Soluble salt content of the alluvial banks of a semi-arid tributary catchment of the Great Fish River

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Abstract

Soil samples were collected from a number of different channel bank locations within the Ecca catchment in the semi-arid eastern Cape Province, Republic of South Africa. At each location, samples were taken at different heights of the vertical bank section and at a series of horizontal depths into the banks. The electrical conductivity (EC) of the water-saturated extracts was used as an index of soluble salt content and the logarithmically transformed data subjected to analysis of variance. EC values were found to be variable and apart from a generalised increase with vertical depth, no spatial structure was evident. Possible causes of these results as well as their implications are discussed.

Introduction

The progressive downstream salination of water in the Great Fish River in South Africa is well documented locally (Tordiffe, 1978; Hall and Görgens, 1978) and much data on the salinity levels of the river are available. Most of these studies speculate on the effect of irrigation return flow on the salt content of the Great Fish River. Reynders *et al.* (1985) monitored the ground water level on one irrigation scheme and found that the fluctuations in the ground water level are strongly influenced by the irrigation practices. The results of the study furthermore stressed the effluent nature of the aquifers beneath the irrigated lands which is indicative of the effect of irrigation return flow on the Great Fish River's salt content. However, very little is known about the salt content of the non-irrigated areas of the Great Fish River. Moolman (1985) reports a mean electrical conductivity (EC) value of 106 $mS.m^{-1}$ for the saturation extracts of the 0 to 300 mm soil layer of a non-irrigated subcatchment within the lower Great Fish River basin. This latter study concentrated mainly on the spatial distribution of soluble salts in the soils of two hillslopes, but did not investigate the salt content of the river banks.

The salt content of channel runoff can be attributed to a number of possible processes. Due to saline seeps, or other causes, salt can accumulate in the surface layer of soils on, for instance, hillslopes. These salts could be removed by dissolution during slope runoff or by erosion of topsoil material. Saline ground water can also seep into the river channel. In semi-arid areas where pre-storm ground water levels are low, this source will only affect baseflow salinity values. A further possible source of salts in channel runoff is the accumulation of salts in the channel bed and alluvial banks and their subsequent removal into the channel runoff during events. Such accumulations could be caused by gradual downslope movement of saline subsurface flow or by bank absorption of river water during recession or baseflow conditions in the channel. Inevitably, the history of preceeding hydrological events (rainfall, streamflow and soil moisture movement characteristics) will determine the degree of accumulation. The characteristics of any single event will determine to what extent the accumulated salts are flushed out into the channel runoff.

The movement of water in channel beds and banks of ephemeral streams often results in the deposition of salts in the surface and near surface layers of the river bank (Rao *et al.*, 1984). In some cases highly soluble salt efflorescence crusts may also form. In the event of a storm the river bank will thus act both as a quick and slow releasing reservoir of soluble salts to the river. However, the extent to which the salt supply capacity of river banks changes with time has not been studied locally. The present study was originally designed to form the first of a series of surveys to assess temporal changes in the soluble salt content of the alluvial banks of the study area. Any temporal changes in salt content should be related to the characteristics of hydrological events and how these affect the movement and re-distribution of soil moisture between successive surveys. However, the success of such a study depends to a large extent upon our ability to describe the spatial variability of salt content from the small scale (in one bank section) to the large scale (over the catchment). Such a description must be achievable on the basis of a sampling design that is practicable. This paper reports on the results of a survey of alluvial bank salt content and discusses some of the implications of these results.

Study area

The study area is located in the eastern Cape Province of the Republic of South Africa and consists of six nested catchments covering an area of 73 km² and drained by the Ecca River and its tributaries (Fig. 1). The majority of the catchment is underlain by interbedded shales and greywackes. The dip is approximately 40°N in the south and progressively decreases to the north. The general strike is west/northwest to east/southeast. The southern watershed (higher parts of catchment E) is underlain by more resistant quartzites and tillites.

