

The Effect of Quality of Rising Capillary Water on Soil Surface Sodicity

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ABSTRACT

Drying is known to increase soil surface salinity and sodicity. However, it is unclear what should be the minimum quality of the irrigation water used and how much of it is required to evaporate from the soil to create deleterious effects at the soil surface to affect its productivity. This information is necessary to assess the impact of rainfall and irrigation water on the chemo-physical properties of the soil surface. Capillary rise of poor quality water affects soil surface sealing and subsequent capping, thus the current study provides early warning to ensure remedial actions to forestall salinisation and sodification. The paper also provides an empirical model of soil surface salinisation and sodification.

Keywords: Salinity, sodicity, evaporation, irrigation

1. INTRODUCTION

Drying increases soil surface salinity and sodicity and this was studied in experiments reported by Kyei-Baffour *et al* (2004) and Rycroft *et al* (2002). They showed that sodicity developing at the soil surface with drying responded to the sodicity of the irrigation water and marginally to the salinity of the base solution. A further study into the impacts of sodicity on soil strength (Kyei-Baffour *et al*, 2004) revealed that high levels of sodium can easily be developed at the soil surface from the evaporation of solutions having a chemical make-up that would otherwise not give cause for alarm. However, the above mentioned reports reflected situations where the soil was irrigated using surface methods with water of known quality and quantity.

These studies did not take into account the situation where salinity and sodicity at the soil surface was influenced by the capillary rise of saline water from the groundwater. This is a common problem in poorly irrigated and drained areas (e.g. arid regions and areas with distinct dry periods). In such scenarios, surface salinity and sodicity are largely controlled by the rate of evaporation and capillary rise. Thus, the extent of salinisation and sodification at the soil surface under such situations is expected to be driven by evaporative conditions. Prediction of the surface sodicity under such scenario is desirable in order to take remedial actions to prevent sodification during the dry periods.

According to Ayers and Westcott (1985), the relationship between the sodium adsorption ratio (SAR) and the total electrolyte concentration expressed in terms of electrical conductivity influences the soils hydro-physical properties. The SAR is used to represent the relative hazard of irrigation water because of high sodium content relative to its calcium and magnesium content. This is in turn linked to the exchangeable sodium percentage (ESP) by the Gapon equation. An important issue in the estimation of potential hazards of irrigation and/or capillary rise on the soil is the extent of the increase in the soils ESP. Any increase in ESP is dependent on the ratio of sodium to divalent cations in solution denoted by the SAR. According to Hanson *et al* (1999), the most widely used classification for soils at risk from

sodicity relies on the ESP, with $ESP > 15\%$ being the most critical value. The ESP is not affected to the same extent, as the SAR in solution because of the high number of exchangeable cations adsorbed on the soil surface (buffering capacity). Thus cation-exchange equations are often used to describe the distribution of cations between the exchange phase and the equilibrium solution.

A typical soil, such as the Efford soil series, contains a range of clay minerals (illite, vermiculite and kaolinite) in decreasing order of content as well as different cations (sodium, calcium, magnesium and potassium), which makes theoretical description of its ionic equilibrium difficult. In this situation, according to Shainberg and Letey (1984), the empirical approach is preferable. It is also much easier to determine the SAR (sodium adsorption ratio) of the solution than the ESP (exchangeable sodium percentage) of the soil (Shainberg and Letey, 1984). In this experiment, sodicity was indirectly measured as SAR in a 1:1 (One part soil to one part water) solution extract from which the ESP was predicted using the Gapon equation. The study aimed to predict the sodicity at the soil surface due to capillary water rise, by exposing the chosen soil to known quantity of saline solution with a pre-determined quality under controlled evaporative conditions. It was further intended to assess the impact of different water qualities and quantities on the evolution of soil surface salinity and sodicity.

2. MATERIALS AND METHODS

Efford soil series (Jarvis *et al*, 1984) known to be capping-prone was used for this study. The clay, silt and sand contents were 133, 459 and 408 g/kg respectively, making it a sandy silt loam according to the British soil textural classification (MAFF, 1985). The soil sample used for the study had an organic matter content of 3% and a cation exchange capacity of 9.5 mmol_c kg⁻¹. X-ray diffraction analysis showed the dominant clay type to be mica with traces of kaolinite and vermiculite with the non-clay portion being quartz. The Efford soils are classified as alfisols in taxonomy and luvisols in UNESCO/FAO classification (1974).

Dry Efford soil sample taken from the surface plough layer was ground and sieved through 2 mm sieve and the finer than 2 mm aggregates packed to a bulk density of 1.28 g cm⁻³ to achieve the *in-situ* dry bulk density recorded in the field under the laboratory conditions. Cylinders with inner diameters of 65 mm and heights of 90 mm (Figure 1) were used for packing the soil samples for the experiments. The soil was packed 72 mm deep in these cylinders to explore salt movement upwards from the bottom of the cylinders towards the soil surface. This was done to confirm findings by Kyei-Baffour *et al* (2004) and Rycroft *et al* (2002) about the soil surface being the most affected by salt migration and capping process.

