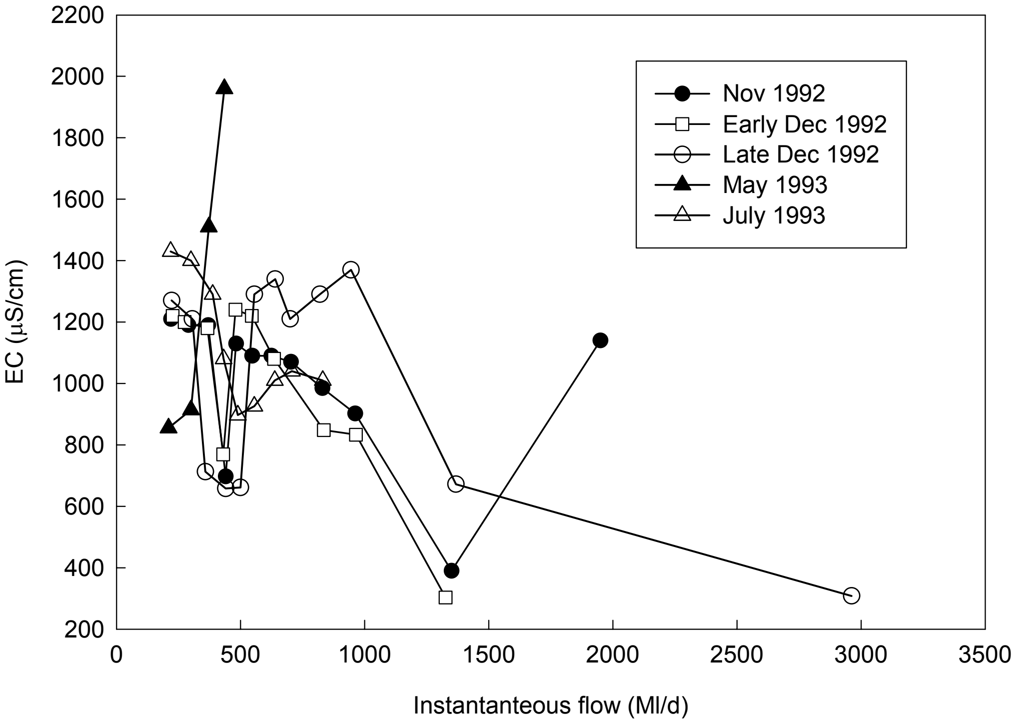

Figure 7. Plot of EC (μS/cm) versus instantaneous flow (ML/d) for five rising stage sample sequences from Muttama Creek.

4.4.3. Jugiong Creek at Jugiong (station number 410025)

Most of the electrical conductivity for high flows were obtained from Rising Stage Sampling during 1992/93. For some of the samples, EC spikes were observed below 2 000 ML/d.

EC data observed for an event on 14/9/93 are illustrated in Figure 8. For the rising stage sample sequence there was doubt about the reliability of the six samples collected for flows less than 2 000 ML/d. Despite this, these samples have been included in Figure 8. Samples in this sequence for flows greater than 2 000 ML/d were regarded as reliable for two reasons. Firstly, they were reasonably close to the peak (thus diminishing the possibility of exchange). Secondly, reliable data points from other events gave credence to the RSS values used for the rising limb in Figure 9). Fortuitously, the termination of the RSS sequence at the event peak coincided with the commencement of an auto-sampling sequence on the falling limb. The falling limb sequence during this event also registered the influence of a second, slightly smaller, flow peak. The data exhibited hysteresis as described earlier.

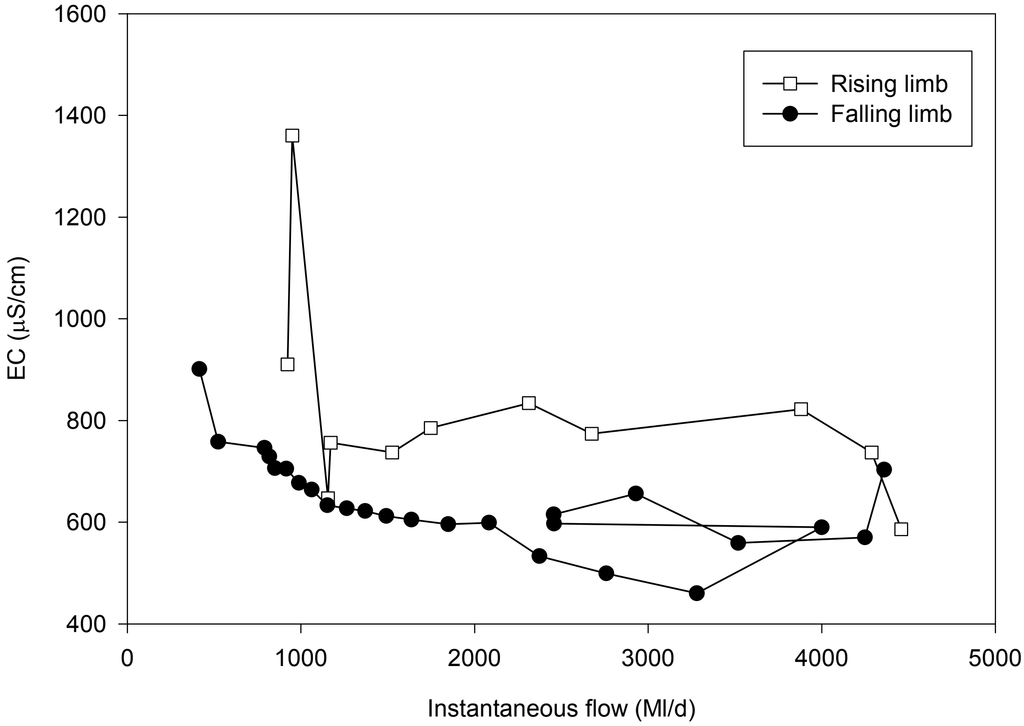

Figure 8. Hysteresis in plot of EC (µS/cm) versus instantaneous flow (ML/d) for data observed at Jugiong.

