

EXPLAINING THE MYSTERIES OF SALINITY, SODICITY, SAR AND ESP IN ON-SITE PRACTICE

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Abstract

Sodium can have significant effects on soil properties and plant growth and these have been well understood for at least half a century by soil scientists, agricultural scientists and irrigation experts. For these reasons, the sodium content of soils and irrigation waters, as well as the modes of occurrence and action of sodium in the soil, have been routinely measured to characterise the quality of soil and irrigation water for cropping and to predict the risk of deleterious impacts.

While sodium, as sodium chloride (NaCl), may be one of the main species in saline soils or saline water many other salts may also be present in highly variable amounts in different landscapes. Sodium sulphate, calcium sulphate (gypsum), calcium chloride, magnesium chloride and sodium bicarbonate will appear in acidic, neutral and alkaline soils in different proportions. They all have in common that, when in water, they dissociate into positively charged cations and negatively charged anions.

In more recent years, optimising the use of soil and vegetation to purify and consume wastewater from municipal, industrial and domestic sources has brought a new requirement to the understanding of salinity and sodicity. Both the consulting engineering profession and government regulators use concepts of soil sodicity, sodium adsorption ratio and exchangeable sodium percentage in their design criteria for wastewater treatment and effluent disposal systems. It is common for these new clients of soil science to display ignorance of the importance and specific problems these concepts mean. This increases the risk of failure of such systems and produces “Tower of Babel” confusion amongst themselves and subsequently among municipal responsible authorities and sewerage bodies further down the regulatory line.

This paper explains the four concepts – salinity, sodicity, sodium adsorption ratio and exchangeable sodium percentage – that relate to salt and sodium in soil and in water, hence in water that is in intimate contact with soil particles, to clear up this confusion.

Keywords

cation exchange, conductivity, exchangeable sodium, salinity, sodicity, sodium adsorption ratio

1 Cations in Soil-Water System

Salinity and sodicity are separate and unique descriptions of all impacts of soluble salts in soil and water environments, of which sodium chloride is one. Salinity refers to the total concentration of all salts in the water or the soil. Soil sodicity represents the relative preponderance of exchangeable sodium compared to other exchangeable cations, chiefly calcium, magnesium, potassium, hydrogen and aluminium. Terms for more complex relations are used to describe the potential effects of sodium.

Sodium absorption ratio (SAR) is a measure of the relative preponderance of dissolved sodium in water compared to the amounts of dissolved calcium and magnesium. The

mathematical form of this measure follows from a theoretically derived and frequently observed relationship with the preponderance of sodium held in exchangeable form in soil, which is in equilibrium with the subject water. Exchangeable sodium percentage (ESP) is the amount of sodium held in exchangeable form on the soil's cation exchange complex expressed as a percentage of the total cation exchange capacity (CEC). These terms are described in the following discussion.

Soil texture refers to varying proportions of sand, silt and clay in a soil. Topsoils also contain humus (organic matter), while there are soils that consist entirely of sand, and less commonly, entirely of clay. In the international system, soil mineral particles are categorised according to their apparent diameter, regardless of their mineralogical composition. Surface area Specific surface area is an important property in terms of adsorption of dissolved materials in the water surrounding the soil particles.

**Table 1. Relationship of Mineral Fragment to Specific Surface Area
(Source: after Foth 1978)**

Soil particle size fraction	Particle size diameter in mm	Specific surface area m ² per gram
Coarse sand	2.00 - 0.20	0.0023
Fine sand	0.20 - 0.02	0.0091
Silt	0.02 - 0.002	0.0454
Clay	<0.002	800.0

The clay fraction virtually always consists of a series of minerals quite different from the sand and silt fractions of a soil. Clays are usually plate-shaped crystalline particles made up of two basic units: 1. tetrahedral silica (Si₂O₅); and 2. octahedral aluminium hydroxide (Al(OH)₃) in alternating layers like a sandwich. Many of these may occur together like pages in a book or like a card house structure with edges contacting faces. Due to imperfections in the crystal lattice structure, every now and then a Si⁴⁺ ion is substituted with an Al³⁺ ion, and some Al³⁺ ions are replaced by Mg²⁺ ions (magnesium). Consequently, clay minerals are deficient in positive electric charge, that is, they have a permanent negative charge, and to make up the deficiency they attract positively charged ions from the soil water surrounding them. A positively charged ion is called a cation.

