Impacts of Applying Purified Recycled Water (PRW) in the Lockyer Valley, Qld: Soil Physical Assessment of PRW Application to Local Soils

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FOREWORD

Water is fundamental to our quality of life, to economic growth and to the environment. With its booming economy and growing population, Australia's South East Queensland (SEQ) region faces increasing pressure on its water resources. These pressures are compounded by the impact of climate variability and accelerating climate change.

The Urban Water Security Research Alliance, through targeted, multidisciplinary research initiatives, has been formed to address the region's emerging urban water issues.

As the largest regionally focused urban water research program in Australia, the Alliance is focused on water security and recycling, but will align research where appropriate with other water research programs such as those of other SEQ water agencies, CSIRO's Water for a Healthy Country National Research Flagship, Water Quality Research Australia, eWater CRC and the Water Services Association of Australia (WSAA).

The Alliance is a partnership between the Queensland Government, CSIRO's Water for a Healthy Country National Research Flagship, The University of Queensland and Griffith University. It brings new research capacity to SEQ, tailored to tackling existing and anticipated future risks, assumptions and uncertainties facing water supply strategy. It is a $50 million partnership over five years.

Alliance research is examining fundamental issues necessary to deliver the region's water needs, including:

- ensuring the reliability and safety of recycled water systems.
- advising on infrastructure and technology for the recycling of wastewater and stormwater.
- building scientific knowledge into the management of health and safety risks in the water supply system.
- increasing community confidence in the future of water supply.

This report is part of a series summarising the output from the Urban Water Security Research Alliance. All reports and additional information about the Alliance can be found at http://www.urbanwateralliance.org.au/about.html.

C. Davis

Chris Davis
Chair, Urban Water Security Research Alliance

CONTENTS

Acknowledgement i

Foreword ii

Executive Summary 1

1. Introduction 2

2. Water Quality and Soil Structural Decline 5

- 2.1. The Application of Purified Recycled Water to Soil 5
- 2.2. Methods for Measuring Soil Structural Degradation 6
- 2.3. Scope for Predicting Possible Structural Degradation 7
- 2.4. Managing Soil Structural Problems 8

3. Local Soil and Water Characteristics 10

- 3.1. Soils of the Lockyer Valley 10
- 3.2. Other Relevant Soil and Water Characteristics in the Lockyer Valley 11

4. Laboratory Tests 13

- 4.1. Emerson Test 13
- 4.2. Mechanical Dispersion 13
- 4.3. R1 Dispersion Ratio 14

5. Discussion and Conclusions 16

References 18

LIST OF FIGURES

Figure 1: The application of rough guides for the suitability of irrigation water (Ayres and Westcot, 1985; left) and the susceptibility of soils to structural degradation (Rengasamy, 2002; right). Here we have plotted soil and water chemistries from the Lockyer Valley within the SAR and EC parameter spaces. L and B refer to Laws and Blenheim soils, respectively, and subscripts 'sur' and 'sub' indicate surface and subsoil, respectively. 8
Figure 2: The five water qualities tested (from left to right – PRW, Voigt bore, University of Queensland bore, Logan Dam and Milli-Q deionised); and clarified Logan Dam water after passing through a 0.45μm filter (right). 12
Figure 3: Emerson dispersion test of four soils (rows) x five waters (columns): air dry small (0.55 – 0.60 g) peds (left); slaked, 2 minutes (centre); and 23 hours after emersion in distilled water. Slaking was observed but no dispersion. The colour associated with the Logan Dam water existed prior to the test (see Figure 2). 13
Figure 4: Samples of the four soils (rows) x five waters (columns) showing settling four minutes (top left), 10 minutes (top right), one hour (bottom left) and 22 hours (bottom right) after agitation. 14
Figure 5: Modified R1 results for the four soils x five waters. Error bars show one standard deviation both sides of the mean of four replicates; numerical labels indicate the EC of each water. 15

LIST OF TABLES

Table 1: Clay mineralogy of some soils of the major stream terraces and plains. 10
Table 2: Summary of analytical data for soils of the stream terraces and plains. 11
Table 3: Chemical properties of the four soils sampled for this study. 11
Table 4: Chemical properties of the five waters used in laboratory experiments and an additional five waters from the Lockyer irrigation district. 12

EXECUTIVE SUMMARY

Increasingly, urban wastewater is being recycled after purification. Disposal or reuse of the water can occur via irrigation or aquifer recharge. It has been proposed that purified recycled water (PRW) be made available to augment irrigation presently based on groundwater and captured surface water in the Lockyer Valley, approximately 80 kilometres west of Brisbane.

The Lockyer Valley is a highly productive area of horticultural, grain and forage crops. Soils are typically deep clays, largely self mulching, with some classified as slightly to moderately sodic, but not spontaneously dispersive. There is some evidence, however, of susceptibility to mechanical dispersion that may be induced by overhead irrigation or raindrop impact. The groundwater quality varies from low to moderate salinity and the surface water is typically of high quality.

This report addresses the possible effects on soil structure of the use of PRW for irrigation and shows that chemistry governing these effects is complex and varied. It is dependent on the chemistry of the soil, the irrigation water, the irrigation history and method of application. The exact effects are therefore difficult to predict.

Our measurements of likely clay dispersion are somewhat inconclusive. However, we consider what might be the worst-case scenario (overhead irrigation following a history of saline groundwater application) and estimate what measures could be taken to ameliorate the effects.

There is likely to be only a small risk of soil structural degradation from the use of PRW for irrigation in the Lockyer Valley. Given that the PRW is very pure, it is likely that any soil structural problems that occur will not differ significantly from those that are reported to occur following rainfall on slightly sodic soils that have previously been irrigated with saline water.

The related rainfall-induced problems have been managed successfully by farmers for some time. There is no reason to believe they would not be able to manage any effects caused by the application of PRW.

1. INTRODUCTION

The water supply security of South East Queensland (SEQ) has been increased by the provision of advanced wastewater treatment plants for potential indirect potable reuse of effluent from urban areas. With a maximum combined production capacity of 232 million litres of purified recycled water (PRW) a day, the Western Corridor Recycled Water Scheme is the third largest recycled water scheme in the world and the largest in the southern hemisphere (Traves *et al.*, 2008).

An option currently being explored by government agencies and the Water Grid managers is to supply approximately 15-25 Gigalitres per year (GL/yr) of PRW to augment the groundwater resources of the Lockyer Valley, approximately 80 kilometres west of Brisbane.