Data were selected from a number of events in order to develop a relationship between EC and high flows. The criteria for inclusion (Fig. 9) were (*i*) the sample bottle filled at or close to the event peak or (*ii*) the value agreed with samples from other events which had been measured close to the peak. EC data obtained from water samples where the sampling container was not changed between events were ignored. Values that contradicted reliable data for similar flows from other events were also ignored. This decision resulted in robustness being sacrificed for the want of data. Three events from early July and September 1993 were used to collate the 'safe' data. For the event in Sept 1993, the samples associated with higher flows are considered reliable. However, data observed in late July 1993 contradict the composite curve, and have been included in Figure 9. These particular data are likely to be incorrect because the event was very large and the sample bottles were overtopped by at least 3 metres. Unfortunately, they cannot be dismissed out of hand. As an interim measure, the trend line for the 'composite' data (from Figure 9) can be adopted for the rising limb. It is recommended that an offset of (-)200 µS/cm be used for the falling limb for flows below 8 000 ML/d as illustrated in Figure 8.

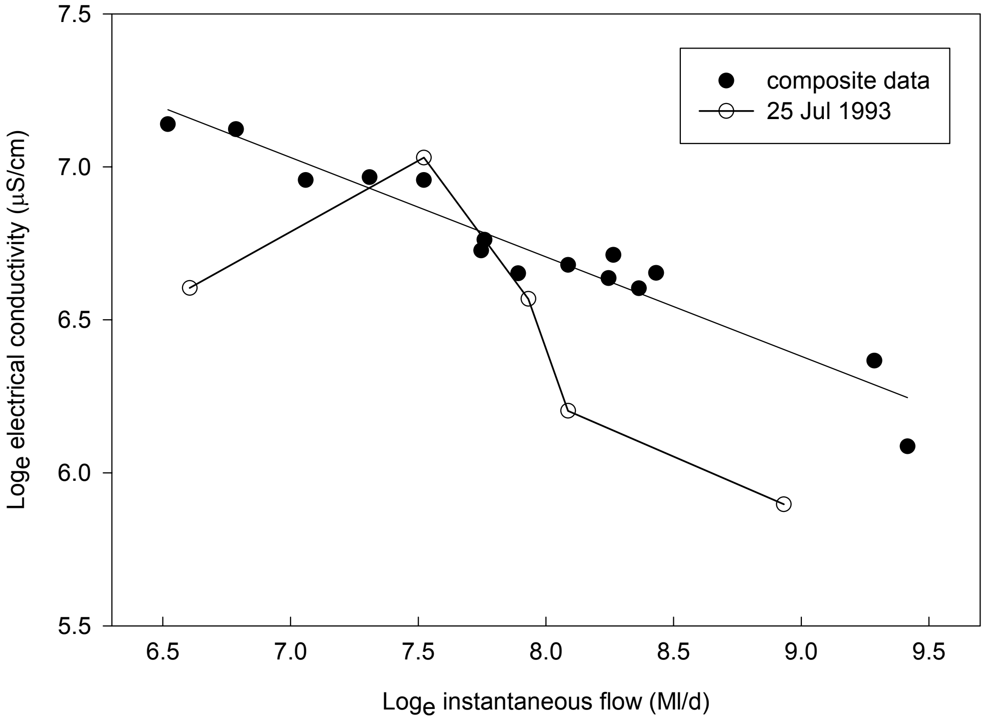

Figure 9. Relationship between $\log_e$ electrical conductivity (µS/cm) and instantaneous flow (ML/d) for high flows at Jugiong. The fitted regression line is $\log_e$ EC = 9.304 – 0.324 $\log_e$ instantaneous flow.

4.4.4. Kyeamba Creek at Ladysmith (station number 410048)

The earlier part of the flow data at this station consisted of daily readings. For that period, it was virtually impossible to determine the hydrograph slope. Consequently no attempt has been made to break the data into the rising or falling hydrograph. There were no observed flows for the rising stage sampling in 1993 and 1994.

4.5. Uninterrupted baseflow sequences.

The electrical conductivity associated with flow events appeared to be discharge dependent, whereas the baseflow EC was best described as being time dependent. Consequently, the two phases have been analysed in entirely different ways.

It is necessary to define what constituted an uninterrupted sequence of baseflow samples, as sometimes a small flow event was observed during what was essentially a long baseflow sequence. The amount of runoff between consecutive samples was used as an indicator, and was used in two forms – total runoff (mm) and a runoff rate (mm/4 weeks). Values were determined for each site, based on an inspection of the data (Table 3). If either value was exceeded then it was likely that the intervening flow contained a significant event. Consequently, the next sample represented the commencement of a new baseflow sequence.

The application of the criterion was somewhat arbitrary, particularly if there had been a series of small events. However, it was adequate in identifying the behaviour of EC during baseflow and provided a means of describing the relationship between consecutive samples during baseflow sequences. The uninterrupted EC sequences were then plotted against time and examined to see if any patterns were apparent. In most cases, the first sample in the sequence was assigned a value of zero days.

