THE EFFECT OF SOIL SALINITY AND SODICITY ON SOIL ERODIBILITY, SEDIMENT TRANSPORT AND DOWNSTREAM WATER QUALITY

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Abstract
There is an abundance of literature on many aspects of soil salinity and sodicity, and the impact of increased salt and sodium on properties, behaviour, management and productivity of soils. However the impact of sodicity on erosion and soil erodibility and sediment transport has received less attention. The aim of this study was to investigate the effects of changing soil salinity and sodicity of two Queensland soils on their erodibilities and erosion losses under simulated rainfall. Erosion measurements were carried out on the two soils in the 1 x 6 m flume of Griffith University's large rainfall simulation facility (GUTSR), with and without sodium treatments. Sediment loss increased for both sodium-treated soils with the Redlands soil showing an eight-fold increase. Mean aggregate/particle size of the eroded sediment decreased with increased sodicity. High sodium concentration thus contributed to the weakening of soil aggregates and their dispersion under the raindrop impact. Electrical conductivity and salt concentration of the runoff decreased exponentially with time from sodium-treated soils.

Additional Keywords: erosion dispersion, sodicity, cation loss, sediment loss, sodic wash

Introduction
Salinization of land and water resources is a major land degradation issue in Australia (Webb 2002). Increased salinity has occurred primarily as a result of anthropogenic land use and includes both dryland and irrigation salinity. About 5.7 million hectares currently lie within regions at risk, or are affected by dryland salinity (Australian State of the Environment Committee 2001), and up to 20 000 km of streams could be significantly salt affected by 2050 (Webb 2002). The deleterious effects of sodium on soil structure, dispersion and hydraulic properties are well recognized and high sodium levels have been linked to increased erosion and runoff. Most field-based studies on erosion from sodic soils have been carried out in the USA, Israel and Southern Europe (Schmittner and Giresse 1999; Evett and Dutt 1985) while laboratory rainfall simulators have been used in a number of countries to examine the effects of rainfall parameters, soil type, polymer cover and water quality on infiltration, conductivity and runoff (Mamedov *et al*. 2000; Levy *et al*.1993 and 1994;Agassi *et al*,1981 and 1994 and others). However, there is little specific information, particularly in Australia, about the effect of sodium on soil erodibility and the subsequent relationship with salt/sediment loss in the runoff and the effect of these losses on the remaining soil and on the soils of low laying regions where deposition takes place. This study therefore aims to provide some data about soil erodibility, sediment loss and quality of runoff water from two Australian soils of contrasting physical and chemical characteristics, due to changing sodicity in the soils. Further studies are underway and it is anticipated that these data will be used for modeling purposes in conjunction with other hydrological studies on salt movement in the landscape.

Materials and Methods
Two soils of contrasting physical and chemical properties were used for this study; a Krasnozem (red clay) from Redlands Bay Research Station and a brown loamy sand soil from the Toohey Forest area of Griffith University (Nathan Campus). Some physical and chemical properties of the two soils used in these experiments are given in Table 1.

Analyses of soils

Surface soils (1-20 cm) were used for this study. Basic chemical and physical properties were determined on sieved soil (<2 mm). Soil particle size distribution and textural classes were determined by the hydrometer method. Soil pHs and electrical conductivities (EC) were measured at a 1: 5 ratio using a TPS meters. Cation exchange capacities (CEC) and exchangeable cations were determined using the ammonium acetate extraction method (Rayment and Higgenson 1992). Indices of dispersion were measured on the soils using an adaptation of Middleton’s dispersion ratio (So and Cook 1993).

Table 1. Analytical data for the two soils used in the experiments

Property	Redlands	Toohey
Sand (2.00-0.02 mm) (g /kg)	360	730
Silt (0.02- 0.002 mm) (g /kg)	210	100
Clay (<0.002 mm) (g /kg)	430	170
Soil textural class	Clay	Loamy Sand
1:5 pH in $CaCl_2$	5.3	5.2
Electrical conductivity (dS/m)	0.064	0.051
Dispersion ratio D_{Si+C}	0.189	0.765
Dispersion ratio D_C	0.176	0.444
Cation Exchange Capacity ($cmoles_+$ /kg)	15.7	9.7
Exchangeable Ca ($cmoles_+$ /kg)	8.7	5.8
Exchangeable Mg ($cmoles_+$ /kg)	6.5	3.6
Exchangeable Na ($cmoles_+$ /kg)	0.2	0.2
Exchangeable K ($cmoles_+$ /kg)	0.1	0.1
Exchangeable Sodium Percentage	1.3	2.0

