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Developing a New Foundational Understanding of SAR-Soil Structure Interactions for Improved Management of Agricultural Recycled Water Use

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Acronyms and Abbreviations

$CROSS_f$	Cation ratio of structural stability f indicates numerical coefficients in the CROSS equation are derived from the relative flocculating power of K and Mg
$CROSS_{opt}$	Cation ratio of structural stability opt indicates coefficients 8 are determined through optimization
K_S	Saturated hydraulic conductivity
$Phyto_{Sodic}$	Phytoremediation of sodic soils
R_H	Proton production in the root zone
R_{PCO_2}	Partial pressure of CO_2 within the root zone
R_{Phy}	Physical effects of roots in improving soil aggregation
S_{Na^+}	Na+ in the above ground biomass
V_A	Potential energy due to van der Waals attractive forces
V_R	Potential energy due repulsive forces
V_S	Potential energy due to the solvent
V_T	Total potential energy
η_0	Concentration of the ions in the bulk solution
Al^{3+}	Aluminum cation
B	Boron
Ca^{2+}	Calcium cation
$CaSO_4\ 2H_2O$	Gypsum
CEC	Cation Exchange Capacity (meq/100g)
Cl^-	Chloride anion
CO_3^{2-}	Carbonate anion
DDL	Diffuse Double Layer
DVLO	Derjaguin, Landau, Verwey, and Overbeek theory
EC	Electrical Conductivity (dS/m)
$EC_{1:5}$	Weight to volume soil salinity measurement obtained by taking 1 part by weight (grams) of air-dried soil and mixing it with 5 parts by volume (mL) of distilled water
EC_{50}	Average root zone soil salinity where 50% yield is predicted
ECe	Average root zone salinity of the saturated soil extract (dS/m)
ECw	Salinity of the irrigation water (dS/m)
E_{Na}	Exchangeable sodium
ESP	Exchangeable sodium percentage (%)
H^+	Hydrogen ion
H_2PO_4	Phosphoric acid
HCO_3^-	Bicarbonate

K^+	Potassium cation
Li^+	Lithium ion
M1W	Monterey One Water
Mg^{2+}	Magnesium cation
Na^+	Sodium cation
$NH4^+$	Ammonium
NO_3^-	Nitrate
P	An empirical shape parameter
PVW	Pajaro Valley Water Management Agency
SAR	Sodium Adsorption Ratio
SO_4^{2-}	Sulphate anion
TDS	Total Dissolved Solids
Yr	Relative yield
ζ	Zeta potential
Π	Solvent permeability
A	Hamaker constant
CCR	Calcium Chloride Requirement
D	Particle separation
GR	Gypsum requirement
PAR	Potassium Adsorption Ratio
T	Temperature in Kelvin
e	Elementary charge of an electron
k	Boltzmann constant
q	Steady state infiltration rate
v	Valences of the ions in solution
z	Characteristic length
ε	Dielectric constant

Executive Summary

ES.I Key Findings

- Sodium Adsorption Ratio (SAR) and Cation Ratio of Soil Structural Stability (CROSS) were assessed in long-term field experiments, greenhouse studies, and soil columns to determine their effectiveness in predicting the negative impacts of using recycled water for irrigation on soil sodicity.
- Overall, CROSS proved to be a more reliable tool for predicting the impact of recycled water reuse on soil sodicity and permeability.
- Continuous irrigation with recycled water having a high CROSS value led to reduced strawberry productivity, and the salt uptake aligned with the cation composition of the water.
- To reclaim sodic soils effectively, it is recommended to employ a combination of management strategies, such as using chemical amendments (e.g., gypsum) along with soil profile modification or implementing phytoremediation techniques. These approaches enhance the effectiveness of sodic soil reclamation.

ES.2 Background and Objectives

Numerous studies have reported reductions in soil permeability resulting from the use of marginal recycled water for irrigation due to increased Exchangeable Sodium Percentage (ESP). The increase in soil ESP causes the breakdown of soil aggregates, followed by the swelling and dispersion of clay particles which leads to soil crusting, loss of porosity, and reduced permeability. If the sodium adsorption ratio (SAR) and the EC of the irrigation water are known, the effect of using recycled water on soil permeability (as a proxy for structure) can be predicted using empirical relationships. There is a vast body of literature on the negative impacts of sodium on soil structure. However, emerging research has shown that potassium and magnesium can also impact soil structure negatively and need to be included in irrigation water quality assessment criteria. A new criterion known as the Cation Ratio of Structural Stability (CROSS) is being advocated as a better predictor of potential soil permeability problems arising from the use of recycled water for irrigation. This is because CROSS accounts for the dispersive effects of exchangeable potassium and magnesium. The study objectives were to:

1. Conduct a literature review to document the state of knowledge.
2. Evaluate recycled water quality requirements to minimize long-term impacts on soil structure.
3. Conduct experiments investigating crop/soil/recycled water interactions in greenhouse and laboratory environments.
4. Evaluate the long-term impact of recycled water use for irrigation on commercial fields.
5. Investigate remediation options for sodium-affected soils.
6. Summarize project findings in a final WRF report.

ES.3 Project Approach

Task 1: The team conducted an exhaustive review of the applicable literature, tracing the state of knowledge on irrigation water quality and its impact on soils and crops. Special attention was reserved for past and most recent scientific research and refinements in the basic understanding of the SAR/CROSS/EC impact on soil permeability.

Task 2: On the basis of the findings from Task 1, SAR values from past studies were recalculated to account for recent findings about other influences on soil structure and its stability. Based on the new calculations, generalized recommendations were made to compensate for the negative impacts and ameliorate the effects of irrigation with recycled water.

Task 3: Conducted experiments investigating crop/soil/recycled water interactions impact on crop yield and soil structure in greenhouse and soil columns.

Task 4: Evaluated sustainability of long-term use of recycled water irrigation using multi-year soil sampling data from field sites in Monterey One Water and Pajaro Valley Water Management Agency. The team compared control sites (i.e., sites that have received recycled water irrigation) to sites that have continuously received recycled water for over 20 years.

Task 5: Investigated pros and cons of various remediation options for sodium-affected soils. Recommended sodic soil management strategies were based on a thorough investigation of practices from different regions of the work.

Task 6: The compilation of a final report was based on summarizing the project findings.

ES.4 Results

In conclusion, the findings of this study confirm that $CROSS_f$ (derived from the relative flocculating power of K and Mg) is a more robust tool for predicting the negative impacts of different recycled water qualities on soil structure compared to SAR. Practitioners should consider using $CROSS_f$ instead of SAR when assessing sodicity impacts. Moreover, changes in $CROSS_f$ proved to be a more reliable indicator of observed differences in recycled water quality delivered to farmers in the Monterey One Water service area along the Central Coast of California. When it comes to agriculture, shallow soil sampling is more likely to detect salinity and sodicity risks when $CROSS_f$ is utilized rather than SAR. Even at sites with recycled water at equilibrium or decreasing salinity, harmful salinity levels were observed in the 24-36" soil profile in poorly drained soils. When Na levels exceed 10 meq/L, the changes in CROSSf levels were more significant than the changes in SAR. Additionally, $CROSS_f$ exhibited a stronger correlation with Catio Exchange Capacity (CEC) compared to SAR.

In greenhouse and soil column experiments, $CROSS_f$ outperformed SAR as a predictor of reduced infiltration rates. For instance, the correlation between infiltration rate and $CROSS_f$ was ($R^2=0.6$), while it was ($R^2=0.2$) with SAR. The average plant biomass showed the highest correlation with cation ratios for different recycled water qualities, particularly with $CROSS_f$. The most commonly used method for reclaiming sodic soils and saline-sodic soils has been the application of chemical amendments, such as gypsum, to replace Na^+ with Ca^{2+} in the exchange complex. Phytoremediation has also proven to be an effective and cost-efficient method for reclaiming sodic soils, as demonstrated in various research studies. In some cases, soil profile modification through deep soiling has successfully reclaimed sodic soils. It is recommended that producers employ a combination of reclamation strategies based on local conditions, considering factors like the cost and availability of gypsum, soil type, and the availability of water for leaching.

The use of recycled water for irrigation has been practiced along the Central Coast of California for 14 (from 2009 PVW) to 25 years (from 1998 M1W). Long-term soil salinity and sodicity studies were initiated to track changes in soil salinity and alkalinity and the negative impacts associated with using recycled water. The team found that the wide-scale adoption of drip irrigation in the study area has resulted in significant decreases in the volume of delivered water and no widespread increases in soil salinity, but more work is needed to evaluate sodicity impacts.

ES.5 Benefits

Growers often need to test the quality of the water they receive on their farms. This testing may be required by state agencies or by buyers of their agricultural products. Utilities, responsible for delivering water including recycled water, have a vested interest in obtaining accurate water quality data for their users. In some cases, this data is necessary for reporting purposes. Depending on the complexity of acquiring and delivering alternative water sources (e.g., recycled water, groundwater, surface water), various methods can be employed to evaluate water quality. However, it is evident that simple averages are not reliable. Therefore, it is crucial to adopt a comprehensive and accurate water quality sampling protocol based on weighted averages. By using the $CROSS_f$ criteria, which better reflects differences in delivered recycled water quality to farmers, utilities can make more informed decisions about recycled water quality assessments.

Notably, harmful salinity levels were observed in the soil profile depth of 24-36 inches, while the delivered water was assessed as having either equilibrium or decreasing salinity trends. This information holds significant importance for agricultural producers. It can be utilized to develop mitigation strategies, such as applying soil amendments e.g., gypsum, modifying tillage techniques, and enhancing drainage, to address the issue. The data clearly demonstrated that deep plowing, which exposes the 24–36-inch soil profile, effectively increased salinity levels in the 1-12 inch soil profile to unacceptable levels. Consequently, it is necessary to develop soil sampling methods that account for temporal and spatial variations in salinity and sodicity, tailored to the specific characteristics of the agricultural production system.

Practitioners should consider using $CROSS_f$ rather than SAR when assessing the impact of soil sodicity. A $CROSS_f$ value of 10 has been identified as the critical threshold, indicating high exchange sodium levels and low calcium and magnesium levels, which can lead to soil permeability issues and potential reductions in crop yields and quality. Utilities are encouraged to utilize this threshold as a guide for interpreting $CROSS_f$ values.

ES.6 Related WRF Research

- Assessing the State of Knowledge and Impacts of Recycled Water Irrigation on Agricultural Crops (4964)
- Addressing Impediments and Incentives for Agricultural Reuse (4956)
- Evaluating Economic and Environmental Benefits of Water Reuse for Agriculture (4829)
- Agricultural Reuse- Impediments and Incentives (4775)

CHAPTER 1

Literature Review

The following extensive literature review has two areas of focus. The first area is a comprehensive discussion of the role that the physical and chemical characteristics of the mineral particle plays in affecting the dispersion or flocculation of different soils (Sections 1.1 - 1.2). The second area focuses on the role of different ions affecting ionic forces on the soil particle surfaces and different methods of evaluating their concentrations and negative or positive effects (Sections 1.3 – 1.4).

1.1 Soil Structure and Aggregation

The arrangement of particles in the soil is called soil structure. Soil structure is very important because it regulates many bio physiochemical processes in soil. For example, the total porosity, size, and shape of the pores in which most processes occur are controlled by soil structure. Soil structure governs the movement of water and nutrients in soil, soil aeration, soil microbes, resistance to soil erosion, and root growth. Soil structure is important for many activities e.g., agricultural, construction, ecology etc. However, it is complex to fully characterize soil structure in geometric terms because soil particles differ in shape, orientation, size, and ways in which they connect and interlink (Hillel, 1998). This is further complicated by the unstable nature of soil structure over time and its lack of uniformity over space. For these reasons, there is no universally accepted method for quantitatively measuring soil structure. Therefore, soil structure remains a qualitative concept rather than a directly quantifiable property (Hillel, 1998). Many methods have been proposed to characterize soil structure, but most are indirect and some are hard to generalize. To characterize soil structure, many methods measure soil attributes that are dependent on soil structure (e.g., drainage) rather than measure soil structure directly. Figure 1-1 below shows the six major classes of structure seen in soils namely single grain, platy, blocky, granular, massive, and prismatic.