The main drainage pattern follows the strike of the rock formation, while the major tributaries are within highly incised valleys at right angles to the strike. Total basin relief is approximately 570 m and the soils are thin and rocky on the hilltops and steeper slopes, with deeper alluvial and colluvial deposits irregularly spaced within the valley bottoms. The alluvial soils within the Ecca catchment are not continuous. They occur as isolated areas, often on only one side of the channel, and separated from each other by stretches of thin non-alluvial soils developed directly on bedrock. Consequently, the major channels pass through relatively permeable alluvium alternating with areas where relatively impermeable bedrock forms the bed and banks. The valley bottom width of the alluvium varies from a few metres to approximately 100 m. The soils forming the alluvial

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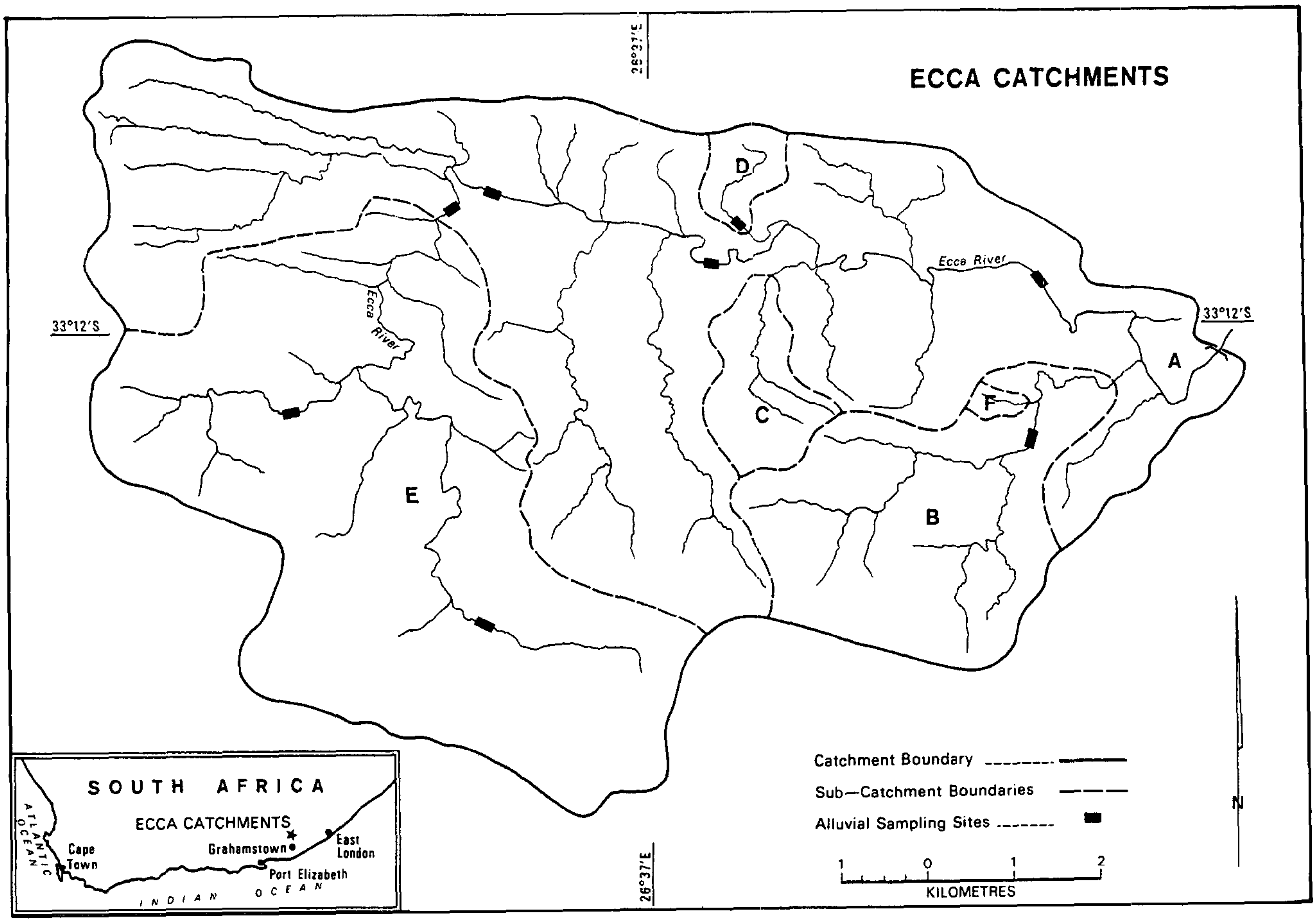