The cylinders were placed in turn in appropriate baths (Figure 1) containing solutions of known volume (40, 80 and 120 mm in equivalent depths), known salinities [Electrical conductivity (EC) = 1 and 4 dS m⁻¹] and known sodicities (SAR's = 0, 4 and 8) as detailed in Table 1. They were then dried under infrared heating lamps to promote drying from the surface until no water was left and the soil was uniformly dry. The solutions in the bath in Figure 1 had maximum depths of 18, 36 and 54 mm because the bath had a much wider cross-sectional area for the corresponding equivalent saline solution depths of 40, 80 and 120 mm respectively which were fixed using the bulk density and porosity of the soil packed in the cylinders. The 250 W infra-red heating lamp was 830 mm from the soil surface creating an average soil surface temperature of 28°C. Each drying with a single lamp had 12 samples arranged tightly beneath in a 3X4 array. The samples were weighed and shuffled around daily

during drying until there was no further weight loss. The baths were covered as shown in Figure 1 to confine evaporation to the open soil surface only. The moisture contents were determined by oven drying for 24 h at 105°C.

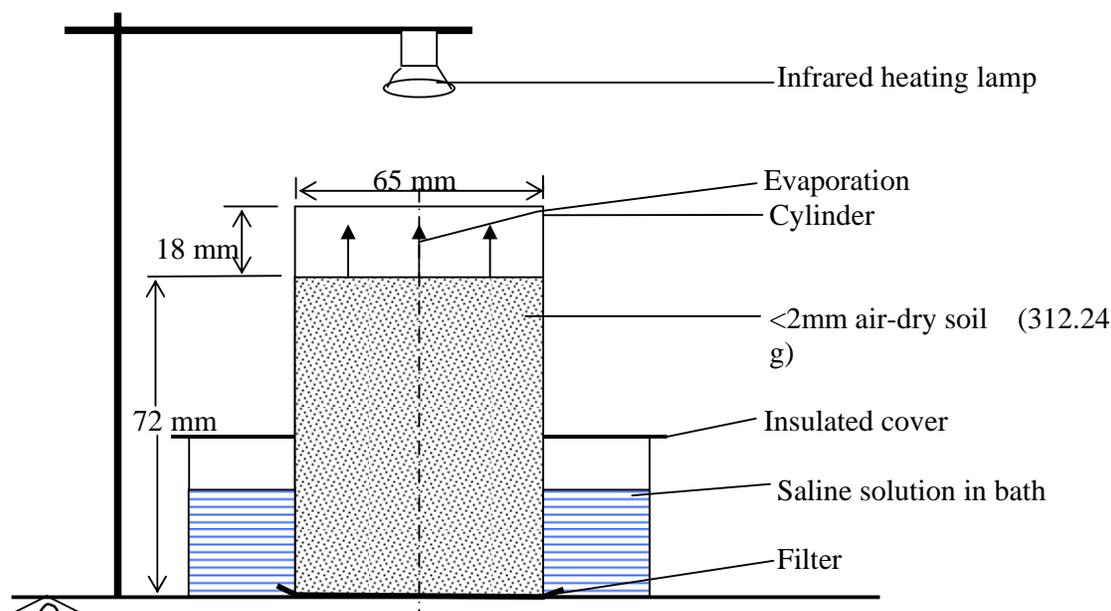


Figure 1. Experimental set-up for the evaporation experiments

The salinities and the cationic compositions of the upper 10 mm of the soil surface were determined after agitating 40 g of the dry soil in 40 cm³ of distilled water on a shaker for one hour and leaving it to settle for 30 minutes. The EC in the 1:1 solution extract was then measured using the conductivity meter. The supernatant suspension was filtered, centrifuged and analysed in a Dionex IC/HPLC for cationic compositions using a 4-mm diameter CS12A (Cation Self-Regenerating Suppressor) and sulfonic acid as the eluent.

Table 1. Properties of salinising solutions

Sodicity(SAR) of salinising solutions	Electrical conductivity (EC) of salinising solutions, dS m ⁻¹					
	1			4		
	Equivalent depth of applied saline water, mm					
	40	80	120	40	80	120
0	+++*	++	++	++	++	++
4	++	++	++	++	++	++
8	++	++	++	++	++	++

*Replications (18 duplicated treatments)

3. RESULTS AND ANALYSIS

The change in average soil mass (after deducting the mass of the column and accessories like the column and bath) with drying is shown in Figure 2. All samples were dried for 38 days until the entire profile was at air dry moisture content. The results show that the drying rate for a particular depth of solution did not significantly vary with the salinity or sodicity of the

solution. This is confirmed by the low coefficient of variation of 1.8 % and a standard deviation of 1.5%, justifying the use of average data for each solution depth as given in Figures 2 and 3.