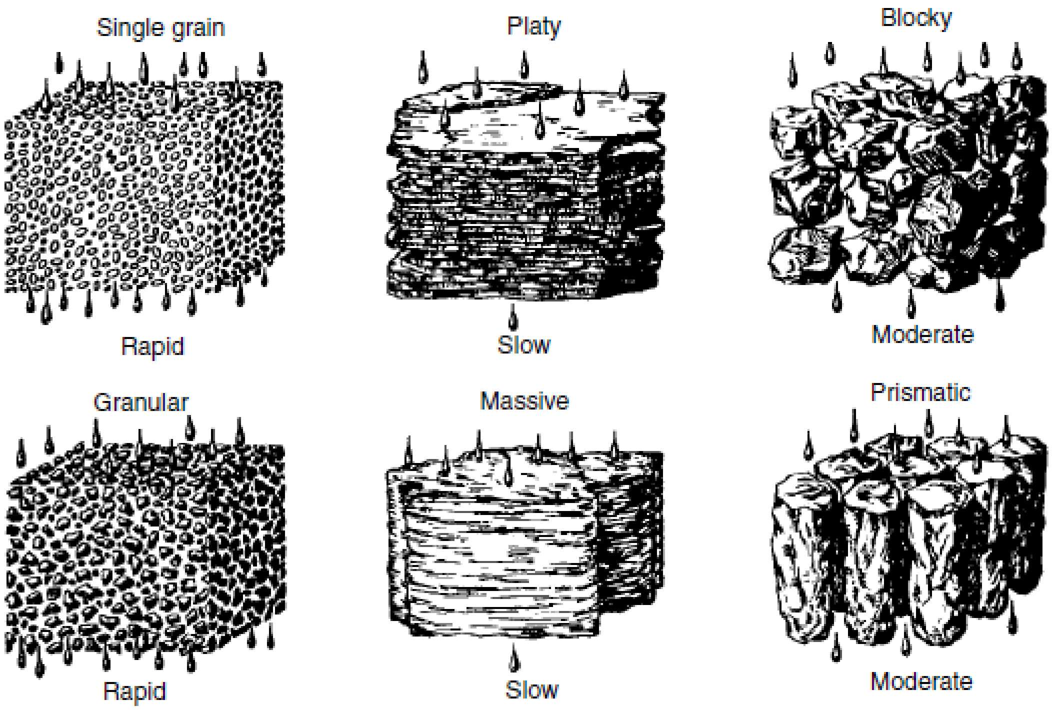


Figure 1-1. Classes of Soil Structure and Their Impact on Drainage. Single Grain and Granular Structures Have Rapid Drainage, While the Platy and Massive Soil Structures Have Slow Drainage. Favorable Soil Structure for Water Relations Are Aggregated Blocky, and Prismatic.

Source: USDA NRCS Section 15 of the National Engineering Handbook.

1.1.1 Structure of Aggregated Soil

In soils with appreciable clay content, soil particles tend to group themselves into composite units called aggregates under favorable conditions (Hillel, 1998). A prerequisite for aggregation is that the clay be flocculated and cementation be present (Bradfield, 1950). Roots play an important role in soil aggregation, they exert pressures that compress aggregates and separate adjacent ones. In addition, water uptake by roots causes differential dehydration, shrinkage, and the opening of numerous small cracks (Hillel, 1998). Root exudations and the continual death of roots and particularly of root hairs promote microbial activity, which results in the production of humic cements (Metting, 1993). Because these binding substances are transitory, organic matter must be replenished and supplied continually if aggregate stability is to be maintained in the long run (Huang and Schnitzer, 1986). This might explain why cover crops would be beneficial for improving soil aggregation over the long term.

Soil microorganisms bind aggregates by a complex of mechanisms, such as adsorption, physical entanglement and envelopment, and cementation by excreted mucilaginous products (e.g., polysaccharides). Such materials are attached to clay surfaces by means of cation bridges, hydrogen bonding, van der Waals forces, and anion adsorption mechanisms (Hillel, 1998). It is worth noting that the cohesiveness between clay particles provides the ultimate internal binding force within microaggregates. Although calcium carbonate, as well as iron and aluminum oxides, have also been demonstrated to impart considerable stability to otherwise weak soil aggregates (Hillel, 1998). From the above discussion, it is obvious that any soil or water management that will affect flocculation and dispersion of clay particles would impact soil structure.

1.1.2 Characterization of Soil Structure

Soil structure can be studied directly using microscopic observations. The structural associations of clay particles have been examined in various studies by means of electron microscopy, using either transmission or scanning techniques (Taina et al., 2008; Kravchenko and Guber, 2020). The structure of single-grained and aggregated soils can be evaluated quantitatively in terms of the total porosity and pore size distribution (Hillel, 1998). The structure of aggregates can be qualitatively assessed by describing the name of the aggregates in the different soil horizons (e.g., granular, prismatic, platy, blocky etc.). Other indirect methods of assessing soil structure involve evaluating mechanical properties (e.g., soil aggregate stability) and soil permeability. Hillel (1998) noted that none of these methods has been universally accepted and the choice of the methods depends on the problem being addressed, cost, soil type, equipment available, etc.

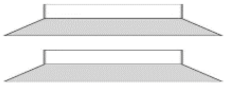
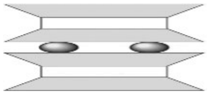
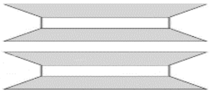
1.2 Clay Water Interactions Impact on Soil Structure

To evaluate the impact of sodicity on soil structure, it is critical to understand clay-water interactions and the processes of dispersion and flocculation. The dispersion and flocculation processes occur mainly due to the interaction of the negative and positive ionic forces in the soil. Both forces can occur simultaneously. However, depending on the dominant interactive force, clay particles may disperse (if the dominant forces are negative) or flocculate (if the dominant forces are positive). Dispersion of clay particles negatively affects soil structure. Clay particles have a high surface area and carry a net negative charge at their surfaces due to mineral weathering processes. To understand the negative charge formation, it is worth noting that soil particles form due to weathering of rocks. Some minerals are more chemically reactive (like micas and feldspars) and some are more resistant (like quartz). Quartz (silicon dioxide SiO2) based minerals remain as individual particles (or grains). Sand is usually available in the form of quartz and it is neutral (i.e., has zero charge). Sands have a range of sizes from 2000 to 50 μm (low surface area). Silt is a granular material with sizes from 50 to 2 μm and is intermediate between sand and clay and composed mostly of broken grains of quartz. Clay particles are characterized as having a diameter smaller than 2 μm and are negatively charged.

There are two main causes of the negative charge on clay particles. At the edges of clay particles formed from weathering e.g., silicates, hydroxides (-OH) are exposed to the soil solution. As the pH of the solution increases, H^+ ions become less strongly bound to oxygen in the -OH radicals, increasing the negative charges on clays (Waring and Running, 2007). In addition, the negative charge can arise from ionic substitutions within silicate clays. Over geologic time, the silicon in the more reactive minerals could be replaced by aluminum (3^+) and aluminum could be further replaced by magnesium (2^+) to form clay particles that have a size of less than 2 μm (high surface area). The loss of cations implies that the clay particles carry more or a preponderance of negative charges on their surfaces. The type of clay mineral depends on the original rock composition. Unlike the first source of negative charge, the second source is permanent because it originates inside the crystal structure and cannot be neutralized by covalent bonding of H^+ from the soil solution (Waring and Running, 2007).

The two structural units of aluminosilicate clay minerals are a tetrahedron of four oxygen atoms surrounding a silicon ion (Si^{4+}) and an octahedron of six hydroxyls or oxygen atoms surrounding aluminum (Al^{3+}) or magnesium (Mg^{2+}) cations. Multiple tetrahedron units form hexagonal network forming a silica sheet while octahedron units form an alumina sheet. The two main types of aluminosilicate minerals (based on the ratio of silica to alumina sheets) are 1:1 and 2:1 (Table 1-1). The common 1:1 mineral is kaolinite [$Al_4Si_4O_{10}(OH)_8$]. The multiple sheets that form kaolinite are held tightly together by hydrogen bonding and water solution cannot enter between the basic layers. Kaolinite crystals have large particles and low specific surface (Table 1-1) compared to other clay minerals therefore, exhibiting less plasticity and cohesion. The 2:1 minerals are usually divided into expanding and non-expanding types. The expanding type is montmorillonite [$Al_{3.5}Mg_{0.5}Si_8O_{20}(OH)_4$]. Unlike kaolinite, the lamellae of the montmorillonite are layered loosely and held together by weak Vander Walls forces. Therefore, water solutions can enter between the lamellae. Those lamellae can be separated into several individual lamellae (1 nm thick). Montmorillonite has high surface area and high tendency to expand and disperse, therefore, huge swelling-shrinking capacity (Table 1-1). The non-expanding type of the 2:1 mineral is illite [$Al_4Si_7AlO(OH)_4K_{0.8}$] where potassium occurs between the layer units and fixes them tightly. Illite has intermediate properties between montmorillonite and kaolinite (Table 1-1).

Table 1-1. Summary of Clay Mineral Characteristics.

Name	Structure	Iso. Sub[1].	CEC[2] (meg/100g)	Interlayer Bond	Sp. Surf[3]. (m2/g)
Kaolinite		Low	0.03-0.1	Hydrogen, strong	20--10
Illite		Moderate	0.2-0.3	Potassium (K) ion, moderate	65-100
Montmorillonite		High	0.8-1.5	Very weak	50-100

[1] isomorphic substitution
[2] Specific surface area
[3] Cation-exchange capacity

Clay particles are made up of platelets that stack together. Depending on the clay type, a particle could be formed due to many or few platelets. To compensate for the negative charges of the clay particles, concentrated cations are attached to the clay surfaces. Those cations are not part of the particles but can be exchanged or replaced with other cations from the soil solution. This property can be measured by cation exchange capacity (CEC, milliequivalent of cations per 100 grams of soil). The CEC depends on the clay amount, clay type (Table 1-1), organic matter content and humus content. The exchange cations could include Al^{3+}, Ca^{2+}, Mg^{2+}, $NH4^{+}$, K^{+}, H^{+}, Na^{+} and Li^{+}. The cations are in order of preference in exchangeability. Montmorillonite has a larger CEC (Table 4-1) because they have many plates and between these plates there are negative charges. Kaolinite has potassium that occupies the negative charges, and the opening is so small for the interaction of water and other cations, therefore, it does not swell as much as Montmorillonite.

When the soil is relatively dry, the cations are attached to the particle surfaces. When hydration takes place, some ions leave the surface and enter the solution. The hydration could occur due to osmosis force [water moves from low solute concentration (soil solution) to high solute concentration (between platelets)] leading to swelling of the soil due to the formation of the diffuse double layer (DDL) (Figure 1-2). Depending on the original rock composition, some clays (like Montmorillonite) have huge swelling capability. The shrinkage curve helps in understanding the dynamic of swelling and shrinking. The curve relates the specific volume (a volume of a unit of mass) of the soil to its water content. Therefore, with higher water content, the specific volume will be higher (because of swelling) and with lower water content, the specific volume will be lower (because of shrinking). The double layer thickness is inversely proportional to the square root of the ion concentrations (Equation 1-1). If the soil-solution is diluted (low EC), the diffusive double layer will become thick, therefore causing clay dispersion due to the net positive charge of the DDL repelling each other. However, the diffusive double layer will become thinner if the soil solution has high EC. Therefore, clays will flocculate due to the formation of a unified positive layer charge among clay particles.

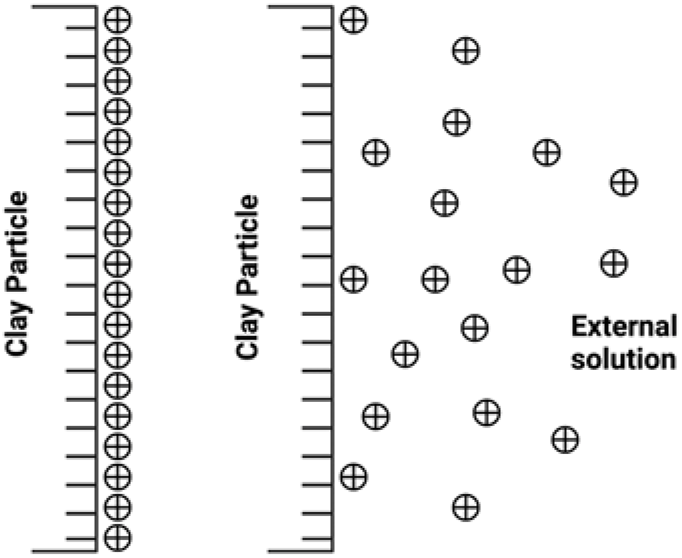


Figure 1-2. Showing Diffuse Double Layer in Dry (left) versus Hydrated Clay (right).
Source: Reprinted from Hillel 1998 with permission from Elsevier.

$$z = \left(\frac{1}{ev}\right) * \left[\frac{\varepsilon KT}{8\pi\eta_0}\right]^{0.5} \qquad \text{(Equation 1-1)}$$

where z is the characteristic length, or extent of the double layer, defined as the distance from the clay surface to where the ionic concentration is very nearly that of the external solution; v is the valency of the ions in solution; e is the elementary charge of an electron; ε is the dielectric constant; k is the Boltzmann constant; η_0 is the concentration of the ions in the bulk solution; and $T$is the temperature in Kelvin (Hillel, 1998).

