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Using ground-based electromagnetic induction to estimate soil salt storage in south west forests

by

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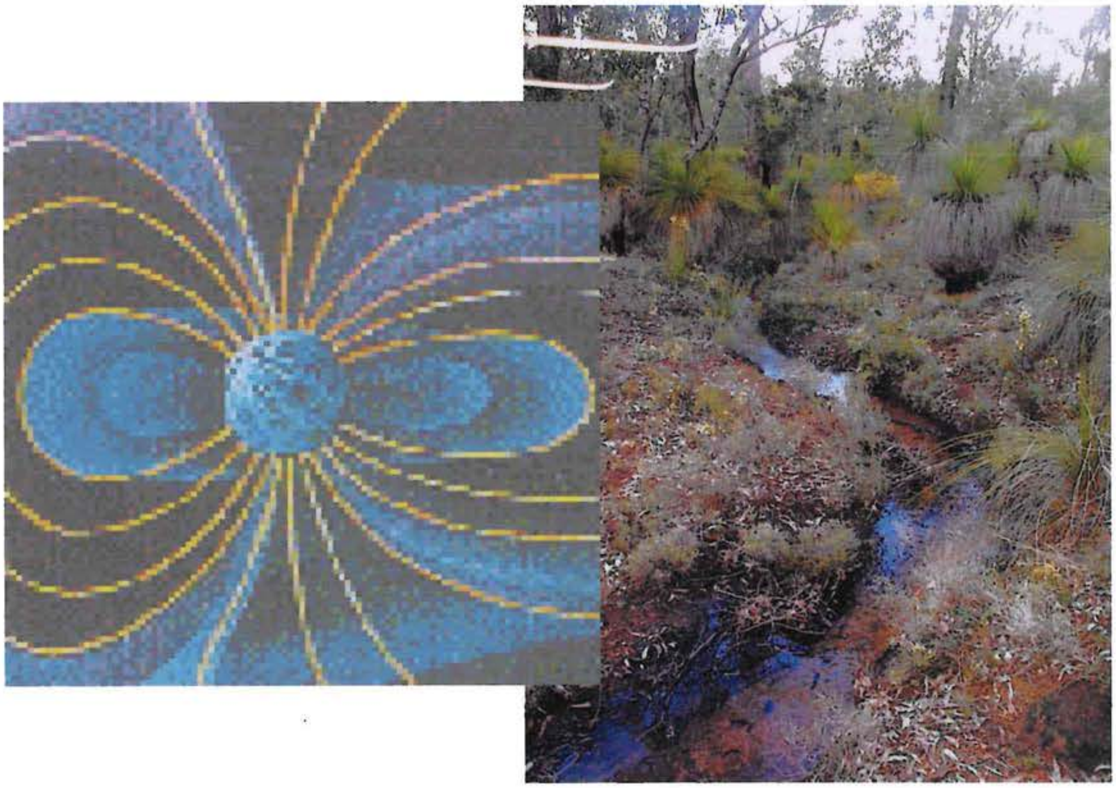


DEPARTMENT OF
Conservation
AND LAND MANAGEMENT

Using ground-based electromagnetic induction to estimate soil salt storage in south west forests

Summary

This study was conducted to

1. test the effectiveness of an EM31 Ground Conductivity Meter for estimating average soil salt storage in the upper 4m of forest soil,
2. determine an appropriate technique for surveying catchments to accommodate spatial variability of stored salt, and
3. apply the survey technique to second order catchments to determine the soil salt storage along the streamzone.

Calibration of the EM31 against forest soil salinity profiles showed that a highly significant ($p<0.0001$) linear relationship exists between apparent electrical conductivity (ECa), measured by the EM31, and average total soluble salts (TSS) in the upper 4m of soil. This indicates that the EM31 is a suitable tool for estimating soil TSS in forested areas. However, the appropriate regression equations must be used when estimating soil TSS since moisture significantly increased soil ECa in spring compared with autumn.

EM31 surveys were conducted in four second order catchments, within an area 20m either side of the streambed, to determine where the highest soil ECa levels were most likely to be encountered. The highest ECa was mostly within 10m of the stream centre. However, there was considerable spatial variation in ECa along the length of the second order stream and the highest levels were not necessarily near the catchment outlet.

Of 24 "environmentally sensitive" catchments surveyed with an EM31, 22 had soil ECa at levels which indicated that stored salt exceeded 2000 mg/L along at least half of the length of the second order streambed. In nine of the catchments, ECa levels indicated that stored salt exceeded 2000 mg/L along the entire length of the streambed.

In two of the "environmentally sensitive" catchments, in which only part of the length of the streambed was surveyed, i.e. 75% and 6%, ECa levels suggested salt storage below 2000 mg/L.

Introduction

Ministerial Condition 16, attached to Forest Management Plan 1994-2003, states:

16-1 Within three years, or such other period as the Minister for the Environment shall nominate, the proponent, on advice from the Water Authority of Western Australia, shall identify second order catchments with a high salt risk.

16-2 Within each catchment identified according to the requirements of Condition 16-1, the proponent shall retain additional river and stream buffers and locate areas temporarily reserved during phased logging operations to the requirements of the Water Authority of Western Australia.

A "second order catchment with a high salt risk' is one which occurs in the intermediate rainfall zone (900-1100mm rainfall per year) but excluding the Whicher Scarp and Donnybrook Sunklands (which do not have high salt concentrations in the soil), and:

1. has a depth to groundwater at the catchment outlet of less than four metres, and

2. has soil solute concentration above this groundwater table greater than 2000 mg/L total soluble salts, and

3. which drains into "an area environmentally sensitive to rises in saline groundwater" (Appendix 1).

Second order catchments in the intermediate rainfall zone which are considered "environmentally sensitive to rises in saline groundwater" are shown in Appendix 1, map 2. These 56 catchments have been least disturbed by past logging or clearing activities and thus are assumed to have the best preserved aquatic ecosystems.

"It is CALM's responsibility to determine which of the second order catchments considered environmentally sensitive to rises in saline groundwater are of a high salt risk. In the absence of other evidence, CALM will assume these second order catchments to be of a high salt risk." Alternatively "CALM may undertake physical measurements of depth to groundwater and/or soil solute concentration, to determine whether these candidate areas meet the definition for a second order catchment of high salt risk" (Appendix 1).

Ground-based electromagnetic (EM) induction has been shown to be a useful technique for estimating soil electrical conductivity and hence for diagnosing and mapping soil salinity in some situations (Johnston *et al.* 1977). Consequently this study sought to determine the effectiveness of EM induction for estimating soil solute concentration in south-west Australian forests and thus as a tool to help identify which of the "environmentally sensitive" catchments may also be a "high salt risk".

The specific aims of this project were:

1. evaluate the effectiveness of an EM31 Ground Conductivity Meter for estimating average soil salt concentration to 4m depth and, if found to be suitable,
2. determine an appropriate method of surveying the streamzone of a catchment with an EM31 to adequately cover the spatial variation in stored salt, and
3. use an EM31 to survey the length of the streamzone of second order catchments which drain into areas "environmentally sensitive to rises in saline groundwater", to determine the average soil salt concentration to 4m.

The directive to conduct the project was made in December 1997. The first field survey was conducted in March 1998 and the last in April 99.

EM31 function

The principles of operation of the Geonics EM31 Ground Conductivity Meter are given by McNeill (1980). The EM31 comprises a 4m long boom, housing a transmitter coil at one end and a receiver coil at the other (Fig. 1). When the transmitter coil is energized with an alternating current, it produces an EM field. The EM field induces eddy currents, at various depths in the soil, which in turn produce a secondary EM field. The receiver coil senses both the secondary and primary EM fields, and the ratio of the two is expressed as soil apparent electrical conductivity (ECa). The magnitude of the eddy currents is determined by the electrical conductivity of the soil. Soil electrical conductivity depends on a number of factors including salt content, moisture, clay content and type, texture, and temperature. Thus an EM31 measurement represents an integration of all these factors over the depth of influence of the EM meter into a single estimate of ECa, usually in units of milliSiemens/metre (mS/m).

Fig. 1. Geonics EM31 ground conductivity meter shown in vertical dipole mode at 0.8m height.

The effect of the EM field is non linear with depth. Hence an EM reading is an average of soil electrical conductivities weighted according to the depth response function. The relative contribution of electrical conductivity from the various depths also depends on the orientation of the meter, i.e., either the vertical magnetic dipole, which is the way the meter is usually carried, or the horizontal magnetic dipole, which is when the meter is rolled onto its side 90° from the vertical. The depth response function for an idealized, homogeneous soil profile, for vertical and horizontal modes is shown in Appendix 2. In vertical mode the EM31 is insensitive to near-surface soil conditions and has peak sensitivity at about 1.5 m depth. In horizontal mode the EM31 is most sensitive to near-surface soil conditions. The effective depth of exploration, with the instrument on the ground surface, is about 6m in the vertical mode, and about 3m in the horizontal mode, with diminishing contribution from greater depths.

The EM31 is portable and, for continuous surveys, may be carried at hip height (about 0.8m) using a shoulder strap. The time constant of the meter, which is about 1 sec, is the time taken to equilibrate when moved to a different location.
To maintain accuracy, the EM31needs to be checked and, if necessary, rezeroed every few days. Three different meters were used in this study, and two varied by about 2mS/m between checks - one meter drifted up and the other down. Records were not kept for the third meter used. The potential for error is relatively greater for low ECa values.

Measures of salinity

The measure of soil salinity used in criterion 3 of the definition of high salt risk is Total Soluble Salts (TSS). The quantity of TSS at a point in the soil is usually stated as either

1. the mass of TSS per unit bulk mass of dry soil, which is referred to as the (gravimetric) solute content (g/kg),
2. the mass of TSS per unit bulk volume of soil, which is referred to as the (volumetric) solute content (kg/m^3), or
3. the concentration of TSS in the soil solution, which is referred to as solute concentration (mg/L).

A disadvantage with using solute concentration to quantify soil TSS is that it depends on soil water content at the time of sampling, and hence of time since last rain, and so will be highly variable with time at any point in the soil. In contrast, solute content is not dependent on soil water content. It is possible to convert precisely between solute concentration and solute content, provided soil porosity (or bulk density and particle density) and soil water content are known at the time of measurement.

Because of the dependence of soil solute concentration on soil water content the quantity 2000 mg/L specified in criterion 3 of the definition for "high salt risk" is assumed to be measured in a saturated soil.

Calibrating the EM31

The value of the EM31 is realized when the ECa that it measures is converted to a salinity quantity for a known depth interval by the process of calibration. This involves establishing a relationship between the ECa readings taken at a number of points and the corresponding salinity measurements of the soil profile at those points.

In this study, the salinity records of soil cores were available in units of one or more of solute concentration (mg/L), and solute content (g/kg or kg/m^3). Solute content was used in this calibration because of the inherent variability of solute concentration.

Aim 1. Evaluate effectiveness of EM31 for estimating average soil salt concentration to 4m depth

Method

EM31 measurements of soil ECa were taken adjacent to boreholes for which there were historical records of salt content in soil cores taken at the time of drilling (Fig. 2, Table 1). The holes were drilled by different operators using different methods, for various research programs by several agencies, over a number of years. The holes were located in a range of topographic positions, mostly in south west forests spanning areas with annual rainfall from 725 to 1100 mm, but also included reforested farmland (725 to 900 mm) and cleared farmland (500 to 700 mm). The boreholes from lower rainfall areas were included in this study to extend the range of salinities sampled.

Table 1. Number of boreholes, date of drilling, and annual rainfall for each site used in the EM31 calibration. The range of ECa shown is for measurements made in vertical mode at 0.8m height in autumn. Location of sites is shown in Fig. 2.