Figure 1
The Ecca catchments showing the major drainage pattern and the location of the sample sites. The letters refer to gauged subcatchments.

river banks vary in depth from shallow to approximately 2 m. They are classified as red soils of the Shorrocks series according to the South African Binomial System (MacVicar *et al.*, 1977).

Vegetation consists of succulent and subsucculent bush with a high proportion of bare ground, while land use is confined to small livestock farming with a complete absence of ground cultivation and irrigation. Much of this information on the characteristics of the Ecca catchments has been drawn from two reports (Roberts, 1978 and Görgens, 1983).

The catchments are in a semi-arid region and all the streams are ephemeral. Mean annual rainfall (1975 to 1984) is 423 mm and falls as either short duration, high intensity convective rain during the summer months or as longer duration and lower intensity frontal or advective rain predominantly in the cooler months. Mean annual A-pan evaporation for the same period was 1 846 mm while mean annual runoff depth amounted to 17 mm (4% of rainfall). Long periods of zero flow can be experienced as was the case for 10 months in 1982 and 14 months in 1984/5. The soil samples were collected in November/December 1984, while the last previous flow event occurred in July/August 1983.

Sampling procedure

The alluvial deposits within the Ecca catchment have been described above as discontinuous and with highly variable depths. It was therefore difficult to conceive of a satisfactory sampling procedure based upon some form of grid. The sampling procedure used was designed to obtain a reasonable distribution of sample sites from the alluvial areas as well as a sufficient number of samples from each site to assess the local variation in the soluble salt content of the soils. What may be considered "reasonable" or "sufficient" is extremely difficult to determine without prior knowledge of the variation, and realistically the number of samples taken is in part dependent upon the amount of time available for collection and analysis. The time between collecting samples from different sites is necessarily limited because a rainstorm occurring during the collection period that affected moisture levels or movement within the soil may invalidate comparison of samples. Eight channel reaches were chosen and between three and five vertical sections evenly spaced throughout each reach sampled. Not all the subcatchments within the study area have alluvial banks that are well defined enough to be sampled. Only catchments A, B, D and E were sampled (Fig. 1) but the eight reaches represent the main areas of alluvial soils within the total catchment area. Where possible top, middle and bottom bank positions were sampled. However, if the bank height was below about 1 m no middle points were selected and when the bank was very low (less than 0,2 m) only a bottom position was sampled.

At each position in the vertical bank profile, samples were taken 0 to 20 mm, 20 to 150 mm, 150 to 300 mm and 300 to 600 mm horizontally into the bank using a bucket auger. Altogether 152 samples were obtained and grouped according to three categories: catchment location, bank position, and depth into the bank. No bottom samples were taken from catchment E as the alluvial soil did not extend down into channel bottom position. The material in the bottom of these banks is coarse alluvial or colluvial sediment that could not be sampled with the bucket auger.

In the laboratory, the samples were crushed and sieved to remove all material greater than 2 mm and a saturation extract obtained from the remaining fraction according to the techniques of Longenecker and Lyerly (1964). With this technique a soil sample becomes saturated through capillary rise of water into the soil. The amount of water uptake, and consequently the saturation percentage, is therefore primarily a function of soil texture. Electrical conductivities were measured and used as an index to estimate the soluble salt content of each sample.