Another significant component that comes into play is the soil solutions exchangeable cations. The main exchangeable cations in the soil solution are sodium, potassium, magnesium, and calcium. The exchangeability is estimated by the cation exchange capacity. Generally, monovalent cations (like sodium and potassium) can be easily replaced/exchanged by trivalent (like aluminum) or divalent cations (like calcium and magnesium) because monovalent cations are attracted to a single charge. Upon negative charge neutralization, a positive charge layer will coat the clay particles (or diffuse double layer, Figure 1-2). The thickness of the positive coating layer depends on the cation type and concentration which will determine the diffusive double layer thickness. Large monovalent cations will neutralize one negative charge (diffuse at a lower rate with distance from the clay surfaces). The net positive layer will be thick causing dispersion to the adjacent particles due to similar charges causing repulsion. Smaller divalent or trivalent cations (2+ or 3+) will neutralize more than one negative charge (their equivalent concentration is higher at the clay surface than that of the monovalent cations) and the layer will be thin causing the particles to come closer to each other such that a unified positive layer might form between two clay surfaces (platelets). A third factor influencing clay swelling and dispersion is the clay type because their shape and structure form are on the original weathered rock composition. Montmorillonite, for example, show extensive dispersion because of their 2:1 layer structure (Buelow et al., 2015). Kaolinite-rich soils, however, are more stable and have a 1:1 layer (McNeal et al., 1966). Illite- and vermiculite-soils are also 2:1 layer (like Montmorillonite) but they have intermediate dispersion capability.

1.2.1 Zeta Potential

Zeta potential (ζ) is a physical property which is exhibited by any particle in suspension. When one of the three states of matter (i.e., solids, liquids, or gas) is finely dispersed in another such a system is called a colloidal system (e.g., clay particles dispersed in a soil solution). In colloidal kinetics, the Zeta potential can be defined as the electrical potential that exists at the slipping plane or plane of hydrodynamic shear shown in Fig 1.3. The value of Zeta potential can be used to assess the tendency for the soil colloids to disperse (Aydin et al., 2004). Colloidal systems are thought to be stable when the ζ-potential of particles is smaller than -30mV or greater than +30mV (Kirby and Hasselbrink, 2004; Marchuk et al. 2013c). It is worth noting that Zeta potential is not a direct measure of surface charge density.

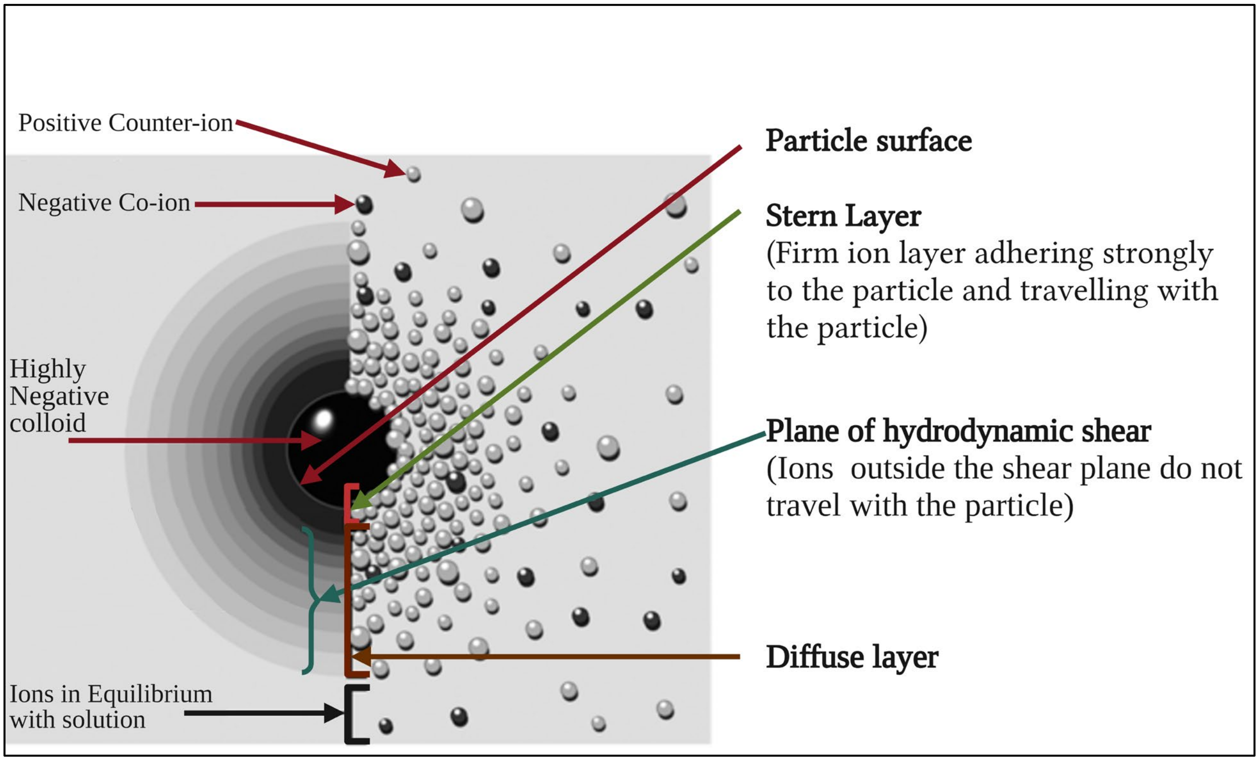


Figure 1-3. Double Layer around a Negatively Charged Clay Particle: The Left View Shows the Change in Charge Density around the Clay Particle; the Right Shows the Distribution of Positive and Negative Ions around the Charged Clay Particle.

Source: Adapted from Zeta-Meter Inc. 1997.

1.2.1.1 Colloidal Stability and DVLO Theory

The well-known DLVO theory was established by Derjaguin, Landau, Verwey, and Overbeek in the 1940s (Derjaguin and Landau 1941, Verwey and Overbeek 1948) and describes the stability of colloidal systems. The DVLO theory suggests that the stability of a particle in solution (e.g., clay particles in soil solution) is dependent upon its total potential energy function V_T (Malvern, 2015). Where V_T is expressed as Equation 1-2:

$$V_T = V_A + V_R + V_S \qquad \text{(Equation 1-2)}$$

Where V_T is the total potential energy, V_S is the potential energy due to the solvent, V_R is the potential energy due to repulsive forces and V_A is the potential energy due to van der Waals attractive forces. It is assumed that the contribution of V_S to the total potential energy is small over a few nanometers of separation. V_A and V_R are much large and operate over long separation distances. The attractive forces are expressed as Equation 1-3:

$$V_A = {}^{-A}\!/_{(12 * \Pi * D^2)} \qquad \text{(Equation 1-3)}$$

where A is the Hamaker constant, Π is solvent permeability and D is the particle separation. The repulsive potential energy in the colloidal system is expressed as Equation 1-4:

$$V_R = 2 * \Pi * \varepsilon * a * \zeta^2 * exp(-\kappa D) \qquad \text{(Equation 1-4)}$$

where ε is the dielectric constant, a is the particle radius, ζ is the zeta potential, κ is a function of the ionic composition, and D is the particle separation. The DVLO theory starts that the stability of a colloidal system is determined by the sum of the van der Waals attractive (V_A) and diffuse double layer repulsive (V_R) forces that exist between colloidal particles as they approach each other due to the Brownian motion. Figure 1-4 shows the variation of these forces with particle separation. Figure 1-4 also shows the net energy between the particles which determines if the particles will disperse or flocculate based on whether V_R or V_A is dominant. For example, if ζ is decreased through increasing salt concentration of the soil pore water, a secondary minimum develops (Figure 1-5) in which the net energy is positive which results in an attraction between colloidal particles as shown in Figure 1-4. Equation 1-4 shows that measuring ζ can be a good tool for assessing the potential for dispersion of clay particles due to irrigating with recycled water of different ionic composition. Chorom and Rengasamy (1995) evaluated the effect of changing electrolyte concentration on dispersion and zeta potential and found that net particle charge was the most important factor controlling clay dispersion and charge reduction resulted in lower zeta potential. Marchuk et al. (2013a) also reported that clay dispersion depends on the unique association of soil components affecting the net charge (measured as negative zeta potential) available for clay-water interaction, rather than the charge attributed to the clay mineralogy and/or organic matter. Marchuk et al. (2013b) reported a high correlation between degree of dispersity and zeta potential (r^2=0.78).

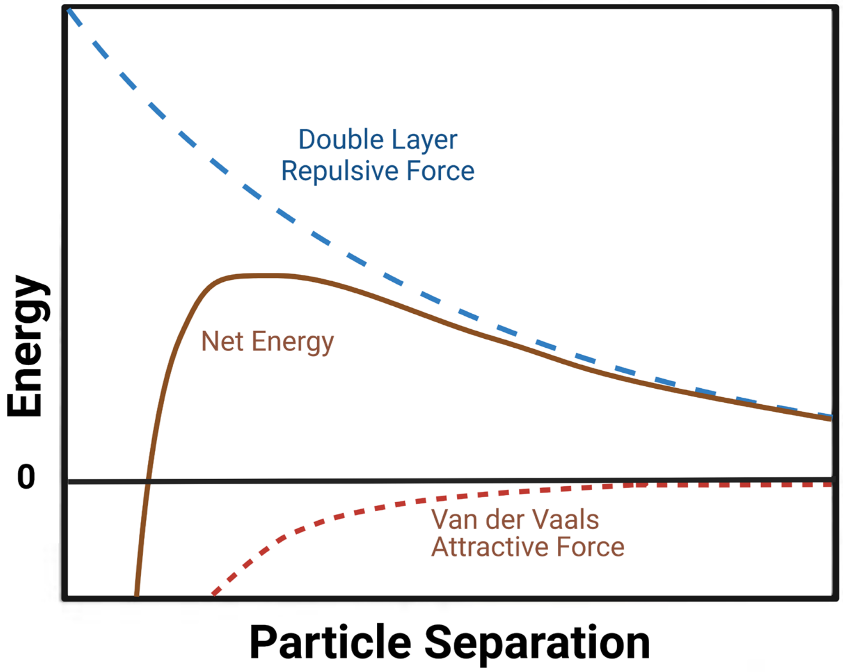


Figure 1-4. Generalization of Variation of Free Energy with Particle Separation according to DVLO Theory.

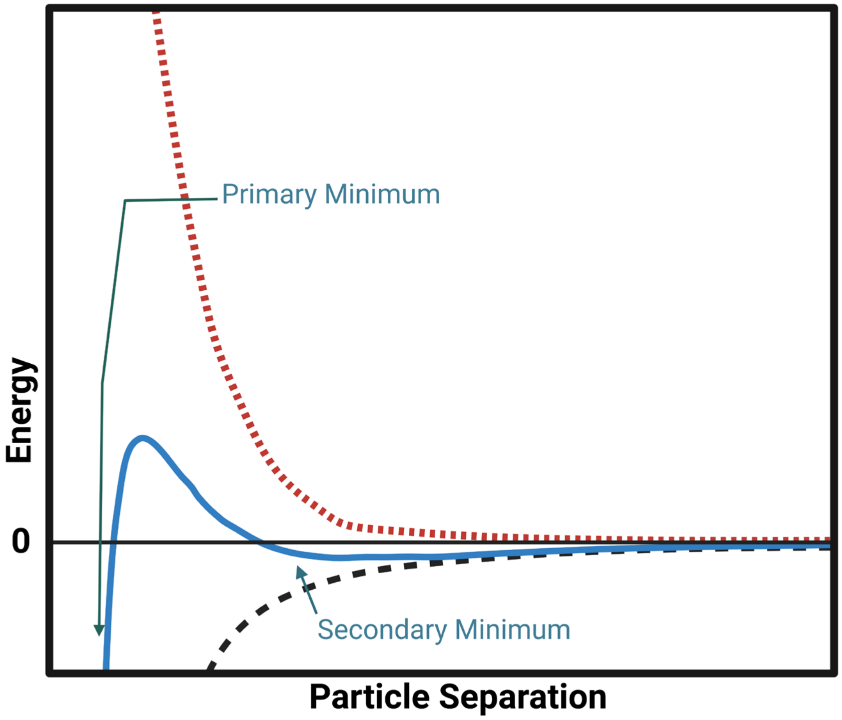


Figure 1-5. Variation of Free Energy with Particle Separation at Higher Solution Salt Concentrations Showing the Possibility of a Secondary Minimum.