Measurements in Griffith University Tilting-Flume Simulated Rainfall Facility

A series of experiments using simulated rainfall were carried out on the soils in the GUTSR. A 80 mm bed of soil (unsieved) was prepared in the 1 by 6 m flume of the GUTSR and 100 mm/hr rainfall (average drop diameter 2.2 mm) applied from nozzles 9 m above the soil surface. Further details on GUTSR are provided in Ghadiri and Rose (1993). The initial run for each soil was performed on saturated soil (using tap water to saturate for 24-48 hr) and the second run was performed after the soil had been saturated for 24-48 hours with a sodic solution (SAR 100 mmoles ^{½} /l ^{½}; C 125 $mmoles_+$ /l). Rainfall consisted of city water (average cation concentrations Ca^{2+}, Mg^{2+}, K^+ and Na^+ of 19, 12, 3 and 32 mg/l respectively).

Collection of runoff and sediment samples from flume

For each flume run, the slope was initially set to 1% and, just before starting the rain, a small composite soil sample (0-2 cm) was taken from five different places in the flume for chemical analysis. Rainfall was then applied and runoff sample collection commenced within 1-2 minutes of the start of rainfall (as soon as the entire flume contributed to the surface runoff). Sets of four 500 ml runoff samples were collected at times of 1, 3, 5 and 7 (or 2, 4, 6 and 8) minutes respectively, after the commencement of runoff, and later analyzed for:

1. sediment load (g/l),
2. chemical analysis (Soluble Ca, Mg, K, Na; pH, EC, Total Dissolved Solids),
3. aggregate/ particle size distribution by wet sieving using 2.0; 1.0; 0.5 and 0.25 mm sieves (Kemper and Rosenau 1986)
4. aggregate/ particle size distribution of <0.5 mm size by the Malvern Mastersizer (Model MSS).

A bulk runoff sample was also collected in a 10 litre bucket and time measured with a stop watch (usually 40- 60 s) at the end of each run and then converted into units of mm/hr. Immediately after collection of the bulk sample rainfall was ceased and a further surface soil sample taken. The same procedure was followed for 3%, and 5%, slopes and the sampling process repeated. Soils were analyzed for exchangeable and soluble cations (Ca, Mg, K, Na) using the ammonium acetate/saturation paste extract methods respectively (Rayment and Higgenson 1992).

Results and Discussion

The different runs on the GUTSR for Toohey and Redland soils (without salt, in natural chemical state) and Toohey and Redland soils (saturated with SAR 100, C 125 Solution) will hereafter be referred to as Toohey 1, Redland 1, Toohey 2 and Redland 2, respectively

Total runoff and sediment load

Runoff rate was primarily determined by the rainfall rate (~100 mm/hr) as the soil was saturated at the start of the experiment but it was also measured using the time taken to fill up the composite sample and its volume. Runoff was slightly higher for the Toohey compared to the Redlands soil (Table 2). Differences in runoff rates could be due to a higher infiltration rate in the Redlands soil or to variations in the applied rainfall rate.

Table 2. Mean runoff rates (mm/hr) for soils in the GUTSR at ~100 mm/hr rainfall

Soil Treatment	<--------------------Slope %-------------------->			Mean by Treatment (std dev)
	1	3	5	
Toohey 1	101.8	111.1	117.2	110.1 (8.0)
Toohey 2	116.0	117.2	108.6	114.1(49)
Redlands 1	97.3	86.2	88.1	90.5 (5.9)
Redlands 2	93.5	100.7	94.9	96.4 (3.8)

Sediment loads from the natural Toohey soil were significantly higher ($p<0.01$) than from the natural and salt-treated Redlands soils (Table 3) due to the lower aggregate stability and higher dispersion ratios of the Toohey soil (Table 1). With the addition of high levels of sodium, sediment loads increased for both soils and the Redlands soil showing a significant increase in load at all slopes ($p<0.01$). The large increase in sediment loss from the sodium-treated soils indicates that the aggregate stability has been greatly decreased due to chemical dispersion. Sediment loads were similar for the 1 and 3% slopes on both soils but tended to increase at 5% slope. (Table 3). The marked increase in sediment loads for the salt-treated soils at 5% slope could be related to a decrease in EC which in the presence of moderate SAR results in greater dispersion and soil loss. This will be explored in more detail later in the paper.