The differences in mass obtained between successive days were then used to determine the volume of water lost through evaporation. This volume was then converted to an equivalent depth of water evaporated, enabling the cumulative evaporation to be determined as presented in Figure 3. The maximum daily evaporation rate measured was less than 3 mm/day.

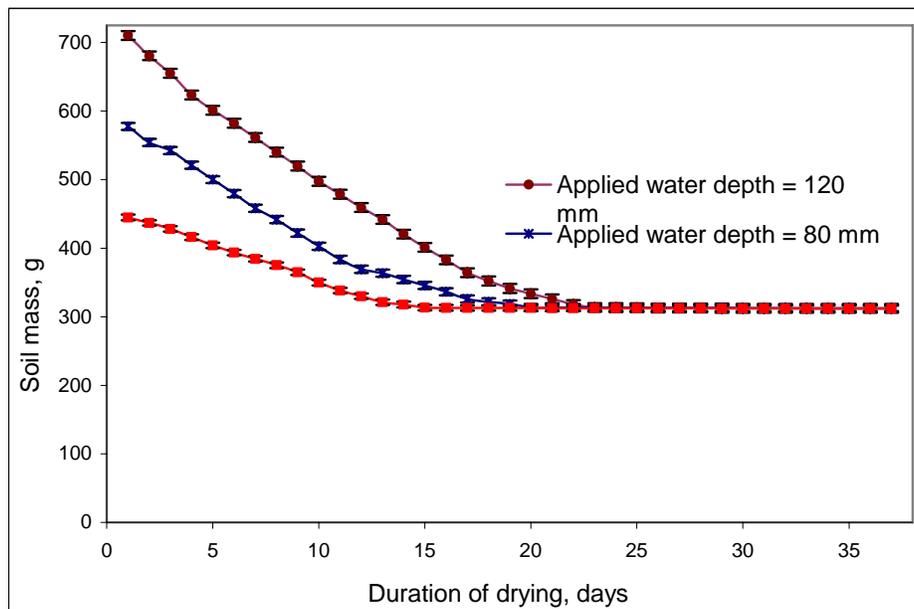


Figure 2. Soil mass during drying

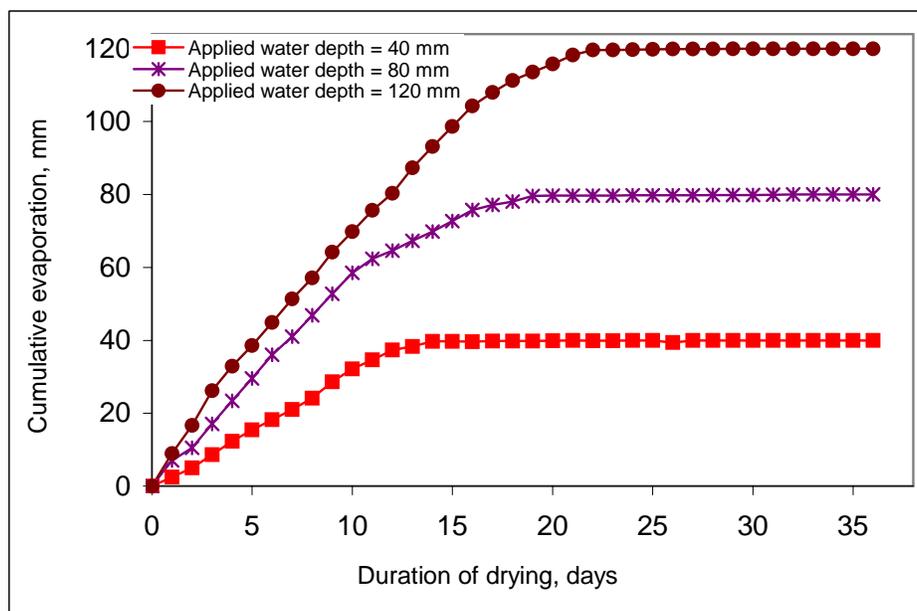


Figure 3 Cumulative evaporation during drying

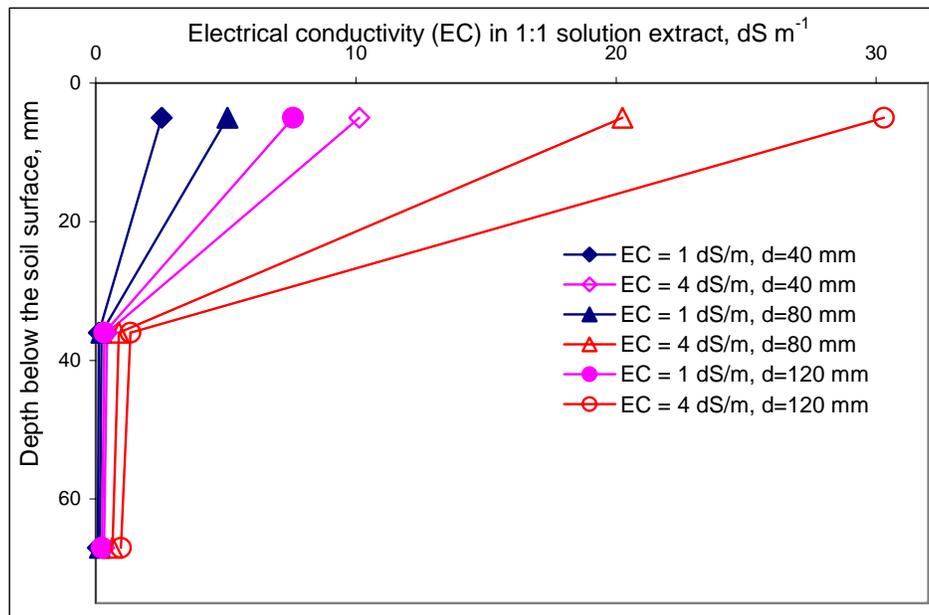


Figure 4 Relationship between drying and soil profile salinity levels for different water qualities and quantities

Figure 4 indicates the effect of drying on different qualities and quantities of solutions on the profile salinity, which drove the salts to the soil surface.