The productivity of clay soils can depend heavily on their macro structure, which affects water entry, water movement and the growth of plant roots. Some soils are predisposed to structural degradation when exposed to raindrop impact, tillage or the application of irrigation. These changes can range between slight (a lowering of productivity, requiring careful management) and severe (complete, irreversible collapse of structure and loss of productivity). It is important, therefore, to be aware of any potential problems associated with the application of water of varying quality to soils that might be predisposed to degradation. At the root of such problems is the clay chemistry, the chemistry of the irrigation water, and combinations of the two.

The chemistry of clay and the attendant physical ramifications are complex. Most of the relevant chemistry pivots around the relative abundance of the sodium cation Na+, and its ability to displace calcium and magnesium cations (Ca2+ and Mg+) in the clay mineral interlayers. Other ions can be involved but these are the main players. Because of the pivotal role of the sodium ion, the term 'sodicity' is used to describe the extent to which a soil is predisposed to chemical and physical changes. Further, because of the role of the sodium ion, the salinity of the soil (measured by the electrical conductivity, or EC, as a proxy for salinity in a 1:5 soil:water extract), and the salinity of any applied water (direct measurement), are used to assess the mechanical behaviour of clay soils.

By structural degradation, we generally mean a change in structure resulting in a lowering of pore volume and accompanying properties such as infiltration, hydraulic conductivity on wetting (thus changing local hydrology and water balances), and an increase in soil strength on drying (affecting tillage, seedbed preparation, seedling emergence and plant root growth). Structural degradation is often associated with a reduction in hydraulic conductivity. At high EC, the structural change is typically soil swelling; at low EC it is typically dispersion (Quirk and Schofield, 1955; Emerson and Bakker, 1973).

Slaking and dispersion are the main processes by which soils lose their structure on wetting. Slaking results from the rapid wetting of soil aggregates and the associated explosion of entrapped air and differential swelling of micro aggregates (Ruiz-Vera and Wu, 2006). This is a mechanical process rather than chemical, but pathways for water movement can be blocked by mobile particles or micro-aggregates. Dispersion is the chemical dissociation of clay particles into suspension, the blocking of pores and the collapse of micro and macro structure. Dispersed soil typically sets hard on drying. This tends to be irreversible without chemical intervention such as the addition of ameliorants (e.g. gypsum; calcium sulphate). Clay dispersion can occur spontaneously (as the clay wets) or only as a result of mechanical disturbance such as rain drop impact, tillage, wheel traffic or trampling by livestock. Swelling, on wetting, is another process of soils with high clay content and is a predecessor to dispersion, but is reversible on drying and structure is typically maintained.

Clay soils, because of their fine particle size (<0.002 nm), plate-like shape and large surface area are chemically very active. Clay particles are principally phyllo-silicates and plate-like in shape. They have a residual negative charge and therefore hold positively charged ions (cations) between them. The space between clay particles is dependent on the distribution of electrostatic charges between the particles, called the 'diffuse double layer'. The full complement of forces acting at the clay particle scale are myriad and complexly related and cannot be fully described here, but we recommend the work of Quirk and Murray (1991) for a detailed account of these.

Because of the different mineralogies, some clays are more reactive than others. Laird (2006) gives a detailed description of the diffuse double layer in montmorillonite, one of the dominant minerals of the vertosols on the Lockyer Valley, but we provide here only a very brief description of the governing principles. The attachment of cations to clay particles is a result of the balancing forces of electrostatic attraction towards, and diffusion away from, the particle surfaces. The former is related to the size (valence) of the charge of the cation and the latter is related to the osmotic pressure within the soil solution, i.e., the tendency for ions to migrate away from the particles and into solution. A simplistic view of 'sticking' of particles together, therefore, occurs as two (or more) negatively charged clay particles 'sandwich' and 'share' a distribution of cations. The thickness of the double layer is inversely proportional to the salinity of the soil water solution (measured as EC in decisiemens per metre (dS/m)), and inversely proportional to the square of the charge on the neutralising ion. If the dominant cations are Ca^{2+} and Mg^{2+}, the particles are held together much more strongly that if Na^{+} is dominant. This 'propensity' to dispersion is typically expressed as the exchangeable sodium percentage (ESP) (see Equation 1), or the sodium adsorption ratio (SAR) (see Equation 2).

$$ESP = \ (100 \times exchangeable\ Na))/(\Sigma [(exchangeable] \ \ Ca + Mg + Na + K + Al)) \tag{1}$$

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

Where

[ ] signifies concentrations in mmolc/L.

ESP and SAR can be easily related under a wide range of conditions (Qadir and Schubert, 2002). ESP is often used to categorise a soil's 'sodicity'. Helliwell *et al.* (2001) points to the work of Sumner (1993) for rough guidelines for labelling a soil as 'sodic': in Australia, soils with ESP ≥ 5; in USA, soils with ESP ≥ 15, because a higher EC tap water was used for the ESP determination.

An alternative index is PAR (or KAR; similar to Equation 1), which can be used where the dominant monovalent cation is potassium K^{+}. A more encompassing index, monovalent cation adsorption ratio (MCAR) (Smith and Smiles, 2004) can be used, which is the summation of SAR and PAR. Jaywardane *et al.* (2011) describe the previously undocumented index of Rengasamy (unpubl.), CROSS, which accounts for the relative flocculating powers (or inverse dispersive powers) of the major ions. They found this to be a more useful indicator for relative change in hydraulic conductivity with change in electrolyte concentration, but this is only half the story.

It is these indices, in combination with the water SAR, that determines whether or not soil structure degrades. In most cases, SAR can be related to EC, as Na^{+} is typically the dominant ion. The more saline the water, the less likely is dispersion as osmotic pressure is greater. Hypersaline water is typically clear, as all sediment will flocculate and settle. In addition, because there is no clear threshold between coagulation and spontaneous dispersion, there exists a continuum ranging from non-dispersive, tendency to disperse, to spontaneously dispersive. Soils that do not spontaneously disperse can become dispersive when mechanically disturbed, for example, by raindrops.

Despite myriad studies and reviews on this topic, it is difficult, even for experts, to predict structural changes in clays for specified clay and water chemistries. Indeed, there are numerous indices for estimating the risk of structural degradation if water of a given salinity is applied to a given soil, and all are indicative only, e.g. Ayres and Wescot, (1985) and Rengasamy (2002). As a starting point, Helliwell *et al.* (2001) provide a succinct background on the issues of concern to us here – the use of recycled water for irrigation.