Clay particles do not have a very strong preference for which cation species helps them to compensate for their built-in negative charge. Therefore, if initially the main adsorbed cation was Ca²⁺, but the soil was being continually irrigated with water rich in Na⁺ ions, the adsorbed Ca²⁺ would gradually be replaced by adsorbed Na⁺. When this happens the ESP, and hence the sodicity, increases. Soils have a preference for cations with more than one positive charge, so it is easier to replace Na⁺ on the exchange complex with Ca²⁺ or with, say, aluminium (Al³⁺) than to replace these in reverse order. Mono-valent ions like sodium are less effective in neutralising the charge on the colloid and preventing swelling and dispersion than bi-valent or tri-valent ions like calcium and aluminium, thus individual colloid particles continue to repel each other and stay in solution (Brady, 1990).

The total negative electric charge per mass of soil is called the soil's cation exchange capacity (CEC). CEC may be thought of as the total amount of iron filings that can be retained by a pile of magnets. If the magnets have a strong magnetic force, they can retain more filings than if they had a weak magnetism. CEC is reported as cmol(+)/kg, a unit having the same numerical value as milliequivalents per 100 g (meq/100 g).

Centimole of charge is found by dividing the concentration of a cation in units of milligrams per 100 g of soil (mg/100g) by its equivalent weight. The equivalent weight of $\text{Ca}^{2+} = 20$, $\text{Mg}^{2+} = 12.15$, $\text{Na}^+ = 23$.

Some types of clay minerals, like montmorillonite or bentonite, which are frequently found in heavy clay soils formed on basalt, or in depressions in areas with a relatively dry climate, or in some soils formed from limestone, have a very high CEC. Humus also has a very high CEC, 2 to 10 times that of clay. Illite clays have an intermediate CEC and kaolinite clay has a low CEC. Sand and silt particles may be regarded as having no built-in negative charge and therefore have zero CEC. Given the identical clay mineral type, a soil with high clay content has a higher CEC than a soil with low clay content.

The CEC of a soil is measured in the laboratory, no suitable field measurement procedure is available. Several methods are in common use as outlined in Rayment & Higginson (1992). It is important to understand the difference between the measurement of the exchangeable cations Ca^{2+} , Na^+ , Mg^{2+} and K^+ in the soil and measurements made of the same four cations plus the H^+ and Al^{3+} cations. The term Effective Cation Exchange Capacity (ECEC) refers to the former measurement where the four cations are accounted for, together with the soluble salts of the soil solution, while the Cation Exchange Capacity (CEC) refers to the latter when H^+ and Al^{3+} are also measured. The soluble salts in the soil solution may be measured as 'soluble salts'. It is often not clear from the laboratory results which method has been used and reporting the method is critical to accuracy of the results where comparison are to be made.

After measuring CEC of the soil, the proportion of exchangeable sodium relative to summation of exchangeable cations is calculated to provide the exchangeable sodium percentage (ESP) for the soil. This simple calculation (units of %) is used to indicate the likely effects that a soil may have with respect to structural stability, because Na^+ ions favour dispersion and Ca^{2+} and Mg^{2+} favour flocculation (opposite to dispersion).

$$\text{Exchangeable sodium percentage (ESP)} = \frac{\text{Conc. Na}^+ \times 100}{\text{Sum of conc. all cations}}$$

or

$$\text{ESP (\%)} = \frac{\text{Conc. Na}^+}{\text{CEC}} \quad \text{Equation 1}$$

where the units of concentration are in $\text{cmol}(+) \text{ kg}^{-1}$ (or $\text{meq}/100 \text{ g}$)

Soils that have more than 6% ESP are considered to have structural stability problems related to potential dispersion, discussed above. Other factors may enhance or limit that potential and 6% ESP should not be taken absolutely. Sodicity is not the only factor involved in clay dispersibility: clays with a given sodicity are more dispersible with a high pH than with a low one (McBride, 1994).