Site code	Number of cored holes	Annual rainfall (mm)	Date bores drilled	Range of ECa in autumn
a	2	820	1975	10 -129
b	7	860	1979	12 - 39
c[1]	59	900-1100	1977-98	0 - 138
d	2	970	1997	28 - 39
e	4	930	1997	7 - 71
f	1	820	1973	14
g	15	725	1977-79	14 - 218
h	12	900	1994	6 - 85
i	11	1100	1997	6 - 24
j	10	850	1992-93	5 - 98
k	1	800	1975	71
l	8	850	1975	15 - 89
m	10	900	1974-75	10 - 28
n	20	1050-1080	1976	6 - 111
o	6	930-960	1997	21 - 62
p	12	700	1994	19 - 249
q	8	500	1998	14 - 107

[1] These holes spanned an area about 7km E-W by 58km N-S

At the time of drilling, subsamples were taken from soil cores at depth intervals between 0.5 and 1m for salt and other analyses. Measures of soil salinity were calculated from the electrical conductivity of a 1:5 soil-to-water extract corrected to 25°C. Cores were selected for this study if solute content data were available in units of g/kg at four depths or more to 4.5m. Solute content in units of g/kg was used in the analysis because there were more records available in these units compared with kg/m^3. Whereas the calibration was for a notional soil depth of 4m, salt data from depths between 4 and 4.5m were included in the analysis.

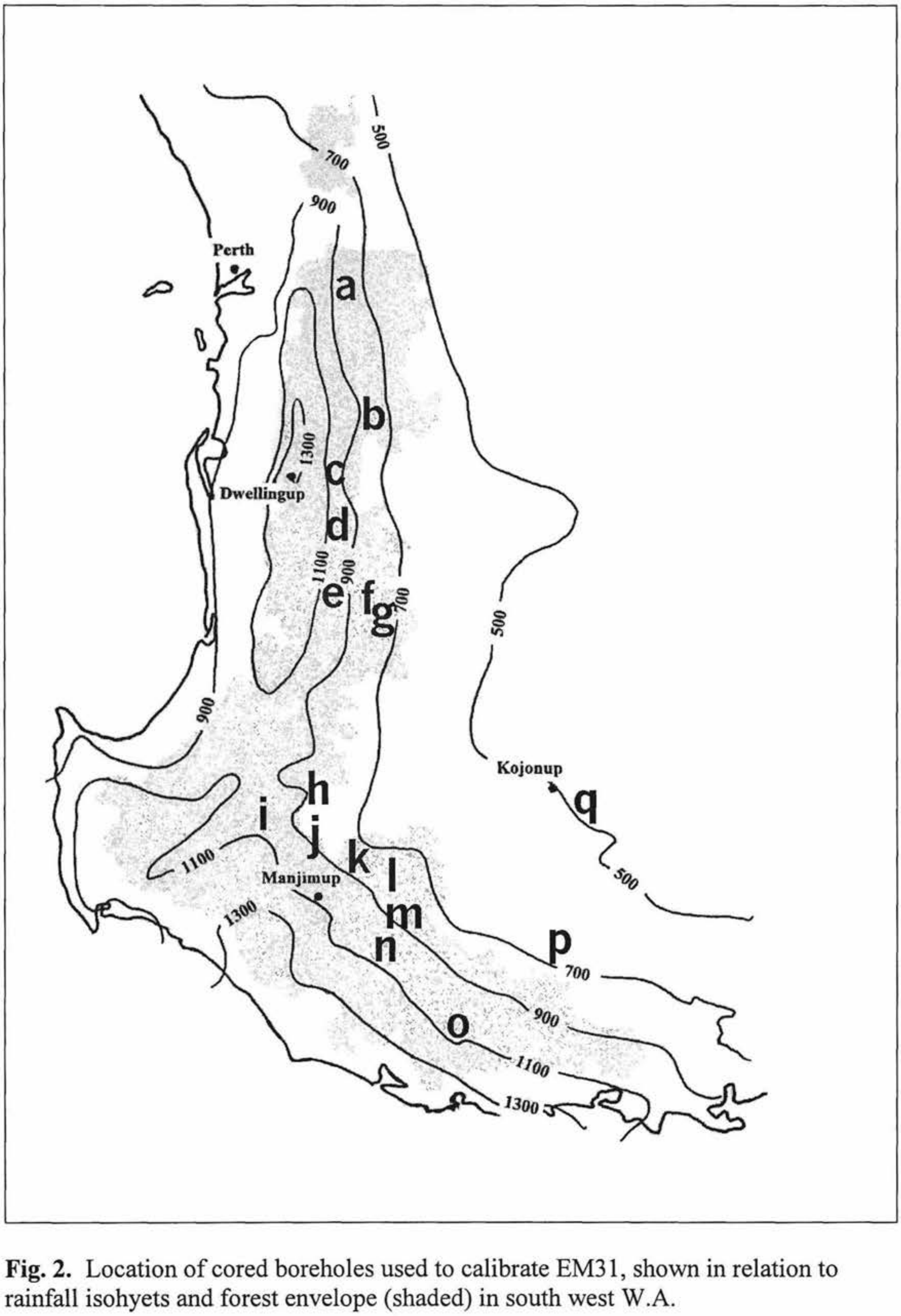


Fig. 2. Location of cored boreholes used to calibrate EM31, shown in relation to rainfall isohyets and forest envelope (shaded) in south west W.A.

At each bore, EM31 measurements were taken in each of four modes to compare the effectiveness of the different modes, i.e. vertical at 0.8m above ground, vertical at ground level, horizontal at 0.8m above ground, horizontal at ground level. Measurements were taken in autumn, when groundwater and soil moisture levels are lowest, and again in spring, when groundwater and soil moisture levels are highest, to provide a measure of the seasonal sensitivity of the EM31. Measurements commenced in autumn 1998 and were repeated in spring 1998.

Three different EM31 meters were used at different times in this study because of the limited availability of any particular meter due to demands from other users. There were only three EM31 meters in W.A. at the time of the study. The meters were: an analog EM31 from Tesla-10 Pty Ltd and a digital EM31 from Agriculture Western Australia (AgWest) which were used for the autumn series of measurements; and an analog EM31 from AgWest which was used for the spring series. The two analog meters were calibrated against the digital meter. Linear regressions were used to convert from analog EM31 values to equivalent digital EM31 values (Appendix 3). All analyses in this study were made in terms of actual or equivalent digital EM31 values which were not corrected for soil temperature.

The relationship between ECa in each mode of meter orientation and height and the arithmetic mean of soil salt content (g/kg) to 4.5m was expressed as a linear regression. The significance of the regressions was determined by an F test. Data were log-log transformed because of the predominance of data with low values; the few high values had a disproportionate influence on the untransformed linear regression. Records with ECa $\leq$5 mS/m were omitted from analysis because of the high potential for inaccurate readings resulting from meter drift, and the relatively high leverage that low values have in a regression when log transformed. The number of bores with ECa and TSS data which were suitable for analysis, after omitting those data with ECa $\leq$5 mS/m or inadequate TSS records vary from 145 to 189 depending on the particular analysis.

The effect of season on the EM31 response, was evaluated in terms of the departure of the slope of the linear regression of spring versus autumn EM31 measurements from a 1:1 relationship. This was done by constructing 95% confidence intervals for the intercept and slope and checking if the intercept equaled 0 and if slope equaled 1. The EM31 measurements were taken in vertical mode at 0.8m height at 189 bores. Data were log-log transformed and records with ECa $\leq$5 mS/m were omitted from analysis for the reasons given above.

Results

Regression analyses of the calibration relationships between ECa and TSS (g/kg) are shown in Table 2. There is a highly significant linear relationship ($P<0.0001$) between average TSS to 4m depth and ECa when measured in either autumn or spring in any of the 4 modes of EM31 orientation and height. R^2 for the regressions ranged between 0.69 and 0.62 in autumn and between 0.69 and 0.64 in spring.

Carrying the EM31 at hip height ($\approx$0.8m) using a shoulder strap and orientated in vertical dipole mode is the most efficient method for taking many measurements such as along a traverse. R^2 for the regression with the EM31 in vertical mode at 0.8m height was 0.66 in autumn and 0.69 in spring. The distribution of data points for the regression TSS in the upper 4m versus ECa in vertical mode at 0.8m height in autumn is shown in Fig. 3.

Table 2. Regression relationships for converting soil Apparent Electrical Conductivity (ECa, mS/m), measured by an EM31, to average Total Soluble Salt content (TSS, g/kg) in the upper 4m of soil. Values in parentheses are standard errors.

Season	EM31 mode	Linear regression equations	R^2	n	P
Aut	vertical ground	$\log_{10}(TSS) = 0.97\ (\pm 0.05) * \log_{10}(ECa) - 1.79\ (\pm 0.08)$	0.69	160	<0.0001
	vertical 0.8m	$\log_{10}(TSS) = 1.02\ (\pm 0.06) * \log_{10}(ECa) - 1.76\ (\pm 0.08)$	0.66	159	<0.0001
	horiz ground	$\log_{10}(TSS) = 0.89\ (\pm 0.05) * \log_{10}(ECa) - 1.52\ (\pm 0.08)$	0.64	152	<0.0001
	horiz 0.8m	$\log_{10}(TSS) = 1.02\ (\pm 0.07) * \log_{10}(ECa) - 1.54\ (\pm 0.09)$	0.62	145	<0.0001
Spr	vertical ground	$\log_{10}(TSS) = 0.95\ (\pm 0.05) * \log_{10}(ECa) - 1.84\ (\pm 0.08)$	0.68	166	<0.0001
	vertical 0.8m	$\log_{10}(TSS) = 1.03\ (\pm 0.05) * \log_{10}(ECa) - 1.87\ (\pm 0.08)$	0.69	164	<0.0001
	horiz ground	$\log_{10}(TSS) = 0.92\ (\pm 0.05) * \log_{10}(ECa) - 1.67\ (\pm 0.08)$	0.69	161	<0.0001
	horiz 0.8m	$\log_{10}(TSS) = 0.97\ (\pm 0.06) * \log_{10}(ECa) - 1.57\ (\pm 0.08)$	0.64	153	<0.0001

There is a significant effect of season on EM31 response (Table 3, Fig. 4). The slope of the spring versus autumn regression is not significantly different from 1, however, the intercept is significantly greater than 0. ECa at a site is higher when measured by an EM31 in spring than when measured in autumn.

Table 3. Linear regression and 95% confidence limits of the relationship between ECa readings taken in autumn (X variable) and spring (Y variable) at the same bores using an EM31 in vertical mode at 0.8m height.

R^2	Observations
0.93	189

	Coefficients	*Standard Error*	*Lower 95%*	*Upper 95%*
Intercept	0.101	0.028	0.046	0.157
X Variable	0.989	0.019	0.951	1.027

Criterion 3 of Ministerial Condition 16 specifies the critical limit of soil salinity in terms of solute concentration, i.e. 2000 mg/L TSS. The EM31 estimates soil apparent electrical conductivity in units of mS/m. To enable EM31 survey data to be interpreted in relation to the 2000 mg/L limit it is necessary to calculate the value of ECa which is equivalent to 2000 mg/L TSS. The conversion involves the steps: solute concentration (mg/L) → solute content (kg/m^3) → solute content (g/kg) → ECa (mS/m). The conversion from 2000 mg/L TSS to its ECa equivalent is given in Appendix 4 and is summarised in Table 4.

Table 4. Equivalent measures of average salinity in the upper 4m of soil and apparent electrical conductivity (ECa) estimated by an EM31 in vertical mode at 0.8m height. A = assuming average values for soil particle density (2.66g/cm^3) and bulk density (1.67 g/cm^3); B and C = range in salinity measures assuming average ± 1 standard deviation values for particle density (0.06 g/cm^3) and bulk density. (0.22 g/cm$^{3)}$. Calculations are given in Appendix 4.