We are interested, in particular, in the likely effects of the application of PRW to sodic soils in the Lockyer Valley. The PRW, compared to most recycled effluent, has a very low EC (0.2 dS/m, compared to local groundwater of up to about 6 dS/m) and low SAR (2.7, compared to local groundwater, up to 32). The soils of interest have SAR ranging between 0.02 and 0.33, with ESP between 0.4 and 4.5% and EC (1:5 water) between 0.4 and 4.5. Below, we list and attempt to address the following topics:

Water quality and soil structural decline

- Reported detrimental impacts following application of desalinated water to soil
- Methods for the measurement of structural degradation
- The scope for predicting possible structural degradation
- Managing soil structural problems

Local soil and water characteristics

- Soils and their distribution in the Lockyer Valley
- Relevant soil and water characteristics in the Lockyer Valley

Laboratory tests

- Spontaneous dispersion test
- Mechanical dispersion test
- R1 dispersion ratio test

Discussion and conclusions

- The likely effects of the application of PRW to Lockyer Valley soils

2. WATER QUALITY AND SOIL STRUCTURAL DECLINE

2.1. The Application of Purified Recycled Water to Soil

There is a very rich body of literature on the, often unwanted, effects of irrigation on sodic soils and several sub topics. For example: sodic soils (Sumner, 1993); irrigation and sodicity (Rengasamy *et al.*, 1992); clay dispersion (Rengasamy, 2002); soil salinity and sodicity (Rengasamy, 2006). Jaywardane *et al.* (2011) look in greater detail at the effects of cation (positively charged ion) combinations on the hydraulic conductivity of soils. There are useful reports on the effects of effluent or recycled water to agricultural soils. Helliwell *et al.* (2001) review the effects of the main player, sodium, when irrigating with wastewater; Balks *et al.* (1998) document the effects of sodium accumulation following irrigation with effluent; Sepaskhah and Sokoot (2010) and Bhardwaj (2008) specifically address the effects of dispersion on saturated hydraulic conductivity. Hulugalle *et al.* (2006) specifically deal with changes in an Australian vertosol following effluent irrigation and Steven *et al.* (2003) discuss the potential dangers of irrigation with saline and high SAR water on the northern Adelaide Plains. As discussed in the introduction, structural degradation can be exacerbated by mechanical disturbance and this can lead to surface sealing and reduced infiltration (Shainberg *et al.*, 1992; Ben-Hur *et al.*, 1998; Pilatti *et al.*, 2006). For a comprehensive review of the interactions of clays, sodicity and salinity and their effects on soil structure and water movement, we recommend to readers the thesis of Ezlit (2009).

However, there is relatively little mention in the literature of the effects of the application of PRW for irrigation. Lahav *et al.* (2010) cite specific problems related to the use of desalinated seawater for use in irrigation, which, particularly with high SAR, can lead to soil dispersion and the associated structural and hydrologic problems. Yermiyahu *et al.* (2007), however, lament the nutrient deficiency of desalinated seawater – useful ions and micro nutrients are removed in the demineralisation process just as effectively as the undesirable ones, and the authors urge that water purification guidelines be reassessed. Tarchitzky (2004) provides a brief review of the potential damage to soil and crops by irrigation with recycled waste water; included in these are sodicity and hydrophobicity. Leaching of clay fractions through the soil profile is another potentially damaging result of irrigation of sodic soils. In a coarse soil type, clay can be dispersed from upper layers (which then become depleted and infertile) and can lead to clogging of lower layers, restricting water movement (Warrington *et al.*, 2007).

Several studies have dealt with possible effects on soil chemistry and structure with the rate of change in the quality of irrigation water. The application of PRW following irrigation with more saline groundwater could cause structural breakdown in sodic clays. The studies most relevant for us here highlight the importance of the irrigation history and the abruptness of changes in the chemistry of irrigation water. Although conducted in coarse textured soils, Keren and Ben-Hur (2003) leached highly sodic soil columns with solutions having gradually decreasing concentrations of calcium carbonate (from 500 mmol/L), down to deionised water (gradual leaching). In this case, hydraulic conductivity decreased gradually to a steady state value and there was no dispersed clay observed in the leachate. This was contrasted with another test with an abrupt change in calcium carbonate from 50 mmol/L directly to deionised water (abrupt leaching), which resulted in a larger reduction in hydraulic conductivity and dispersed clay was observed in the leachate.

Bauder *et al.* (2008) undertook wetting and drying tests with saline and sodic water, followed by leaching with distilled water to simulate a rainfall event. The study reinforced the supposition that rainfall following irrigation with saline water can lead to dispersion in clay soils. Investigation of the behaviour of Na and Ca in the exchange complex showed lower hydraulic conductivity (and more dispersed clay in the leachate) in separate soil columns with progressively lower EC leaching water, and SAR of 15 (Dikinya *et al.*, 2007). Erratic changes in hydraulic conductivity were interpreted as the breakdown of macrostructure and ped swelling. Suarez *et al.* (2008) investigated the effects of irrigation waters with SAR 2, 4, 6, 8 and 10 $mmol^{1/2}/L^{1/2}$ and EC 1 and 2 dS/m, alternated with simulated rain (deionised water – 0.016 dS/m – from a sprinkler). The authors described in detail the effects on the increasing SAR on reducing soil hydraulic conductivity. Although alluding to the effects of subsequent “rainfall” of low EC exacerbating dispersion, this issue is not explored as fully as we would hope.

In summary, there are abundant reports of the deleterious effects on the structure of sodic soils following the application of sewage, wastewater and treated wastewater. Some of these effects are attributed to mechanical blocking of pores by suspended solids. Most of the effects are related to combinations of soil ESP and the (low) EC and/or (high) SAR of the applied water. There are a small number of studies describing surprisingly poor results from applying desalinated seawater to agricultural soils. One study reports nutrient deficiencies in plants due to the highly demineralised water; another report warns of potential soil structural decline from irrigation with low EC but high SAR water. We found no reports of the use of PRW of the very high quality (potable) that we are dealing with in this study, being applied to sodic soils. There are a small number of studies which confirm the potential dispersion of sodic clays on application of distilled water, which have previously experienced irrigation with a higher EC. The authors point to this as evidence that rain events could cause dispersion in these cases. In fact, we have observed and there is also anecdotal evidence for, exactly this result in the Lockyer Valley. We note that the application of distilled water (probably with EC <0.01 dS/m) might be an approximation of the effects of the application of PRW, in these cases.

