

SEASONAL SODIUM FLUX IN A WOODLOT SOIL IRRIGATED WITH SECONDARY TREATED EFFLUENT.

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Abstract

Previous research has shown woodlot soils receiving secondary treated effluent undergo an increase in Exchangeable Sodium Percentage (ESP) over time. Increased soil ESP influences micro-aggregate/soil pore stability and, particularly when subject to irrigation waters of specific low electrolyte concentrations, results in decreased soil permeability and a subsequent need to reduce application rates. The hypothesis is that sodium flux will directly alter hydraulic conductivity over time and if the range of seasonal sodium flux is too great, potentially dispersive conditions are more likely to occur. This study aimed to quantify seasonal sodium dynamics (flux) in a woodlot soil receiving secondary treated effluent in order to predict the effect variations in soil ESP and effluent/rainfall electrolyte concentration have on relative soil permeability. The principal outcome finds the seasonal sodium flux is greater than could have been previously recognized in other studies and that proven theories can be used to conceptualise a continuum for micro-aggregate/soil pore stability in the soil profile. This in turn can be used as a management tool for assessing relative permeability for soils receiving secondary treated effluent. The implication is that the prediction of potentially dispersive irrigation/rainfall events can be employed to direct and maximize effluent irrigation scheduling.

Additional Keywords: permeability, micro-aggregate stability, soil pore stability, continuum.

Introduction

Soil ESP influences micro-aggregate/soil pore stability (Cass and Sumner, 1982; So and Aylmore, 1993). Application of irrigation waters of specific low electrolyte concentrations, results in decreased soil permeability and a subsequent need to reduce application rates (Quirk and Schofield, 1955; Rengasamy *et al.*, 1984; Halliwell *et al.*, 2001, Quirk, 2001). It has therefore been necessary to implement strategies to remove excess sodium from the root zone to maintain optimum permeability of the receiving soil. To maintain the optimum, an understanding is needed of seasonal extremes in the sodium flux within the soil under irrigation conditions. The ability to define the sodium flux over time depends on the frequency of soil sampling and the ability to interpret the net loss/gain in soil sodium in relation to the applied hydraulic load. Past research has measured soil ESP on an annual basis, or longer, making it impossible to interpret seasonal sodium flux. This paper reports results from a two-year monitoring regime of the seasonal sodium flux in a woodlot soil receiving secondary treated effluent at Branxton, NSW. Every two months, soil samples were taken at designated sites and at different depths (10, 20, 40, 60 and 80 cm). These samples were analysed for exchangeable cations (Ca^{2+} , Mg^{2+} , Na^+ and K^+) and the ESP was calculated from exchangeable cation data. The net loss/gain of exchangeable sodium (as ΔESP) at different depths and times was compared with the cumulative soil moisture surplus/deficit (ΔSW) over time, where the ΔSW was based on water balance calculations. Volumetric soil moisture (θ) was also measured on a weekly basis. The impact of increasing sodium on soil structure is graphically described as a continuum, where soil ESP and effluent electrolyte concentration (as a Sodium Adsorption Ratio – SAR) must be taken into account when assessing irrigation scheduling and making soil management decisions. This appears to be the first time that sampling at this frequency, which enables the sodium flux to be determined, has been carried out.

Study Site

The Branxton Waste Water Treatment Works (WWTW) is located in the Hunter Valley, approximately 60km west of Newcastle, NSW (32°21'S, 151°21'E). The 1.32-hectare woodlot, to the south of the WWTW, has been receiving secondary treated effluent for approximately 12 years. The average root zone depth within the woodlot is approximately 1 m. The woodlot soil has received approximately 26.6 ML of effluent containing (on average) 107 mg/L sodium (Na^+) from January 2002 and October 2003. The soil can be described as a loamy clay sand, with an abrupt natric B-horizon containing a greater percentage of clay than the mildly leached A-horizon. Over the sampling depth of 80 cm, the depth to the B-horizon ranged between 20 and >80 cm. The soil can be internationally classified as an orthic Solonetz (FAO, 1974), or nationally by the Australian Classification System (Isbell, 1996) as a Brown (AB), Mottled – Hypernatric (FP), Magnesian (DB) Sodosol.