4.6. Electrical conductivity characteristics during baseflow sequences.

During baseflow sequences, the EC generally rose with time if there were no significant intervening flow events. Each catchment displayed characteristic unique rates of increase. The Jugiong baseflow sequences were tested after the removal of three baseflow spikes. Spearman rank correlation showed that there was no correlation with flow, but there was a significant correlation with time elapsed since sequence commencement (Table 4).

Table 4. Spearman Rank correlation coefficients of electrical conductivity (μS/cm) with the number of days since the commencement of sequence (C O S) and stream flow (ML/d) for Jugiong Creek station
ns, not significant; *, $p < 0.05$; **, $p < 0.01$; ***, $p < 0.001$.

Baseflow time sequence	Sample size	Spearman Rank correlation coefficient	
		Days since C O S	Streamflow
1970-71	3	1.00***	-0.50^{ns}
1972	4	1.00***	-0.40^{ns}
1974-75	6	0.83*	-0.14^{ns}
1975-76	6	0.83*	-0.43^{ns}
1978-79	6	0.64^{ns}	-0.38^{ns}
1982	5	0.60^{ns}	-0.70^{ns}
1984-85	4	0.80^{ns}	-0.40^{ns}
1985-86	4	1.00***	0.40^{ns}
1986-87	4	1.00***	0.40^{ns}
1987-88	4	0.80^{ns}	−1.00***
1990-91	16	0.96***	-0.24^{ns}
1993	19	0.73***	-0.04^{ns}
1995-96	6	0.93**	0.58^{ns}
1996-97	9	0.996***	0.18^{ns}
1997-98	8	0.95***	0.29^{ns}
1998-99	7	0.96***	-0.04^{ns}

The sequences used for Jugiong Creek are illustrated in Figure 10. ANCOVA indicates that the slopes of the individual sequences differ significantly from one another ($F_{15, 79} = 3.19$, $p < 0.001$) (Table 5). However, this interaction effect, although significant, explained only a small proportion of the total variation in the data and a linear model that included separate intercept terms for each sequence but a common term for the rate of change in EC with number of days, was still a reasonable model ($F_{16, 94} = 60.11$, $p < 0.001$; RSQ = 0.91; Jugiong data). The rate of change is 2.24 ± a standard error of 0.12 EC units per day. The daily rate of EC increase has been calculated for a number of individual EC events (Table 6).

Table 5. Summary of analysis of covariance for baseflow EC sequences at Jugiong Creek

	Degrees of freedom	Sum of squares	Mean square	F value	Pr (F)
Sequence	15	5 272 570	351 500	53.8	< 0.001
No. of days	1	3 209 610	3 209 610	491	< 0.001
Interaction	15	312 970	20 870	3.19	< 0.001
Error	79	516 020	6 530		

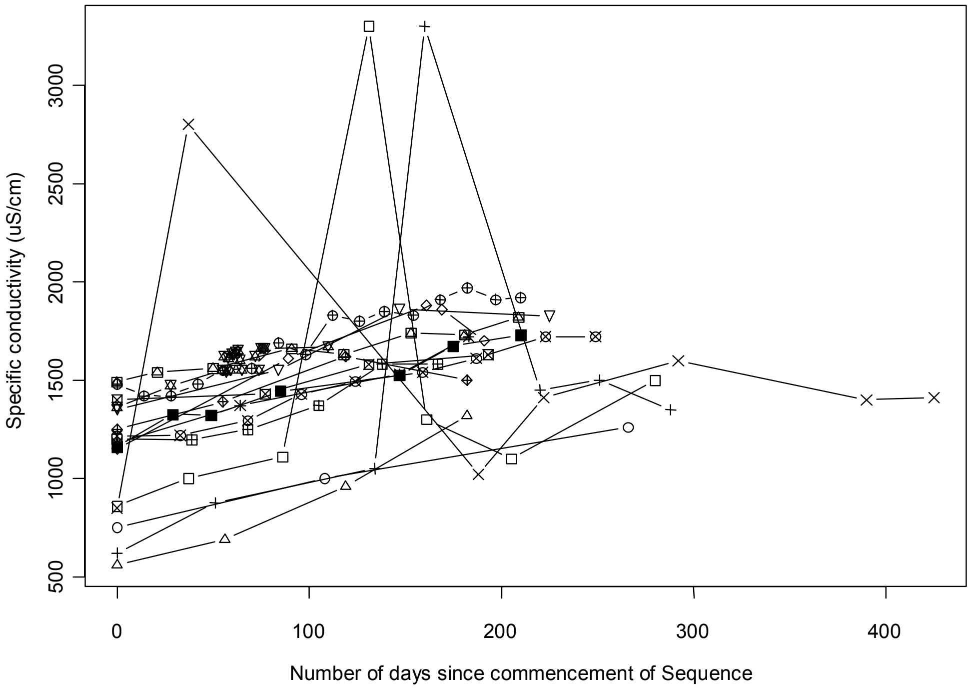

Figure 10. Baseflow sequences of electrical conductivity (µS/cm) over time for Jugiong Creek at Jugiong.