Soil salinity is a characteristic of soils relating to their content of water-soluble salts (Charman & Murphy, 2000). Typically inorganic salts are crystalline ionic products that dissociate in water to form positively charged cations (Ca^{2+} , Mg^{2+} , Na^+ , K^+ , Al^{3+} , Cu^{2+} , Zn^{2+} , Fe^{2+}) and negatively charged anions (Cl^- , NO_3^- , PO_4^{3-} , SO_4^{2-} , CO_3^{2-} , HCO_3^-). Soluble salts dissociate in water to release cations and anions that can conduct an electric current. Thus, the simple measurement of how much current an aqueous solution will carry can be related directly to the amount (concentration) of salt present. Electrical conductivity is measured using a conductivity meter and electrical conductivity (EC) is reported in the international units of measure as deciSiemens per metre (equivalent to milliSiemens per centimetre).

Smaller units of microSiemens per centimetre are commonly used for low salinity recordings.

$$1 \text{ dS m}^{-1} = 1 \text{ mS cm}^{-1} = 1000 \text{ }\mu\text{S cm}^{-1}$$

It is completely erroneous, and misleading, to use EC as a unit of measure. EC is the abbreviation of electrical conductivity, measured in units of deciSiemens per metre.

Salinity in soil is measured by making slurry of water and soil and measuring the electrical conductivity of the slurry (saturation extract). The more salt the higher the electrical conductivity. Therefore it is important to use uniform mixing ratios of soil and water to get results that can be correlated with other processes, such as plant growth. Internationally, the so-called electrical conductivity of the saturation extract, EC_{SE} , often reported as E_{ce} , is the most commonly used indicator of salinity in terms of plant growth. The EC_{SE} is measured on a soil-water paste that is just saturated enough to flow. In Australia, EC is often also measured on a soil to water ratio of 1:2 and 1:5. Clearly, the same soil will produce the highest EC reading when it is measured in the paste, followed by the 1:2 soil-water mixture, followed by the 1:5 mixture. Not giving the method of measurement results in a meaningless EC value. Methods for measuring EC in soil are given in Rayment & Higginson (1992).

A conversion factor for translating EC_{SE} to $EC_{1:5}$ will depend upon the clay content of the soil and should be used with caution. Charman & Murphy (2000) quote a factor of $1/8.6 = 0.116$ for converting a clay loam EC_{SE} to $EC_{1:5}$, $1/7.5 = 0.133$ for a light clay and $1/5.8 = 0.172$ for medium or heavy clays. For example, if the $EC_{1:5}$ in a light clay was 0.45 dS m^{-1} then EC_{SE} would be $0.45 \times 7.5 = 3.38 \text{ dS m}^{-1}$ as EC_{SE} , or conversely, if $EC_{SE} = 3.38 \text{ dS m}^{-1}$ then $EC_{1:5} = 3.38 \times 0.133 = 0.45 \text{ dS m}^{-1}$.