Figures 5 and 6 explain the effects of water quality and quantity on the sodium adsorption ratio (SAR) in a 1:1 water solution extract at the surface for the base salinities of 1 and 4 dS m^{-1} respectively. For example, a solution with EC of 1 dS m^{-1} and an SAR of 8 evaporating 40 mm resulted in an $\text{SAR}_{1:1}$ of 15.32 (Figure 5). A similar solution with EC of 4 dS m^{-1} , recorded a slightly higher $\text{SAR}_{1:1}$ of 15.8. The similarity between Figures 5 and 6 is apparent.

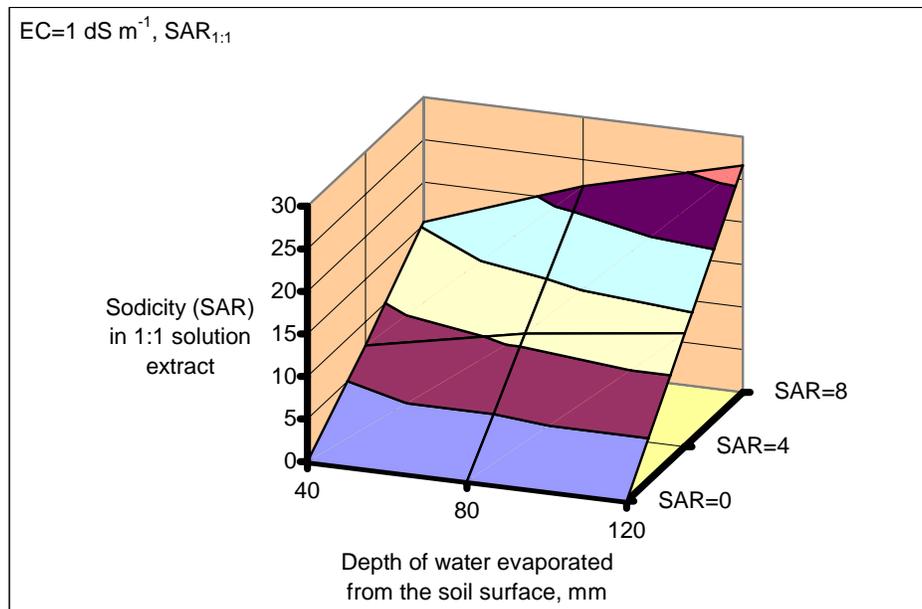


Figure 5. The effect of sodium adsorption ratio (SAR) and water quantity on the SAR at the surface in a 1:1 solution extract (Salinising solution EC = 1 dS m⁻¹)