	Solute concentration (mg/L)	Solute content (kg/m3)	Solute content (g/kg)	ECa (mS/m)	
				Autumn	Spring
A	2000	0.74	0.44	25	31
B	2000	0.54	0.29	19	23
C	2000	0.93	0.64	32	40

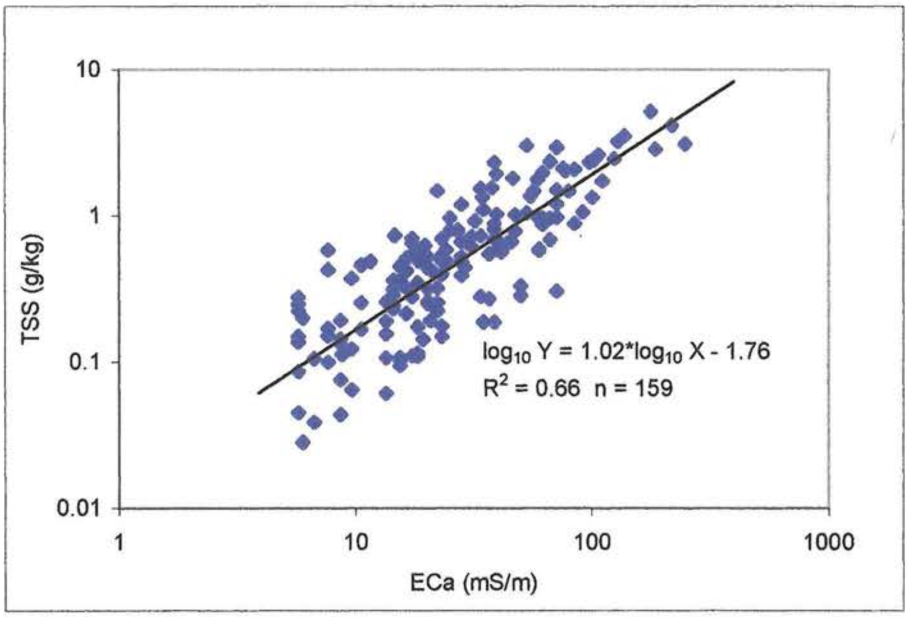


Fig. 3. Regression of mean solute content in upper 4m of soil versus apparent electrical conductivity measured using an EM31 in vertical mode at 0.8m in autumn.

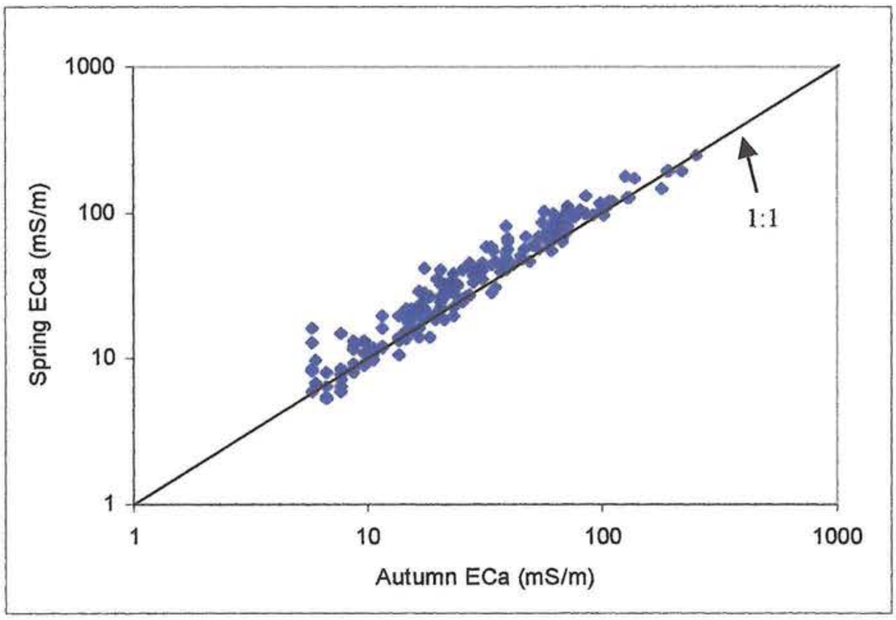


Fig. 4. Comparison of ECa readings, taken at the same bores in autumn and spring, with a 1:1 line. EM31 used in vertical mode at 0.8m height.

Discussion

The highly significant relationship between soil ECa measured by the EM31 and average soil TSS content to 4m depth indicates that the EM31 is a suitable tool for predicting soil TSS in forested areas in the IRZ.

The seasonal variation in ECa at the same sites is probably due to changes in soil moisture content and temperature. However, these two factors are likely to have opposite effects. ECa increases with increasing soil moisture, although the relationship is not linear and is not clearly understood (Rhoades *et al.* 1976, Williams *et al.* 1990). ECa of a soil solution is also directly related to temperature (McNeill 1980). Hence the increase in ECa in spring compared with autumn is the net result of an increase in ECa due to higher soil moisture, and a decrease in ECa due to the lower temperature of the spring soils. Evidently the effect on ECa of soil moisture in spring is greater than the effect of lower soil temperatures and would be greater than the observed increase if the counteractive effect of temperature was removed.

The EM31 may be used in either autumn or spring with an acceptable degree of accuracy provided the appropriate seasonal conversion equation is used. From a practical viewpoint, autumn is preferable to spring for field surveys. In autumn, the generally dry surface soil conditions allow more opportunity for access into Disease Risk Areas. Also, streambeds are mostly dry in autumn and thus more readily traversable.

The significant relationship between ECa and soil salt content is also noteworthy considering that some of the soil salinity data from forested areas were acquired up to 23 years earlier and there could be concerns over changes in soil salt content with time. However, soil salt content is considered to be relatively stable over time periods of decades, even following the release of soil salts to streams that occurs with clearing for agriculture. For example, Peck and Hurle (1973) estimated that following clearing it would take some 200 to 400 years for soil salts to leach to the extent that a new salt balance is reached. In view of these estimates, the soil salt data in this study that were acquired from cleared land up to four years earlier, or from reforested previously cleared land up to 21 years earlier, would not be expected to have changed significantly over these periods.

Aim 2. Determine appropriate method of surveying streamzone with EM31 for stored salt

Method

Four second order catchments were surveyed in autumn 1998 using an EM31 in vertical mode at 0.8m height at a slow walk. Seven traverses were surveyed in the streamzone along the length of the second order stream in each catchment in the following locations: along the streambed, along each stream bank, 10m each side of the stream centre, and 20m each side of the stream centre. Readings were taken at between 1 and 2m intervals. A Tesla10 analog meter with a data logger attached was used in Thomson's Brook catchments 2 and 3. Readings were electronically recorded by pressing a trigger on the meter. A digital meter was used in Canning River 9 and Harris River 1 and readings were recorded on a voice recorder.

An ANOVA was performed to determine which of the seven traverses in the streamzone was the most likely to encounter the highest ECa levels. This was done by considering each traverse to consist of 100m replicate sections. Hence there were 8 sections along each traverse at Harris 1, and 22 sections along each traverse in the other three catchments. The ECa readings in each section were averaged and log transformed. The overall mean em reading was compared between positions with contrasts and using Tukey's Studentized Range (HSD) test.

Results

There is significant variation in ECa along second order streams, at different distances from the stream, and between second order catchments (Table 5). The highest ECa levels were recorded mostly within 10m of the streambed (Table 6).

Table 5. ANOVA of ECa reading in relation to position in landscape.

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Site	3	12.066	4.022	28.64	0.0001
Replicate 100m sections	70	9.831	0.140	15.45	0.0001
Traverse	6	2.036	0.339	37.34	0.0001
Site*Traverse	18	1.168	0.065	7.14	0.0001
Error	420	3.817	0.009		

Table 6. Mean $\log_{10}$ECa reading for each traverse. Means with the same letter are not significantly different by Tukey's Studentized Range Test (HSD).

Mean	N	Traverse	
1.64177	74	south bank	A
1.63783	74	bed	A
1.63021	74	north bank	A
1.59720	74	south+10m	A
1.51567	74	south+20m	B
1.50092	74	north+10m	B
1.45282	74	north+20m	C

The results of the ECa surveys in the four catchments are shown in Appendix 5. Local high points in ECa occurred throughout the length of the second order streams and changes in ECa occurred abruptly within the space of a few metres. Depressions or eroded scours in the streambed frequently coincided with a spiked increase in ECa. There were no marked differences in ECa between areas of streambed that were wet from seeps and the adjoining streambed. Exposed or shallow granite outcrops consistently registered relatively low readings of ECa.

Discussion

The EM31 streamzone surveys in the four catchments indicate considerable spatial variation in ECa and show that the highest levels, although generally close to the streambed, are not necessarily near the catchment outlet. The surveys illustrate the advantage of measurement at many points instead of at a limited number of locations when characterizing the soil salinity status of a streamzone.

A suitable method of estimating soil salt storage of a streamzone to 4m depth would entail an EM31 survey along the length of the second order stream in the vicinity of the streambed. The EM31 is most practically carried in vertical mode at hip height with the boom parallel to the direction of travel. Readings taken at 2-3 m intervals are feasible and would provide a large data base to characterize the variation of salt storage along the stream line.

In this study, carrying a 4m long boom along a usually sinuous streambed incised at up to one metre, and occasionally deeper, through streamzone vegetation provided quite a challenge to the operator. Access to the streamzone and traversability along the streambed would be improved in areas burnt in the previous year.

Aim 3. EM31 survey of streamzones of "environmentally sensitive" catchments

Method

The streambeds of the sections of second order streams which were traversable were surveyed using an EM31 in vertical mode, at 0.8m height, at a slow walk, recording at about 2 m intervals. All catchments except Thomson's Bk 2 and 3 (see Aim 2 Method) were surveyed using a digital EM31 and voice recorder. The surveys were conducted in autumn of 1998 or 1999.

The streambed of part of a second order stream, near Russell Rd, in Urbrae Block in the High Rainfall Zone was also surveyed for comparison with the IRZ surveys.

Results

The streambeds of 24 of the 56 catchments were surveyed along as much of the second order stream as possible, ranging from hundreds of metres through to kilometres (Table 7). Of the remaining 32 catchments, dense vegetation either made access to the streamzone or traversing the streambed very difficult. The results of the surveys are shown in Figs 5a-f in relation to an ECa of 25mS/m which assumes an average soil particle density of 2.66 g/cm^3 and bulk density of 1.67 g/cm^3 (Table 4).

The results of the surveys are shown in Figs 5a-f in relation to an ECa of 25mS/m. The ECa of 25mS/m assumes an average soil particle density of 2.66 g/cm^3 and bulk density of 1.67 g/cm^3 (Table 4).

22 of the 24 environmentally sensitive catchments surveyed had ECa levels in the upper 4m of the soil in the streamzone greater than 25mS/m which suggested stored salt at levels exceeding the 2000 mg/L TSS threshold level. In nine of the catchments the threshold level was exceeded along the entire length of the second order stream, and in the remaining 13 of the catchments the threshold level was exceeded along more than half of the length of the stream.

In Canning R 3 the ECa levels in the upper 4m of soil in the streamzone were less than 25 mS/m. The salinity status of the lower ¼ of this stream is unknown since it was untraversable and was not surveyed. Only 6% of the length of Donnelly R 5 second order stream was traversable and the ECa levels in that section were below the 25 mS/m threshold.

The EM31 survey of the lower half of a second order stream near Russell Rd in Urbrae Block in the HRZ is shown in Fig. 6. ECa in the upper 4m of soil in the streambed reached 17 mS/m at one point but was mostly below 10 mS/m.

The surveyed streamzone ECa levels may also be compared with the range of ECa measured adjacent to boreholes in the EM31 calibration exercise shown in Table1. The two sites with the highest borehole ECa levels were on bare salt scalds in cleared agricultural areas, i.e. site p (Kent River) with a maximum ECa of 249 mS/m, and site g (Bingham River)with a maximum ECa of 218 mS/m. At Broomehill the highest ECa measured near a borehole on cleared farmland was 107 mS/m. In comparison, the highest ECa recorded in the forest streambed surveys was 261 mS/m, about 70 m upstream from the catchment outlet in Thomsons Bk 5 (Fig. 5f).

Table 7. List of 56 second order catchments "environmentally sensitive to rises in saline groundwater" and characteristics of second order streamzone.