Clay particles in a soil in contact with the water in the soil will strive to be in chemical equilibrium with that water. If the clay has a high CEC, in other words its surfaces are densely populated with adsorbed cations, there will also be more cations in the film of water surrounding the particles themselves. If, amongst the adsorbed cations, the majority consists of, say, sodium, then there will also be a greater proportion of sodium ions in the surrounding watery solution. Conversely, if the water percolating through a soil has a high relative concentration of sodium, the proportions of adsorbed cations will adjust themselves to that. This is where the concept of sodium adsorption ratio (SAR) has been developed. Where ESP and sodicity are properties of the soil, SAR is a property of the water and is defined as:

$$SAR = \frac{Na}{\sqrt{(Ca + Mg)/2}} \quad \text{Equation 2}$$

where: Na, Ca and Mg are respectively sodium, calcium and magnesium concentrations in centimoles (+) per litre (same as milli-equivalents per litre)

Note that SAR is a ratio and therefore has a numerical value but no units.

When the relative preponderance of Na^+ in water is expressed as SAR, there is for many soils a reasonably consistent relationship with the soil's ESP. This relationship can be used to predict the long-term effect of irrigation with water with a known SAR on the soil's ESP.

The sodium in a soil occurs in two main forms: the fraction adsorbed on negatively charged clay and humus colloids and the fraction that exists as free salt in between the soil particles.

The fact that sodium ions only have a single positive charge and that it is "smeared out" over a relatively large hydrated sodium ion (Na^+ surrounded by water molecules) causes clays with a high relative proportion of adsorbed sodium to swell in water, and to make them more dispersive. The latter means that the individual clay particles tend to separate from one another and become suspended in the water. How do we know that clay is dispersed? Water in farm dams with suspended (dispersed) clay is very turbid. This is undesirable in a soil that is to be used for wastewater re-use, as dispersed clay causes the permeability of the soil to decline, or even to become almost zero.

Emerson (1977) stated that it was not possible to obtain a universal relationship between ESP of a soil and minimum concentration of the electrolyte needed to prevent deleterious swelling and dispersion, rather a “dispersion test” was preferred. The Emerson dispersion test is now an accepted method of assessing dispersion potential.

In the first part of the test, air-dry soil aggregates, 3-5 mm diameter, are immersed in water and the amount of swelling, slaking or dispersion is reported. The test should be performed with water being used for irrigation. In the case of domestic on-site systems a water with SAR 5 and EC <1.5 dS m⁻¹ should be used to reflect the typical quality of septic tank effluent.

In a soil with stable structure, the clay particles remain aggregated together (flocculated) so that the voids between the aggregates are larger and the material is more permeable and less likely to become or remain waterlogged. This is also desirable for aeration of the soil and for root penetration and plant growth. Farm dams with flocculated clay bottoms have clear water.

Once again, those clay minerals with high CEC are more susceptible to deleterious impacts from high sodium than those that have low CEC, and sand with no CEC is not affected.

Finally, a highly saline soil (high EC) also causes the clay to be flocculated. This explains why turbid river water at the mouth of a river soon becomes crystal clear seawater in the highly saline marine environment. The larger flocs of clay quickly settle to the bottom. Highly saline soils are usually quite permeable, but leaching the salts out using low salinity water causes the soils to close up. Therefore, when saline soils are reclaimed, people use gypsum, another salt, but based on calcium not sodium, so that the “salinity” remains high, but gradually the sodium is replaced by calcium, which maintains flocculation.

We can now consider the effects of misunderstanding these phenomena.

2. Unpredicted Lagoon Leakage

New sewage lagoons were constructed at Echuca, Victoria, in the late 1980s. The designers took samples of the clay soils, had them compacted to specifications, and then tested their permeability to calculate losses of water to the groundwater table and predict potential rises of the water table. The compacted samples were tested with de-ionised water, ie. water with zero salinity (EC < 0.01 dS m⁻¹). The clays were already somewhat saline by nature. The permeating zero-salt water caused the present salts to be washed out, so that the clay became dispersive and more strongly swelling. The leaching with de-ionised water of a clay soil containing sodium chloride did not only lower the salinity but increased the ESP and the sodicity. The soil closed up by swelling. As the clay had a high CEC the effect was even more pronounced. As a result the final measured permeability was very low and led to predicting very low seepage losses. High ESP and low EC induce sodicity.