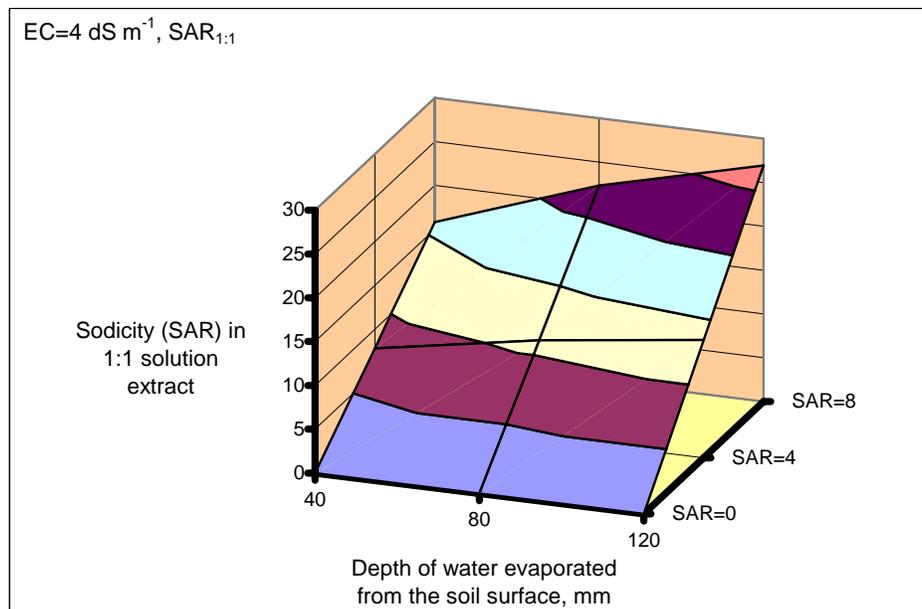


Figure 6. The effect of sodium adsorption ratio (SAR) and water quantity on the SAR at the surface in a 1:1 solution extract (Salinising solution EC = 4 dS m⁻¹)

The Gapon equation was then used to estimate the expected exchangeable sodium percentage (ESP) in equilibrium with the saturation paste extract of the soil at a moisture content of 39 % (w/w) as presented in Figures 7 and 8. They similarly show the effect of water quality and quantity at the surface with drying on the saturation paste extract of the soil at the base salinities in the salinising solutions of 1 and 4 dS m⁻¹ respectively.

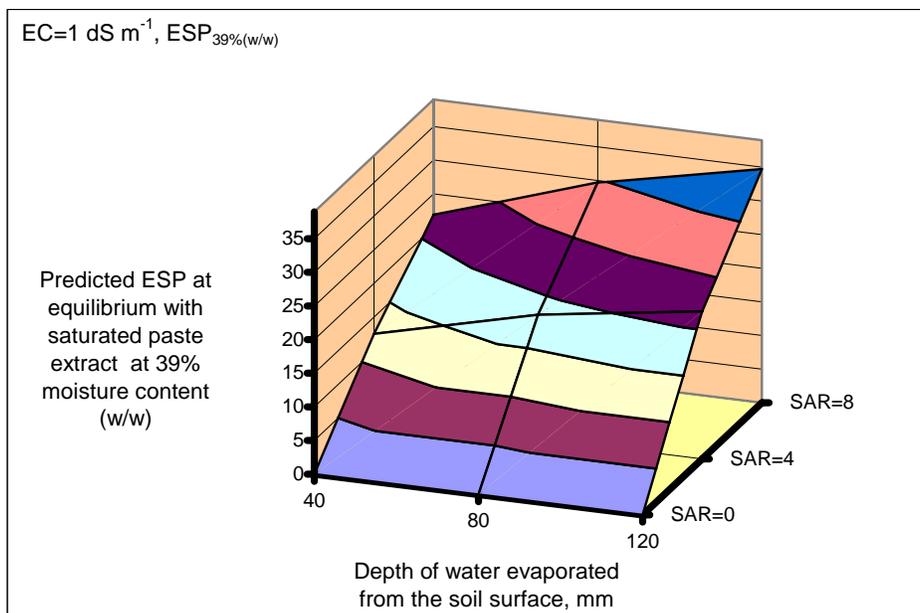


Figure 7. The predicted effect of water quality and quantity on the exchangeable sodium percentage (ESP) at the surface (Salinising solution EC = 1 dS m⁻¹)

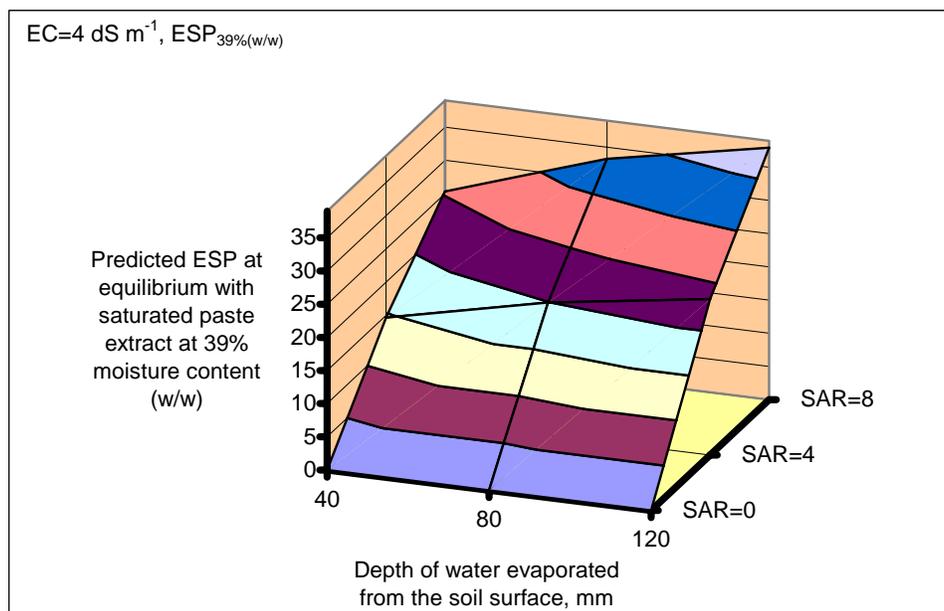


Figure 8. The predicted effect of water quality and quantity on the exchangeable sodium percentage (ESP) at the surface (Salinising solution EC = 4 dS m⁻¹)

Figures 5-8 confirm that a solution having a sodicity of SAR 4 and an electrical conductivity of 1 dS m⁻¹ evaporating between 40-80 mm through the soil surface will lead to the development of critical sodicity at the soil surface. When the SAR was increased to 5, 40 mm of evaporation through the surface was sufficient to generate these critical values.