2.2. Methods for Measuring Soil Structural Degradation

Good soil structure implies the existence of peds, crumbs and pores and the associated interstices that allow the passage of water and nutrients and the growth of plant roots. As discussed above, at the heart of this structure is the chemical bonding of clay particles and, in particular, that related to the exchange of sodium, calcium and magnesium ions between clay particles and the soil water solution.

Structural degradation begins with the swelling of clays (as particles become less tightly bound to each other) and ending in the disintegration of groups of clay particles. The most direct measurements of structural degeneration are, therefore, measurement of (changes in) hydraulic conductivity, surface hydrology (e.g. infiltration; overland flow) or both. Overland flow on degraded soils necessarily results in surface erosion.

Experts in this field will generally agree that the ‘best’ measurements will be those made on undisturbed soils during a rainfall or irrigation event (Suarez *et al.*, 2008). While such studies are undertaken, the practical difficulties and the large resources required make them relatively rare. Some of the most extensive and famous uses of large scale field rainfall simulation have formed that basis for the widely used USLE erosion index (Wischmeier and Smith, 1965; 1978). Although not the central objective, such studies often measure Hortonian overland flow (Horton, 1933), which can result (although not necessarily) from structural degradation at the surface.

Ellis *et al.* (2006) describe the use of a 60 m^2 rainfall simulator to measure overland flow and (Leguédois *et al.*, 2008) describe the effects on sediment transport, partly from structurally degraded zones. However, rainfall simulators need not be so large and can provide useful answers when only a few m^2 in size, e.g. Colloff *et al.* (2010). Lysimeters can also provide opportunity for measurements of soil structural transitions (Warrington *et al.*, 2007). Rainfall simulators can be constructed in laboratories but, at this scale they are invariably applied to disturbed soil samples, e.g. Hairsine *et al.* (1999).

Wet sieving of aggregates - typically on disturbed samples - gives a measure of aggregate break down under the action of mechanical disturbance by water, e.g. Hignett *et al.* (1995), applied by Ellis *et al.* (submitted). This can result from slaking or dispersion and, in the latter case, the results are typically spectacular. Soil columns lend themselves much better to controlled laboratory experiments and can similarly be used to measure aggregate break-down under rainfall (Legout *et al.*, 2005) In the context of structural degradation and clay dispersion, columns are typically used to measure the change in saturated hydraulic conductivity (K_{sat}) of disturbed samples (Dikinya *et al.*, 2007; Sepaskhah and Sokoot, 2010; Browning *et al.*, 2007; Bauder *et al.*, 2008), but occasionally undisturbed cores are used, e.g. (Balks *et al.*, 1998). Detailed descriptions of methods for hydraulic conductivity measurement can be found in McKenzie *et al.* (2002) and Bond *et al.* (1998).

2.3. Scope for Predicting Possible Structural Degradation

Because the above field and laboratory measurements of the effects of structural degradation are laborious, specialised and costly, there have been various attempts to develop easily applied indices to quantify the propensity of a soil to clay dispersion. Emerson (2002) provides a contemporary account of his original dispersion indices devised for assessing the suitability of clay soils for building foundations. The Emerson tests fall into two categories: 1) the introduction of air-dry peds to distilled water to observe any spontaneous slaking or dispersion; and 2) the remoulding of wet peds and reintroduction to distilled water to test susceptibility to mechanically induced dispersion.

Rengasamy (1984) developed a less direct but more quantifiable method for measuring the amount of clay in suspension following agitation, compared to the amount of clay in suspension from complete chemical dispersion - see Wöbcke (2009) for the methodology. Rengasamy (2002) described several categories of structural degradation and used this to 'map' zones in the EC – SAR (of the soils) space which can be used to approximate the risk of dispersion in clays. A similar exercise was previously undertaken by Ayres and Westcot (1985a and b) to characterise water chemistry that is likely to cause structural problems on irrigated soils.

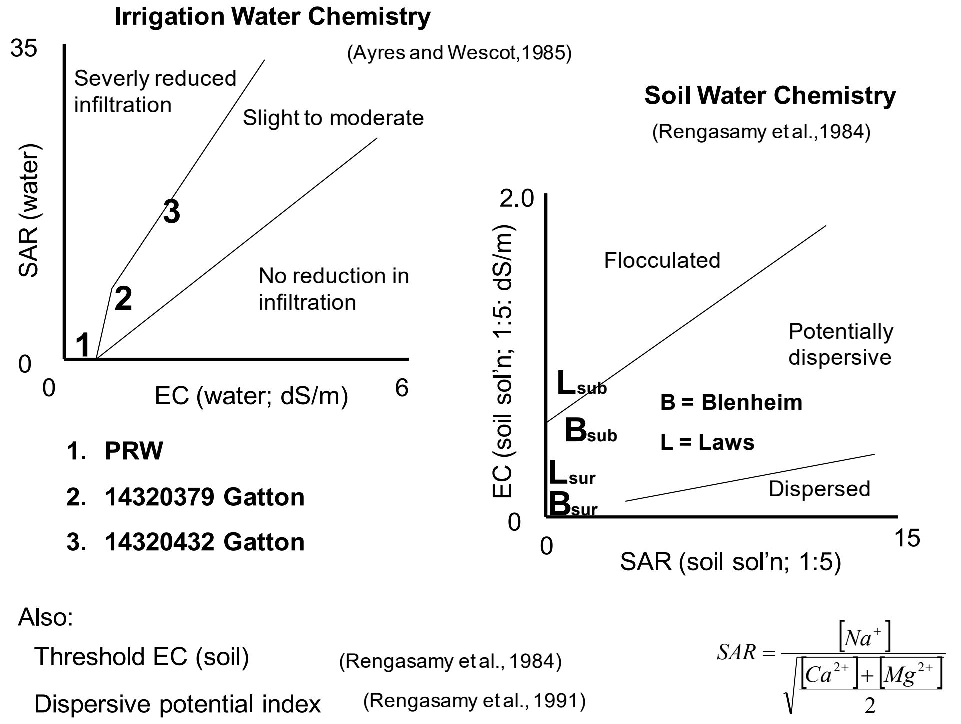
Suarez and Simunek (1997) in their model HYDRUS 1D, use a model, based on the clay swelling model of McNeal (1968), to predict changes in saturated hydraulic conductivity K_{sat}, with changes in water chemistry, for a given soil chemistry (SAR-EC-K_{sat} parameter space). Ezlit (2009) evaluated this model with soil column tests in the laboratory and showed it performed poorly for a vertosol and a sodosol (Isbell, 1996). In an attempt to better quantify all the variables, and to provide more specific guidelines for the use of saline mine effluent, Ezlit (2009) provided a modified version of the model but also found it performed rather badly, possibly because of the lack of representation of the role of pH. Raine et al. (unpublished) used similar investigations of the SAR-EC-K_{sat} parameter space and produced a 3-dimensional surface for each soil, from which they arbitrarily chose a contour in the SAR-EC plane representing K_{sat} equal to a 20% reduction from that determined using a 'normalising' solution of calcium chloride. The 20% value was possibly adopted from Quirk and Schofield (1955), who defined a threshold electrolyte concentration at which a 20% reduction in hydraulic conductivity occurs, for a given ESP. The new relationships were then provided to the clients to guide decisions concerning the limits to SAR and EC combinations of the effluent water that could be applied to the soil without causing structural damage. This allowed estimates of the most appropriate 'shandies' of effluent water of different qualities for irrigation.