The same rigorous testing was not applied to the other sites. Compared with the other sites, the range of the Tarcutta Creek baseflow EC, and its daily rate of increase are both quite small. As can be seen from Table 6, four sequences for a duration of less than 60 days exhibited daily increases of 1.8 µS/cm or less. However, long duration sequences early in the record did not exhibit good correlations. In the 1990s, the Spearman correlation coefficients for four long sequences varied from 0.46 to 0.93. Despite the sometimes marginal correlations for Tarcutta Creek, forecasting baseflow EC behaviour for river management at Tarcutta and Jugiong would be a relatively straight-forward exercise, based on the data in Table 6. For Jugiong, the increases are fairly consistent but for Tarcutta the observed increases are quite small.

In contrast, the daily increases at Muttama (410044) and Kyeamba (410048) showed large variations among baseflow sequences. While this behaviour might be linked to poor choices in the baseflow separation process, an examination of the Muttama data indicates that even small flow events seem to have a large impact on baseflow EC behaviour. However, regardless of the observed rate of increase, the EC at this site peaked in the proximity of 2 100 µS/cm. The different rates of increase in baseflow EC (Table 6) may indicate one groundwater source is superimposing itself on another, or that a major source is cutting in and out. Whatever the cause, the table implies that there are some years when consistency is maintained.

An example of poor choices in baseflow separation is illustrated in Figure 11. The slope of the first points in sequences is steeper than the slope of the rest of the sequence. This suggests that the initial choice of baseflow slope described in Section 4.3 (and Table 3) may have resulted in the sequence starting too early for some catchment conditions at Tarcutta Creek (station number 410047).

Table 6. Average daily increases in electrical conductivity (μS/cm) during baseflow sequences

Station Name and number	Description of uninterrupted sequence and/or comment	Average daily increase in electrical conductivity (μS/cm)
Jugiong Creek, 410025	Ten sequences 1970 – 1991 (170 - 455 days range)	1.5, 1.9, 2.9, 4.2, 1.9, 3.0, 2.3, 2.4, 1.3, 3.5
	Four sequences in 1990s (200-250 days)	2.5, 3.4, 2.0, 2.5
	Based on steeper parts of sequences (forecasting)	6 to 7
Muttama Creek, 410044	Six short sequences (less than 70 days)	7, 1.5, 11,-3.5, 12, 10
	Three long sequences (> 100 days) 1978-81	4.6, 0.46, 4.3
	Three long sequences 1981 – 85 (150 - 200 days)	6.5, –0.2, 3.0
	Four long sequences (>100 days) late 1990s	3.5, 1.3, –0.4, 2.3
	Based on steeper parts of sequences (forecasting)	24
	Steeper parts of sequences (before 1985)	13
Tarcutta Creek, 410047	Four short sequences (less than 100 days)	1.8, 1.4, 1.0, 1.5
	Four long sequences (> 100 days) 1969-81	0.1, 0.3, –0.2,–0.3
	Four long sequences (> 100 days) mid - late 1990s	0.9, 0.4, 0.3, 0.4
	Based on steeper parts of sequences (forecasting)	2 to 4
	A 15 day sequence in 1977	11
Kyeamba Creek, 410048	Four sequences 1971 – 73 (55 - 255 days range)	2.4, 5.3, 2.4, 0.5
	Four sequences 12/1974 – 2/1977 (47- 205 days)	12.6, 12.0, 12.2, 3.0
	Three sequences 4/1977 – 7/1979 (60 -310 days	5.7, 2.0, 3.6
	Four sequences 10/1979 – 1/1982 (40 -118 days)	15.8, 20.7, 6.2
	Three sequences 11/85 – 5/1987 (52- 118 days)	2.1, 8.0, 2.1

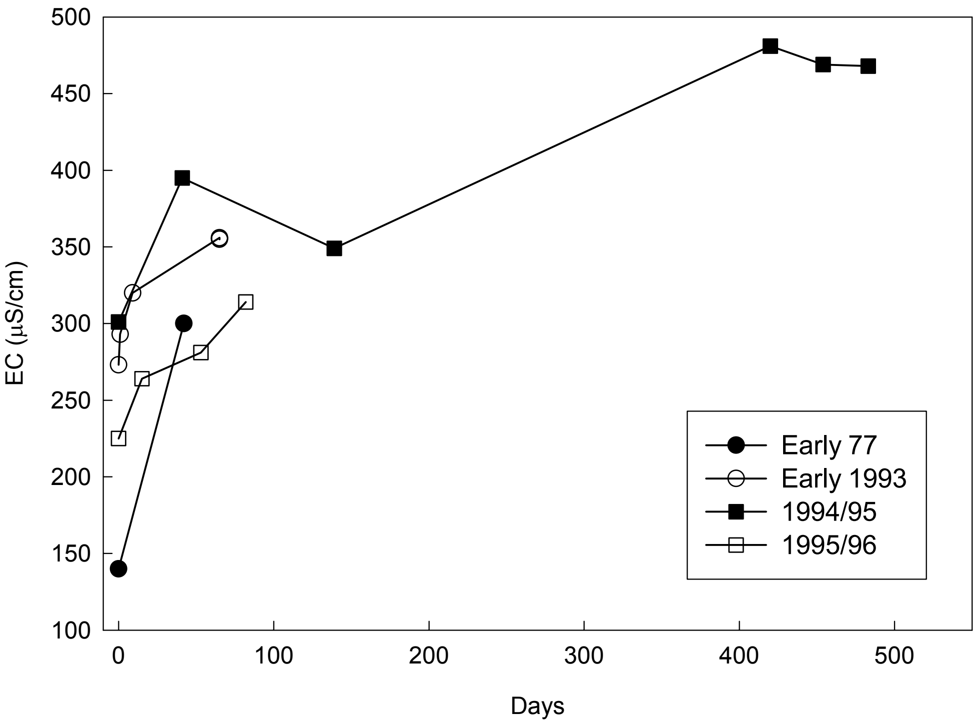

Figure 11. Plot of EC (μS/cm) versus time (days) suggesting poor baseflow separation. Data are for uninterrupted baseflow sequences observed at Tarcutta.