Statistical analysis

Initially, the complete data set as well as the data for each category (catchments, bank positions and depths) were analysed to determine their frequency distribution characteristics. The raw EC values are highly skewed as is clearly demonstrated in Figure 2, which shows the frequency distribution of all the data. This observation is consistent with often reached conclusions about the distribution characteristics of soil parameters (Nielsen, *et al.*, 1973; Moolman, 1985). The distribution of natural logarithm (Ln)-transformed values is also given in Figure 2. Although not exactly Normal, the transformation has removed the severe skewness. The arithmetic mean of the raw EC values is 615 $mS.m^{-1}$ while the back-transformed mean of the Ln (EC) values is 387 $mS.m^{-1}$. The subdata sets for each category follow the same pattern and the subsequent analysis of variance was therefore confined to the Ln values.

In order to convert the EC values of the saturation extracts to more meaningful values in terms of potential salt supply from the banks, a correction was applied to account for the amount of coarse material in each sample as well as the water content of the saturation pastes (saturation percentage). The following procedure was used (Richards, 1954) to estimate values for an index of the percentage salt in the soil:

Pss = (Psw * Pw)/100
where Pss = Percentage salt in the soil ($g.\ 100g^{-1}$)
Psw = Percentage salt in water = (EC * 6.4)/10 000
Pw = Percentage water in soil corrected for coarse content
= (1 − fraction of material > 2 mm) * saturation percentage content of material < 2 mm)

The distribution analysis and analysis of variance was repeated using the Pss variable. Again, a natural log transformation reduced the high degree of positive skewness in the raw data.

Results

A number of authors (for example Nielsen *et al.*, 1973; Wagenet and Jurinak, 1978 and Moolman, 1985) have referred to the skewed nature of the distribution of measured soil properties. They have drawn attention to the difficulties of using the arithmetic means of such data and recommend a natural logarithmic transformation and the use of the "true" mean (also referred to as the geometric mean) back-transformed from the mean of the Ln values. The data presented here are no exception as Figure 2 illustrates and consequently the results are based upon transformed values throughout.

The true means of the EC values are given in Table 1 for the different sampling categories according to catchment location, vertical bank position and horizontal depth into the bank. These values indicate that differences may exist between catchments as well as between bank positions but not between horizontal depth location. However, Table 1 does not include any figures to express the variation within each sampling category. The range of values within each catchment defined by one standard deviation either side of the mean (using back-transformed Ln values) is A, 162 to 1 265; B, 305 to 1 806; D, 122 to 652 and E, 94 to 893. None of the true means are significantly different from each other at the 1% level although B for example is significantly different (higher) from D and E at the 5% level. A more complete impression is given in the first part of Table 2 (electrical conductivity), which presents the results of an analysis of variance test. Differences between catchments are still evident but only the trend of increasing EC with vertical bank position is statistically significant at the 1% level.