As discussed above, the 'proof of the pudding is in the eating'; and the predictor of the effects of combinations of specific water and soil chemistries is to apply the water that will be used to the soil in the field. What is consistent among the above studies, and the opinions of other experts, is that indices of dispersive behaviour can only be described as 'rough guides' and that the exact behaviour of specific soils in the presence of specified water chemistry is very difficult to predict (Helliwell *et al.*, 2001).

The Australian guidelines for the use of recycled water (http://www.ephc.gov.au/taxonomy/term/39) specify in general terms that the appropriate application of wastewater for irrigation must take into account any potential damage to soil structure. However, only general guides such as those of Ayres and Westcot (1985) are cited.

Quirk (2001) also observed a widely held misconception that the EC required for flocculation of dispersed clay is the same as the EC required to maintain structural integrity of a soil. This is largely due to the dispersion process involving the face-to-face swelling and separation of clay particles, whereas flocculation involves end-to-face attraction and coagulation. These processes are quite different, involve different forces and are not the inverse of each other.

Overall, changes in soil structure and hydraulic properties are very difficult, if not, impossible, to predict with our current knowledge. The best available and practically applied information for our purposes include the 'guides' produced by Rengasamy (2002) and Ayres and Westcot (1985), although there are others. Figure 1 provides some guidance regarding: 1) the likely risks of applying local groundwater and PRW to soils in the Lockyer Valley (Ayres and Westcot, 1985a); and 2) the propensity of some Lockyer soils to disperse (Rengasamy, 2002). The approximate nature of these guides augers badly for any precision regarding the prediction of the effects of specific combinations of soil and water.



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

Figure 1: The application of rough guides for the suitability of irrigation water (Ayres and Westcot, 1985; left) and the susceptibility of soils to structural degradation (Rengasamy, 2002; right). Here we have plotted soil and water chemistries from the Lockyer Valley within the SAR and EC parameter spaces. L and B refer to Laws and Blenheim soils, respectively, and subscripts 'sur' and 'sub' indicate surface and subsoil, respectively.

We also describe, in the second part of this study, Emerson (2002) and modified Rengasamy (Rengasamy *et al.*, 1984) tests on Lockyer soils undertaken in an effort to predict the likely effects of applied PRW. There are other complicating factors surrounding the presence and type of organic matter, but this typically does not improve structural reactions at the clay particle scale. The best use for organic matter in preventing structural degradation is for protecting the soil surface from raindrop impact, although some improvements due to biological activity have been noted (Valzano *et al.*, 2001). Moreover, we have really only considered soil changes under saturated conditions. Under unsaturated conditions, results are even less predictable because of the changes in pore size distributions.

2.4. Managing Soil Structural Problems

The best management of potential soil structural problems is avoidance. That is, avoid potentially troublesome chemistries of irrigation water (i.e. SAR/EC ratios; Ayres and Westcot, 1985) or potentially problematic soil chemistries (i.e. EC/SAR ratios; Rengasamy (2002). We note, again, that there are not, and not likely to be, any simple guidelines for predicting the effects of combining specific soils and waters.

The second most important strategies are to avoid mechanical disturbance on the soil in a moist or wet state. The mechanical energy of raindrop impact significantly increases the risk of clay dispersion and structural break down in all soils, but is most pronounced in sodic soils. The only methods available to farmers for doing this is to ensure that soil surface is covered, as much as possible, by stubble or crop residue, to absorb the energy of raindrops. It follows that overhead irrigation similarly increases the risk of mechanical dispersion and that soil cover should be optimised. We note, however, that many of the horticultural husbandries in the Lockyer Valley require fine tilth and 'clean' seedbeds, and are not conducive to maintaining soil cover. Similarly, soil disturbing actions (e.g,. tillage; wheel traffic; animal traffic) should also be minimised and especially avoided on wet soil. Chemical methods such as the application of calcium sulphate (gypsum) prior to rainfall or irrigation (Brinck and Frost, 2009) - or in fact dissolved in the irrigation water - increases the opportunity for Ca^{2+} to occupy sites on clay particles, rather than Na^{+}.

Our principal concern in this study is the possible effects of the application of the low EC, low SAR PRW to sodic soils, previously irrigated with saline groundwater. The EC of the groundwater counteracts, to some extent, the diffusion (via osmotic forces) of ions away from clay surfaces and allows the electrostatic attractive forces to be more persuasive, and binds the clay particles. If PRW were to be applied, there would be a risk of the reduced EC of the soil solution increasing osmotic forces, leading to clay swelling and dispersion. We have not applied PRW in field experiments in the Lockyer Valley, however this is supported by observations of clay dispersion on sodic soils following rainfall (particularly summer storms; Craig Henderson, pers. comm.) and the application of low EC surface-harvested irrigation water. It is interesting, however, that at least one farmer in this situation uses the low EC surface water for irrigating early growth stages of crops (particularly beetroot) before reverting to irrigating with higher EC groundwater, as beetroot plants are tolerant of this in later growth stages. This is counter to the expectation that the low EC water is more likely to cause crusting and seedling emergence problems – apparently in this particular situation it is not of concern.

There are anecdotal reports that some farmers manage the potentially deleterious effects of low EC water on their sodic soils by blending or 'shandying' surface water with groundwater (Ashley Bleakley, pers. comm.). If this method is successful, it is likely that it could also be used to reduce any deleterious effects produced by PRW.