5. Statistical analysis

5.1. Statistical analysis – general patterns.

Prior work (Gregory and Walling, 1973; Cassie *et al*., 1996; Asselman, 2000) successfully fitted and advocated a power relationship between electrical conductivity and flow data. When the data were plotted on a log-log scale (Figure 3) it was clear that a power function would not capture the obvious breaks in slope. A linear relationship could be specified above a threshold flow. The low flow thresholds occurred at approximately 20 ML/d for Jugiong Creek, 15 ML/d for Muttama Creek and 5 ML/d for Kyeamba Creek. For two cases, (Muttama and Jugiong), the EC below these thresholds were virtually independent of flow and it was decided to remove the low flow data points for the three sites because interest was in modelling the dependency between EC and flow.

No attempt was made to truncate the data for Tarcutta Creek, because there was not a sharp threshold in the EC-flow relationship. The change in the electrical conductivity-flow behaviour for Tarcutta Creek occurred in the flow range 3 000 – 5 000 ML/d (Sect. 3.4). The observed breaks suggest that a polynomial regression or piecewise linear regression might provide a more suitable model for some catchments. If a power function is to be used, it would be prudent to plot the data in log-space to see whether a slope change is evident at the upper extremity. The observation also suggests that care needs to be applied to any extrapolation.

The effects of removing the low flow data prior to curve fitting are very significant. If all data were used, it is likely that the regression coefficients would be very sensitive to small vagaries in the data points at either extremity. For example, when a power function was fitted to all the Jugiong data for the period of record 1970 to 1989, it was noted that the 'b' coefficient changed from – 0.105 to – 0.175. This depended on whether or not the samples for flows less than 1 ML/d were removed. The later period of record (1990-1999) at Jugiong was not vulnerable to the same sensitivity because no samples were collected when the flows were less than 10 ML/d.

5.2. Trends in electrical conductivity

The increasing trend in salinity is more realistically described as a smooth increase rather than as three arbitrary step changes with each decade as in the preliminary analysis. While the smooth increase is likely to be more physically realistic, it is possible that there might be an episodic element to the change; this possibility has not yet been investigated. The following regression model incorporates a nonlinear temporal trend in electrical conductivity and was fitted for all stations:

$$\mathrm{Log}_e(\mathrm{EC}) = b_0 + b_1 \log_e(\mathrm{instflow}) + s(\mathrm{yrtime}, 3) + \mathrm{error} \qquad (2)$$

where instflow is instantaneous streamflow (units: megalitres per day), s(yrtime, 3) represents a nonlinear (cubic spline) function of time, yrtime = year + fraction of year (e.g. 70.274 for day one hundred in 1970) and b_0 and b_1 are regression coefficients.

The regression models were fitted using the range of data for which there was a linear relationship between $\log_e$ (EC) and $\log_e$ (flow). It would also have been possible to fit a smooth, nonlinear function to flow and use all of the data, and this is worthy of investigation at some future stage. The regression models provided reasonable fits of the relationship of electrical conductivity with flow over time for all the stations (Table 7). The fit for Tarcutta Creek was poor, relative to the other three stations because of some nonlinearity in the relationships. Possible reasons for this are discussed in Section 6.1.

Table 7. Summary of the estimated coefficients (with standard errors in parentheses) for the semiparametric regression model of electrical conductivity (μS/cm) for all stations.

Station	Intercept (b_0)	Estimated coefficient of $\log_e$ (instantaneous flow) (b_1)	Linear trend component (% increase/yr)	RSQ
Jugiong Creek (inst flows > 20 ML/d)	6.678 (0.145)	−0.243 (0.011)	1.73	0.77
Tarcutta Creek (all flows)	5.169 (0.128)	−0.137 (0.011)	1.25	0.58
Muttama Creek (inst flows > 15 ML/d)	6.721 (0.288)	−0.291 (0.013)	1.78	0.82
Kyeamba Creek (inst flows > 5 ML/d)	5.047 (0.553)	−0.312 (0.025)	3.13	0.73

The nonlinear component of the time trend was highly significant for all sites (Jugiong: $F_{1,2} = 19.4$, $p < 0.001$; Tarcutta: $F_{1,2} = 7.30$, $p < 0.001$; Muttama: $F_{1,2} = 31.6$, $p < 0.001$; Kyeamba: $F_{1,2} = 4.25$, $p < 0.05$) but there was also a strong linear component to the trends for all stations. For Jugiong Creek, there was an increasing trend in the early seventies. For the other stations, conductivities did not begin to increase until the early eighties (Figures 4 and 12). Conductivities increased linearly throughout the eighties and peaked in the early nineties, after which the trend seems to have levelled off. The were few data for Kyeamba Creek for the nineties but a high flow reading taken in 2000 indicates that the trend probably levelled off for this station as well. This is an important observation, with implications for salt-load projections.