The requirement for generating critical sodicities with more concentrated solutions (EC of 4 dS m⁻¹) is similar. Under such scenario, SAR's of 4-5 with evaporation of 40-80 mm will generate the critical sodicities. Figure 9 shows the direct relationship between measured sodium adsorption ratio (SAR_{1:1}) and the corresponding predicted exchangeable sodium percentage (ESP_{39%}) using the Gapon equation. Figure 9 shows that an SAR_{1:1} of 8 creates the critical exchangeable sodium percentage (ESP_{39%}) at the soil surface irrespective of the salinity. Thus Figure 9 makes the interpretation of the results shown in the 3-dimensional diagrams in Figures 5-8 easier.

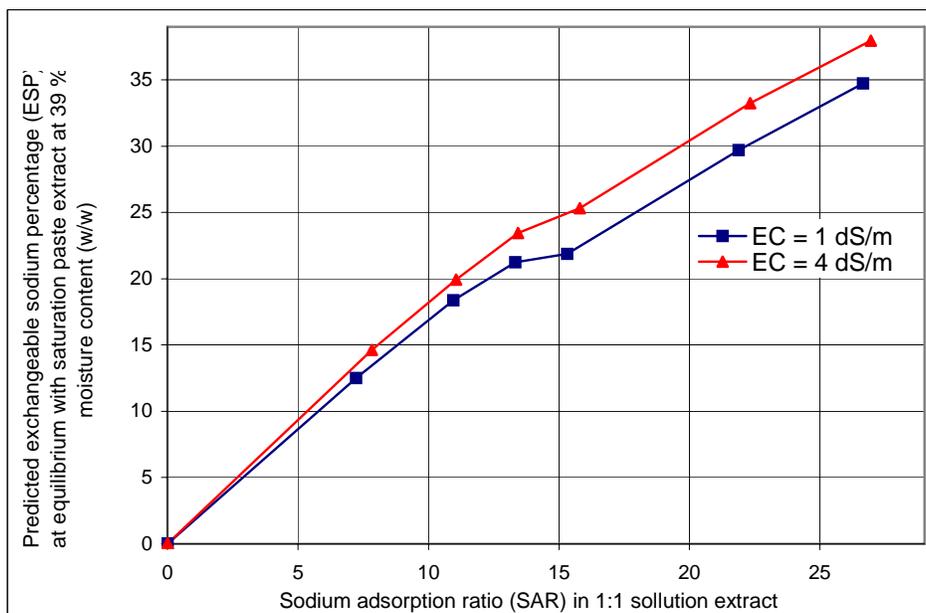


Figure 9 Relationship between sodium adsorption ratio (SAR) in 1:1 solution extract and exchangeable sodium percentage in saturation paste extract at 39 % moisture content (w/w)

The planes generated in Figures 5-8 were fitted with regression equations using Sigma 2000 plot computer programme. Table 2 gives regression equations for the 3-dimensional surfaces in Figures 5-8. Equations 1 and 2 representing the fitted plane in the three-dimensional diagrams (Figures 5 and 6) further confirming the similarities between the Figures. They gave very high degrees of correlation as presented in Table 2.

Table 2. Regression analysis of the relationships between water quality/quantity on soil surface SAR_{1:1} and ESP_{39%}

Number of regression equation	Electrical conductivity (EC) of salinising solution, dS m ⁻¹	Regression Equation (valid for 40 ≤ d ≤ 120)	Correlation coefficient, R
1	1	*SAR _{1:1} = 2.6607 SAR + 0.0726 d - 5.8558	0.9423
2	4	SAR _{1:1} = 2.7107 SAR + 0.0698 d - 5.6063	0.9460
3	1	**ESP _{39%} = 3.5959 SAR + 0.0929 d - 6.3552	0.9356
4	4	ESP _{39%} = 4.0213 SAR + 0.0895 d - 6.0744	0.9486

*SAR_{1:1} is sodium adsorption ratio in 1:1 solution extract at the soil surface

SAR is sodium adsorption ratio in the irrigation water

d is cumulative evaporation in mm

** $ESP_{39\%}$ is exchangeable sodium percentage at the soil surface in equilibrium with the saturation paste extract of the soil which had a moisture content of 39% (w/w)

Table 3. Predicted depth of evaporation to generate critical sodicity.