Methods

Four monitoring programs were devised: i) the water balance, to determine the cumulative soil water surplus/deficit (ΔSW); ii) θ , to validate wetting and drying trends over time for (i); iii) effluent/rainfall chemistry, to determine the “net” Sodium Adsorption Ratio (SAR) of the application waters; iv) the sampling and analyses of soil sites within the woodlot to calculate soil ESP and change in ESP over time (ΔESP).

Water Balance, Soil Water Surplus/Deficit (ΔSW) and the Sodium Adsorption Ratio (SAR)

The principle of the water balance used in this study was to prevent surface runoff and excessive groundwater leaching. The equation is as follows (EPA, 1995):

$$\text{Applied Effluent (Qe) + Precipitation (Qp)} \leq \text{Evapotranspiration (ET) + Runoff (R) + Deep Drainage (D)}$$

At the field site, an arbitrary point on the time scale was selected that represented the site when saturated. The equation was then re-arranged, which then became the soil water surplus/deficit (ΔSW). For example,

$$\Delta SW = ET + R + D - (Qe + Qp)$$

With respect to an irrigation scheme and rainfall measurement, the cumulative values for ΔSW plotted over time defined seasonal wetting and drying cycles of the soil profile. Studies by Quirk and Schofield (1955) showed that laboratory hydraulic conductivity was a function of the relative proportion of exchangeable sodium or of a related solutional parameter, the Sodium Adsorption ratio (SAR), whilst also developing the concept of “threshold concentrations” for micro-aggregate stability (Quirk, 2001). The Sodium Adsorption Ratio (SAR) was calculated from the following:

$$SAR = \frac{[Na^+]}{\sqrt{(Ca^{2+} + Mg^{2+})/2}}$$

The SAR of the applied effluent was sampled and analysed monthly for Ca^{2+} , Mg^{2+} , Na^+ and K^+ (in meq/L), which were determined by ICP-AES. The SAR of rainwater was also determined by similar methods and, using a simple mixing model, the net SAR for the application waters for any given day was calculated:

$$netSAR = \frac{CeVe + CpVp}{Ve + Vp}$$

where Ce is the SAR of applied effluent, Ve is the volume of effluent applied, Cp is the SAR of rainfall and Vp is the volume of rainfall. For example, if 20 mm of effluent (SAR = 10) was applied and rainfall was 10 mm (SAR = 1.0) on a given day, the resulting SAR of the total applied water would be 7.0 for that day. With respect to the monitoring frequency, this assumes the monthly variation in effluent/rainfall SAR is minimal. The net SAR versus time is presented during Results and Discussion and is used in conjunction with other site data and the continuum to identify dispersive conditions throughout the monitoring period.

Soil Sampling and the Soil Exchangeable Sodium Percentage (ESP)

A 50mm “cookie-cutter” type corer was used to sample the 10, 20, 40, 60, and 80 cm horizons at four sites, every two months throughout the monitoring period (February 2002 – October 2003). On each sampling occasion, the soil sample was taken within a two-metre radius of the initial site position and during the last week of each month. These sites were selected based on soil texture and horizon boundaries. Each soil site selected for long-term monitoring adequately portrayed the variability of textural classes within the study site. Analyses began immediately upon return to the laboratory, where samples were weighed, dried at 40^oC for 48 hours and then re-weighed to obtain the gravimetric soil moisture content. Each sample was then sieved at 2 mm to yield <2 mm and >2 mm fractions. The >2 mm was crushed to approximately 2 mm with a Jacques jaw-crusher and re-sieved at 2mm. The <2 mm then became the prepared sample for analyses. Soil samples were analysed using methods from Rayment and Higginson (1992), which included exchangeable cations (Method 15A1 - Ca^{2+} , Mg^{2+} , Na^+ , and K^+) and the exchangeable sodium percentage (ESP) (Method 15N1 - calculated from exchangeable cation data). Soil ESP was calculated from the following equation, where all units are in cmol/kg:

$$ESP = \frac{[Na^+]}{(\sum Ca^{2+}, Mg^{2+}, Na^+, K^+)} \times 100$$

Soil ESP values were plotted over the study period for each depth. The ΔESP represents the net loss/gain in ESP between soil sampling times. Micro-aggregate/soil pore stability was interpreted using the continuum based on the Threshold Concentration and Turbidity Concentration equations cited in Quirk (2001). Note that the SAR values involved in these equations are in fact converted soil ESP values, where it is commonly accepted that at values between 0 and 32, ESP and SAR are approximately equal (Quirk, 2001).

