



Validating laboratory assessment of threshold electrolyte concentration for fields irrigated with marginal quality saline-sodic water



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ABSTRACT

The use of marginal quality saline-sodic (MQSS) water for agricultural production is important in water limited environments and with a growing demand for food and fibre. Soil structural response to irrigation water quality is known to be a function of sodium contained in the irrigation water and the electrolyte concentration of that water. The threshold electrolyte concentration (C_{TH}) is classically used to determine the suitability of water to be applied to a soil, and is usually conducted as a laboratory analysis utilising saturated hydraulic conductivity. This work aimed to validate the laboratory based semi-empirical disaggregation model approach to C_{TH} against field soils where MQSS water had been applied for an extended period of time. Unirrigated locations proximal to long-term irrigation sites were paired to provide control conditions and the C_{TH} was determined. Reduction in hydraulic conductivity from the control was determined as both observed and predicted data. Results supported validation of the approach, indicating the disaggregation model as useful for proactive planning of irrigation systems with regard to water quality and a good measure for identification of MQSS water as a strategic resource. Applicability of the results to irrigation guidelines was discussed with particular focus on removal of generalised guidelines and identification of what constitutes tolerable hydraulic conductivity reduction.

1. Introduction

Marginal quality saline-sodic (MQSS) water is an important resource for agricultural irrigation, be it groundwater, or industry by-product water (Qadir and Oster, 2004). Such waters are generally high in Na, which may cause irreparable soil structural issues via the exchange and equilibrium processes that occurs between the soil soluble and solid phases (Ezlit et al., 2010; Raine et al., 2007; Rengasamy and Olsson, 1993). The ensuing instability of soil aggregates leads to clogging of pores, a reduction in soil hydraulic conductivity, reduced nutrient movement and eventual productivity decline (So and Aylmore, 1993). Where the electrolyte concentration (directly proportional to electrical conductivity; EC) is high enough to maintain the clay domain via osmotic compression of the diffuse double layer, the hydraulic conductivity and infiltration rate can be maintained to a reasonable extent, albeit still reduced compared to a Ca saturated system (McNeal et al., 1968; Quirk and Schofield, 1955; Shainberg and Letey, 1984). Therefore, the ability of soil to receive MQSS is a function of both the Na concentration and the EC.

Quirk and Schofield (1955) demonstrated that permeability of a soil irrigated with high sodium adsorption ratio (SAR) solution could be

maintained provided that the EC was sufficiently high. Notably, where Ca saturated clays were investigated, reduction in EC did not cause hydraulic decline, but maintained a relatively consistent clay platelet spacing, which they termed as a potential minima (absolute stability). On the other hand, the introduction of Na into the system resulted in gradual decline of hydraulic conductivity and was highly sensitive to reduction in EC. They subsequently defined the threshold electrolyte concentration (C_{TH}) as a 10% reduction in saturated hydraulic conductivity (rK_{sat}) from the absolute stability condition. Importantly, from the condition of absolute stability the clay domain gradually expands due to disaggregation processes (intracrystalline swelling and diffuse double layer development) approaching the threshold turbidity concentration (C_{TU}), which is beyond the C_{TH} and represents the aggregate–dispersion boundary. This insinuates that the rK_{sat} occurring up to the C_{TU} is due to somewhat reversible processes, as dispersion has not yet occurred, which was the premise of the disaggregation model of Ezlit et al. (2013) based on the work of McNeal and Coleman (1966). Ezlit et al. (2013) define the C_{TH} as $rK_{sat} = 20\%$ on the basis that departure from absolute stability occurs gradually with Na addition and that the reduction threshold needs to be beyond the measurement error in order to be a practical measure. This concept is applied for beneficial

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use of industry by-product water (Bennett et al., 2016; Bennett and Warren, 2015; Smith et al., 2015) and is applicable to agricultural water management (Agassi et al., 1981; Frenkel et al., 1977; Marchuk and Rengasamy, 2012; Menezes et al., 2014).

Of great importance is the fact that the C_{TH} is soil-specific (Bennett and Raine, 2012; Marchuk and Rengasamy, 2012; McNeal and Coleman, 1966). This implies that soil characteristics must be understood in order to properly predict the response of a particular soil to MQSS, meaning that modelling approaches based on water quality parameters alone, such as Mallants et al. (2017a) and Mallants et al. (2017b), have considerable potential to result in environmental harm for some soils. The ability to predict the soil-specific response to MQSS application does not yet exist, despite mathematical investigations (Mau and Porporato, 2015) and semi-quantitative clay mineralogical suite investigations (Bennett et al., Submitted). The semi-empirical disaggregation model (Ezlit et al., 2013) compromises between direct measurement of the C_{TH} and complete prediction, relying on rK_{sat} from small core experiments within the laboratory.

While there is some short-term evidence for laboratory C_{TH} assessment reliability in the field (Bennett et al., 2016), it would be desirable to produce a greater body of evidence for longer-term irrigated sites. Given that the C_{TH} varies with soil type, and that clay content (Frenkel et al., 1977; Goldberg et al., 1991; McNeal et al., 1968), clay mineralogy (Churchman et al., 1995), carbonates (Chorom and Rengasamy, 1997), iron oxides (Deshpande et al., 1964; Goldberg, 1989), as well as organic matter type and content (Nelson and Oades, 1998) are suggested to affect C_{TH} , irrigation with MQSS water under field conditions may have unexpected results. Field conditions are very rarely saturated, except within the very near surface during furrow irrigation (Raine et al., 2007), existing as unsaturated environments, which presumably would affect equilibrium conditions. Furthermore, the timescale of the semi-empirical assessment of C_{TH} occurs over a much shorter timescale than the evolution of field soil structure under irrigation with MQSS water and regional rainfall (Minhas, 1996). On this basis, the aim of this study was to validate C_{TH} laboratory assessment against soils that had been irrigated with MQSS water for multiple years.