1.2.2 Effect of pH on Dispersion

Soil pH has a direct impact of dispersion and the effect depends on the CEC (Rengasamy and Churchman, 1999). For example, Suarez et al. (1984) showed that at constant SAR and EC, clay dispersion increased with the increasing pH for predominantly kaolinitic soils. While Chorom and Rengasamy (1995) showed that that pH affected clay dispersion of soils dominated by illite, kaolinite and smectite by changing the net negative charge on clay particles. All the three soils in the Chorom et al. (1994) study showed an increase of pH resulted in an increase in net negative charge and zeta potential corresponding with an increase in clay dispersion.

1.3 Past and Current Knowledge on Soil Structure Impacts from Recycled Water Reuse for Irrigation

Numerous studies have reported reductions in soil permeability resulting from use of marginal recycled water for irrigation (Coppola et al., 2004; Rengasamy and Marchuk, 2011; Laurenson et al., 2012; Assouline et al., 2015; Bourazanis et al., 2016). Irrigation with recycled water typically results in increased Exchangeable Sodium Percentage (ESP) resulting in reductions in soil permeability. The increase in soil ESP can cause breakdown of soil aggregates, followed by the swelling and dispersion of clay particles which leads to soil crusting, loss of porosity and reduced permeability especially after rainfall or irrigation with low salinity water. If the sodium adsorption ratio (SAR) and the EC of the irrigation water are known, the effect of using recycled water on soil permeability (as a proxy for structure) can be predicted using the relationships in Figure 1-6 following Pedrero et al. (2020). There is a vast body of literature on the negative impacts of sodium on structure/soil permeability. However, emerging research has shown that potassium and magnesium can also impact soil structure negatively and need to be included in irrigation water quality assessment criteria (Sposito et al., 2016). A new criterion known as the Cation Ratio of Structural Stability (CROSS) is being advocated as a better predictor of potential soil permeability problems arising from the use of recycled water for irrigation. This is because CROSS accounts for the dispersive effects of exchangeable potassium and magnesium. Dissolved organic carbon (DOC) has also been shown to influence the potential impact of recycled water reuse for irrigation on soil permeability.

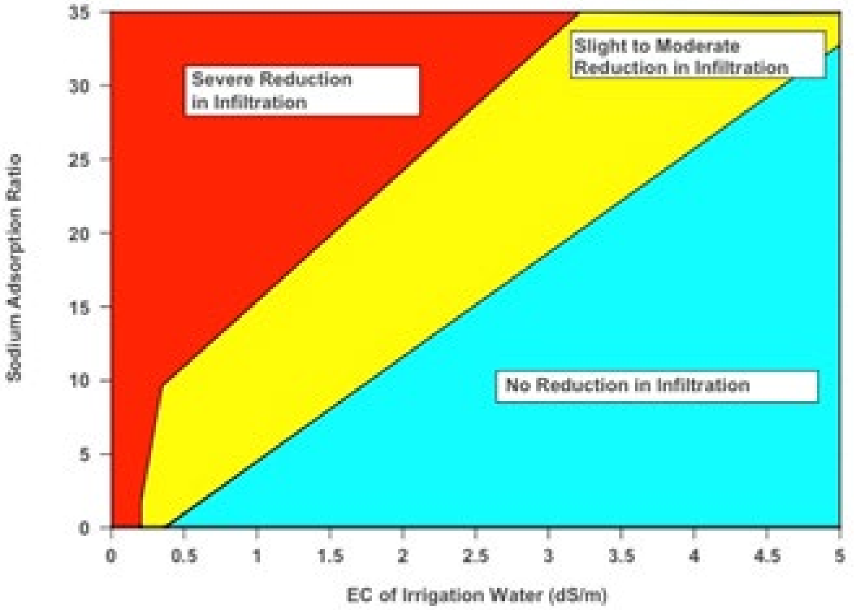


Figure 1-6. Effect of Irrigation Water Salinity and Sodium Adsorption Ratio (SAR) on Soil Infiltration.
Source: Reprinted from Agricultural Water Management 241(2000); by Pedrero, F., S.R. Grattan, A. Ben-Gal, and G. A. Vivaldi; Opportunities for Expanding the Use of Wastewaters for Irrigation of Olives; p. 106333; Copyright (2020), with permission from Elsevier.

1.3.1 Effect of Exchangeable Magnesium on Soil Permeability

In the assessment of sodicity hazard from use of marginal irrigation water, exchangeable Mg has traditionally been thought of as promoting soil structure (Assouline et al., 2016; Sposito et al., 2016). However, some research studies have shown that exchangeable Mg can have negative impacts on soil permeability (hydraulic conductivity) as reported by Alperovitch et al. (1981) and Yousaf et al. (1987). In recognition of the potential negative impacts of exchangeable Mg on soil structure, the Food and Agriculture Organization of the United Nations (FAO) defines a sodic soil as having 15% or more exchangeable Na and Mg on the exchange complex within 50 cm of the soil surface (Sposito et al., 2016). However, such a generalized definition for a sodic soil has not been made in the United States. This is in part because negative impacts of exchangeable Mg on soil structure can be masked by the negative impacts of exchangeable Na (McNeal et al. 1968; He et al., 2013). It is worth noting that the negative impacts of exchangeable Mg are more pronounced in soils with clay minerology (e.g., montmorillonite and kaolinite). Horn (1983) investigated the effects of cations on soil structure and reported that for a clay soil with ESP between 3% and 8%, Mg was the dominant exchangeable cation, saturated hydraulic conductivity was equal to one third of its value when exchangeable Ca was dominant. However, when ESP was greater than 15%, saturated hydraulic conductivity was greatly reduced by exchangeable Na and the negative effects of Mg were substantially masked.

1.3.2 Exchangeable Potassium and Soil Permeability

Use of recycled water for irrigation that is high in potassium was reported to negatively impact soil structure and soil infiltration (Arienzo et al., 2009; Buelow et al., 2015). SAR (Equation 1-5) has traditionally been used as a gold standard diagnostic tool for assessing potential sodicity hazard from use of marginal irrigation water (Sposito et al., 2016).

$$SAR = \frac{Na}{\sqrt{(Ca+Mg)/2}} \qquad \text{(Equation 1-5)}$$

Na, Ca, and *Mg* indicate concentrations in mmol/L. Another diagnostic tool called the Potassium Adsorption Ratio (PAR) expressed as Equation 1-6 was proposed in the classical U.S. Salinity Laboratory Handbook 60 (U.S. Salinity Laboratory, 1954). But currently no irrigation water quality assessment based on PAR have been proposed and widely adopted.

$$PAR = \frac{K}{\sqrt{(Ca+Mg)/2}} \qquad \text{(Equation 1-6)}$$

K represents concentration of potassium in mmol/L. The problem of K-rich recycled water for irrigation is most commonly associated with wastewater from livestock feeding operations, diaries, and food processing operations such as tomato processing plants, and wineries due to K-based cleaning products and animal diets (Sposito et al., 2016). Smith et al. (2015) reported that the ordering of the negative effects on soil permeability could be summarized as Na >K>Mg> Ca with sodium having the greatest effect and Ca least effect. For a thorough assessment the interactions between cations needs to be considered, for example the effect of exchangeable *K* on ESP needs to be considered. Laurenson et al. (2011) reported that in soils irrigated with wastewater high in K, the relationship between SAR-ESP was “moderated” and that the soil ESP was lower than predicted using the US Salinity Lab SAR-ESP model. Therefore, the lowering of ESP by exchangeable *K* indicated that irrigation water quality assessment criteria should not be solely based on SAR.

1.3.3 Diagnostic Tools for Assessing the Potential Sodicity Hazard on Soil Structure from Using Recycled Water for Irrigation

Rengasamy and Marchuk (2011) proposed a generalization of SAR called CROSS (cation ratio of structural stability) expressed as Equation 1-7. CROSS accounts for the differing effects of Na and K as dispersing cations that negatively impact soil permeability and the differing effects of Mg and Ca as flocculating cations that enhance soil permeability:

$$CROSS_f = \frac{(Na+0.56K)}{[(Ca+0.60Mg)/2]^{0.5}} \qquad \text{(Equation 1-7)}$$

where the subscript $_f$ represents the fact that the numerical coefficients in the CROSS equation are derived from the relative flocculating power of K and Mg following Rengasamy and Marchuk (2011). The dispersing power of K relative to Na is 0.56 while the flocculating power of Mg relative to Ca is 0.6. Rengasamy and Marchuk (2011) evaluated $CROSS_f$ as a diagnostic irrigation water quality assessment tool for predicting soil sodicity hazard, they reported that although SAR correlated with dispersed clay in selected Australian soils, the correlation of $CROSS_f$ and dispersed clay was superior. They concluded that including the dispersive effects of K in addition to Na and differentiating the flocculating effects of Mg from Ca caused CROSS to have higher values compared to SAR implying that it was a more conservative diagnostic tool for assessing negative impacts on soil structure and soil permeability (Oster et al., 2016). Smith et al. (2015) provided a generalization of Equation 1-8 to allow for a broader interpretation of its coefficients. Where the coefficients a and b in Equation 1-8 are determined through optimization.

$$CROSS_{opt} = \frac{(Na+\boldsymbol{a}K)}{[(Ca+\boldsymbol{b}Mg)/2]^{0.5}} \qquad \text{(Equation 1-8)}$$

Oster et al. (2016) suggested that Equation 1-8 be interpreted as the weighted sum of a generalized SAR and PAR, with the weighting factor $a < 1$ interpreted as a measure of the lesser negative impact of PAR on soil permeability relative to SAR. The coefficient $b < 1$ can be interpreted as a multiplier of the actual concentration of Mg to produce an “effective concentration” of Mg.

1.3.3.1 Using CROSS to Assess Recycled Irrigation Water Quality

CROSS is the only irrigation water quality assessment tool currently available that accounts for the effects of all four major cations (Na, K, Mg, Ca) on soil structure and soil permeability. The use of CROSS as a diagnostic tool should be similar to the use of SAR (Oster et al., 2016). Consequently, the interpretative guidelines for irrigation water quality involving SAR and CROSS should be similar. Oster et al. (2016) evaluated $CROSS_{opt}$ and SAR values for wastewater and other water sources in California and reported sodicity hazard for some of the waters changed from none to slight to moderate when $CROSS_{opt}$ was used as the assessment criteria instead SAR. For example, Figure 1-7 shows representative recycled water qualities from different wastewater utility agencies in California and their potential impact on soil structure in the form of infiltration rate reduction. It is plausible that if the Y-axis were changed from SAR to CROSS, the potential of some of the recycled water qualities from different utility agencies to impact soil structure would shift from the “No Reduction in Infiltrate Rate” zone on the graph to the “Slight to Moderate Reduction in Infiltration Rate” (Figure 1-7). This change to the CROSS calculation, which calculates less favorable infiltration rates, has important implications for the long-term use of recycled water from different wastewater sources.