Volumetric Soil Moisture (θ)

Weekly θ measurements were obtained from nine access sites within the woodlot using a capacitance probe attached to an incremented staff and hand-held data logger. Field Capacity for each monitored depth was identified insitu, by manually saturating the area immediately around the capacitance probe access tube and logging the θ value. The θ values obtained for Field Capacity were also similar to peak values obtained to arbitrarily start this study (February 2002). As a result of monitoring nine sites between February 2002 and October 2003, the average of all sites monitored each week was plotted throughout the study period.

Results and Discussion

The results of this study are represented by the monitored outputs discussed previously, namely the ΔSW , θ , net SAR of application waters, soil ESP and ΔESP (Figures 1A, 1B, 1C, 1D and 1E respectively). Figure 1A shows the cumulative ΔSW , calculated on a daily basis between January 2002 and October 2003. In order to quantify the seasonal sodium flux, identified trends over selected periods will be described with respect to monitored trends in the θ , net SAR of the application waters and sodium flux (ΔESP). January 2002 is relatively unknown as no initial/boundary parameters were established. The initial/boundary condition was that of site saturation. Site saturation was observed in early February 2002 (see Figure 1A) where there was a surplus ΔSW ranging from 0 to approximately +100 mm and near maximum θ values for all depths to 80 cm (Figure 1B). The surplus hydraulic load was predominantly from rainfall, which had an SAR of approximately 1. The effluent had an SAR as high as 6 and the temporal variation between the two has consequences for soil permeability at a known soil ESP (refer Figure 2). The net SAR of the applied waters (effluent + rainfall) for any given day in the study period is shown in Figure 1C.

Soil ESP measured during the study period is shown in Figure 1D. Each column in Figure 1D represents a specific depth and is an average of four-soil sample sites within the woodlot. The 95% Confidence Interval (CI) for data in Figure 1D is shown in Table 1. Figure 1E shows the sodium flux (ΔESP) between successive soil sampling times using soil ESP data from Figure 1D. For example, the sodium flux between February 2002 and April 2002 is represented by the columns in April 2002 (Figure 1E), the sodium flux between April 2002 and June 2002 is represented by the columns in June 2002 and so on. The net loss/gain in soil ESP was assumed to infer the sodium flux for that period. Figure 2 shows the soil ESP/effluent SAR continuum for micro-aggregate/soil pore stability as referred to in this paper. Variations in this continuum have ramifications for soil permeability, thus the ability of the woodlot soil to receive irrigation at previously designed rates. This continuum represents a sliding stability envelope for the theoretical behaviour of clay particles in soils of known ESP, particularly the upper 10 cm, under applied waters of varying SAR values. The equations for defining critical stages in this continuum are shown in Figure 2, namely the Threshold Concentration (C_{TH}) and Turbidity Concentration (C_{TU}) (refer to Quirk, 2001).

After initial site saturation a decreasing ΔSW was observed between February and April 2002 in Figure 1A (from 100 mm to approximately -70 mm). θ values decreased at all depths in Figure 1B, although had increased to saturation by the end of April 2002. Irrigation was reduced in lieu of rainfall and for several weeks the net SAR was approximately 1 (Figure 1C). The relatively lower net SAR of the applied waters tends to push the continuum towards dispersion, thus decreasing soil permeability (Figure 2). Note that references to Figure 2 apply to the 10 cm depth only, as this is the initial contact boundary most susceptible to micro-aggregate/soil pore instability. Soil permeability was not directly measured, but was assumed to be lower as prolonged ponding occurred over approximately 0.3 hectares of the woodlot. Soil ESP values for February 2002 in Figure 1D increased with depth and ranged from 11 – 30%, although become the arbitrary zero readings for February 2002 in Figure 1E. Being highly soluble, soil sodium would be downwardly mobile with the relatively higher ΔSW and θ conditions present, although the first sodium flux value gained is not within this period.