Critical sodicity	EC of saline water applied water, dS m^{-1}	Sodicity of saline applied water	
		4	5
Predicted evaporation to generate critical sodicity, mm			
$SAR_{1:1} = 15$	1	141	104
$SAR_{1:1} = 15$	4	140	101
$ESP_{39\%} = 15$	1	75	36*
$ESP_{39\%} = 15$	4	56	11*

*Values are outside the range used in deriving the equations and may therefore be unreliable

Table 3 indicates the salinity and sodicity in the salinising solutions and the required level of evaporation needed for creating critical sodicities in the upper 10 mm of soil. The concentrations of salt in the solution do not seem to affect the $SAR_{1:1}$ in the solution extract.

Finally, the measured sodium adsorption ratio ($SAR_{1:1}$) values and their corresponding predicted exchangeable sodium percentage ($ESP_{39\%}$) values using the Gapon equation are shown in Figure 10. They also show a linear relationship and a high degree of correlation as depicted in Table 2.

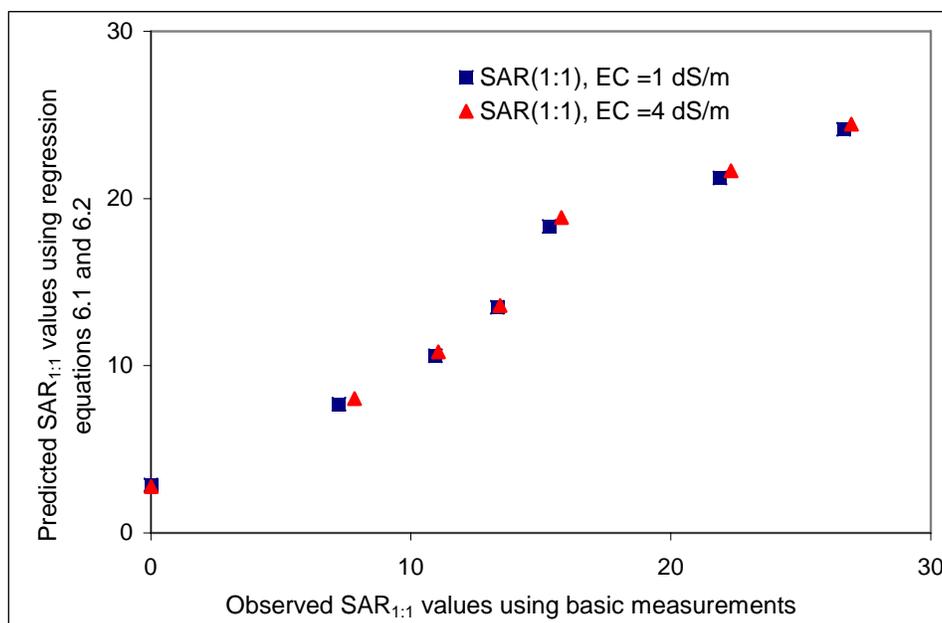


Figure 10. Observed sodicity values plotted against predicted sodicity values

4. DISCUSSIONS

The investigation aimed to assess the impact of different water qualities and quantities on the evolution of soil surface sodicity. It is worth noting that the preceding work (Kyei-Baffour *et al.*, 2004) had shown that drying increased the surface sodicity, irrespective of the level of salinity in the applied water.

Given that the relative particle density of the packed aggregates was 2.65, the porosity of the packed soil was 51.7 %. The relative amounts of air and water in the pore space, however, were expected to fluctuate continuously during the experiments. The restrictive conditions imposed on this experiment ensured that changes in moisture quantities originated from capillary water rise and evaporation since other surfaces were covered. The soils dried from the surface downward, with total water loss varying slightly with the rate of drying (Fig 2). Since evaporation rate was not too high (<3 mm/day), the surface layers dried out to a minimum water content (2.1 % w/w), unaffected by further evaporative losses which continued to occur from the lower layers of the soil.

The net water transported through each soil each day (evaporation) was calculated from the daily weight loss. Summing the daily evaporations gave the cumulative evaporation. Evaporation from the soil surface changed daily in response to prevailing environmental conditions, limited by using one 250-W infrared heating lamp, 830 mm from the soil surface *per* drying session. Thus the mean daily evaporation data (Fig. 3) was used for modelling the process, since this was practically measurable.

Two major factors influenced the evaporation process. These were the position of the drying front in the soil causing soil moisture from below to move to the soil surface by mass flow and/or diffusion. The movement of soil moisture in the profile continued throughout the drying process. This put the movement of water in the soil into a two-phase system. In the uppermost part of the soil, above the drying front, water loss was basically in the vapour phase only. This situation complicated the evaporation process, which was measured directly and was not the subject of the model. Evaporative demand declined continuously from the initial moisture content to the air-dry moisture content.

In principle, the potential evaporation was maintained until the soil moisture content was equal to the air dry moisture content, after which time the surface moisture content remained at the air dry moisture content level since the surface moisture content could not fall below the air dry moisture content. The soil surface was maintained at the air-dry moisture content using the heating lamp and the surface of the soil had the highest sodicity and salinity, making it prone to sealing.