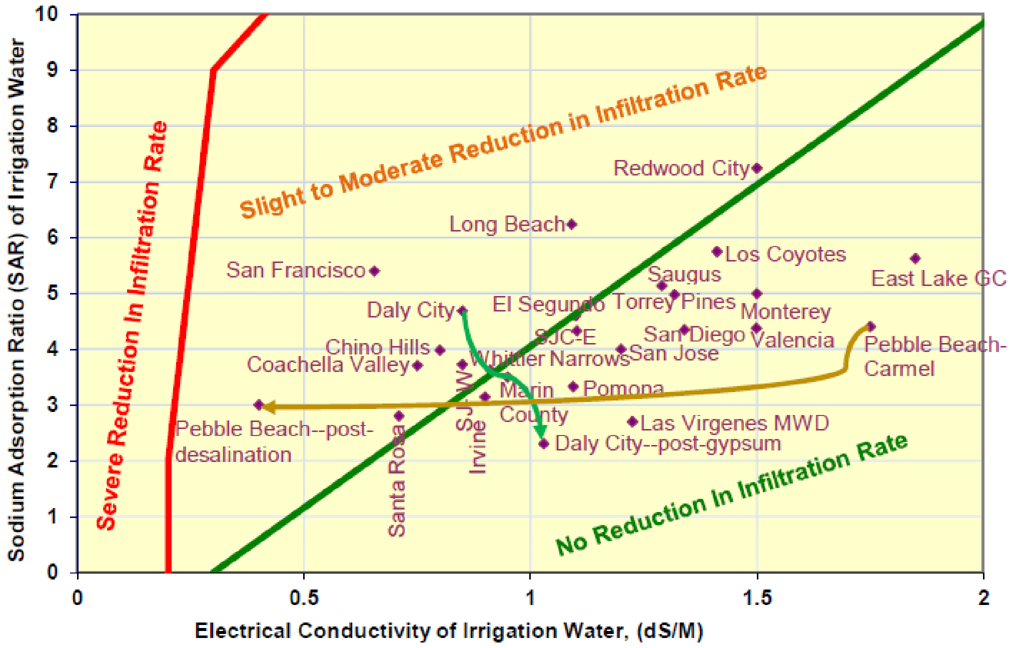


Figure 1-7. Shows Representative Recycled Water Qualities from Different Wastewater Utility Agencies in California and Their Potential Impact on Soil Structure in the Form of Infiltration Rate.

1.4 Salinity Impacts

Treated municipal waste waters contain mineral salts, but the concentration and composition of these salts vary widely among locations and sources of water (Ayers and Westcot, 1985; Wallender and Tanji, 2012). These salts dissolve in solution to form ions (cations and anions), where the most common cations are calcium (Ca^{2+}), magnesium (Mg^{2+}), and sodium (Na^{+}) and most abundant anions are chloride (Cl^{-}), sulfate (SO_4^{2-}) and bicarbonate (HCO_3^{-}). Potassium (K^{+}), carbonate (CO_3^{2-}), nitrate (NO_3^{-}), phosphate ($H_2PO_4^{-}$), boron (B) and trace elements also exist in soils and water supplies but most often their concentrations are comparatively low even though their presence can still influence crop growth and management. The overall concentration of these constituents reflects the overall salinity of the water which can be characterized in different ways.

The salinity of the irrigation water is usually expressed by its electrical conductivity (ECw) because the salts dissolved in the water form ions and conduct electrical current (USDA-USSL Staff., 1954). The standard unit of ECw is decisiemens per meter (dS/m), which is numerically equivalent to millimhos per centimeter (mmho/cm). The EC of water is readily measured using a conductivity meter standardized to its reading at 25°C (USDA-USSL Staff, 1954).

Salinity is also expressed as total dissolved solids (TDS) with units reported in mg/L which is numerically equivalent to parts per million (ppm). TDS represents the mass of salt that remains after a liter of water is evaporated to dryness. This term is still reported by many analytical laboratories and is used widely by wastewater engineers. The salinity parameters ECw and TDS are, for the most part, linearly related to one another over the concentration range where most crops are impacted. The most common conversion is TDS = 640 * EC (dS/m) (USDA-USSL Staff, 1954) but this conversion is dependent upon the composition and concentration of the water.

As such, Rhoades et al (1992) suggests an approximate relationship of a water as ECw of 1 dS/m = 10 mmolc/L = 700 mg/L. For ECw > 5 dS/m, Hanson et al. (2006) suggests that the conversion TDS (mg/L) = 800 EC (dS/m) is more accurate.

Irrigation water supplies that are low in salinity are in limited supply across the globe, particularly in arid and semi-arid climates. Therefore, waters of poorer quality will be used more and more to satisfy crop water needs including recycled wastewater. And, with a changing climate and uncertainty in precipitation patterns, recycled wastewater will likely play a larger role supplementing irrigation water supply. However, due to their higher concentration of salts, recycled wastewater presents challenges for sustained long-term use in irrigated agriculture.

1.4.1 Past and Current Knowledge on Salinity Impacts

Salinity has impacted irrigated agriculture for thousands of years. In ancient Mesopotamia, the Fertile Crescent was inundated by salts due to inadequate drainage which led to the destruction of this ancient hydraulic civilization (Hillel, 1998). But salinity was not unique to the Middle East. In the early part of the 20th century, it was recognized by the United States Department of Agriculture (USDA) that agricultural production in the western part of the United States was being impacted by salinity. To address this concern, the USDA Salinity Laboratory was established in Riverside, California shortly after World War II to study the effects of salinity on soils and crop production. The Salinity Laboratory published the famous USDA Handbook 60 in 1954 to help with the diagnosis and improvement of saline and alkali soils (USDA-USSL, 1954) and continues to be a reference cited by salinity researchers across the globe.

The US Salinity Laboratory made a distinction between soils that were saline and alkaline. Saline soils were those with an electrical conductivity of the saturated soil paste > 4 dS/m while alkaline soils were those having an exchangeable sodium percentage (ESP) > 15 (USDA-USSL, 1954). Therefore, there are four general categories: 1) Non-saline, non-alkaline 2) Non-saline, alkaline, 3) Saline, non-alkaline and 4) Saline, alkaline. Because ‘alkaline’ refers to soils with above neutral pH, typically above 7.5, the term ‘sodic’ soil has replaced ‘alkaline’ (Wallender and Tanji, 2012). It has been recognized for decades that crops vary widely in their tolerance to salinity (USDA-USSL, 1954) as well as the basic physiological responses that account for these differences (Bernstein and Hayward, 1958). It is understood that crop growth was impacted by osmotic inhibition of water absorption for the soil solution and by ion specific effects. These processes are not entirely independent upon one another and often impact the crop collectively.

Salinity reduces the osmotic potential of the soil solution thereby requiring the plant to osmotically adjust by concentrating solutes (i.e. ions or organic solutes) inside their cells in order to readily extract water via osmosis. This concentration process requires metabolic energy (ATP) but its ultimate cost to plant growth depends on ion transport efficiencies across membranes and energy requirements to synthesize organic solutes, which differs among species and varieties within a species (Munns et al., 2020). As such, the efficiency of transport processes involving specific ions (e.g. Na^+) will affect the overall osmotic response. As a result, salt-stressed plants are stunted, even though they may appear healthy in all other regards

(Bernstein, 1975). Both processes of adjustment (accumulation of ions and synthesis of organic solutes) occur but the extent to which one process dominates over the other is dependent upon the crop type and level of salinity (Läuchli and Grattan, 2012). And within the cell, compartmentalization is critical to keep toxic ions away from sensitive metabolic processes in the cytoplasm (Munns and Tester, 2008; Hasegawa et al., 2000). Such compartmentation is controlled by transport processes across the plasma membrane (i.e. cell membrane) and tonoplast (i.e. vacuolar membrane).

Specific ion effects can be directly toxic to the crop, due to excess accumulation of Na, Cl or B in its tissue, or they may cause nutritional imbalances (Grieve et al., 2012). While specific ions reduce the osmotic potential of the soil solution, ion toxicities are rarely observed in annual crops grown in the field (with the exception of certain beans and soybeans) provided the ion ratios (e.g. Na^+/Ca^{2+}; Cl^-/SO_4^{2-}) are not extreme or salinity is not too high. However, when Na^+ dominates the cations or Cl^- concentrations are sufficiently high, these constituents can accumulate in older leaves and produce injury. Specific ion toxicities are particularly prominent in tree and vine crops and injury becomes more prevalent over the years. But rootstock selection plays a major role in controlling the amount of Na^+, Cl^- and boron that accumulates in the scion (i.e. the variety grafted upon the rootstock) and thus their tolerance to these specific ions (Grieve et al, 2012). For example, in grapes, some rootstocks can differ in the transport of Cl^- to their leaves by as much as 15-fold (Bernstein, 1975). Specific ions can also induce nutritional disorders due to their effect on nutrient availability, competitive uptake, transport and partitioning within the plant (Grattan and Grieve, 1999). For example, excess Na^+ can cause a sodium-induced Ca^{2+} or K^+ deficiency in many crops (Bernstein, 1975). These effects may be more subtle than direct ion toxicities but nonetheless affect the crops performance.

While osmotic and specific ion effects can occur concurrently, typically osmotic effects occur early while specific ion effects occur later (Munns and Tester, 2008). In the field, Na^+ and Cl^- toxicities can be observed in salt-affected fields after several years of tree or vine growth. Often Cl^- toxicity occurs in tree crops sooner than Na^+ toxicity as Na^+, unlike Cl^-, is retained in woody tissue, only to be released when sapwood converts to heartwood (Bernstein, 1975).

1.4.2 Expressions That Characterize Crop Salt-Tolerance

Root zone salinity has traditionally been characterized by the electrical conductivity of the saturated soil paste (ECe) (USDA-USSL, 1954). While other methods such as 1:1; 1:2.5 and 1:5 extract ratios are quantitatively more reproducible and under Cl^- dominated conditions have shown good correlations with the chemistry in the saturated paste (Sonmez et al., 2008), the US Salinity Laboratory promoted the later method because 1) the chemistry of the saturated soil extract is close to that of the soil water and 2) the chemistry could nonetheless vary due to dissolution and precipitation of sulfate and carbonate minerals should larger soil water dilutions be used.

Because crops vary in their tolerance to salinity, scientists found it necessary to characterize their salt tolerance by developing simplistic models to predict their relative yield in the field as a function of seasonal average root zone salinity. The most comprehensive approach was done in the 1970's by scientists at the US Salinity laboratory (Maas and Hoffman, 1977). They collected and analyzed research papers describing salinity studies on a wide range of crops. When comparing studies, they understood, as did their predecessors (USDA-USSL Staff, 1954), that using absolute yield (mass/area) was an unreliable parameter to compare different crop types grown under a range of different conditions. Rather, the salt tolerance of crops can better be defined as a function of relative yield decline across a range of salt concentrations. Maas and Hoffman (1977) found that salt tolerance can be adequately measured on the basis of two parameters: 1) a “threshold” parameter which is the maximum root zone salinity (described as electrical conductivity of the saturated soil extract, ECe) that the crop can tolerate above which yields decline and 2) the “slope” which describes the rate by which yields decline with increased soil salinity beyond the ‘threshold’ (Figure 1-8). Slope is simply the percentage of expected yield reduction per unit increase in salinity above the threshold value.

For soil salinities exceeding the threshold of any given crop, relative yield (Yr) or "yield potential" can be estimated using the following equation:

$$\text{Yield}\ (\%) = 100 - s(ECe - t) \qquad \text{(Equation 1-9)}$$

where t = the ‘salinity threshold’ soil salinity value expressed in dS/m; s = the ‘slope’ expressed in % yield decline per dS/m; and ECe = average root zone salinity of the saturated soil extract. The most current up-to-date listing of specific values for "t" and "s", called “salinity coefficients,” are found in a book chapter by Grieve et al. (2012). The greater the threshold value and lower the slope, the greater the salt tolerance.