Table 3. Normalized sediment loads in g/l for soils in the GUTSR at 100 mm/hr rainfall

Soil Treatment	<--------------------Slope %-------------------->			Mean by Treatment (std dev)
	1	3	5	
Toohey 1	19.9	18.4	24.7	21.0 (5.4)
Toohey 2	19.9	20.2	35.1	25.0 (8.8)
Redlands 1	2.0	1.6	1.8	1.8 (0.4)
Redlands 2	7.9	8.5	21.1	12.5 (6.5)

The sodicity-induced erosion could have serious field implications. To give an example of this potentially increased erosion (Table 4), meaned sediment loads for the different treatments were converted into soil losses (ton/ha.yr) using 50 mm of runoff (e.g. 500 mm/yr annual rainfall with 10% runoff). Increased sodicity in the soils could result in a ~20 % (+2.0 ton/ha) increase in soil loss for the Toohey soil and a 600 % (+5.4 ton/ha) increase for the Redlands soil under these experimental conditions.

Table 4. Potential soil loss with 50 mm runoff (at 100 mm/hr rainfall)

Soil Treatment	Runoff (g/l)	Runoff (ton/ha.yr)	Increased soil loss due to added salts (ton/ha)
Toohey 1	21.0	10.5	**2.0**
Toohey 2	25.0	12.5	
Redlands 1	1.8	0.9	**5.4**
Redlands 2	12.5	6.3	

Size distribution of aggregates/particles in runoff sediment

There were a significantly larger ($p<0.01$) proportion of > 2.00 mm aggregates/particles in the runoff from the Redlands soil, compared to the Toohey soil for both the respective no-salt and salted soils (Table 5). This is to be expected due to the greater degree of aggregation in the Redlands soil as a result of its higher clay and iron content. The sodium treatment reduced the percentage of >2 mm aggregates for both soils indicating that there was some chemical breakdown of the aggregates with addition of sodium, although there were large variability in the data. Similarly the mean weight diameter (MWD) decreased with the addition of sodium, indicating a greater proportion of fine material in the runoff. Increased fine material in the runoff as a result of sodicity could contribute to increased pollution of waterways as fine material has the ability to carry sorbed pollutants such as pesticides and remain in suspension longer (Ghadiri and Rose 1993).

Table 5. Aggregate size distribution of sediment as determined by wet sieving

Soil Treatment	% of sediment >2 mm in size	Mean weight diameter of sediment (mm)
Toohey 1	4.81	0.524
Toohey 2	3.90	0.495
Redlands 1	29.36	1.165
Redlands 2	22.04	1.067

The size-distribution of finer aggregates/particles in the sediment (<0.5 mm) was investigated using the Mastersizer analyses (Table 6). The sediment in the runoff from the Redlands soil had much larger volume weighted mean diameters and modes than the Toohey soil indicating larger particle/aggregate sizes. This concurs with the increased proportion of larger aggregates in the Redlands soil from the wet sieving determinations (Table 5). The addition of sodium significantly decreased the mode (the most likely size of particles) for the Toohey soil ($p<0.01$) but otherwise caused no significant changes in the other size parameters (Table 6). Addition of sodium to the Redlands soil also decreased the mode but increased the volume weighted mean diameter and uniformity ($p<0.01$). This indicates that the <0.5 mm sediment from the salt-treated Redlands soil had a broader range of particle sizes with an increased mean diameter overall.

Table 6. Summary data from Mastersizer analysis of <0.5 mm sediment in runoff water

Soil Treatment	Volume weighted mean diameter in µm	Mode (Most likely size) in µm	Uniformity# of distribution curve
Toohey1	20.07	7.77	2.25
Toohey2	18.01	6.98	2.15
Redlands 1	24.60	31.50	1.97
Redlands 2	42.42	11.58	3.27

uniformity = description of the deviation from the median diameter

Chemical analyses of runoff

1. Electrical conductivity and pH

For the Toohey and Redland natural soils, EC of the runoff waters remained fairly static throughout the rainfall event at around 0.470 and 0.400 dS/m respectively. With the sodium-saturated soils however, there was an exponential decrease in EC as rainfall progressed for both soils (Figure 1), which leveled off after 7-8 minutes of rainfall. Continued rainfall at greater slopes further decreased the EC , but at slower rates, for both soils. Runoff from the Toohey soil showed a much larger decrease in EC (~6.5 dS/m) than the Redlands soil (~3.00 dS/m) over the 3 rainfall events, indicating a faster loss of salts in runoff water. This is probably due to the greater macroporosity and lower clay content in the Toohey soil which allowed faster flushing of added salts. Power curves fitted to the combined data indicated that the EC of the runoff water would reduce to that of the applied rainfall (EC= 0.355 dS/m for city water) after ~ 102 mm and 2080 mm at a rate of 100 mm/hr in the Toohey soil and Redlands soil respectively under these experimental conditions. This implies that the Redlands soil will require much more rainfall to flush out surface salts and reduce conductivity.