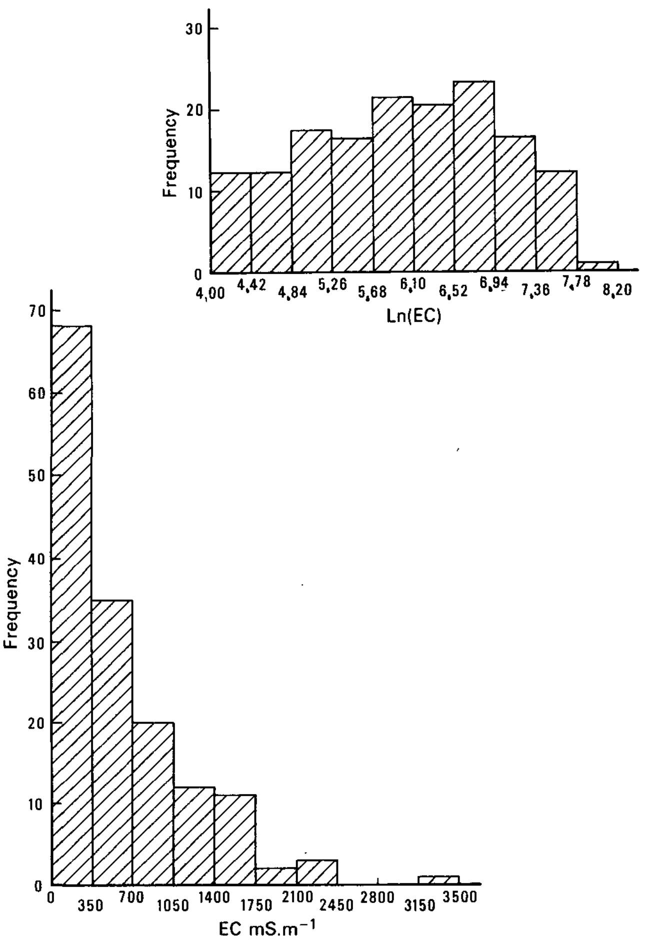

Figure 2
Frequency histograms for the complete data set (a) Raw values (b) Ln transformed values.

TABLE 1
MEAN VALUES FOR THE DIFFERENT SAMPLING CATEGORIES: VALUES FOR EC AND SATURATION PERCENTAGE OF THE SOIL

Sampling category	Category codes (Key below) 1	2	3	4
EC (true means back-transformed from Ln values) $mS.m^{-1}$				
Catchment	469(83)	742(5)	281(34)	290(30)
Bank position	290(52)	428(54)	478(46)	
Horizontal depth	369(43)	407(40)	388(38)	388(31)
Population mean	388(152)			
Saturation percentage of the soil (Pw)				
Catchment	28(83)	33(5)	27(34)	35(30)
Bank position	30(52)	31(54)	27(46)	
Horizontal depth	31(43)	29(40)	29(38)	27(31)
Population mean	29(152)			

Key to category codes:

Catchments	1 = A	, 2 = B	, 3 = D	, 4 = E
Bank positions	1 = Top	, 2 = Middle	, 3 = Bottom	
Horizontal depths (mm)	1 = 0-20	, 2 = 20-150	, 3 = 150-300	, 4 = 300-600

Sample sizes are given in brackets.

TABLE 2
RESULTS OF ANALYSIS OF VARIANCE BETWEEN THE THREE SAMPLING CATEGORIES USING TRANSFORMED DATA: VALUES FOR EC AND PERCENTAGE SALT IN THE SOIL

Electrical conductivity ($mS.m^{-1}$)

Category	Sum of squares	DF	Mean square	F
Catchment	11,13	3	3,71	3,47
Bank position	10,77	2	5,39	5,04*
Horizontal depth	0,44	3	0,15	0,14
Residual	125,09	117	1,07	

Percentage salt in the soil ($g.100g^{-1}$)

Category	Sum of squares	DF	Mean square	F
Catchment	13,04	3	2,89	2,30
Bank position	9,95	2	4,34	3,46
Horizontal depth	0,10	3	4,97	3,97
Residual	146,76	117	1,25	