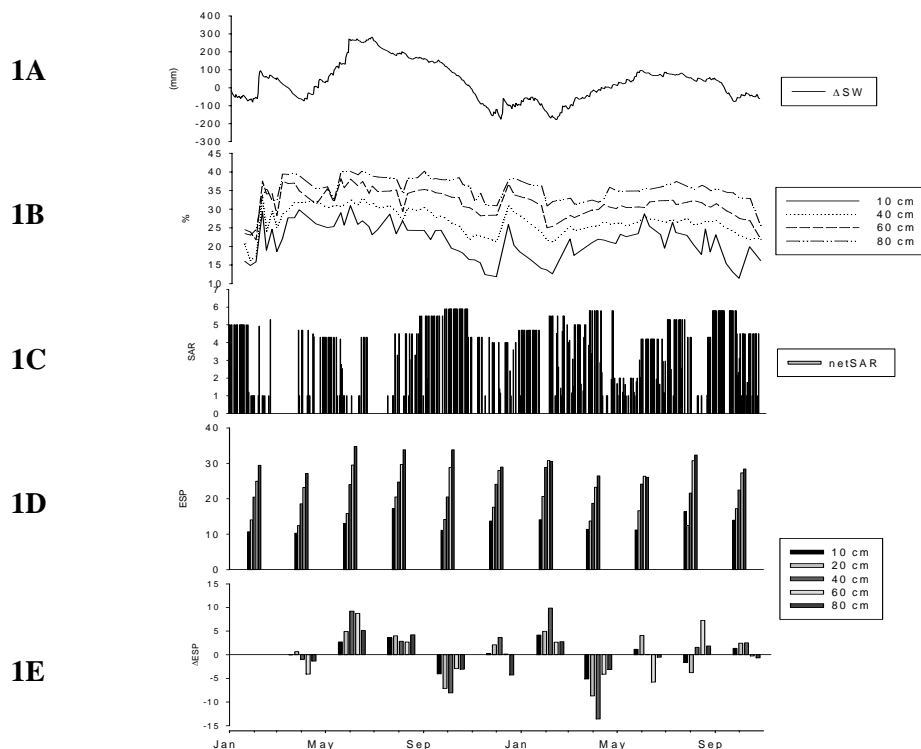


Figure 1. Monitored parameters versus time

Table 1 shows the 95% confidence interval (CI) for the data presented in Figure 1D, which highlights the inherent variability of all soils throughout the woodlot. Figure 2 represents the soil ESP/effluent SAR continuum for micro-aggregate/soil pore stability as referred to in this paper.

Table 1. 95% CI for soil ESP data in Figure 1D.

	DEPTH (cm)				
	10	20	40	60	80
Feb-02	5.1	8.6	10.2	13.2	9.3
Apr-02	8.6	10.2	13.2	9.3	5.1
Jun-02	10.2	13.2	9.3	5.1	17.3
Aug-02	13.2	9.3	5.1	17.3	13.3
Oct-02	9.3	5.1	17.3	13.3	9.4
Dec-02	5.1	17.3	13.3	9.4	11.3
Feb-03	17.3	13.3	9.4	11.3	8.3
Apr-03	13.3	9.4	11.3	8.3	4.2
Jun-03	9.4	11.3	8.3	4.2	12.4
Aug-03	11.3	8.3	4.2	12.4	17.9
Oct-03	8.3	4.2	12.4	17.9	18.8