Second order catchment	Forest Block	Accessible streamzone?	Traversable streambed?	Length of 2° stream (m)	% of 2° stream surveyed	Date surveyed	Comments
Canning R #1	Canning	Yes	No				
Canning R #2	Ashendon	Yes	No				
Canning R #3	Ashendon	Yes	Partly	1600	75	3 Apr 99	Lower 400m vegetation too dense
Canning R #4	Ashendon	Yes	Yes	450	100	3 Apr 99	
Canning R #5	Ashendon	Yes	Yes	200	100	3 Apr 99	
Canning R #6	Clare	Yes	Yes	1300	100	3 Apr 99	
Canning R #7	Dale	Yes	Yes	2100	100	7 Apr 99	
Canning R #8	Dale	Yes	Yes	1400	100	7 Apr 99	
Canning R #9	Dale	Yes	Yes	2205	100	15 May 98	
Deep R #1	Spring	Yes	Yes	670	100	31 Mar 99	
Deep R #2	Spring	Yes	Yes	750	100	31 Mar 99	
Deep R #3	Spring	Yes	Partly	800	50	31 Mar 99	Lower 400m vegetation too dense
Deep R #4	Spring	Yes	Yes	720	100	31 Mar 99	
Deep R #5	Thomson	No	No				
Deep R #6	Thomson	No	?				
Deep R #7	Thomson	No	?				
Deep R #8	Long	Yes	Yes	400	100	1 Apr 99	
Deep R #9	Long	Yes	Partly	3000	50	1 Apr 99	Upper~ 50% vegetation too dense
Deep R #10	Rocky	Yes	No				
Deep R #11	Long	Yes	No				
Deep R #12	Long	No	?				
Deep R #13	Long	Yes	No				
Deep R #14	Thomson	No	?				
Deep R #15	Lochart	Yes	No				
Deep R #16	Thomson	Yes	No				
Deep R #17	Lochart	No	?				
Deep R #18	Long	No	?				
Deep R #19	Long	Yes	No				
Deep R #20	Long	No	?				
Deep R #21	Lochart	Yes	No				

Table 7 continued

Second order catchment	**Forest Block**	**Accessible streamzone?**	**Traversable streambed?**	**Length of 2° stream (m)**	**% of 2° stream surveyed**	**Date surveyed**	**Comments**
Donnelly R #1	Beaton	Yes	Partly	1200	30	30 Mar 99	Traversable 170m upstream & 200m downstream of Chris Rd
Donnelly R #2	Beaton	Yes	No	5000			
Donnelly R #3	Nelson	Yes	No	2000			
Donnelly R #4	Gregory	Yes	No	300			
Donnelly R #5	Dalgarup	Yes	Partly	2000	6	30 Mar 99	Traversable 90m upstream & 40m downstream of Brockman Hwy
Donnelly R #6	Nelson	No	No	2800			
Donnelly R #7	Nelson	Yes	No	2500			
Donnelly R #8	Nelson	Yes	No	1200			
Donnelly R #9	Nelson	Yes	No	400			
Donnelly R #10	Nelson	Yes	No	3500			
Donnelly R #11	Nelson	Yes	No	3000			
Donnelly R #12	Nelson	Yes	No	1800			
Donnelly R #13	Nelson	Yes	No	1200			
Harris R #1	Surface	Yes	Yes	810	100	16 May 98	
Harris R #2	Surface	Yes	Yes	100	100	8 Apr 99	No distinct 2° stream
Mungalup Bk	Mungalup	Yes	Yes	4500	70	29 Mar 99	Lower 3300m surveyed
Pascoe Bk	Pascoe	Yes	Partly	10000	25	8 Apr 99	Lower 2km surveyed
Quinninup Bk #1	Dordagup	Yes	No	3000			
Quinninup Bk #2	Dordagup	No	No	3500			
Thomson Bk #1	Preston	Yes	Yes	570	100	12 Feb 99	
Thomson Bk #2	Preston	Yes	Yes	2210	100	14 May 98	
Thomson Bk #3	Preston	Yes	Yes	2500	100	14 May 98	
Thomson Bk #4	Preston	Yes	Yes	2800	100	11 Feb 99	
Thomson Bk #5	Preston	Yes	Yes	2000	100	12 Feb 99	
Tinkers Bk #1	Kinkin	Yes	No	4000			
Tinkers Bk #2	Kinkin	Yes	No	2500			

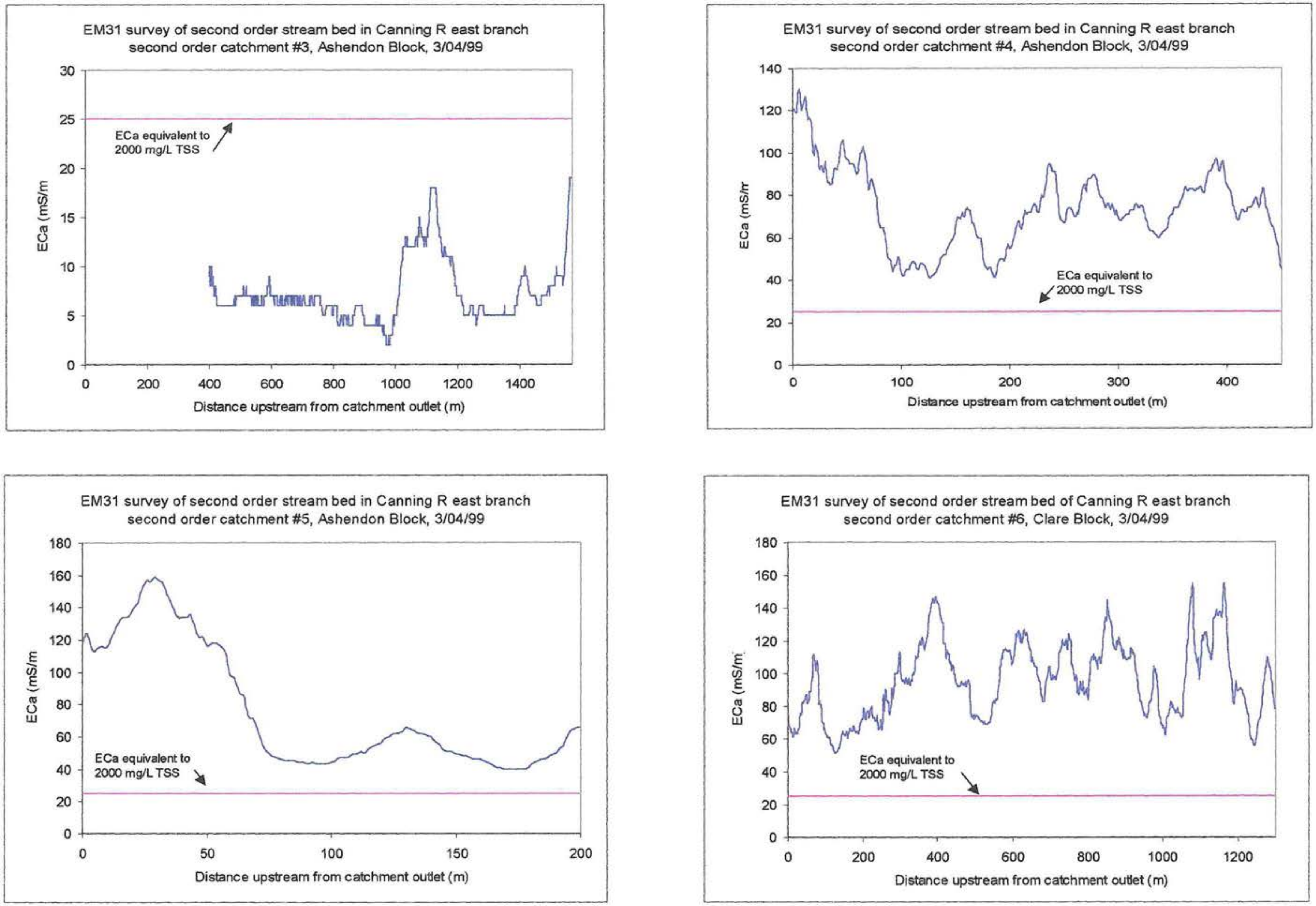
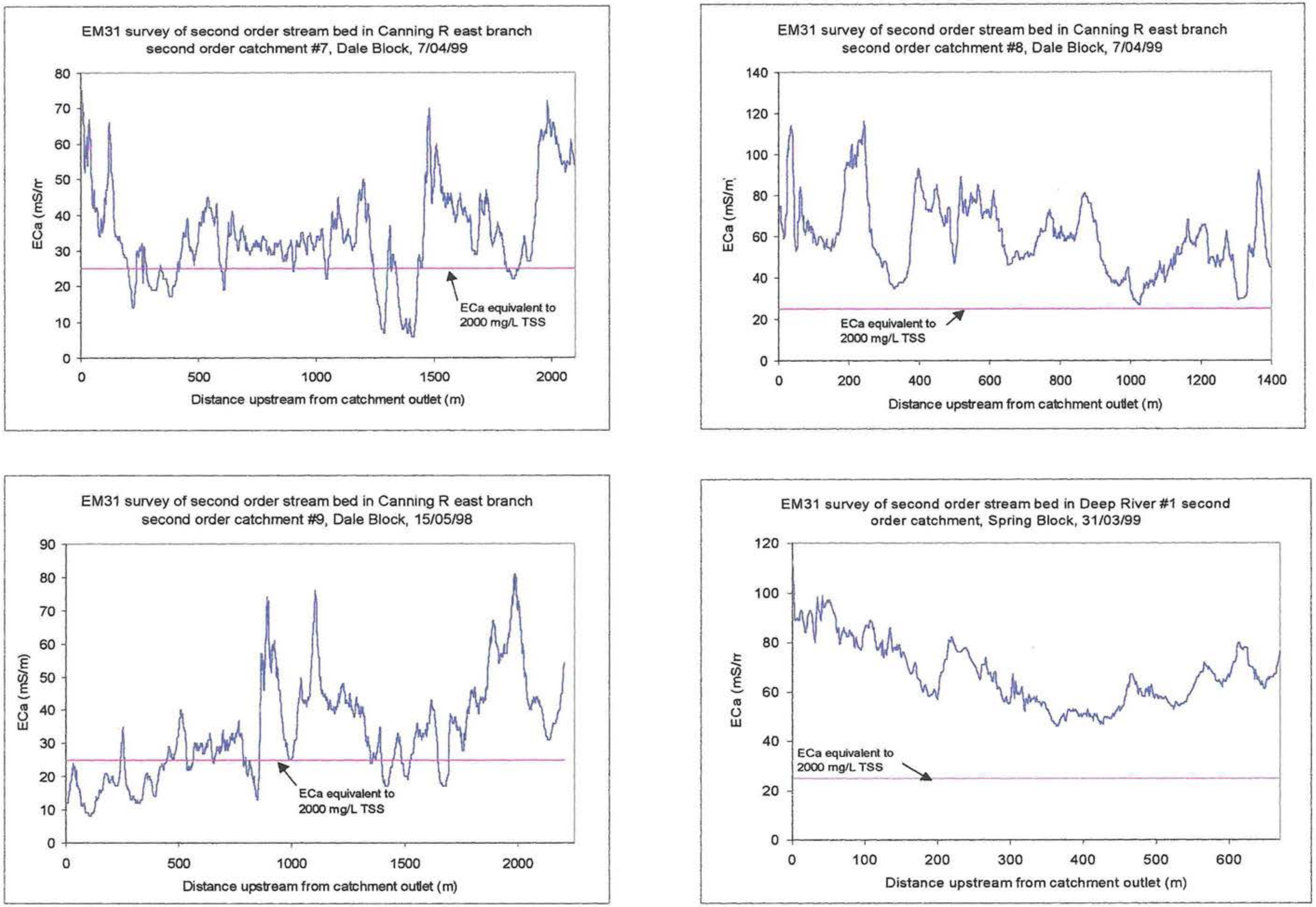


Fig. 5a. Results of EM31 surveys of streambeds of second order streams in "environmentally sensitive" catchments.