For Jugiong Creek, the linear trend in conductivity over the period of record equates to a linear rate of increase of 1.7 % per annum (a 95% confidence band of 1.4 – 2.0% in electrical conductivity. This represents a value of 20.8 μS /cm p.a. (a 95% confidence interval of 17.0 – 24.4 μS /cm p.a.) if based on a mean EC over the period of 1210 μS /cm. At Tarcutta Creek there was a 1.2% per annum trend, (95% confidence interval of 1.0 – 1.2 %), Muttama Creek had a trend of 1.8 % per annum (1.2 – 2.4% confidence band) and Kyeamba Creek had a trend of 3.1 % p.a. (1.7 – 4.6 % confidence band).

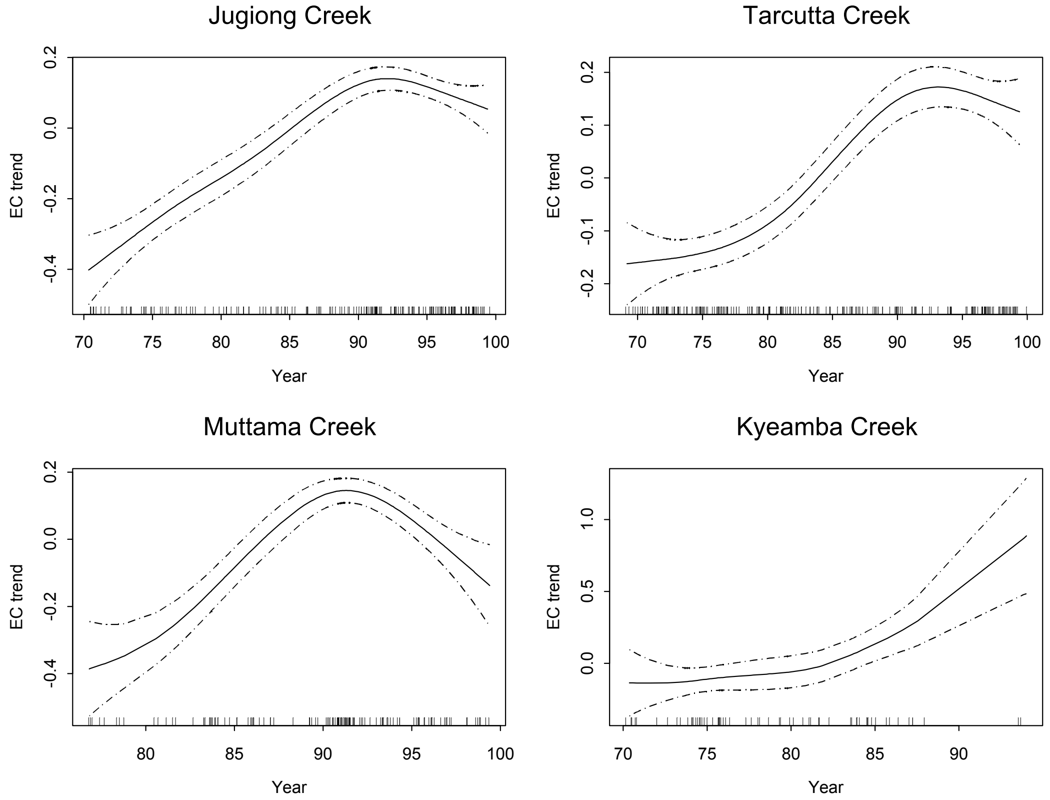

Figure 12. EC trends at the four study sites. Sampling density is indicated by tabs on the time axis. The EC trend axis indicates variation from linearity expressed in standard deviations. The dashed lines indicate ±1 standard error of the mean.

5.3. The Power coefficient in the EC versus flow relationship.

The relationship between the grab sample conductivity and flow can be described by a power equation (1) for all sites. There is, however, a breakdown in the relationship for low flows. The 'b' term of (1) is equivalent to the b_1 term in (2) and Table 7. It is a measure of the slope of the EC versus flow relationship, and was found to be reasonably consistent for each station for the period of record. It is also noteworthy that the b term for three of the sites is similar (Table 7). Only Tarcutta Creek is different from the rest.

If 'b' doesn't change, then it is the 'a' function that holds the key to explaining the changes in the relationship between EC and flow. The 'a' term in the power function represents a combination of the intercept and nonlinear trend terms. That is, it is varying over time as a function of the temporal trend in conductivity (Table 8).

Table 8. Estimates of the *a* parameter in the power equation for various time periods.
The *a* term is the summation of the intercept term and the nonlinear time trend of Eqn 2.

Station	Year						
	1970	1975	1980	1985	1990	1995	2000
Jugiong Creek	2 459	2 763	3 134	3 592	4 083	4 142	3 831
Tarcutta Creek	458	476	502	563	629	642	618
Muttama Creek.	-	2 764	2 958	3 727	4 621	4 299	3 599
Kyeamba Creek	1 550	1 607	1 723	2 082	-	-	-

6. Discussion

Perhaps the most significant finding of this study is the apparent pause in the upward EC trend at the study sites in the early 1990s. Prior to the pause, the upward trend was steep, and its magnitude provides warning that long-term trends need to be taken into account when attempts are made to generate any EC - flow relationship. Conversely the variations in EC across the flow range are also quite substantial (Table 1) and it would be risky to assess long-term EC trends without accounting for the impact of flow magnitude on individual EC samples. Recent work by Jolly *et al*. (2001), indicate that the ratio of salt output/salt input might reach a maximum within 25 years of vegetation clearing for some catchments. From there, the ratio might be expected to gradually decrease. In the context of Jolly *et al.* (2001), the hiatus in EC might be of major significance for the sites investigated in this study.