3. LOCAL SOIL AND WATER CHARACTERISTICS

3.1. Soils of the Lockyer Valley

Powell *et al.* (2002) provide a comprehensive description of landforms and assessment of the suitability of soils for irrigation on the Lockyer alluvial plains (Quaternary alluvium). Of major interest agriculturally are the mainly black and brown cracking clays and gradational clay-loams. Of specific interest to this study, because of their location with respect to delivery points for PRW, are the soils of the “major stream terraces and plains”, particularly ‘Blenheim’:

> *Dark self mulching, cracking medium to heavy clay with dark, brown or grey calcareous subsoil to 1.5 m deep or over medium to heavy clay palaeosol.*

and ‘Laws’:

> *Dark self mulching, cracking medium clay with dark or brown calcareous subsoil to 0.1 to 1.4 m deep over brown friable lighter textured layers.*

soil classes, as defined by Powell *et al.* (2002). These soils are dominated by smectitic clays, which are responsible for their swelling and cracking nature. X-ray diffraction analysis undertaken during this study confirms this mineralogy. Table 1 gives the clay mineralogy of the four soils samples (a, b, c and d) of interest from the major stream terraces and plains.

Table 1: Clay mineralogy of some soils of the major stream terraces and plains.

Soil	Quartz	Goethite	Hematite	Kaolin	Smectite[1]	Augite	Anorthite/ Andesine	Magnesite
(a) DPI Gatton Laws soil	CD		T	T	CD		CD	T
(b) Super Sat site Blenheim soil	SD		T	M	D	T	SD	T
(c) Forrest Hill “sodic” site Blenheim soil	SD		T	T	CD	M	CD	T
(d) Forest Hill 0805 0806 Blenheim soil	CD		T	T	CD	T	SD	T

Note: D, CD, SD, M and T denote dominant (>60%), co-dominant (sum of components >60%), sub-dominant (20-60%), minor (5-20%) and trace proportions (<5%), respectively.

Although there are fluctuating areas of secondary dryland salinity, principally resulting from historical land clearing in the uplands, some also have resulted from irrigation with saline groundwater. Powell *et al.* (2002) make some cursory, inconclusive, comments regarding the susceptibility of these soils to salinisation by irrigation. They quote Shaw and Thorburn (1995), although it appears they mean Shaw and Thorburn (1985), as indicating that there would be significant deep drainage in these soils. They then cite Shaw and Dowling (1985), who attribute this to the smectite-rich clays and other macro structural characteristics found in well structured clay soils. This observation is echoed by Churchman *et al.* (1993).

The implications of these observations with respect to the potential application of PRW to these soils are unclear. It is possible to infer that the saline irrigation water in some way helps maintain the structure of the clay, which is consistent with the theory. However the very high calcium content somewhat refutes this (Table 2).

Table 2: Summary of analytical data for soils of the stream terraces and plains.

Horizon	pH (1:5)	EC (dS/m)	Silt %	Clay %	CEC (cmol(+)/kg)	Dominant cations	ESP	CEC/%clay
A	7.0-8.3	0.03-0.24	16-29	31-62	21-65	Ca^{2+}, Mg^{2+}	1.5-5.9	0.63-1.1
B	7.0-9.3	0.09-0.94	11-35	40-74	31-71	Ca^{2+}, Mg^{2+}	1.2-26	0.67-1.2
Substrate	7.4-8.5	0.03-0.62	9-30	16-43	19-51	Ca^{2+}, Mg^{2+}	1.8-10	>1.2

Source: Powell et al. (2002).

Powell *et al.* (2002) also draw attention to the possibility of the Lockyer soils being irrigated with recycled wastewater, as this has been a topic of discussion for some time. They also cite a report by Heiner *et al.* (1999), which was commissioned to determine the sustainability of agricultural systems in the Lockyer Valley and Darling Downs if they were to use recycled water. The water considered in this report was to be Class A (quoted EC 0.6 – 1.2 dS/m; SAR 3.2 – 6.1), rather than the highly purified PRW that is currently in the offing (see Table 4). Despite this, Heiner *et al.* (1999) determine that irrigation with the recycled water is likely to be sustainable in the Lockyer Valley provided soil salinity, sodicity and groundwater were managed and monitored. It appears that their conclusions rest heavily on the dissertation of Shaw (1995), although the authors cite this work as Shaw (1996). Heiner *et al.* (1999) appear to have taken Shaw's sketch of SAR-EC parameter space, indicating zones of likely effects on soil permeability (similar to the figure of Ayres and Westcot, 1985) and performed calculations to estimate the maximal permissible SAR irrigation water ranging from 100% effluent, 50-50% effluent-groundwater to 100% groundwater. While this is a reasonable approach, Powell *et al.* (2002), in alluding to this work, provide the following cautionary note:

> *With so many variables, reliance on predicted salinity and dispersion effects should be done cautiously. Further critical examination of these interactions is required to determine the impacts of long-term irrigation management using saline water.*

3.2. Other Relevant Soil and Water Characteristics in the Lockyer Valley

Four soils were chosen from the group "major stream terraces and plains" identified by Powell *et al.* (2002) using the following rationale:

- They are likely to be receiving PRW, should it be made available for irrigation use;
- They were known to be relatively sodic for Lockyer Valley soils; and
- They had displayed dispersive behaviour.

The relevant chemical properties of these soils are shown in Table 3.

Table 3: Chemical properties of the four soils sampled for this study.

Site and soil	pH	EC (dS/m)	$[Ca^{2+}]$ (meq/100g)	$[Mg^{2+}]$ (meq/100g)	$[Na^{+}]$ (meq/100g)	$[K^{+}]$ (meq/100g)	ESP (%)	CEC (meq/100g)
(a) DPI Gatton Laws soil	7.3	0.08	19.1	13.2	0.13	1.18	0.4	36
(b) Super Sat site Blenheim soil	7	0.77	9.97	11.7	1.02	1.37	3.8	27
(c) Forrest Hill "sodic" site Blenheim soil	7	0.18	17	12.4	1.77	0.66	4.5	39
(d) Forest Hill 0805 0806 Blenheim soil[1]	7.6	0.12	18.9	18.1	1.61	1.75	3.4	48

For this study we were interested in the likely behaviour of the four soils if PRW were to be applied as irrigation water. It was important to compare these results with a ‘standard’, such as the Emerson test (Emerson, 2002) and the Rengasamy test (Rengasamy *et al.*, 1984), which used demineralised water. In addition, we also compared the effects of local irrigation waters: Logan Dam water (a surface water storage for irrigation); and groundwater from two bores (Voigt and the University of Queensland). Figure 2 shows the relative colours of the five waters and the effect of filtering suspended sediment from the Logan Dam water. Table 4 gives some relevant chemical properties of these waters and others sampled form the Lockyer irrigation district.