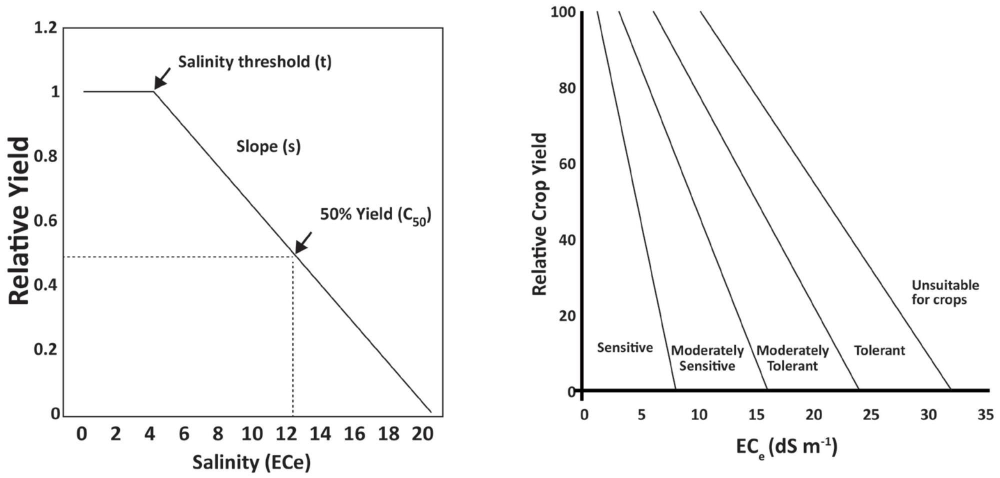


Figure 1-8. Salt Tolerance Parameters ‘Salinity Threshold’ (t) and Slope of Yield Decline (s) for Salinity That Exceeds the ‘Threshold’ (left) and Salt Tolerance Categories First Described by Maas and Hoffman, 1977 (right).
Source: (Left) Reprinted from Scientia Horticulturae 78(1998); by Shannon, M.C., and C. M. Grieve; Tolerance of Vegetable Crops to Salinity; p. 5-38; Copyright (1999), with permission from Elsevier.
(Right): Adapted from Maas and Hoffman 1977.

Most agronomic grain crops such as barley, oats, rye and wheat are more tolerant to salinity than most horticultural tree and vine crops such as almond, berries, citrus, grapes and stone fruits (Grieve et al., 2012). As indicated earlier, salinity adversely affects crops by a combination of mechanisms including osmotic influences, toxic ion effects (i.e. chloride, sodium and boron) and nutritional imbalances (Läuchli and Grattan, 2012). Depending upon the crop, growth stage, duration of salinity exposure and environmental conditions some mechanisms may be more influential than others (Munns and Tester, 2008). Tree and vine crops, for example, are particularly susceptible to ion toxicity relative to most annual crops and this effect becomes more pronounced over the years and foliar injury is particularly prominent later in the season.

There is considerable uncertainty regarding the "yield-threshold" (t) soil-salinity values and that such "threshold" values, for the most part, lack physiological justification. The salinity coefficients (yield threshold (t) and slope values (s)) for the slope-threshold model of Maas-Hoffman expression (Equation 1-9) are determined by non-linear least-squares statistical fitting that determines the slope and threshold values from a particular set of experimental data. Despite investigators controlling salinity and minimizing all other stresses that would affect plant yield in salt tolerance studies, the standard errors associated with the 'threshold' values can be 50 to well over 100% (Grieve et al., 2012). Obviously, these large percentages represent considerable uncertainty and suggest that actual 'threshold' values do not exist (Steppuhn et al., 2005 a, b). This is not surprising given the variability of soil structures in different locations and the variability of crop sensitivity due to cultivar. Therefore, the salinity threshold (t) becomes a multifactorial issue. Because of the uncertainty with the 't' value, others have suggested an ECe_{90} parameter (soil salinity that equates to 90% yield) as a substitute for the yield threshold parameter (van Straten et al., 2019).

Over the past few decades, scientists have since developed non-linear expressions that fit the data better and are more scientifically justified from a physiological response perspective (van Genuchten and Gupta, 1993; Steppuhn et al., 2005 a, b). The non-linear equation can be seen in Figure 1-9 and is described as follows;

$$Yr = 1 / [1 + (EC/EC_{50})^{p}] \qquad \text{(Equation 1-10)}$$

where, *Yr* is relative yield, *p* is an empirical shape parameter that varies between (x-y), *EC* is the average root zone soil salinity expressed as the electrical conductivity of the saturated soil paste and EC_{50} is the average root zone soil salinity where 50% yield is predicted.

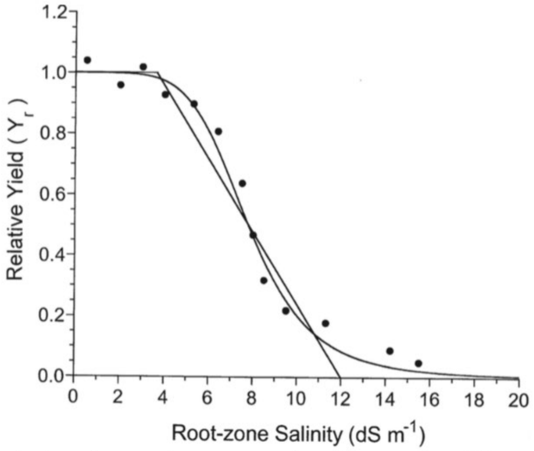


Figure 1-9. Typical Non-linear Response Curve Superimposed on the Maas-Hoffman Slope-Threshold Model.
Source: Steppuhn et al., 2005b.

In some cases, the response function indicates that yields of salt-tolerant crops may in fact increase slightly with mild increases in salinity and then decrease at higher levels. Despite the slightly better data fit with non-linear expressions as compared to the Maas-Hoffman ‘threshold’ and ‘slope’ model, all expressions fit the data very well.

1.5 Summary

Soil structure is a very important property because it regulates many biophysiochemical processes in soil (e.g., soil water cycling, nutrient cycling, microbial activities, etc.). Soil structure is important to many activities such as agricultural production, construction site conditions, and ecological assessments. However, it is complex to fully characterize soil structure in geometric terms because soil particles differ in shape, orientation, size, and ways in which they connect and interlink. Therefore, soil structure remains a qualitative concept rather than a directly quantifiable property.

To evaluate the impact of sodicity on soil structure, it is critical to understand clay-water interactions and the processes of dispersion and flocculation. The dispersion and flocculation processes occur mainly due to the interaction of the negative and positive ionic forces in the soil. Depending on the dominant interactive force, clay particles may disperse (if the dominant forces are negative) or flocculate (if the dominant forces are positive). Dispersion of clay particles negatively affects soil structure. Sodium has a strong opposite effect to that of salinity on soils in relation to clay dispersion. High concentrations of sodium in irrigation water cause clay platelet dispersion and aggregate swelling. On the other hand, increasing electrolyte concentration reduces the potential for dispersion. The Zeta potential (ζ) which is an electro kinetic potential in colloidal systems such as clay particles in a soil water solution can be used as a good tool for assessing the potential for dispersion of clay particles due to irrigating with recycled water of different ionic composition. Soil pH also has a direct impact on soil dispersion and the effect depends on the cation exchange capacity. Research has shown that clay dispersion increased with increasing pH for predominantly kaolinitic clay soils.

Numerous studies have reported reductions in soil permeability resulting from use of marginal recycled water for irrigation due to increase in exchangeable sodium percentage. Traditionally if the sodium adsorption ratio (SAR) and the EC of the irrigation water were known, the effect of using recycled water on soil permeability (as a proxy for structure) could be predicted using the empirical relationships. However, emerging research has shown that potassium and magnesium can also impact soil structure negatively and need to be included in irrigation water quality assessment criteria. A new criterion known as the Cation Ratio of Structural Stability (CROSS) is being advocated as a better predictor of potential soil permeability problems arising from the use of recycled water for irrigation. CROSS is the only irrigation water quality assessment tool currently available that accounts for the effects of all four major cations (Na^+, K^+, Mg^{2+}, Ca^{2+}) on soil structure and soil permeability. The interpretative guidelines for irrigation water quality involving SAR and CROSS are similar.

Treated municipal waste waters also contain mineral salts, but the concentration and composition of these salts vary widely among locations and sources of water. Salinity adversely affects crops by a combination of mechanisms including osmotic influences, specific ion toxic effects (i.e., chloride, sodium and boron) and nutritional imbalances (e.g., sodium induced Ca^{2+} or K^+ deficiency in some crops). Agronomic grain crops such as wheat are more tolerant to salinity than most horticultural e.g., grapes and nut crops. Crop specific empirical models (i.e., stepwise, and non-linear model) exist that can predict reduction in yield due to increasing root zone salinity. Despite the slightly better data fit with non-linear expressions as compared to the stepwise model of Maas-Hoffman, all expressions fit the data very well. However, there is a need to develop process-based models that predict crop response to a combination of mechanisms including osmotic influences, specific ion toxic effects and nutritional imbalances.

CHAPTER 2

Assessing Long Term Changes in Recycled Water Irrigation Quality and Its Impact on Soil in California Central Coast

This chapter has two main sections. The first section (2.1 - 2.6) evaluates historical soil sampling data using both SAR and CROSS to evaluate the variability and relationship to soil quality and the changes in irrigation water quality applied over time. The second section (2.7 – 2.8) focuses on sampling techniques for various types of recycled water delivery systems and grower irrigation practices, soil amendments and tillage techniques to mitigate potential issues with sodicity and salinity.

2.1 Introduction

Since 1954 when USDA Agriculture Handbook No. 60 was published, soil scientists and agricultural producers in the Western United States have relied on the Sodium Adsorption Ratio (SAR) to evaluate the risk of creating sodic soils. This ratio evaluates the amount of Sodium (Na) in an irrigation water or soil sample as compared to the amounts of Calcium (Ca) and Magnesium (Mg). With the use of recycled water for agricultural production in many parts of the world, soil scientists have proposed that an alternative ratio be evaluated. The proposed Cation Ratio of Soil Structural Stability (CROSS) includes adding Potassium (K) into the ratio and varying the weighting of it and Mg. This would incorporate concerns in areas where soils may contain large amounts of K and also factor in larger amounts of Mg from recycled water sources (Rengasamy and Marchuk, 2011). The two ratio equations are as shown in Equations 2-1 and 2-2:

$$SAR = \frac{Na^{+}}{\sqrt{Ca^{2+} + Mg^{2+}}} \qquad \text{(Equation 2-1)}$$

where Na^{+}, Ca^{2+} and Mg^{2+} are the concentrations of the ions in mmol/L. SAR considers sodium as the major cation responsible for the sodicity hazard. It ignores potassium's effect as a dispersive agent, even though its dispersive effect is less, and overestimates the flocculation power of magnesium (Arienzo et al., 2009; Rengasamy and Marchuk, 2011; Smith et al., 2015). To further improve the predictability of the sodicity hazard, Rengasamy and Marchuk (2011) developed the Cation Ratio of Soil Structural Stability (CROSS):

$$CROSS_{f} = \frac{Na^{+} + 0.56 * K^{+}}{\sqrt{Ca^{2+} + 0.60 * Mg^{2+}}} \qquad \text{(Equation 2-2)}$$

where K^{+} is the concentration of the potassium ion in mmol/L. The subscript *f* indicates that the factors of K and Mg “are based on the relative flocculating power.” Equation 2-2 has been observed to have better rate of soil infiltration prediction (based on dispersive clay percentage) than SAR.

The analyses within this case study evaluate the variation and predictability of the new CROSS criteria as compared to the SAR criteria. The datasets evaluated include water quality data and soil sample data from two long term studies on the Central Coast of California. It is important to note that the mineral soils in these studies do not have high loads of K; it is usually less than 0.5 meq/L which is defined as deficient for crop production. In addition, source waters in the area contain fairly high amounts of Mg, but this is offset by also high levels of Ca in both the water and the soils. Therefore, this case study is not intended to validate the effect of adding K as a factor, since it is in such small quantities. However, it is clear that reducing the weight of Mg would significantly increase the effect of the Na and K levels when comparing the CROSS ratio to SAR. The following analysis will summarize the differences between SAR and CROSS values for the following ranges of data and different values:

- Variation in annual average soil and water quality values for the entire soil profile
- Spatial variation in soil values for the sub-profiles, 1-12”, 12-24” and 24-36”
- Correlations between Na levels and SAR and CROSS values
- Comparison of SAR and CROSS values with Cation Exchange Capacity[1] (CEC) values for both the entire soil profile and sub-profiles
- Analysis of trends in % exchangeable Na, Ca and Mg in comparison to trends in SAR and CROSS values.

The data to be analyzed is a total of 31 years of soil sampling conducted at multiple sites by local agencies delivering recycled water to agricultural producers. This large data set will be subdivided into subsets based on the significant differences in delivered water quality over different timeframes. The subsets are based on salinity trends and a secondary goal is to evaluate CROSS values for consistency and robustness under varying conditions of salinity.