The pH of the runoff water from both soils generally increased slightly with slope and with addition of salts but the effective range of pH variation was very small, with mean values of 7.1-7.7 and 7.8-8.0 for the Toohey and Redland soils respectively.

2. Cations

With the natural soils, cation concentrations of runoff waters were low and did not vary greatly with rainfall duration or slope. Mean cation concentrations in runoff from the Toohey soil were 0.7, 2.5, 0.05 and 5.5 mg/l for Ca, Mg, K and Na respectively whilst in the Redlands soil they were for 18.9, 26.3, 0.3 and 22.5 mg/l respectively.

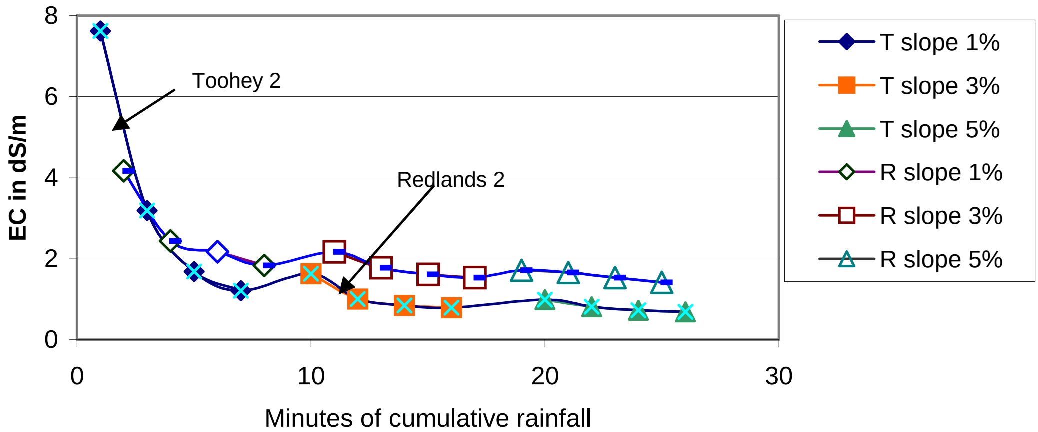

Figure 1. Merged data showing change in EC of runoff from Toohey 2 and Redlands 2 soils with cumulative rainfall at different slopes

However in the salt-treated soils, cation concentrations generally decreased exponentially with time during the first rainfall application at 1% slope, with most decrease occurring during the first five minutes of runoff. Thereafter concentrations decreased more linearly with time at increased slope. Examples of these decreases are shown for sodium in the Toohey 2 and Redlands 2 soils in Figure 2. Salt losses were considerably higher from the Toohey soil, especially in the case of sodium with runoff from the Toohey soil reducing from 859 to 76 mg/ l during the first rainfall event compared to 293 to 134 mg/l from the Redlands soil (Figure 2). Calcium losses from the Redland soil continued at higher slopes in contrast to the Toohey soil, where calcium levels remained almost constant. For both soils, cation concentrations of the runoff waters did not reduce to the original levels of the runoff from the natural soils even after the 3 rainfall events, indicating that further salt loss was likely under continued rainfall.

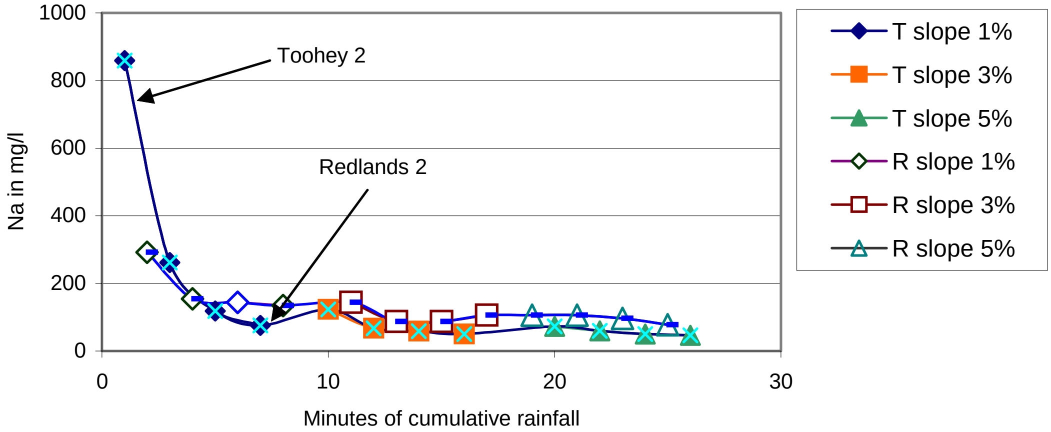

Figure 2. Merged data showing changes in Na concentration of runoff from Toohey 2 and Redlands 2 soils with cumulative rainfall at different slopes