6.1. Trend analyses

Where flow data are available, attempts can be made to generate historical salinity data. The regression analyses suggest that the ‘b’ values (Eqn. 1) stay fairly constant for each station over the observed record period. This seems to be applying for all four sites for all the data (except small flows). Three of the four stations (except Tarcutta) have ‘b’ values that are similar (Table 7), and this may be a regional characteristic.

The fact that the ‘b’ values remain stable suggests that the ‘a’ coefficient of (1) may be a convenient way of describing the temporal trend in the EC-flow relationship. In Table 8, ‘a’ values have been produced for a range of calendar years. Using the ‘a’, ‘b’ and available flow data, a time-series of EC data could be generated.

The patterns which have emerged in this study, enable the combination of EC and flow data to be treated in much the same way that river gaugings are used to quantify rating tables at a river site where the control is gradually changing. An EC-flow curve can be produced based on a number of ‘spot’ measurements. Because there is reasonable confidence in the ‘b’ value at the site, a curve that defines the ‘a’ value can be produced for the current catchment conditions. Prior knowledge of the variations in ‘a’ behaviour as per Table 8 and Figure 12, enables a manager to perhaps extrapolate the 'a' curve over the next (say) 12 months. This option would enable some forecasting of salinity trends.

Another application involves using a nearby site that might have very little EC data. The EC-flow relationship can be estimated by fitting a line to the data. Its slope would be defined by a regional estimate of ‘b’ and the few observed points virtually define the ‘a’ value.

6.2. Baseflow spikes at Jugiong

Three very large EC spikes occurred during baseflow in the mid-late 1970s. They did not seem to be strongly associated with any flush phenomena. At first it was considered that the anomalies were caused by field errors. An examination of trends in the flow data indicated that all three occurred when the catchment was drying out after a comparatively wet period. Possible reasons for this are:

(i) based on a short-term recharge condition, a small highly saline source temporarily was a major contributor to ‘baseflow’ before drying up;

(ii) this mechanism has since been permanently ‘drowned out’ by a rising groundwater table; or

(iii) this source activates only briefly, and later sampling may not have coincided with the event;

(iv) the source no longer exists, or is no longer operating as a point source.

6.3. The significance of anomalous data during events

For catchments of this scale (Table 1), the times of travel from the remote parts are more likely to be measured in days rather than hours. Even when the rainfall is widespread, it is unusual for the duration of the surface runoff to exceed the catchment time of concentration. Many of the flow events associated with the RSS sequences passed the gauging stations as multiple peaks. The temporal pattern of rainfall over the catchment is one possible cause, as are the differences in flow travel time from the various parts of the catchment.

The four catchments studied here are much larger than many of the sites referenced in Section 1. As a consequence, the hysteresis behaviour observed at Jugiong Creek (Figure 8) may be more a consequence of the spatial scale of the catchment rather than those generally attributed to the phenomena. For small catchments, it is generally assumed that any difference in solute concentration between the rising and falling limb is a reflection of the difference between surface and groundwater sources within the same area of the catchment. For very large catchments, the differences in EC associated with the rising and falling hydrograph could be as much a consequence of the catchment configuration as of the rainfall-runoff pattern. The EC hysteresis might be an indication of non-homogeneity within the catchment. For example, the upper part of the falling limb could represent the initial input from an upper tributary of the catchment and any observed variations in EC should be considered in this context.

For two of the catchments (Muttama and Tarcutta), anomalous EC behaviour was observed in the form of spikes on the rising limb of the hydrograph. As likely indicators of non-homogeneity, these anomalies are the subject of further investigation. For Muttama at Coolac, four RSS sequences showed an inverted spike early in the event, when the flow reached 500 ML/d (Figure 7). It is possible that faulty bottle design could explain this pattern. Also, at that particular river height, flow regimes may be increasing the risk of exchange. It does seem improbable, however, that this would have occurred for four events. It is more likely that the spike is a true indication of the event, and is describing non-homogeneous EC behaviour upstream.

Two other items of evidence support the theory that there is a source of relatively low EC in the lower part of the catchment. For bimodal events (with a higher second peak) at this site, the EC of the second peak is higher than that of the first (Section 4.4, Figures 7). This behaviour goes against the general perception that the concentration of the solute would decrease as the flow increases (Williamson *et al.,* 1997; Hem, 1989; Gregory and Walling, 1973; Olive and Reiger, 1987; Cassie *et al*., 1996). The behaviour suggests that the influence of the low EC source is diminishing as the flow event continues.

The baseflow behaviour for Muttama (Table 6) is also suggestive of catchment non-homogeneity. The daily EC increase at both Tarcutta and Jugiong Creeks are quite uniform when compared with the behaviour observed at Muttama (Table 6), where the lack of consistency from event to event might be explained by variations in the runoff from different parts of the catchment.

Tarcutta at Old Borambola experienced its largest EC readings during events in the form of spikes (Section 4.4). In this catchment also, there was some evidence of spatial variability in EC. Most of the events associated with RSS sequences showed signs of being multi-modal. For some events, more than one EC spike was observed. For the remaining events, it was suspected that there may have been more spikes, but the sampling density may have missed them. In a number of instances, there seemed to be a link in time between the arrival of the EC spike, and the timing of a flow peak. In some cases, the first EC spike lasted 2-3 hours. It was concluded that one or more sources were briefly contributing comparatively large slugs of EC.

Johnson (1943) identified consistent behaviour between sediment load distribution and the rising limb of the hydrograph. In view of his work, there seems scope to make use of the spike behaviour, to locate anomalous EC sources within a catchment. Potentially, this might be achieved by using the timing of the EC spikes in relation to rising limb of the hydrograph.