* Significant at the 1% level or better

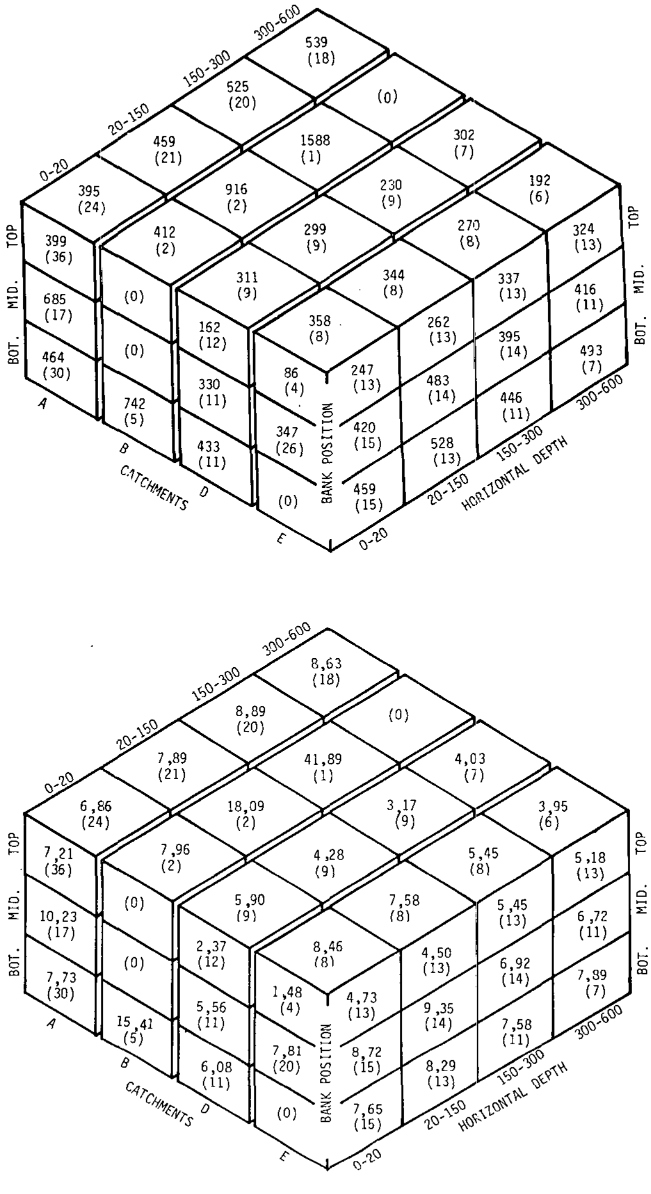

Figure 3

Matrix diagrams of two-way comparisons of true means between category pairs (bracketed values are sample sizes) for EC ($mS.m^{-1}$) and percentage salt ($*10^2$) in the soil ($g. 100g^{-1}$).

Figure 3a (top) is an attempt to further illustrate the difference between categories. Each face of the cube (left, right and top) represents a pairwise comparison within two of the categories (catchment with position, depth with position and catchment with depth) regardless of the third category. The values given are the means for the category pairs; for example the mean value of 30 samples taken from catchment A for all bottom bank positions irrespective of depth into the bank is 464 $mS.m^{-1}$ (extreme bottom left of left face) and for 8 samples taken from catchment E at 0 to 20 into the bank irrespective of bank position is 358 $mS.m^{-1}$ (extreme bottom right of top face).

The right hand face of the cube shows that there is a consistant trend of increasing EC down the bank for all horizotal depth positions, regardless of catchment. This trend is repeated in the bank position – catchment comparison (left face of cube) although the middle bank EC's for catchment A are higher than the bottom bank EC's. The pattern of values on the upper surface, showing depth – catchment comparisons (for all bank positions) has no structure, suggesting that surface salt accumulation is not a widespread phenomenon in these catchments.

The lower part of Table 2 presents the analysis of variance results for the Pss (percentage salt in soil) variable and it is clear from the F values that no statistically significant trends are present in the data. Figure 3b represents the same type of two-way comparisons as Figure 3a but using the Pss data. The left and right faces of the cube indicate that the top bank positions still have lower values, but in some cases the mid-bank position is now higher than the bottom. It is assumed that, in disturbed soil samples, the saturation percentage (Pw) is effectively a correction factor for soil texture (coarser material tends to have lower Pw values), Figure 3b illustrates that Pss values are still lower for top bank positions than bottom, despite the lower percentage water values in the bottom (Table 1). The conclusion that lower concentrations of soluble salts reside in the upper layers is therefore strengthened.

Discussion and conclusions

The results of this study confirm the highly variable nature of the soluble salt content in natural catchments previously reported by Wagenet and Jurinak (1978) and Moolman (1985). This high variability was found both on the micro-scale, i.e. samples within a few metres of each other, as well as the macro-scale, i.e. samples taken in different subcatchments or river reaches. The variable nature of the data collected from this undisturbed (i.e. uncultivated) catchment, suggests that the movement of water and salt into and out of the river banks is very localised. This localised movement might be due to the presence of preferential flowpaths. It could be argued that if a geostatistical sampling approach (Vieira *et al.*, 1981) had been used, more information about the spatial structure of the soluble salt content of the banks of the Ecca River could have been obtained. A previous soluble salt survey (Moolman, 1985) conducted on the valley sides of a 28 ha subcatchment of the Ecca River, in which samples were collected on a 25 to 50 m grid basis, failed to show spatial structure in the data in a sampling direction which ran parallel to the river channel. It is thus concluded that the application of geostatistics to the 73 km^2 Ecca catchment would be a wasteful exercise, as an impracticably large number of samples would have to be collected for such an analysis. In addition, the area of interest for this study was restricted to the alluvial zones adjacent to the channel and their discontinuous nature precludes the application of geostatistics.