To assess the cumulative cation loss, the data for the three slopes were merged and equations were fitted to the resultant curves. The curves indicate that losses of sodium from the salt-treated Toohey soil would be ~100 kg/ha in contrast to 1 kg/ha from the natural soil after 10 minutes of rainfall (at 100 mm/hr). This magnitude of salt loss could have serious implications for contamination of water bodies or could cause further sodification of downslope soils. Sodium losses from the treated Redlands soil would be slower but more prolonged with comparative losses of 39 kg/ha after 10 minutes of 100 mm/hr rainfall. Losses of calcium and magnesium followed similar trends to sodium, although at much lower rates of loss while potassium concentrations of the runoff water remained low throughout (<2 mg/l) and were below the concentration of tap water indicating some degree of adsorption or fixation by the soil. Sodium adsorption ratios (SAR) of the runoff waters from both soils also tended to decrease exponentially during the first rainfall event but again the Toohey soil showed a far larger decrease in SAR compared to the Redlands soil (~12 and ~2 respectively), correlating with the greater loss of sodium in the Toohey runoff.

Changes in soil chemistry during rainfall simulation

Soil analyses performed at the start and end of each rainfall simulation at different slopes showed that there were decreases in soluble and exchangeable salt concentrations for both soils, particularly for the salt-treated soils. The ECs (saturation paste extracts) decreased from ~22 to 17 and from ~8 to 4 dS/m for Toohey 2 and Redlands 2 respectively. ESP changes were variable, decreasing in the case of Toohey 2 but increasing slightly in Redlands2. For the Toohey soil, SAR values (of saturation extracts) varied from ~50 to 30 during the rainfall simulation, whilst for the Redlands soil, SAR decreased from ~8 to 2. It is likely that as rainfall flushes the salts from the soil and the EC/SAR are reduced, this will in turn cause further dispersion and breakdown of aggregates. This might account for the accelerated loss of sediment that occurred towards the end of the rainfall simulation (at 5% slope) for the salt treated soils (Table 2). However further examination of the link between the changes in soil chemistry and soil loss is required in order to clarify this accelerated loss.

Conclusion

When the soils are subjected to high energy rainfall, sediment loss is significantly greater for the Toohey soil than for the Redlands soil, due to the greater dispersibility of the Toohey soil. The Redlands soil in contrast has stable aggregates that are not easily dispersed. However, the Redlands soil showed a more pronounced reaction to the addition of sodium and sediment loss was increased eight fold overall compared to the natural soil. The increased sodium levels translated into increased soil loss of ~ 2.5 and 5.3 ton/ha.yr in 50 mm of runoff for the Toohey and

Redlands soil respectively. The sediment from the sodium-treated soils contained fewer >2 mm aggregates and a decreased modal size in the < 0.5 mm sediment indicating some dispersion of aggregates, particularly in the Redlands soil. Ca, Mg and Na ions were removed by applied rainfall with exponential decreases in concentration occurring from the salt treated soils. Losses of salts from the Toohey soil were initially greater than for the Redlands soil but decreased rapidly with time. Extrapolations from fitted curves indicated salt losses of up to 100 and 39 kg/ha could occur within 10 minutes of heavy rainfall from a sodic Toohey and Redlands soil respectively, which could greatly increase salt loads in streams or downslope depressions. The electrical conductivity of both soils was decreased by the applied rainfall with the Redlands 2 soil showing a ~ 50 % reduction. SAR was also reduced by rainfall and the combination of lowered electrolyte concentration combined with a reduction in SAR seemed to increase soil erodibility and sediment loss. The interaction between sodicity and soil erodibility is more pronounced in clay soils with a high degree of aggregation. The reduction in SAR and EC during the erosion process generally indicates that the chemical condition of these sodic soils can be improved with heavy rainfall but this is accompanied by, aggregate breakdown, dispersion and increased soil loss and salt flushes into the landscape.

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