During the drying process, water and salts lost from lower layers move into layers immediately above, raising the salt contents of those layers. Loss of water by capillary action continued until equilibrium was established. This process continued from layer to layer until all available water was evaporated from the surface, leaving the salt contents behind, mainly in the surface layers. This situation is depicted clearly in Figure 4 showing the salinity profile for the different water qualities and quantities. During evaporation from the soil surface, no ions were lost to the atmosphere. In the lower layers, however, losses occurred almost entirely in the liquid phase by capillary action.

Evaporation began at the surface of the soil (Figure 1). Upcoming saline water mixed with the soil solutes in contact within soil layers. The solutes from lower layers were carried to higher layers. This process was repeated until the water reached the soil surface where it evaporated leaving the salts behind at the surface.

The recorded evaporation, sodium adsorption ratio (SAR) in 1:1 solution extracts and the SAR of the applied water were combined in order to develop an empirical model of the

process. This information could be used to predict the consequence of evaporation on soil surface sodicity under the situation of prolonged drought.

Salt movement within the soil profile (Figure 1) occurred by mass flow through the pores (Addiscot, 1977). The presence of aggregates and cracks in the profile at the tail end of drying, however, may have encouraged preferred pathways for the movement of water and ions but this could only happen towards the end of the experiment when the soils had virtually dried out.

An electrical conductivity of 1 dS m^{-1} , as in this experiment, is widely encountered in the soil solution in arid and semi-arid regions of the world where irrigation is practised intensively, but shortage of water may not allow sufficient excess water to be applied to leach out salts. Poor drainage might worsen this situation. Evapotranspiration rates in such areas also tend to be very high, as the water table creeps closer to the soil surface and salt build-up at the soil surface becomes inevitable.

Under the scenario described above, a soil solution having a salinity of 1 dS m^{-1} and a sodicity of SAR 4 needs between 40-80 mm of saline soil solution (Figures 5 and 6) to evaporate solely through the soil surface to generate critical sodicity at the surface. When the sodicity of the soil solution is increased slightly to SAR 5, only about 40 mm evaporating is enough to generate the critical sodicity. Figures 5 through 8 confirm these findings. The implication of the work is that the sodicity of the soil solution is much more important than the salinity when it comes to soil surface sodification.

In the unlikely situation where the salinity and sodicity of the groundwater are even higher ($\text{EC} = 4 \text{ dS m}^{-1}$, SAR 4-5), depth of evaporation of 40-80 mm can create critical sodicity at the soil surface. Any rainfall or irrigation application after such a sodic surface is created is bound to aid sealing process. The chemistry at the surface is critical, whilst the energy of the rain and the purity of the rainwater are likely to enhance the problem further. This is also confirmed with results presented in Figure 9, where an $\text{SAR}_{1:1}$ of 8 gave the critical $\text{ESP}_{39\%}$ of 15 % irrespective of the solutions salinity.

The observed $\text{SAR}_{1:1}$ values were plotted against their predicted $\text{SAR}_{1:1}$ values and this can be seen in Figure 10 showing very high degrees of correlation ($R = 95-96 \%$). Figure 10 therefore shows a much closer predicted $\text{SAR}_{1:1}$ values, an indication that salinity is insignificant during soil surface sodification. Thus, once again the salinity seems to make very little difference to the sodicity generated at the surface.

5. CONCLUSIONS

It can be concluded that an SAR value in the range 4-5 in a saline soil solution is enough to generate critical sodicities at the soil surface when 40-80 mm of such water is evaporated continuously from the surface without rainfall or irrigation interruption.

Under irrigation, the evaporation data in this study could be replaced by the evapotranspiration measured for the project in question using existing evapotranspiration measurements or estimation techniques during intervening dry periods when surface conditions of the soil are most affected by evaporation and capillary rise. This study can be combined with the quality of the groundwater information to predict the expected salinity and sodicity at the onset of the next rainfall or irrigation season.

It is apparent from Table 3 that as the sodicity of the applied water increased, the depth of evaporation needed to generate critical sodicities became even less. The fact that these scenarios are feasible in arid and semi-arid areas make it imperative for measures to be taken to prevent soil sodification and capping at the implementation stage of irrigation projects at least by ensuring adequate drainage and/or the application of gypsum.

The study confirms the important role played by sodium in affecting soil surface chemical status and subsequent deterioration of structure when it rains or good quality irrigation water is applied. It could therefore be postulated that, the salinity of the applied water, be it 0.5, 1, 4, etc. dS m^{-1} may not necessarily matter since the sodicity is the most important aspect of the soil that damages the structure. What is not certain is whether at much lower sodicities than those reported in this work (e.g. 0.5 dS m^{-1}) there will be sufficient sodium in solution to swamp the buffering capacity of the soil to generate critical sodicities with evaporation. Further work is therefore recommended in this area.

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