Figure 2: The five water qualities tested (from left to right – PRW, Voigt bore, University of Queensland bore, Logan Dam and Milli-Q deionised); and clarified Logan Dam water after passing through a 0.45µm filter (right).

Table 4: Chemical properties of the five waters used in laboratory experiments and an additional five waters from the Lockyer irrigation district.

Water	EC (dS/m)	ESP	Ca(mg/L)	Na (mg/L)	Mg (mg/L)	K (mg/L)	pH	SAR
Lab (Milli Q)	<0.01	0.06						
PRW	0.22 – 0.23		18.1	10.0	9.3		8.1	2.70
Logan Dam	0.26		6.3	37.0	5.3	5.0	8.2	
Voigt Bore	6.32 - 6.49		142.0	807	304.0	4.0	7.6	
UQ[1] Bore	1.33 - 1.36		74.4	104.0	83.7	<2	8.0	
Av. Lockyer groundwater			103.6	346.2	120.1			32.7
Bore 14320379 Gatton	0.85		54.2	51.6	52.4		7.8	7.07
Bore 14320432 Gatton	1.83		87.0	146.0	107.0		8.0	14.8
Lockyer Creek	0.38		21.7	28.0	16.0	5.0	7.6	6.45
Creek bed drainage	0.464		36.7	24.0	15.8		7.5	4.68

[1] University of Queensland

4. LABORATORY TESTS

4.1. Emerson Test

To determine if the four soils (Table 1; Table 3) were susceptible to spontaneous dispersion, we conducted Emerson dispersion tests (Emerson, 2002) in demineralised water, PRW, Logan Dam water and groundwater from the Voigt and the University of Queensland bores (Table 4).

Figure 3: Emerson dispersion test of four soils (rows) x five waters (columns): air dry small (0.55 – 0.60 g) peds (left); slaked, 2 minutes (centre); and 23 hours after emersion in distilled water. Slaking was observed but no dispersion. The colour associated with the Logan Dam water existed prior to the test (see Figure 2).

No spontaneous dispersion was observed by any of the four soils in the any of the five waters.

4.2. Mechanical Dispersion

To investigate the effects of mechanical energy on the dispersion, the four soil x five water combinations were tested as follows:

1. ~1g of air dry soil introduced to a vial of 50 ml of water;
2. Vial shaken manually (reciprocated end-to-end) 100 times (~30 seconds);
3. Allowed to stand; and
4. Settling observed visually.

Figure 4 shows the appearance of the agitated samples between four minutes and 22 hours after agitation. As a general observation, all soils in the 'fresh waters' (PRW, deionised and Logan Dam) remained suspended for a longer period, from which we inferred that the clay particles remained dispersed. Whereas the 'saline' bore waters (Voigt and UQ) appeared to cause flocculation and the supernatant was less turbid and became clear more rapidly. The 'sodic' soil (C), second row from the front, remained dispersed in PRW more than the other soils.

Figure 4: Samples of the four soils (rows) x five waters (columns) showing settling four minutes (top left), 10 minutes (top right), one hour (bottom left) and 22 hours (bottom right) after agitation.

4.3. R1 Dispersion Ratio

The R1 test has been designed to indicate the tendency for a soil to mechanically disperse and quantifies this as the ratio of suspended sediments (measured by hydrometer) from mechanical dispersion to that from (complete) chemical dispersion. The procedure for this is described in detail in Wöbke (2009), who provides 3 references: (Puri and Keen, 1925; Quirk, 1950; Richie, 1963). The laboratory procedure is similar to that described by Rengasamy (2002) and involves the mechanical dispersion of a small soil sample (by agitation) and the complete dispersion of a small soil sample by agitation in the presence of a dispersive agent, sodium hexametaphosphate. In both the 'mechanical' and the 'complete' cases, deionised water is used. R1 is calculated as follows:

$$R1 = \{[R^1{}_5 + 1.0 + 0.00746(T^1{}_5)^2 - 2.9767].100 \text{ x } 30\} / \{[R_5 + 1.0 + 0.00746(T^1{}_5)^2 - 2.9767 - 2.4].100 \text{ x } 50\} \qquad (3)$$

Where:

R1 = dispersion ratio and the numerator relates to 'mechanical dispersion and denominator relates to 'complete' or chemical dispersion;

$R^1{}_5$ = Initial hydrometer reading in aqueous suspension;

$T^1{}_5$ = Initial temperature reading in aqueous suspension;

R_5 = hydrometer reading @ 6 min. (g L^{-1}) in chemical reagent suspension; and

T_5 = temperature reading @ 6 min. (°C) in chemical reagent suspension.

However, there is no mention of the calculation of, nor typical values for, R1 in any of the above references. Approximate ranges of 0.6 < R1 < 0.8 and 0.8 < R1 < 1.0 reportedly (Dave Lyons pers. comm.) delineate "potentially dispersive" and "very dispersive", respectively.

The tests for our project were undertaken by the laboratories of Environment and Resource Sciences, Department of Environment and Resource Management, 41 Boggo Road Dutton Park QLD 4102 (contact Dan Yusaf). Because we were interested in the behaviour of the four soils in the PRW, the bore waters and the dam water, we had the R1 tests evaluated for each soil, but using each of the five waters listed in Table 4. These tests were replicated four times and the results are shown in Figure 5 as "Modified R1"; in each case the numerator of Equation (3) was determined using the test water, whereas the denominator was determined using a the reference deionised water. It should be noted that the denominator (chemical dispersion) will be equal, no matter what water is used.