2.2 Long Term Use of Recycled Water for Irrigation in the Central Coast of California

Recycled water has been used by agricultural producers on the Central Coast of California since 1998. In 2000, the first of two long-term soil salinity studies were initiated by Monterey One Water (M1W). Figure 2-1 shows M1W’s sources of municipal wastewater and the 12,000 acre recycled water delivery zone. Pajaro Valley Water Management Agency (PVW) following Monterey One’s example initiated their long-term soil salinity study in 2005, before making water deliveries to the agricultural producers. Figure 2-2 shows PVW’s groundwater basin and recycled water delivery zone of 5,000 acres. Detailed descriptions of the soil and water sampling methodology for both studies are written up in additional documents (Appendix A).

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[1] CEC values are calculated for only the base cations (Na, K, Ca and Mg); all soil pH values are > 7 and therefore there is no acid cation contribution (Tisdale, S.L. et al., 1993).

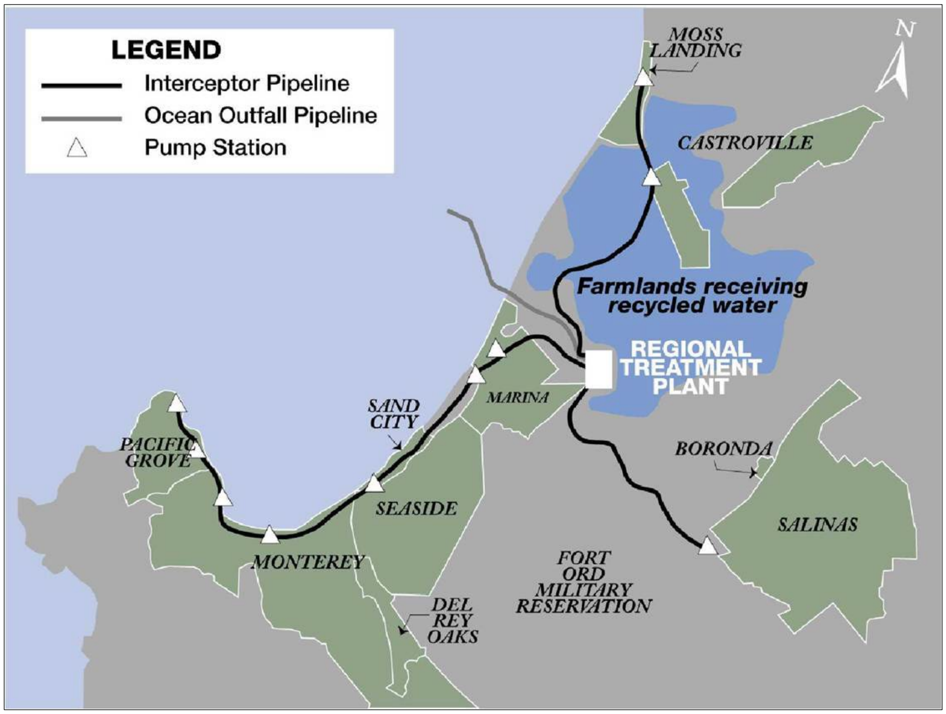


Figure 2-1. Monterey One Water (MIW) Recycled Water Sources and Delivery Zone.

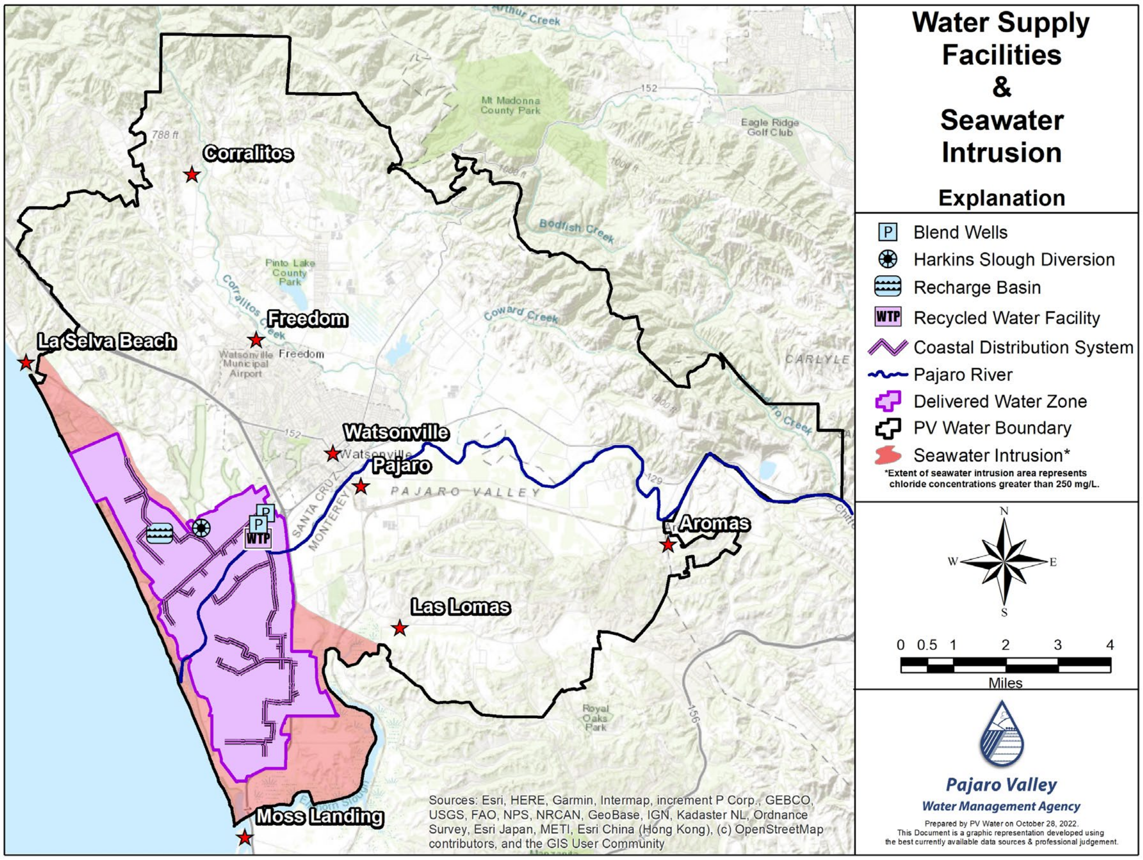


Figure 2-2. Pajaro Valley Water (PVW) Groundwater Basin and Recycled Water Delivery Zone.

For both water agencies, delivered water quality has varied over time and Table 2-1 summarizes the range of values (M1W, 2000-2019, PVW, 2009-2019). While the variation in these water quality values may not seem significant, the variation in soil type and drainage between the soil testing sites selected could significantly affect the accumulation of salts. In addition, prior use of poor-quality irrigation water from seawater intruded wells created a pre-existing salt load at some sites. In addition to the variation in water quality during the different timeframes, there was also significant variation in seasonal rainfall for the same periods (Table 2-1). More seasonal rainfall decreased use of recycled water and the agricultural producers also developed more efficient use of recycled water as the projects matured. Recycled water use for 2000-2009 averaged 20.5 in./acre per year (1.71 acre-feet/acre per year) as compared to 16.3 in./acre per year (1.36 acre-feet/acre per year) for 2010-2019. The increased rainfall and decreased recycled water use increased the likelihood of decreases in soil salinity in addition to the improved delivered water quality (Platts and Grismer, 2014).

Table 2-1. Ranges of Water Quality Delivered between 2000-2019 by the Monterey One Water and Pajaro Valley Water Management Agency.

Location and Timeframe	Range of Na (ppm)	Max. SAR	Max. CROSS	Avg. Rainfall[1]	Avg. Acre Feet/Acre
M1W 2000 – 2009	81 - 168	4.73	7.31	12.4	1.71
M1W 2010 – 2019	138 - 150	3.87	6.14	14.3	1.36
PVW 2009 - 2019	85 - 104	2.93	4.67	13.9	NA[2]

[1] Data obtained from California Irrigation Management Information System (CIMIS), Castroville station

[2] PV Water does not deliver enough water to its customers to be the only source of irrigation water; while Monterey One Water delivers over 90% of the irrigation water used by its customers

The subsets of the data from the different time periods and locations were evaluated with the Mann-Kendall Test. The Mann-Kendall test determines whether a time series has an upward or downward trend without requiring that the data be normally distributed or linear (Esterby, 1996). An alpha value of 0.10 was used since the data is not from a controlled experiment where the only variable would be water quality; different agricultural producers farm each site with different methods. The results of this Mann-Kendall statistical test allowed for the classification of each site into one of the three trend categories, no trend, or increasing or decreasing salinity. The sites with no trend are assumed to be at equilibrium since they are fluctuating around a consistent average value over a ten-year period.

This statistical trend analysis produced the first difference between the SAR and CROSS values (Appendix A). The annual variation in SAR values showed that seven of the data sets had no trend, while two data sets had increasing trends in salinity and two data sets had decreasing trends in salinity. In contrast, the CROSS values produced four sites with no trend, three sites with increasing salinity and four sites with decreasing salinity. The CROSS results are more indicative of the differences in delivered water quality and individual site characteristics of soil type and drainage (Table 2-2).

Table 2-2. Soil Salinity Trends for CROSS by Timeframe at Sites Receiving Recycled Water Either from Monterey One Water (M1W) or Pajaro Valley Water (PVW).

Location	Salinity[1] Level/Drainage	2000 – 2009	2010 – 2019
M1W Site 2	low/excellent	Equilibrium	Equilibrium
M1W Site 4	low/good	**Increasing**	**Decreasing**
M1W Site 3A	moderate/poor	**Increasing**	Equilibrium
M1W Site 5A	harmful/poor	Equilibrium	**Decreasing**
M1W Site 7	harmful/extremely poor	**Increasing**	**Decreasing**
PVW Site 3	harmful/extremely poor	No data until 2008	**Decreasing**

[1] The designation of harmful salinity level is based on SAR soil values greater than 6 when EC would be greater than 1.9 causing yield loss and % exchangeable Na greater than 50%. A&L Laboratories, Guidelines for Interpreting Irrigation Water Analysis Reports, Western Fertilizer Handbook

Based on Table 2-2, each of the conceptual analyses (i.e., variation in annual values, spatial variation in the soil profile, correlation with Na values, etc.) will provide data for each of the trend groups to ensure that the evaluation of the CROSS values includes varying conditions of salinity.

2.3 Variation of Annual Values of SAR and CROSS for the Entire Soil Profile and the Correlation to Na Levels

Analysis of the annual variation in salinity values indicates that SAR values have less variation compared to CROSS values. The difference in the ratio equations when applied to actual data in this study creates CROSS values that are approximately two or more times the SAR values (Tables 2-3 – 2-5). Additionally, when Na levels are greater than 10 meq/L the increased or decreased CROSS levels are greater than the changes in SAR (Tables 2-4 and 2-5). For all sites, at equilibrium, increasing or decreasing, the correlation of Na to SAR is inconsistent, but the correlation of Na to CROSS is uniformly 0.99.

Table 2-3. Salinity Values for the Entire Soil Profile at Equilibrium Sites in the Monterey One Water Recycled Water Service Area along the Central Coast of California.

Entire Profile 1-36”	M1W Site 2 2000-2009	M1W Site 2 2010-2019	M1W Site 3A 2010-2019	M1W Site 5A 2000-2009
Avg. Na (meq/L)	6.27	6.75	10.12	17.19
Initial SAR	2.30	2.98	3.43	8.94
Final SAR	2.58	3.24	4.57	6.64
SAR Correlation to Na	0.79	0.63	0.86	0.58
Initial CROSS	5.25	7.64	9.24	17.90
Final CROSS	7.70	7.40	11.77	19.12
CROSS Correlation to Na	0.99	0.99	0.99	0.99

Table 2-4. Salinity Values for Entire Soil Profile for Increasing Sites in the Monterey One Water Recycled Water Service Area along the Central Coast of California.

Entire Profile 1-36”	M1W Site 4 2000-2009	M1W Site 3A 2000-2009	M1W Site 7 2000-2009
Avg. Na (meq/L)	5.85	10.59	18.58
Initial SAR	2.03	3.37	7.12
Final SAR	3.69	4.02	7.24
SAR Correlation to Na	0.91	0.51	0.78
Initial CROSS	4.03	6.97	18.41
Final CROSS	6.98 (+2.95)	11.35 (+4.38)	26.52 (+8.11)
CROSS Correlation to Na	0.99	0.99	0.99

Table 2-5. Salinity Values for Entire Soil Profile for Decreasing Sites in the Monterey One Water and Pajaro Valley Water Recycled Water Service Area along the Central Coast of California.