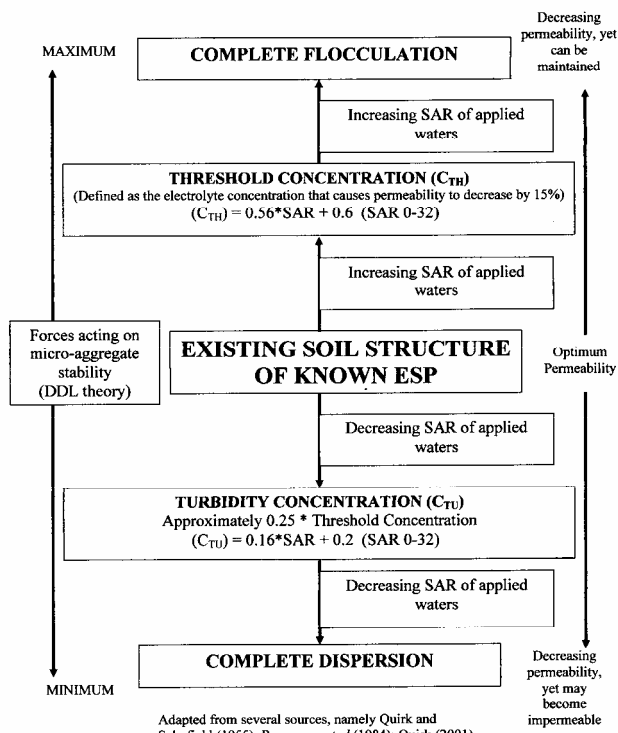


Figure 2. Soil ESP/effluent SAR continuum for micro-aggregate/soil pore stability.

In Figure 1A, the February to June 2002 period shows an increasing ΔSW that ranged from -80 mm to approximately 280 mm (maximum surplus for the monitoring period). Figure 2 shows that the θ ranged between 25 to 40 % for all depths, with the net SAR of the applied waters averaging approximately 4 (Figure 1C). At saturation, it would be expected that soil ESP would be decreased by leaching and according to Figure 1E this appears to be the case. The April 2002 ΔESP values show that soil sodium remained similar to February 2002 in the upper 10 cm, increased by approximately 1 % at 20 cm, whilst all other depths recorded some decrease (range -1.5 to -4 % in Figure 1E). Soil ESP data and the continuum (Figure 2) infer that an average net SAR value of 4 for the applied waters will prevent dispersion (\gg Turbidity Concentration), thus promoting micro-aggregate/soil pore stability and permeability. Whenever there is sufficient soil water present, highly soluble sodium will be hydrodynamically dispersed through moist interstitial pore space and in the direction of soil water movement (Shaw, 1994). Also, processes such as bioturbation and preferential soil water flow around tree roots enhance any advective solute movement through the soil profile (White, 1997).

Figure 1A shows a decreasing ΔSW (drying out period) between June 2002 and December 2002 that ranged from 280 mm to -110 mm. The θ ranged between 12 – 33 % throughout this period, with noticeable declines in the upper 40 cm. As a result of increased irrigation during October/November 2002, the net SAR of the applied waters averaged nearer to 4. At this time it would be expected that soil ESP would be increasing due to woodlot water use and evaporative concentration. Figure 1E suggests this, as a positive ΔESP occurs for two consecutive sampling periods (April 2002 - June 2002 and June 2002 - August 2002) (Figure 1E). The ΔESP shows that sodium increased at all depths and, summed from both soil-sampling periods, ranged from 7 to 12 %. During October/November 2002, additional irrigation was applied to encourage leaching of the accumulated sodium experienced during this period. Soil ESP data and the continuum (Figure 2) suggests that an SAR value of 4 will prevent dispersion (\gg Turbidity Concentration < Threshold Concentration).

An increasing ΔSW occurred as a result of increased irrigation after October/November 2002 (Figure 1A). The θ ranged between 14 – 40 %, with noticeable increases at all depths during December 2002 (Figure 1B). The net SAR of the applied waters averaged 4.6 (Figure 1C), therefore preventing dispersion (\gg Turbidity Concentration). Permeability at this time was assumed to be optimum since the θ for all depths increased within approximately three weeks of the rising ΔSW , inferring relatively rapid permeability to the sampled depth of 80 cm. Soil ESP would be expected to be decreasing if optimum permeability occurred. Figure 1E suggests this is the case, as a negative ΔESP occurred for the August 2002 to October 2002 period, ranging from -3.5 to -8 %. The October 2002 to December 2002 period experienced sodium accumulation at < 40 cm and leaching at lower depths.

From late December 2002 to mid February 2003, the ΔSW drops further into deficit (approximately -140 mm, the maximum deficit for the monitoring period). At all depths over the same period, the θ decreased by, on average, approximately 11 %. As a result of low ΔSW /low θ , the soil ESP would be assumed to be increasing. Figure 1E shows this to be true with ΔESP values ranging from 3 to 8 %. Irrigation was increased between late February 2003 and May 2003, which is reflected by the increasing ΔSW in Figure 1A and the slowly rising θ values in Figure 1B. Significant rainfall occurred during this time, although irrigation continued at a lower rate in an attempt to maintain a relatively higher net SAR to promote optimum permeability. The ΔESP ranged from -3 to -14 % for the February 2003 - April 2003 sampling period (Figure 1E) and represents the largest decrease for any two month period and subsequently for the entire monitoring period.