EM31 survey of second order stream bed in Canning R east branch second order catchment #7, Dale Block, 7/04/99

EM31 survey of second order stream bed in Canning R east branch second order catchment #8, Dale Block, 7/04/99

EM31 survey of second order stream bed in Canning R east branch second order catchment #9, Dale Block, 15/05/98

EM31 survey of second order stream bed in Deep River #1 second order catchment, Spring Block, 31/03/99

Fig. 5b. Results of EM31 surveys of streambeds of second order streams in "environmentally sensitive" catchments.

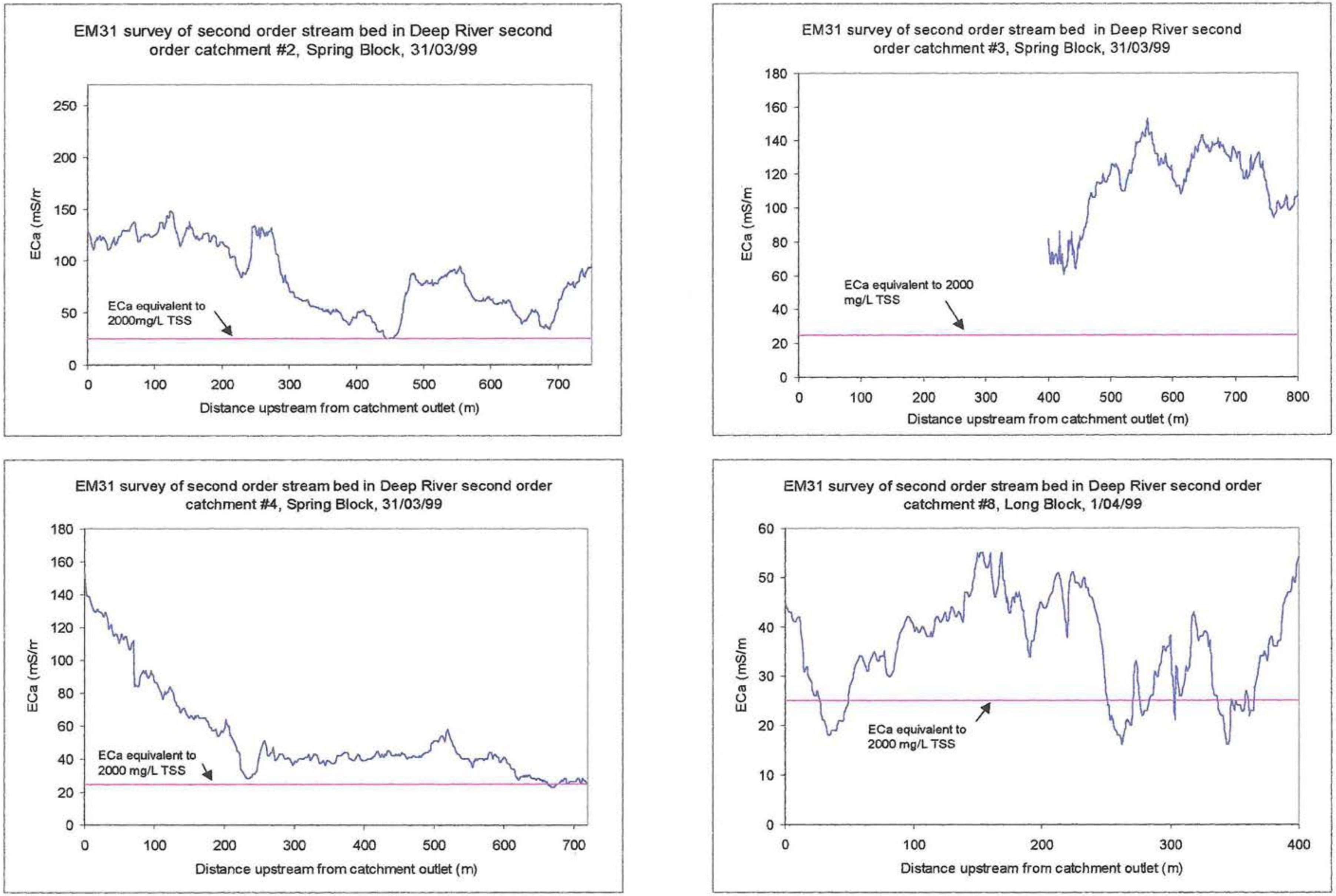
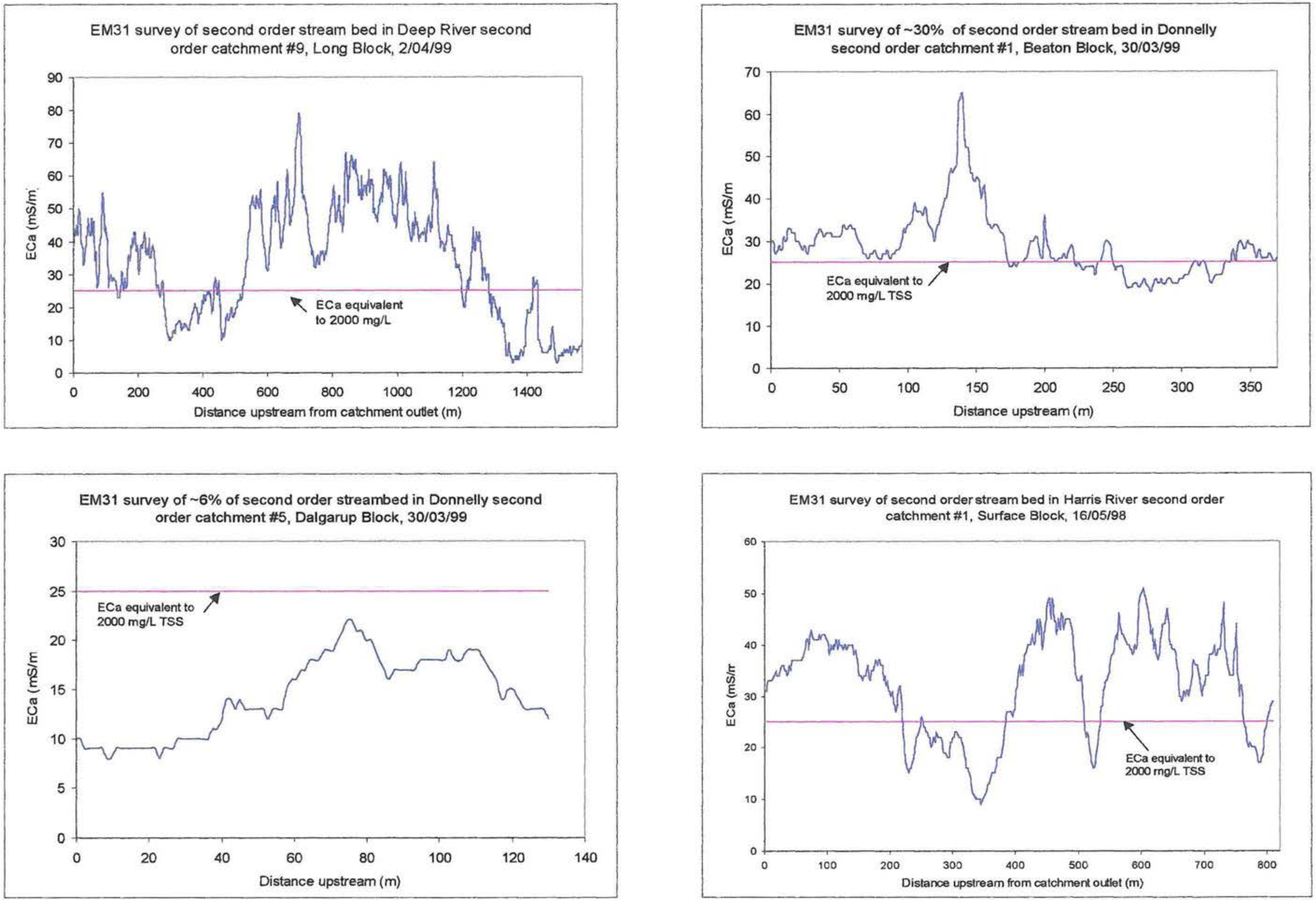


Fig. 5c. Results of EM31 surveys of streambeds of second order streams in "environmentally sensitive" catchments.



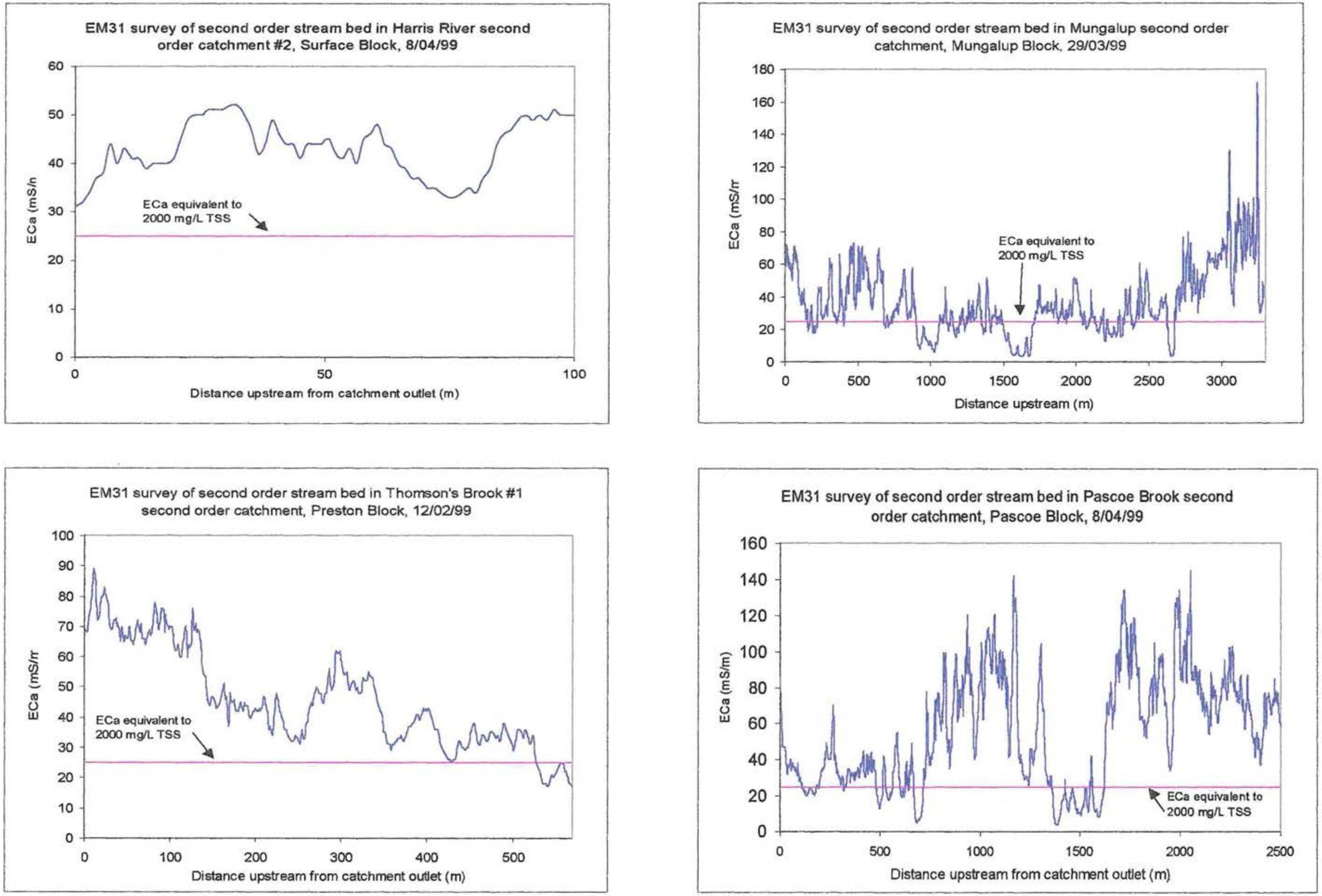
EM31 survey of second order stream bed in Deep River second order catchment #9, Long Block, 2/04/99

EM31 survey of ~30% of second order stream bed in Donnelly second order catchment #1, Beaton Block, 30/03/99

EM31 survey of ~6% of second order streambed in Donnelly second order catchment #5, Dalgarup Block, 30/03/99

EM31 survey of second order stream bed in Harris River second order catchment #1, Surface Block, 16/05/98

Fig. 5d. Results of EM31 surveys of streambeds of second order streams in "environmentally sensitive" catchments.