After construction of the lagoons, they were filled with highly saline wastewater (Echuca had an abattoir where hides were treated with salt), and the clay bottoms proved much more permeable than predicted and leaked like a sieve. The water balance model of the lagoons proved to be quite wrong and water tables in the zone of some 200-m around the lagoons reached the surface within three years. The consultant was taken to court for professional negligence, and the Municipality of Echuca lost much of their investment in the system.

Apparently, the standard method used for measuring soil permeability in the laboratory required the use of de-ionised water, and this was clearly erroneous. The dispersion test (AS1289.3.8.1) requires that the water used shall be distilled or water in which the soil will be in contact. However, AS/NZS 1547:2000 does not indicate the quality of water required for the permeability test (Appendix 4.1F). It is important that the measuring liquid should have

the same chemical composition as that of the predicted effluent. For septic tank effluent, a solution of SAR 5 and EC 1.0-1.4 dS m⁻¹ should be used.

3. SAR in Permeability Testing

The ramifications of the above example, and no doubt similar others in the country, have led to some regulating authorities and consultants becoming aware of SAR and to specify the SAR of water used for permeability testing. By not simultaneously specifying total salinity of the testing solutions, it is clear that lessons of earlier mistakes are still not truly understood.

A soil exposed to a high SAR and high salinity water will remain permeable because the clays remain flocculated. However, high SAR and low salinity will cause the soil to become much less permeable. If the purpose of the testing is to shed light on the likely behaviour of the soil when irrigated with a particular effluent, testing must use water resembling that effluent.

Table 1. Examples of Irrigation Water with Varying SAR

Source of irrigation water	Na (mg/L)	Ca (mg/L)	Mg (mg/L)	EC (uS/cm)	SAR	Safe for soil	Effects
A. Typical septic tank effluent (STE)	80	25	6	1100	4	maybe	
B. STE + gypsum	80	250	6	2500	1.5	yes	high Ca
C. low salinity water	7	9	1	77	0.6	yes	non-sodic
D. saline town water	231	5	1	935	28	no	long term Na ⁺
E. Sewage treatment works effluent	127	35	22	890	4.1	yes	long term Na ⁺
F. Abattoir effluent	397	14	6	2950	22.4	no	long term Na ⁺
G. Tannery effluent	98250	1	2	84000	incal.	NO!	long term Na ⁺

(Data sources: Patterson, 1994)

As seen in Table 1, typical septic tank effluent, Liquid A, is mostly safe to apply to the soil, but this depends on the clayeyness of the soil and the type of clay mineralogy. If the clays are of a high CEC type, the soil's permeability may be reduced in the long run. However, if the trench receives raw septic tank effluent, the clogging layer that develops at the wetted surface may reduce the transmission rate so much that the lower permeability of the soil behind it is still adequate to let the water flow through. If the clay particles are strongly bound together by other cementing substances the soil will not be damaged either.

Liquid B has a higher salinity than A due to the EC contribution from the gypsum but is totally safe for all soils because of its low SAR and elevated EC.

Liquid C (town water Lismore NSW) has a very low salinity and is suitable for non-saline, non-sodic soils, but presents long-term risk to saline soils. It leaches salts from the soil solution, decreasing electrolyte concentration and allowing Na⁺ to come off the exchange sites and cause sodicity problems by dominating the soil solution.

Liquid D is the town water from Boomi, NSW and is a sodicity hazard because of its high SAR and low EC. The water would cause significant problems even for the home lawn.

Liquid E is a typical sewage treatment works effluent (Dubbo NSW) and is likely to maintain soil permeability in the short term and with management of accumulation of sodium. Additional leaching with the same water can be used to move Na⁺ salts out of the rootzone.

Liquid F is from an abattoir (Repton, NSW) and would result in significant Na^+ build-up unless leaching occurs. The high SAR results from low Ca^{2+} that can be amended with gypsum or lime.