The characteristics of the spikes at both Tarcutta and Muttama have warranted further investigation. The consistency of their flow range, timing and magnitudes have almost eliminated the prospect that they are the result of poor data collection. As a consequence, their behaviour should be the subject of an ongoing investigation, using reliable data techniques, other than rising stage sampling.

6.4. Applications

The links observed here between EC and flow (or time) have many applications in stream management. Three examples of such applications are:

(i) Uncharacteristic changes in EC behaviour can be easily monitored. For example, a discrete sample with a high EC value might not be unusual in a catchment that exhibits high baseflow EC. However, if the high EC reading was monitored during a flood event, and the catchment had no history of high EC during high flows, then the incident might be indicating a change in salinity behaviour within the catchment. The converse would be true for a catchment like Tarcutta Creek, where the highest EC results occur as spikes during a flood event. The registration of a high EC reading during baseflow may be an indication that a change in behaviour was occurring.

(ii) Archive tools in packages such as HYDSYS that are usually applied to height and flow data, can now be applied to EC using algorithms described in this work. For example, salt loads can be quickly generated from flow data. EC and salt load duration curves can be produced

(iii) The identification of predictable EC trends during periods of baseflow enables salinity conditions to be forecast during times of low flows. This is beneficial for river management because it provides ample warning of unfavourable saline conditions, e.g. exceeding statutory or recommended EC limits that may have been defined for industry or agriculture. In developing the concept of EC behaviour for low flows, there is need to discuss what is encompassed by the term 'baseflow'. Nathan and McMahon (1990) make the following comments on the practice of partitioning the recession curve into surface runoff, interflow and baseflow: 'while a useful device, (it) is somewhat divorced from reality. The distinctions between interflow and baseflow are unclear — baseflow itself may be composed of a number of components, each of which may vary seasonally, and each with a different recession constant." There is an irony if flow slope is used as a means of hydrograph separation for the purpose of grouping EC samples. Under normal circumstances, it is likely that the EC data might provide the best means of separation. The primary task here was to define the point where the EC-flow relationship changed. Initially, identifying the commencement of baseflow by established separation techniques was seen as the way to achieve this. However, the change in EC behaviour was not necessarily synonymous with the arrival of baseflow (Pilgrim, 1979). In this study, it was not considered essential to define the point of hydrograph separation precisely. If the initial estimate was incorrect, an adjustment could be made as an iterative process. Considering that the observed EC samples were 4–6 weeks apart, any later boundary adjustment was not likely to be time-consuming or involve many data points.

7. Conclusion

It is not conclusive that the discrete sample data has been able to provide definitive information as to salinity behaviour in the four catchments. To some extent, parts of the data sets are under question, whether it is by virtue of the use of RSS, or the general lack of field protocols over the years.

However, the concepts described by Gregory and Walling (1973), Cassie *et al*. (1996) and Asselman (2000) have been partly successful when applied to the sparse data sets available for this study. Indeed, it appears that the limited data are capable of providing considerable information. The study indicates that tentative relationships can be developed between the magnitude of the discrete EC sample and instantaneous flow over most of the data range. For low flows, however, the relationship is virtually non-existent and EC versus elapsed time was found to be a better description of baseflow sequences (Tables 4-6). The four examined catchments exhibited the following characteristics: (a) similarity and consistency in the slope of the power function (Table 7) and (b) similar trends in EC over the period of record (Table 7 and Figure 12). There seems to be the potential for developing both of these characteristics into regional parameters.

At some sites, there is the possibility that the electrical conductivity – flow relationship is quite consistent for certain flow ranges. Only time and more data will confirm this. By using the flow-EC hypothesis, it has been possible to identify the following behaviour for each catchment:

- Larger EC readings are associated with smaller flows, i.e. baseflow or as ‘spikes’ in the early portion of a flow event. Smaller EC readings occur during large flows.
- For the study sites, the data implies that the EC has been rising steadily since at least the early 1980s (Figure 12). It appears to have stopped rising sometime in the early 1990s.
- If the power function $C= aQ^{b}$ was used to fit the data, it was observed that the b value for each station stayed reasonably constant over the record period. It was also noted that three of the sites had similar values for b. The log-space scatter plots sometimes indicated curvature rather than a straight line indicating that care should be taken when fitting a power function to data from this region (Figure 3). The regression equation might not provide a good description of electrical conductivities during extremely low or high flows. Polynomial regression or piecewise linear regression models should overcome this problem.
- At two of the sites, Jugiong and Tarcutta Creeks, daily increases in EC can be estimated for uninterrupted baseflow sequences. These are catchment specific (Table 6). Knowledge of this characteristic enables short-term EC forecasting; for Jugiong, Muttama and Kyeamba Creeks the EC was independent of flow during low flow.
- For the four catchments studied, there were not many EC samples associated with flow events. However, tentative electrical conductivity – flow relationships have been determined for high flow conditions in Tarcutta and Jugiong Creeks (Figures 5 & 9).
- Muttama Creek gave indications of a quite complex EC versus flow relationship (Figure 7) and warrants further field investigation. Extreme non-homogeneity is likely, based on the following observations: (*i*) an inverted EC spike on the rising limb of the hydrograph; (*ii*) characteristic bimodality with the EC noted as being much higher on the second peak; (*iii*) erratic changes in EC baseflow sequences.
- The available data at Jugiong Creek (station number 410025) illustrates hysteresis (Figure 8).

8. References

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