EM31 survey of second order stream bed in Harris River second order catchment #2, Surface Block, 8/04/99

EM31 survey of second order stream bed in Mungalup second order catchment, Mungalup Block, 29/03/99

EM31 survey of second order stream bed in Thomson's Brook #1 second order catchment, Preston Block, 12/02/99

EM31 survey of second order stream bed in Pascoe Brook second order catchment, Pascoe Block, 8/04/99

Fig. 5e. Results of EM31 surveys of streambeds of second order streams in "environmentally sensitive" catchments.

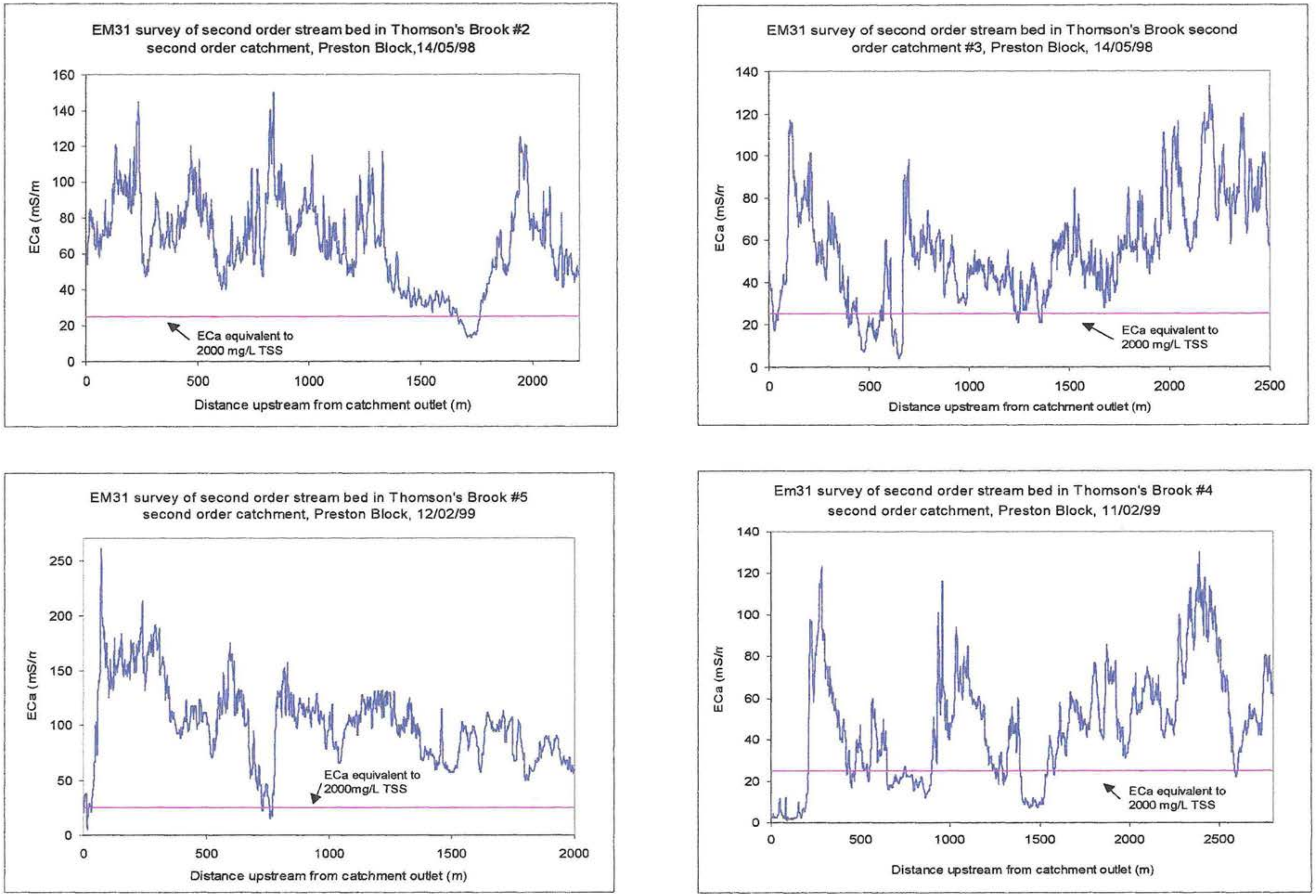


Fig. 5f. Results of EM31 surveys of streambeds of second order streams in "environmentally sensitive" catchments.

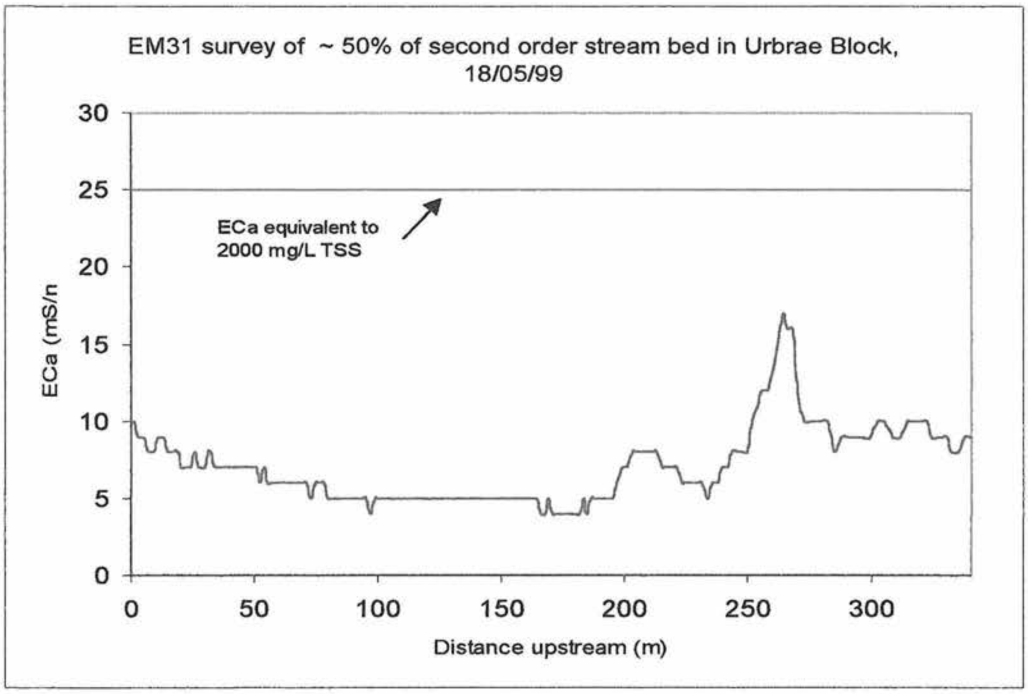


Fig. 6. EM31 survey of streambed of second order stream in Urbrae Block in the high rainfall zone.

Discussion

Estimated salt storage in the upper 4m of the soil profile of parts of the streamzone of 22 "environmentally sensitive" catchments was higher, and in some cases considerably higher, than 2000 mg/L. The salinity levels inferred from the streamzone surveys may be put into a broader context by comparing them with salinities in other rainfall zones and in non-forest sites. The ECa levels at Russell Rd are consistent with the empirically-based generalization that soil salt storage in the HRZ is low relative to the IRZ and that, although groundwater levels frequently intersect the surface and discharge to streams, the streams are relatively fresh (Schofield *et al.* 1989). The IRZ forest streamzone surveys indicate salt storage closer to the levels occurring in relatively lower rainfall zone agricultural sites. However, it is important to note that salinisation in the agricultural areas has resulted from a combination of high salt storage and high groundwater.

A threshold level of 25 mS/m ECa is shown in Figs 5 and 6 as equivalent to a soil TSS concentration of 2000 mg/L. This is appropriate since the surveys were conducted in autumn. EM31 surveys in spring would result in higher ECa readings, however, the threshold level would be correspondingly higher at 31 mS/m.

In some catchments, the streamzones were unable to be surveyed because of the density of vegetation that either prevented pedestrian access to the streamzone from distant roads or access along the streambed. Access would be improved following a prescribed burn. Several of the surveyed catchments had been burnt in the previous year and it was evident from the density of vegetation in unburnt patches that access would have been considerably more difficult prior to the burn.

Acknowledgements

I wish to thank Matt Williams for providing the statistical analyses for this study, and Geoff Stoneman and Ian Abbott for helpful comments on the manuscript.

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Schofield, N.J., Stoneman, G.L., and Loh, I.C. (1989) Hydrology of the jarrah forest. *In* 'The Jarrah Forest: A Complex Mediterranean Ecosystem'. (Eds B. Dell, J.J. Havel, and N. Malajczuk) pp. 179-201. (Kluwer, Netherlands)

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Appendix 1. Record of Agreement between CALM and Water and Rivers Commission that relates to Ministerial Condition 16 attached to Forest Management Plan 1994-2003.

WATER AND RIVERS
COMMISSION

Record of Agreement

between

The Water and Rivers Commission
and
The Department of Conservation and Land Management

for

The Implementation of "Ministerial Condition 16" as set by the Minister for the Environment and attached to the Forest Management Plan 1994-2003

The Department of Conservation and Land Management (CALM) and the Water and Rivers Commission (WRC) recognise that Condition 16 of the "Ministerial Conditions" relating to the Forest Management Plan 1994-2003 requires joint action by the agencies.

CONDITION 16:

16-1 Within three years, or such other period as the Minister for the Environment shall nominate, the proponent, on advice from the Water Authority of Western Australia, shall identify second order catchments with a high salt risk.

16-2 Within each catchment identified according to the requirements of Condition 16-1, the proponent shall retain additional river and stream buffers and locate areas temporarily reserved during phased logging operations to the requirements of the Water Authority of Western Australia.

For the present purposes the Water Authority of Western Australia has been superseded by the Water and Rivers Commission.

This record of agreement documents the understanding that has been reached between the Department of Conservation and Land Management and the Water and Rivers Commission for identification and management of forests by CALM to comply with this condition. The agreement incorporates

a) the advice of the Water and Rivers Commission on the areas that should be considered by CALM for additional protection, as required by Condition 16-1, and
b) the requirements of the Commission for additional protection of "second order catchments of high salt risk" as specified in Condition 16-2.

BACKGROUND

The salinity impacts of forest logging operations on large water resources is very low. However, it is the smaller water resources of the intermediate rainfall zone of the Darling Range, where the minor impacts of forest logging have their greatest effect. Research has shown that for small streams in this area, base flow salinity in excess of 1000 mg/L TDS can result following logging. Logging practices have subsequently been modified to reduce the potential impact on water resources; these modifications are reflected in the Forest Management Plan 1994-2003 and in Ministerial Condition 12.

As a further precautionary measure, Ministerial Condition 16 operates to provide additional protection to "second order catchments with a high salt risk". It is the aquatic ecosystems associated with the streams of these catchments that are considered the most vulnerable water resource value. Condition 16 therefore is used to provide identification of and additional protection for, the best preserved aquatic ecosystems. These best preserved aquatic ecosystems are considered to be environmentally sensitive to rises in saline groundwater.

Consequently, CALM and WRC agree that areas environmentally sensitive to rises in saline groundwater, where the risk of temporary salt discharge following logging is high, should receive additional protection measures that minimise the risk of such saline discharges. In this way the original intent of Condition 16 is achieved by ensuring that the potential impact of logging operations is minimised on areas of high environmental value.

STREAM AND CATCHMENT ORDERS

Ministerial Conditions 12 and 16 establish second order catchments as the unit for management of salt risk. Second order catchments are defined as the catchments of second order streams. In order to use such streams and catchments as a basis for managing timber harvesting operations, a stable corporate data set showing all second order streams and catchments in relevant areas has been established and will be maintained by CALM.