2. Methodology

2.1. Experimental design

This work used uncultivated and unirrigated soil proximal to long-term cultivated and irrigation sites as the basis of comparison. The principal issue in validating the Ezlit et al. (2013) approach is that direct measurement under field conditions would require the saturated hydraulic conductivity to be assessed initially as a benchmark condition prior to an irrigation regime commencing and these points within a field tracked over multiple seasons. Field variability, compaction due to traffic, and shrink-swell structural conditions would all introduce vast error. However, the direct in-field comparison of uncultivated land to cultivated and irrigated land presents confounded conditions in terms of soil hydraulic network continuity and bulk density. For this reason, soils were sampled from either irrigated or unirrigated regions, homogenised (within region, not between region), and then brought back to the laboratory for comparison as reconstituted cores.

The unirrigated samples were used for C_{TH} assessment consistent with the method of Ezlit et al. (2013). Replicated subsamples (5) of each irrigated soil were wet to a nominal field capacity of -10 kPa using a hanging column and then subject to centrifuge drainage to obtain the soil solution at this suction, consistent with the method described in Bennett et al. (2016). These data were used to prepare field condition equilibrium treatment irrigation solutions. All soil samples were taken uniformly from 0 to 0.2 m to ensure the highly dynamic surface conditions (influenced greatly by small rain events) did not override the long-term unsaturated conditions. Additionally, irrigation water records over the lifetime of irrigation application were used to

produce a weighted mean water quality treatment; weighted in terms of poorest quality as a function of magnitude of application. The true equilibrium condition would lie between the field capacity and weighted mean irrigation water qualities. Hence, these treatments were used to generate a steady state saturated hydraulic conductivity and subsequently compared to the C_{TH} assessment of unirrigated soils to test the hypothesis and seek to validate the Ezlit et al. (2013) approach.

2.2. Soil selection and characteristic analysis

Eight cotton farms in southeast Queensland that had undertaken irrigation with marginal quality water were selected. From each farm, a sample was collected from the irrigated site, and a sample was also collected from a nearby plot that had never been irrigated. A total of 16 soil samples (two from each farm) were collected from a 0–0.2 m depth, air-dried and gently ground to pass a 2 mm sieve. Bulk sample to fill a 44 gallon drum was taken from throughout the field using the uniform sampling method to provide a representative sample.

Soil pH and electrical conductivity (EC) were determined in 1:5 soil:deionised (DI) water using a Radiometer analytical ION 450 m. Exchangeable cations were determined using a Perkin Elmer NexIon-ICP MS (Inductively Coupled Plasma – Mass Spectrometer). For exchangeable cations, the soluble salts were washed with deionised water and then the samples were extracted with 0.5 M NH_4Cl pH adjusted to 7.2 or 8.2 to match the pH of the soil analysed (Marchuk and Rengasamy, 2012). The extracted soluble cations were put through a centrifuge for 30 mins, and analysed on the ICP-MS to calculate SAR (Rayment and Lyons, 2011).

The tendency of clay colloids to disperse was assessed as electrophoretic mobility by use of zeta potential (ζ) measured using a Malvern Zetasizer (Marchuk and Rengasamy, 2012). For spontaneous dispersion in water, 1:5 soil:DI water suspensions were prepared and upended carefully three times. These were left to sit for 4 h before extraction of the suspended clay in solution and measurement of this via a Malvern Zetasizer. Turbidity (NTU) was also measured on this clay suspension using a NACH 2100N turbidimeter. The clay mineral suite was semi-quantitatively determined consistent with the methods presented in Marchuk et al. (2016) using the sedimentation method of Jackson (2005) for clay separation without addition of dispersing agents or chemical treatments (such as for organic matter or oxide removal). Interpretation of data was also consistent with Marchuk et al. (2016) using CSIRO software XPLOT for Windows (Raven, 1990) comparing the XRD patterns with the International Centre for Diffraction Data (ICDD) database of standard diffraction patterns using computer aided search/match algorithms.

All 5 soils had a two-component clay mineral suite of montmorillonite ($d \approx 15.8 \text{ \AA}$) and kaolinite ($d \approx 7.15 \text{ \AA}$) dioctahedral types (060 patterns not shown) in addition to accessory minerals anatase ($d \approx 3.52 \text{ \AA}$), hematite ($d \approx 2.70 \text{ \AA}$) and the primary mineral quartz ($d \approx 3.34 \text{ \AA}$). The quantitative estimation of clay phases for all 5 soils are presented in Table 1. Soils were generally Montmorillonite

Table 1

Mineralogical composition of clays (%) from XRD analysis. No difference between irrigated and unirrigated soils were evident in terms of mineralogy so a single suite is provided below per soil.

Soil	Montmorillonite	Kaolinite	Anatase	Hematite	Quartz
Soil 1	76	10	4	1	9
Soil 2	23	21	4	0	52
Soil 3	72	7	3	1	17
Soil 4	62	6	3	0	29
Soil 5	60	7	4	1	28
Soil 6	1	29	0	0	63
Soil 7	13	34	0	0	53
Soil 8	79	6	0	0	15

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