Surface salt accumulation on the banks of the Ecca River does not appear to be a widespread phenomenon; a result that is contrary to expectations, as the stream is ephemeral and crosses salt bearing Ecca shale and greywacke deposits. The general absence of salt efflorescence on the river bank, as well as the increase in salt content with depth down the bank, might be related to the two types of rainstorms which prevail in this catchment. The high intensity convective storms seldom have total rainfall depths geater than 20 to 30 mm per event and because of the steep slopes of the catchment, often give rise to short duration runoff events. These events are mostly attributed to overland flow. Field observations (data not presented here) have shown that during such storms, the soil is seldom wetted deeper than 100 to 150 mm, indicating minimal infiltration of rainfall. Vertical displacement of soluble salt to the deeper soil layers is therefore also restricted. The extensive rill and gully system on the hillslopes of the Ecca catchment generally terminates in the stream channel itself, which suggests that the overland flow generated on the upslope areas does not infiltrate into the channel banks, It is thus likely, and has been observed, that during high intensity convective storms, streamflow can take place in the presence of relatively dry river banks. According to the results of Rao *et al.* (1984) such a condition is not favourable for the formation of salt crusts on the surface of the river banks.

Field observations have also shown that the type of low intensity advective rainfall common in the study area results in limited vertical wetting of the soil. The field capacity of the soils in the Ecca catchment varies between 0,145 and 0,235 m^3 .m^{-3}. As is common in semi-arid catchments where evapotranspiration exceeds rainfall, the soil water content of the Ecca is usually very low (except for short periods following major rainstorms). It can therefore be concluded that a considerable amount of low intensity rain is necessary for subsurface flow to occur. The absence of lateral subsurface flow again emphasises that climatic conditions in the Ecca catchment do not favour the widespread formation of salt crusts on the river banks. This does not preclude the possibility of salt crusting subsequent to prolonged rainfall which gives rise to extreme soil wetting. The results of this study suggest, however, that such crusting is not a permanent feature.

From the previous discussion it follows that the movement of water and salt, though limited, will be in a predominantly vertical direction down the river bank. The presence of coarse material at the bottom bank position means that redistribution of salt and water due to capillary action is restricted. Soluble salts will therefore tend to accumulate and remain at the bottom of the bank, as is suggested by the data in Figure 3.

The overriding conclusion of this study is that the present knowledge of the salt transporting mechanisms in this semi-arid catchment is still limited. This can be illustrated by comparing the so-called readily available and easily transportable salt content present in the alluvial banks of the Ecca River, with the 1 712 t of salt removed from the catchment during a 9 day continuous streamflow event recorded at catchment A. This figure has been estimated from samples taken at irregular intervals during the event and can be approximately divided up into 1 000 to 1 200 t during storm runoff (several peaks over 3 days) and 500 to 700 t during baseflow runoff. Assuming a total alluvial bank length of 40 km, a mean bank height of 1 m, and a soil bulk density of 1 400 kg. m^{-3}, it can be calculated that the mean salt content of all the samples used in this study represents about 20 t of salt in the 0 to 0,6 m horizontal bank depth. This estimate, although rough, is nevertheless two orders of magnitude less than the streamflow salt load mentioned above. The remaining proportion of the total salt load must therefore originate from the outlying areas, i.e. further away from the channel.

The absence of generally occurring salt efflorescence, as well as the variability of the horizontal depth distribution of salt into the bank found in this study, indicate that the role of the river bank as conduits for water and salt is still poorly understood, especially in semi-arid catchments. The high variability of soil soluble salt content at the micro-scale, indicates that a repeat survey at a future date would be inconclusive in terms of an assessment of temporal change.

Acknowledgements

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