DEFINITION OF SECOND ORDER CATCHMENTS WITH A HIGH SALT RISK

- A "second order catchment with a high salt risk" is one which occurs in the intermediate rainfall zone (900-1100 mm rainfall per year) but excluding the Whicher Scarp and Donnybrook Sunklands (which do not have high salt concentrations in the soil), and:

    1. has a depth to groundwater at the catchment outlet of less than four metres, and

    2. has soil solute concentration above this groundwater table greater than 2000 mg/L total soluble salts, and

    3. which drains into "an area environmentally sensitive to rises in saline groundwater".

- "An area environmentally sensitive to rises in saline groundwater" is one which:

    1. A. in part or in its entirety falls within the intermediate rainfall zone (900-1100 mm rainfall per year) but excluding the Whicher Scarp and Donnybrook Sunklands (which do not have high salt concentrations in the soil), and
    B. is fed by catchments which remain over 90% naturally vegetated, and any cleared portion is in the high rainfall zone [the rationale is that agricultural clearing would probably have raised salt levels in the stream already], and
    C. has had no past forest or plantation harvesting in the intermediate rainfall zone or the adjacent low rainfall zone of the type which potentially may have yielded groundwater rise sufficient to have raised the salinity of headwater streams in the past.

Or

2. is the largest, least-disturbed stream system within each natural resource zone which in part or in its entirety falls within the intermediate rainfall zone but excluding the Whicher Scarp and Donnybrook Sunklands. The rationale for this is that even though there may be no stream systems in these natural resource zones which fulfil the preceding three attributes (that is, 1A, 1B and 1C), giving additional protection to the largest, least-disturbed stream will give the greatest potential for aquatic biota to recolonise other streams if any are impacted by some future event.

The rationale for the above method of identifying areas environmentally sensitive to rises in saline groundwater, is to identify areas where the likelihood of past episodes of saline groundwater discharge were low. In turn, this was assessed by identifying streams where past logging and clearing activities in their catchments were either non-existent or at a minimum. The aquatic ecosystems associated with such areas were assumed to be the best preserved aquatic ecosystems.

The streams to be considered as "environmentally sensitive to rises in saline groundwater" are shown in Map 1. Second order catchments in the intermediate rainfall zone of streams which are considered environmentally sensitive to rises in saline groundwater are shown in Map 2.

It is CALM's responsibility to determine which of the second order of catchments considered environmentally sensitive to rises in saline groundwater (Map 2) are of a high salt risk. In the absence of other evidence, CALM will assume these second order catchments to be of a high salt risk . Alternatively, CALM may undertake physical measurements of depth to groundwater and/or soil solute concentration, to determine whether these candidate areas meet the definition for a second order catchment of high salt risk.

Additional River and Stream Buffers to Apply in Second Order Catchments With a High Salt Risk

In second order catchments identified as having a high salt risk, CALM will implement the specified additional phased logging procedures in accordance with Condition 16-2.

General protection measures to prevent saline discharge into these water courses will include:

- **a permanent 50 metre stream buffer on either side of the stream for the portion of the stream that occurs in the intermediate rainfall zone (900-1100 mm rainfall per year); being from the centre of the stream for watercourses less than 3 metres wide or from the edge of the stream for watercourses (which shall include associated wetlands) wider than 3 metres;**
- **a two-phased logging operation for the portion of the catchment that occurs in the intermediate rainfall zone (900-1100 mm rainfall per year) that ensures that:**
    - **an unlogged area of at least 30% (unless otherwise agreed by the Water and Rivers Commission) of the upslope cut over area is maintained adjacent to the water course during both logging phases; and**
    - **each logging phase is separated by at least 15 years.**

Syd Shea

Syd Shea
EXECUTIVE DIRECTOR
Department of Conservation and Land Management

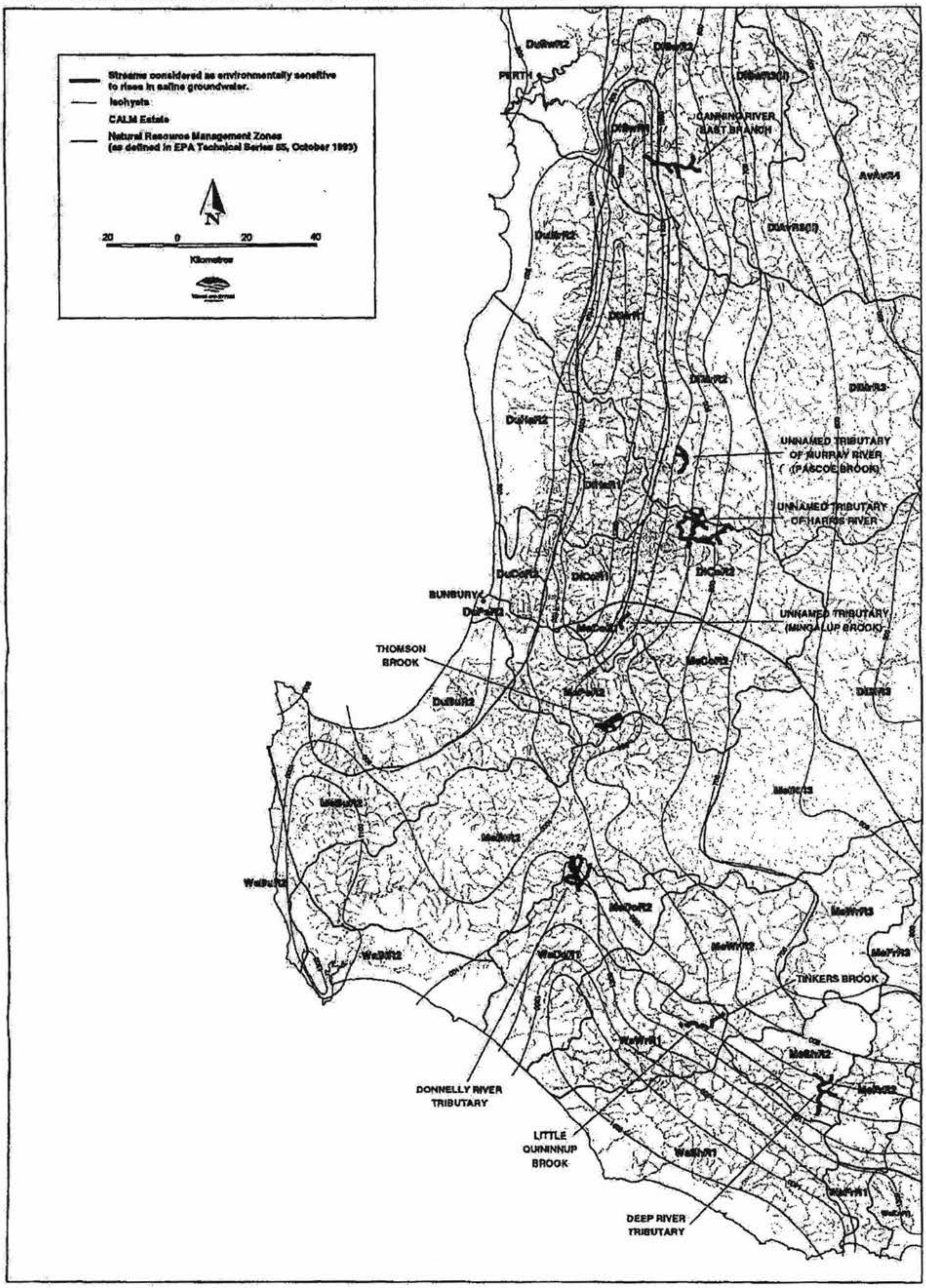
Date: 19.12.97

Roger Payne

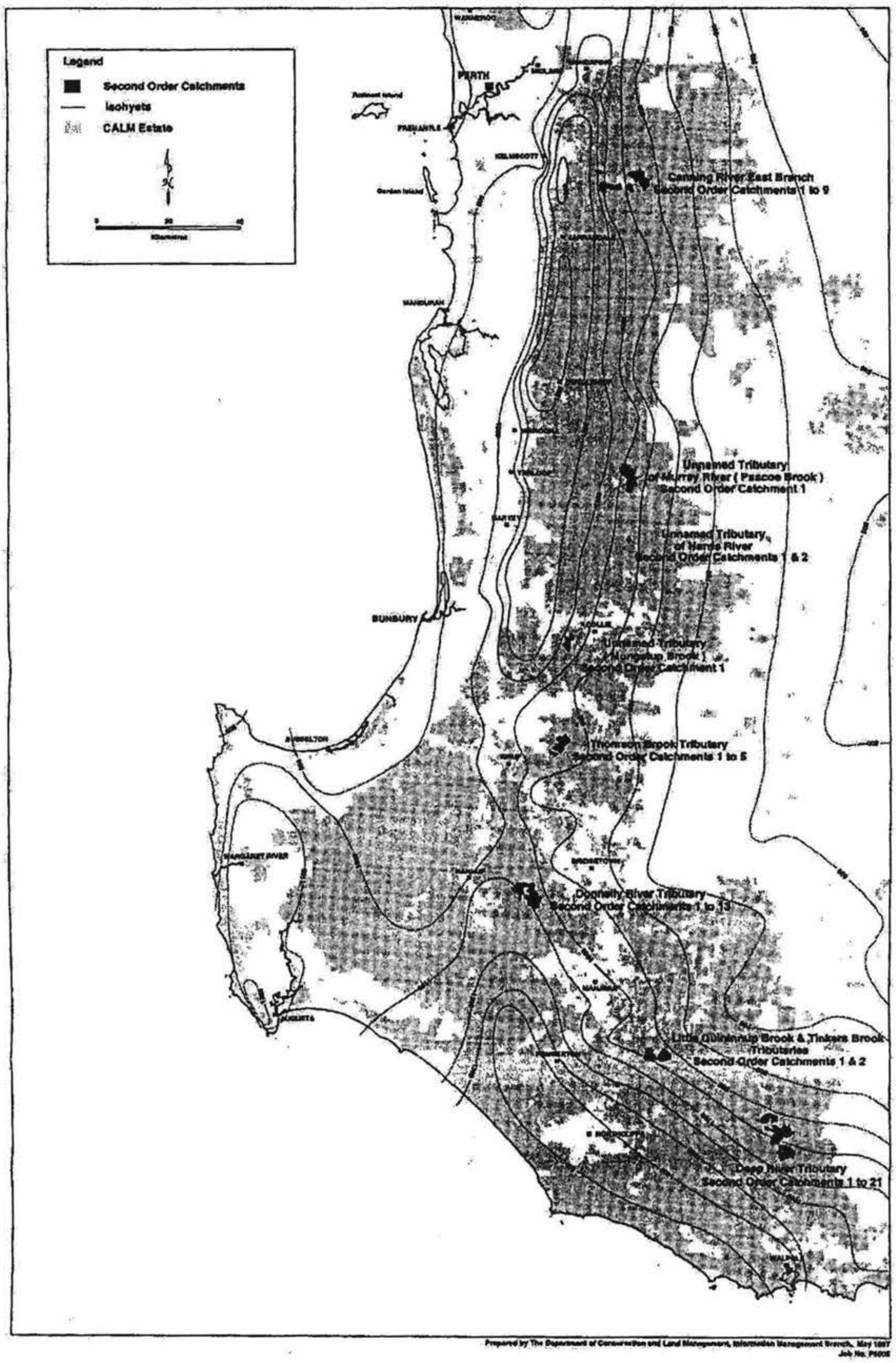
Roger Payne
CHIEF EXECUTIVE OFFICER
Water and Rivers Commission

Date: 18.12.97

Map 1 : Streams considered as environmentally sensitive to rises in saline groundwater.