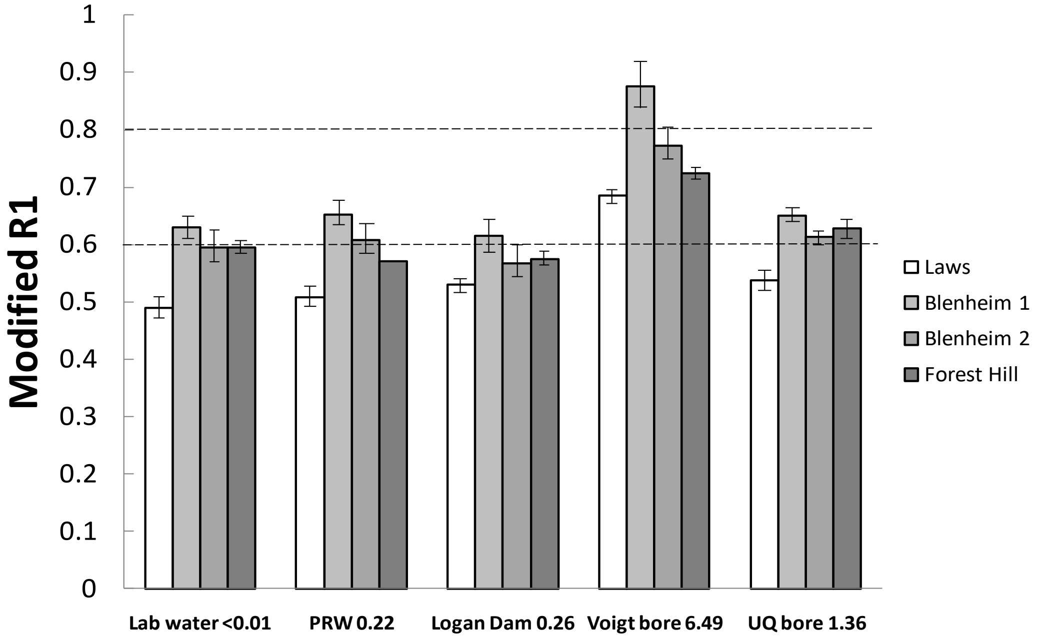


Figure 5: Modified R1 results for the four soils x five waters. Error bars show one standard deviation both sides of the mean of four replicates; numerical labels indicate the EC of each water.

5. DISCUSSION AND CONCLUSIONS

The use of high quality PRW for irrigation of crops carries the risk that it could cause structural degradation of the soil, via clay dispersion, leading to lowered porosity, lower hydraulic conductivity, water entry, seedling emergence and crop growth. This risk would be associated with sodic soils which have a high exchangeable sodium percentage (ESP). In the presence of the low electrical conductivity (EC) PRW, the reduced osmotic pressures, together with the relatively wider diffuse double layer between clay particles, could lead to the spontaneous dispersion of clay. If conditions were not sufficiently severe for spontaneous dispersion, mechanical dispersion would be more probable. These reactions are more significant in clay soils dominated by smectitic clays such as montmorillonite, due to their greater surface area and chemical reactivity.

The productive soils of the Lockyer Valley are largely vertosols, rich in montmorillonite, and are irrigated mostly with groundwater of low to moderate EC. Some soils of the Lockyer Valley are considered to be slightly sodic and minor dispersive structural degradation is regularly observed following summer storms (mechanical dispersion) on unprotected soil (no crop or stubble cover). This is consistent with clay chemistry theory, however, the significant body of literature covering this topic overwhelmingly reinforces that it is difficult, if not, impossible, to accurately predict the effects of the application of water to sodic soils – except in the extreme cases.

There is a complex interplay between the clay chemistry, the water chemistry and the electrical conductivity of the water, particularly in relation to the presence and exchangeability of sodium ions. One can confidently predict, however, that low EC, high SAR (sodium adsorption ratio) applied to sodic soils will lead to significant and irreversible structural decline. On the other hand, high EC but low SAR water will likely not lead to much structural change, but would reduce plant production for other reasons. If, however, low EC and low SAR water (e.g.,PRW) was applied to moderately sodic soil, the response is difficult to predict. There are numerous guidelines which help determine the likely risk of soil-water-chemistry combinations, but they are of limited use for the case we are considering here. In addition, there is very little reported in the literature of the use of PRW for irrigation at all, although deleterious effects of desalinated, high SAR are reported for a few cases.

We therefore undertook some laboratory tests using deionised water, PRW, local bore water and local surface water on four representative Lockyer Valley soils. These showed there was no risk of spontaneous dispersion with any of the soil-water combinations using the Emerson test (Emerson, 2002). However, mechanical dispersion was a risk in all cases. Two mechanical dispersion tests: 1) agitation and qualitative turbidity observation; and 2) a similar, quantified dispersion test (Wöbke, 2009) showed some discrepancies.

Results from (1) aligned with the theory that predicted a greater tendency for dispersion of sightly sodic soils, with decreasing EC but (2) showed the highest risk for dispersion was related to the combination of the highest EC (bore) water, for all soils. The latter contradicts clay chemistry theory. Both of these tests were repeated with almost identical results and we do not, at this stage, have a suitable explanation for these differences other than possible differences stemming from the two agitation methods. Quirk (1950) shows that the degree of disaggregation of clays is quite dependent on the duration of agitation (shaking) used. Thorburn and Shaw (1987) describe discrepancies between measurements made using a stirring agitation (R1) and a reciprocating shaker method, suggesting that this may be the cause of our results.

Despite this discrepancy, and from a broader perspective, it is unlikely that the application of PRW, even to the mildly sodic soils in the Lockyer Valley, will cause structural degradation worse than is already reported from rainfall during summer storms (Ashley Bleakley; Craig Henderson pers. comm.). Table 4 shows PRW to have EC ~0.2 dSm^{-1} and SAR 2.7, and is therefore relatively pure and, although it is difficult to find similar data on rainwater, it is safe to assume that it would be in a similar range and therefore would have a similar effect to rainwater on sodic soil. It is clear from our tests that there is a risk due to mechanical dispersion from rainfall or overhead irrigation with ‘fresh’ water, and it is also clear that the farmers of the Lockyer Valley manage these effects satisfactorily.

Typically, the best management of the risk of mechanical dispersion is to avoid it, by protecting the soil surface with crop residue. However, this is not always possible, especially in an intensive horticultural zone where ‘clean’ (free of crop residue) soil condition is often required for appropriate tillage, seeding and planting operations. Gypsum (calcium sulphate) is occasionally applied in the Lockyer Valley to ameliorate structure for better aeration and root growth, but the costs typically outweigh the benefits. Matthew *et al.* (1989) report some deep tillage and gypsum trials to ameliorate sodic duplex soils in the Lockyer Valley with view to increasing crop production, but they did not record any increased crop production. Neither did they report changes in soil structure.

In summary, there is likely to be only a small risk of soil structural degradation from the use of PRW for irrigation in the Lockyer Valley. Any such effects would be small, and not worse than those already induced by rainfall or overhead irrigation with ‘fresh’ surface water. Farmers are accustomed to managing these effects and there is no reason to believe they would not be able to manage any effects caused by the application of PRW.

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