Liquid G is from a tannery in northern NSW and has a salinity three times that of sea water. The high salinity and incalculable SAR will maintain soil permeability in the irrigation area, but, it is unlikely any vegetation will grow and over time the land would become a salt bowl.

Gypsum is also a salt but is much less soluble in water than sodium chloride, common sea salt. Even a saturated gypsum solution does not have an EC that is likely to damage plants.

4. Mistaken Interpretation of Sodicty and ESP

A recent Victorian EPA guideline (Publication 746, 2001: Assessment of Land Capability for On-Site Disposal of Septic Tank Effluent), produced for the EPA by a private consultant, inaccurately defines sodicity (exchangeable sodium percentage) as “the amount of sodium in the soil”. It also uses a single critical value to consign a soil to being “unsuitable” for on-site effluent disposal, inferring that with an ESP in excess of that threshold value a soil will disperse without taking into account the associated clay mineralogy, EC of soil solution, CEC, pH, or the relative amounts of the cations and obviously disregarding any amelioration potential or leaching fraction.

This misguided definition has already led to clouding the important issue of soil structure stability and permeability and hence will be counterproductive in terms of on-site planning and management. Sodicty is a measure of the preponderance of sodium in the cation exchange complex of the soil. ESP measures the preponderance.

Table 2 shows three soils, all with an equal “amount” of sodium, but only one being “sodic” enough to warrant concern about dispersion.

Table 2. Sodicty Relationship for Three Soils

	Soil A	Soil B	Soil C
Texture	Loam	Humus-rich Loam	Sand
Clay Mineral type	Kaolinite	Montmorillonite	No clay
CEC $\text{cmol}(+) L^{-1}$	5	25	0
“Amount of Na” mg/kg	690	690	690
ESP % of CEC	60	12	No exch. Na All Na as free salt
Sodicty	Very high	Low	Nil
Indicative dispersion	Maybe severe	Insignificant	Nil

Clay soils may be very stable in spite of high ESP if at the same time they are very acid, say with pH values in water below 5.0, and/or also have extremely high organic matter contents.

It is a mistake to provide a guideline that can easily be interpreted as providing absolute judgements based on single factors when several factors are simultaneously important, especially if these are also defined in imprecise language, and have not been given a reference to a definitive source. Not only is it imperative that consultants are aware of the need to integrate many factors to understand soil structural stability, but laboratories must also be alert to the need to better define the methods they use to measure and report these factors.

5. CONCLUSIONS

While the salinity issue is contentious in rural areas with irrigation issues, rising water tables and measuring only of soil electrical conductivity, the issue also cause concern among those professionals working with on-site domestic wastewater. This paper has addressed the issue from two perspective; one where the knowledge of salinity and sodicity are reasonably well understood in soil science yet being ignored by other sectors; and the second where maybe well-meaning but ill-informed regulators are leading the uninitiated down a false path with poor appreciation of the complexity of salt and sodium issues. The improper definition of the concepts and the incomplete specification of test methods can only lead to delays in better design. Improper definition also does not assist the lay person, such as the municipal environmental health officer, who is not a soil scientist, to better understand the issues.

Three general conclusions are drawn from this paper:

1. The definition of soil and effluent parameters needs to be standardised within the re-use and land application arena. Such actions will ensure that salinity and sodicity are understood as separate yet intertwined measures of salt within the environment, and that SAR and ESP are tools, rather than prescriptive limits, for understanding the effects of sodium upon the structural stability and plant physiology.
2. The measurement of parameters such as EC, SAR, ESP, CEC, pH should be analysed and reported in a form which allows both consultants and determining authorities to better predict appropriate design for sustainable practices in returning effluent to the hydrologic cycle.
3. Measures are available for ameliorating effluent quality and soil chemical properties to better manage all soils as the terminal system for domestic effluent treatment, and these measures relate to the basic principles for EC, CEC, SAR, ESP, pH and soil texture analysis. Management ought to be part of these assessments.

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