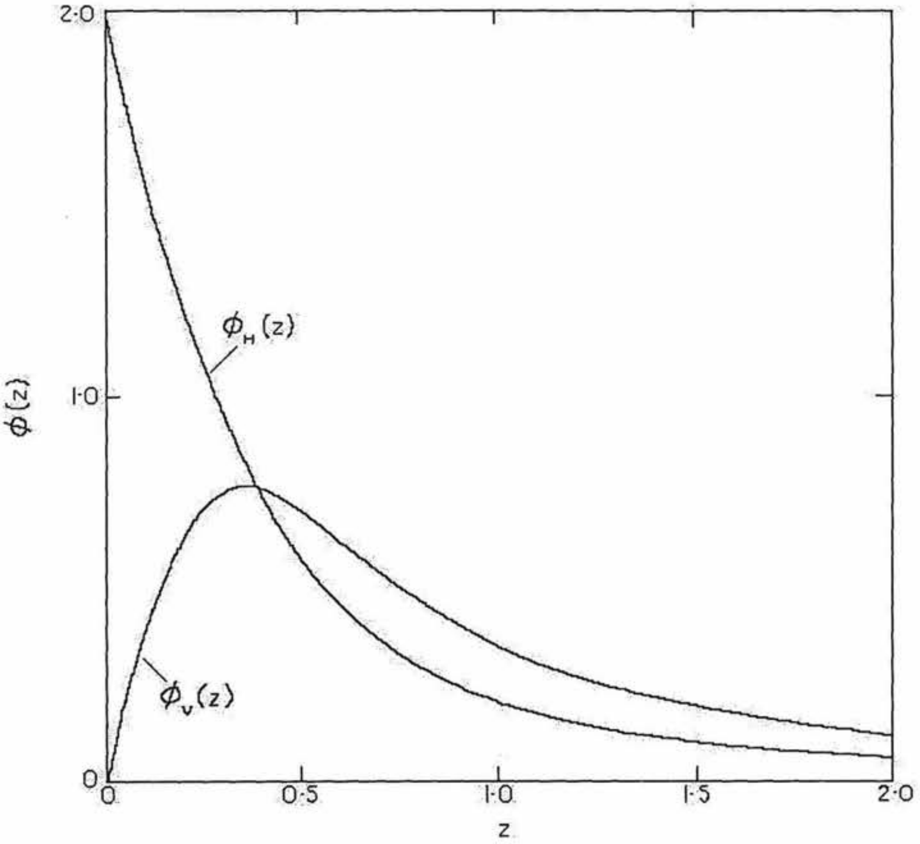


MAP 2 : SECOND ORDER CATCHMENTS OF STREAMS WHICH ARE ENVIRONMENTALLY SENSITIVE TO RISES IN SALINE GROUNDWATER

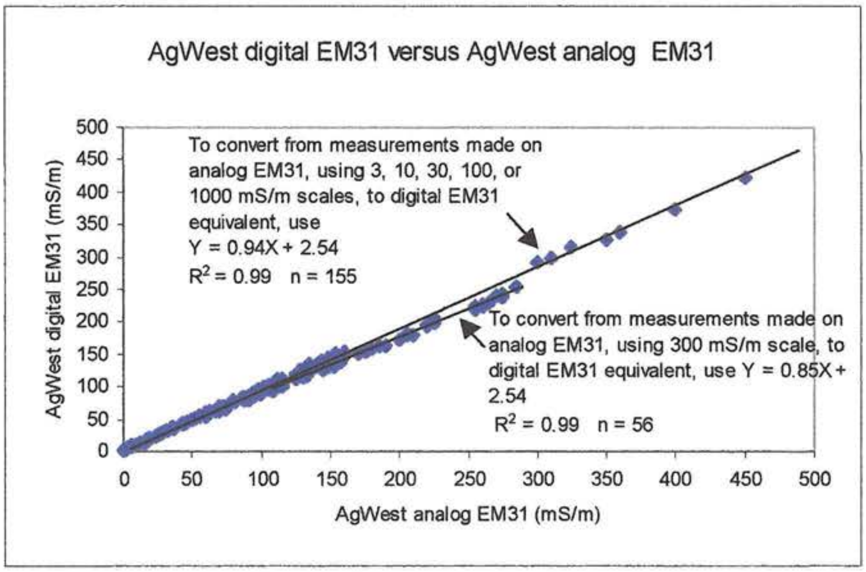


Prepared by The Department of Conservation and Land Management, Information Management Branch, May 1997
Job No. P6008

Appendix 2. Relative depth responses of EM31 vertical ($\emptyset_v$) and horizontal ($\emptyset_H$) dipoles, where z is the actual depth divided by 3.7m, the intercoil spacing (McNeill 1980).

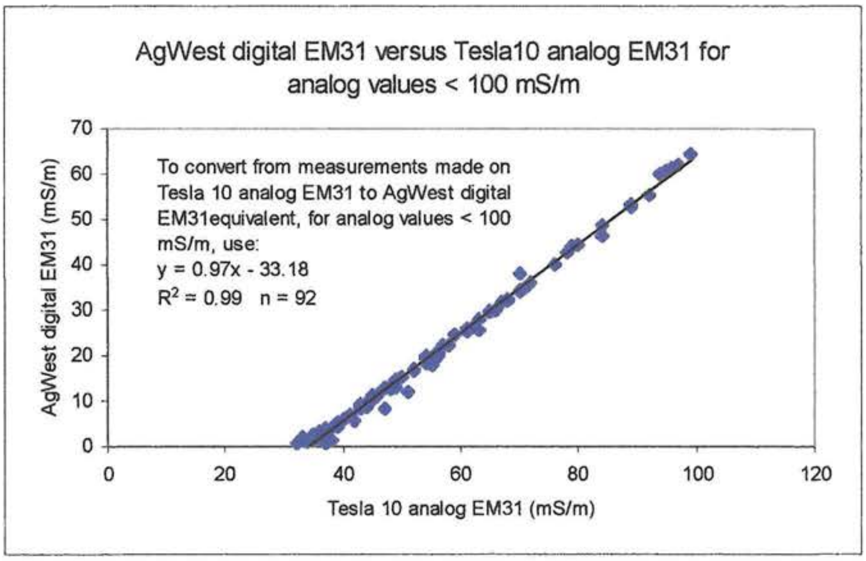


Appendix 3. Linear regressions used to convert analog EM31 values to equivalent digital EM31 values.

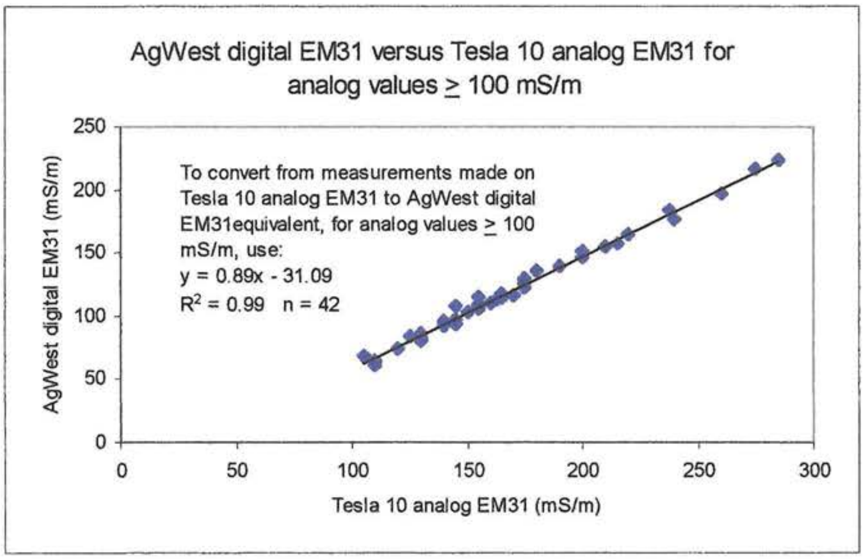

AgWest digital EM31 versus AgWest analog EM31

To convert from measurements made on analog EM31, using 3, 10, 30, 100, or 1000 mS/m scales, to digital EM31 equivalent, use
$Y = 0.94X + 2.54$
$R^2 = 0.99$ n = 155

To convert from measurements made on analog EM31, using 300 mS/m scale, to digital EM31 equivalent, use $Y = 0.85X + 2.54$
$R^2 = 0.99$ n = 56


AgWest digital EM31 versus Tesla10 analog EM31 for analog values < 100 mS/m

To convert from measurements made on Tesla 10 analog EM31 to AgWest digital EM31equivalent, for analog values < 100 mS/m, use:
$y = 0.97x - 33.18$
$R^2 = 0.99$ n = 92


AgWest digital EM31 versus Tesla 10 analog EM31 for analog values $\geq$ 100 mS/m

To convert from measurements made on Tesla 10 analog EM31 to AgWest digital EM31equivalent, for analog values $\geq$ 100 mS/m, use:
$y = 0.89x - 31.09$
$R^2 = 0.99$ n = 42

Appendix 4. Conversion from 2000 mg/L solute concentration to an equivalent ECa.

Conversion assuming mean values of soil particle density and bulk density

The regression equations shown in Table 2 enable measurements of ECa (mS/m) to be converted to an equivalent estimate of solute content (g/kg). To convert from g/kg to mS/m requires the inverse regression relationship, i.e. for EM31 in vertical mode at 0.8m:

Autumn: $\log_{10}(ECa) = 0.65*\log_{10}(TSS) + 1.63$ (1)

Spring : $\log_{10}(ECa) = 0.67*\log_{10}(TSS) + 1.73$ (2)

Converting from mg/L to kg/m^3 entails finding the mass (kg) of TSS in a m^3 of dry soil which, when it is saturated, will have a salt concentration of 2000 mg/L. The volume of the pore spaces (and hence water content when the soil is saturated) will vary according to the porosity of the soil, i.e. the size and distribution and packing of its particles (compare clay with sand for instance). Porosity is calculated from the formula (Marshall and Holmes 1979):

*Porosity% = (particle density – bulk density)/particle density * 100%*

However, soil bulk density and particle density vary spatially. Since it is impractical to measure bulk density and particle density for all possible soil types that may be encountered in the "environmentally sensitive" catchments it is necessary to assume average values for each,

i.e. *particle density =2.66 g/cm^3 and bulk density = 1.67 g/cm^3.*

Particle density (mean 2.66, standard deviation 0.06) is calculated from 95 cores, primarily from mottled, pallid and weathering zones at Collie CSIRO experimental catchments (Colin Johnston, pers. comm.). Bulk density (mean 1.67, standard deviation 0.22) is calculated from 427 subsamples from 78 cores at various depths down to 4m, in valley and lower slope sites, used in this calibration study
Substituting into the formula:
Porosity = (2.66 – 1.67)/2.66*100%
≈ 37%
∴ Soil at saturation holds 37% water
∴ 1 L soil holds 370ml water
If soil salt concentration is 2000 mg(TSS)/L(water)
Then 1L soil has 370/1000*2000 mg TSS
= 740 mg (TSS)/L(soil)
= $740*10^{-6}$ kg (TSS)/L(soil)
= $740*10^{-6}*10^{3}$ kg (TSS)/m^3 (soil)
i.e. saturated soil with solute concentration = 2000 mg/L TSS
has solute content = 0.74 kg/m^3 TSS.

To convert from kg/m^3 to g/kg salt per unit soil, divide by bulk density,

i.e. $0.74/1.67$

≈ 0.44 g/kg

Substituting 0.44 g/kg TSS into equations (1) and (2), gives

0.44 g/kg TSS $\approx$ 25 mS/m in Autumn with EM31 in vertical mode at 0.8m

and $\approx$ 31 mS/m in Spring with EM31 in vertical mode at 0.8m.

Sensitivity of conversion to soil particle density and bulk density variation

The sensitivity of the conversion from 2000 mg/L solute concentration to an equivalent ECa, to variation in porosity, was determined using values of particle density and bulk density which varied by one standard deviation from the mean. Using the same reasoning as above, the lowest and highest values of ECa when using an EM31 in vertical mode are

ECa $\approx$ 19 and $\approx$ 32 mS/m in Autumn

$\approx$ 23 and $\approx$ 40 mS/m in Spring.

Reference

Marshall, T.J. and Holmes, J.W. (1979) 'Soil Physics.' (Cambridge University Press, Melbourne)