From April 2003 until October 2003 the ΔSW appears to mildly fluctuate into and out of surplus (Figure 1A). This would provide optimum conditions, that is, relatively high θ , relatively high ΔSW (slight surplus) and suitable net SAR of application waters, for promoting solute movement through the woodlot root zone. For the same period, the θ in the upper 10 cm is quite erratic; while lower depths appear to have remained relatively stable (Figure 1B). The net SAR of the application waters was approximately 2 during May/June 2003, whilst the 10 cm depth had a soil ESP of 11.5 % (see Figure 1D). Since the C_{TU} would be approximately equal to 2, then a decrease in optimum soil permeability would be expected (Figure 2). Although generally decreasing, the θ exhibits an erratic trend from July to late September 2003, particularly in the 10 cm depth. During this time, the irrigation system was experiencing problems and coupled with several intermediate rainfall events resulted in inconsistent application and the erratic nature of θ at 10 cm depth may reflect this (Figure 1B).

The interesting aspect of Figure 1E is that after irrigation, Δ ESP values displayed a cyclic loss/gain for the last three soil sampling periods (April 2003 – June 2003, June 2003 – August 2003, August 2003 – October 2003) (Figure 1E). Δ ESP data within these soil sample periods exhibit positive values for some depths and negative values for others. Positive Δ ESP for April 2003 – June 2003 (10, 20, 40 cm) became negative Δ ESP for June 2003 – August 2003, whilst the negative Δ ESP for April 2003 – June 2003 (60, 80 cm) became positive Δ ESP for June 2003 – August 2003. This infers sodium movement through the root zone, particularly from the < 40cm to the > 40 cm depths (Figure 1E). This could be a direct result of light rainfall events not permeating to lower depths, then being “piggy-backed” during successive irrigation episodes. If so, then this appears to show the sodium accumulation or leaching “front” moving through the root zone, the rate of which is governed by the slope of plotted Δ SW over time and validated by θ values.

Conclusions

The inherent complexity of monitoring soil ESP over time is due to the heterogeneous nature of the soil itself. In this study, an attempt was made to observe the sodium flux (Δ ESP) in view of the soil water deficit/surplus (Δ SW), volumetric soil moisture (θ) and the net SAR of the application waters. A high Δ SW/high θ /suitable net SAR of irrigation waters tends to provide optimum permeability of the receiving soil and reduce soil ESP, whilst a low Δ SW/low θ /unsuitable net SAR of irrigation waters tends to reduce permeability of the receiving soil and increase soil ESP. The maximum seasonal flux can occur over a four-month period and vary as much as 24 % (February 2003 – May 2003). The cyclic loss and gain of ESP (sodium flux) between most sample periods indicate that the woodlot soil regularly experienced optimum permeability conditions and/or efficient irrigation scheduling; meaning the leaching of sodium downward through the root zone was maintained. One limitation of Figure 1E is that many of the Δ ESP values lie within the 95 % CI from Table 2 and it may have been more beneficial if each soil site was assessed individually. The temporal variation in net SAR of the application waters ranged from 1.0 (indicative of rainfall only) to approximately 6.0 (indicative of effluent only) and using the continuum, provides evidence that some hydraulic application events are more susceptible to causing dispersive conditions than others, especially during frequent and intense rainfall. Overall, the net SAR values appeared to have maintained micro-aggregate stability, at least to the sampled depth of 80 cm, throughout the monitoring period. In addition, the continuum presented can be used as a management tool for irrigation scheduling and /or soil management decisions, particularly when variations in soil ESP or effluent SAR are anticipated.

Acknowledgements

The author would like to thank Phillip Geary (The University of Newcastle) and Russell Drysdale (The University of Newcastle) in appreciation of their time and comments during the length of this project, the Australian Research Council for funding the scholarship and the Hunter Water Corporation for allowing unfettered access to the sensory delights of the Branxton Waste Water Treatment Works and effluent irrigated woodlots.

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