Entire Profile 1-36”	M1W Site 4 2010-2019	M1W Site 5A 2010-2019	M1W Site 7 2010-2019	PVW Site 3 2009-2019
Avg. Na (meq/L)	7.71	12.69	17.33	39.66
Initial SAR	3.86	7.24	6.86	14.02
Final SAR	4.28	5.76	5.02	13.28
Correlation to Na	0.41	0.87	0.94	0.32
Initial CROSS	8.25	20.16	24.47	52.73
Final CROSS	5.89 (-2.36)	9.82 (-10.34)	10.10 (-14.37)	39.95 (-12.78)
Correlation to Na	0.94	0.99	0.99	0.99

Figure 2-3 shows the difference in annual variation for SAR and CROSS for the equilibrium sites. In both cases, it is clear that each site is fluctuating around an average. The CROSS values consistently show larger magnitudes of change between years. Figure 2-4 shows the magnitude of change for the CROSS values at the increasing and decreasing sites. While the graphs of the SAR values are not shown, Tables 2-4 and 2-5 show the increasing final SAR values to range from 3.69 to 7.24 as compared to 6.98 to 26.52 in the graph below. Similarly, the decreasing final SAR values range from 5.02 to 4.28 as compared to 10.10 to 5.89 in the graph below. Figure 2-4 does not include the data for PVW site 3 where the magnitude of difference between SAR and CROSS values is the greatest (Table 2-5). The SAR values decrease from 14.02 to 13.28 (-6 %), while the CROSS values decrease from 52.73 to 39.95 (-25%). Seven of the eleven sites have Na levels greater than 10 meq/L and CROSS values greater than 10. PVW site 3 has Na levels averaging 39 meq/L (2009 -2019) and a CROSS value of 39.66. For evaluation of the annual variation in soil salinity values throughout the entire soil profile (1-36”) the CROSS ratio is much more sensitive to changes regardless of salinity levels from low to high. However, the magnitude of difference in CROSS vs. SAR is greatest when Na is greater than 10 meq/L. The CROSS ratio, under the soil types and water quality history on the Central Coast of California, is perfectly correlated with Na levels.

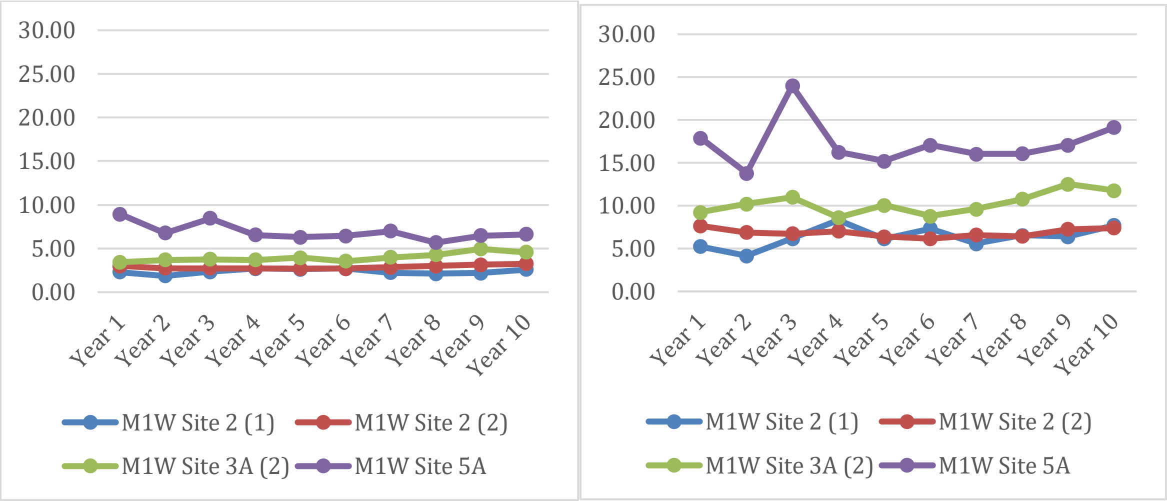


Figure 2-3. Annual SAR and CROSS Values for Entire Soil Profile for Equilibrium Sites in the Monterey One Water Recycled Water Service Area along the Central Coast of California.

Figure 2-4. Annual CROSS Values for Entire Soil Profile for Increasing and Decreasing Sites in the Monterey One Water Recycled Water Service Area along the Central Coast of California.

2.4 Spatial Variation of the Annual Values of SAR and CROSS and Correlation to Na Levels

During the M1W study, spatial variation in soil salinity values was observed. Sites with good drainage had higher salinities in the shallow profiles or uniform salinities throughout the entire soil profile, while sites with poor drainage had higher salinities deeper in the profile. Based on this information, a comparative spatial analysis was done for each group of sites. Tables 2-6 – 2-8 contain the details of the comparisons and the first factor for evaluation is the variation in salinity levels for the 1-12” profile. Most agricultural producers collect soil samples for nutrient and salinity analyses from the top of the soil profile. In Coastal California, the rooting depth of most of the cool season vegetable and fruit crops is around 12” deep. A few crops have rooting depths up to 24”. There is the potential for SAR values for the 1-12” profile normally sampled to underestimate salinity risk due to the influence of Ca amendments applied to offset Na accumulation. These amendments traditionally were broadcast and incorporated across the whole field. However, increases in growing costs have caused agricultural producers to make bed top applications and thus concentrate the Ca in the rooting zone of the soil profile. This increases the concentration of Ca in a soil sample from the planting bed as compared to the broadcast method. Therefore, the SAR value for the 1-12” depth is decreased, but not indicative of the entire soil profile and the potential risk for Na accumulation.

The variation of CROSS values in the 1-12” soil profile is greater than the variation in SAR values. This indicates that shallow soil sampling may detect salinity risk better with CROSS values. All of the M1W sites have acceptable SAR values (2.39-4.94) in the 1-12” soil profile indicating no significant salinity risk. In contrast, the larger variation in M1W CROSS values (6.1-14.58) is more indicative of the difference between the sites with good drainage and no legacy salt load compared to sites with poor drainage and historical salt loads (see Figure 2-5). PVW 3, the most impacted site is the only one with an unacceptable SAR value (10.68). Therefore, the effect of applying and concentrating Ca in the topsoil profile is not reflected in the variation of CROSS values.

Table 2-6. Spatial Variation in Root Zone Salinity at Equilibrium Sites in the Monterey One Water Recycled Water Service Area along the Central Coast of California.

Depth (inches)	Site 2 SAR	Site 2 CROSS	Site 3A SAR	Site 3A CROSS	Site 5A SAR	Site 5A CROSS
1-12”	2.39-2.98	6.10-6.89	4.05	10.31	5.37	14.72
12-24”	2.52-2.96	6.93-7.05	4.04	10.54	6.29	16.51
24-36”	2.21-2.71	6.05-6.59	3.87	9.90	9.11	20.50
Correlation with Na by depth	0.43-0.78	0.99-1.00	0.64-0.94	1.00	0.36-0.64	1.00

Table 2-7. Spatial Variation in Salinity at Sites with Increasing Salinity in the Monterey One Water Recycled Water Service Area along the Central Coast of California.

Depth (inches)	Site 4 SAR	Site 4 CROSS	Site 3A SAR	Site 3A CROSS	Site 7 SAR	Site 7 CROSS
1-12”	3.44	6.73	2.84	9.66	4.94	16.37
12-24”	2.86	5.96	3.37	10.64	5.76	16.93
24-36”	2.10	5.02	4.54	11.76	8.39	22.84
Correlation with Na	0.83-0.96	1.00	0.75-0.19	1.00	0.93-0.73	1.00

Table 2-8. Spatial Variation in Salinity at Sites with Decreasing Root Zone Salinity in the Monterey One Water and Pajaro Valley Water Recycled Water Service Area along the Central Coast of California.

	M1W 4 SAR	M1W 4 CROSS	M1W 5A SAR	M1W 5A CROSS	M1W 7 SAR	M1W 7 CROSS	PVW 3 SAR	PVW 3 CROSS
1-12”	4.25	7.83	4.86	10.34	4.85	14.58	10.68	28.50
12-24”	4.18	7.76	5.75	12.00	5.82	16.46	13.56	40.52
24-36”	3.92	7.71	7.53	15.91	8.22	21.39	18.04	54.37
Correlation with Na	0.66-0.26	0.99	0.57-0.89	0.99	0.93-0.81	0.99	0.56-0.72	0.99

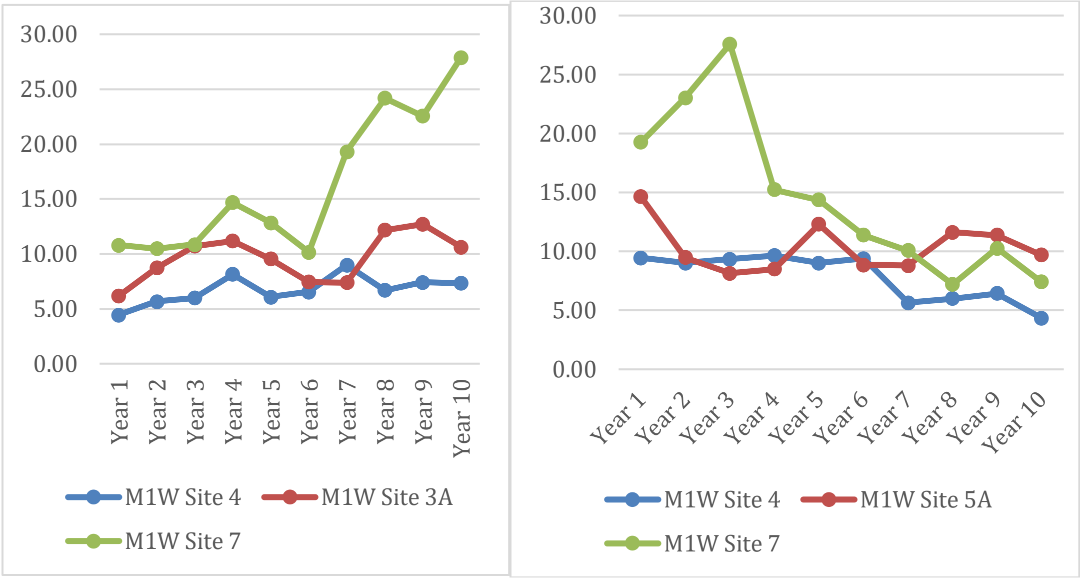


Figure 2-5. Spatial Variation in CROSS Values for 1‑12" Soil Profile for Sites with Increasing or Decreasing Salinity Trends in the Monterey One Water Recycled Water Service Area along the Central Coast of California.

The next factor to evaluate is the uniformity of spatial variation from shallow to deeper soil profiles. M1W sites 2 and 4 with the best drainage and no legacy of salt loading have uniform salinity throughout the soil profile regardless of being at equilibrium or having increasing or decreasing salinity. M1W site 3A with a moderate level of salinity has uniform salinity values thorough out the soil profile at equilibrium, but an increasing level of salinity deeper in the profile when its salinity was increasing. M1W sites 5 and 7 with poorer drainage and historical salt loading have increasing levels of salinity deeper in the soil profile. Lastly, similar to the entire soil profile analysis, CROSS values have high correlations with Na levels regardless of the soil profile depth.

M1W sites 5A and 7 have harmful salinity levels in the 24-36" profile while at equilibrium or during periods of increasing or decreasing salinity. This is important knowledge for agricultural producers. This data can be used to develop mitigation strategies such as changing tillage techniques and improving drainage. A subset of data has been evaluated to ascertain the effect of deep plowing (Personal Communication). The data clearly showed that deep plowing, turning up the 24-36" soil profile, effectively increased the 1-12" soil profile to unacceptable levels. It is clear that any site with increasing salt loads at 24-36" should receive improvements in drainage to aid in cation movement out of the rooting zone.

2.5 Predicting Soil Salinity Values Based on CEC

An important concept related to predicting soil salinity is the observation that over time soil extract salinity values will reach equilibrium values that are 1.5 – 3 times the salinity value of the irrigation water (Western Fertilizer Handbook). This is also described as the Cation Exchange Capacity (CEC) reaching a steady state relative to the cations in the soil solution, which are derived from the irrigation water (Ag. Handbook No. 60). This concept assumes that consistent water quality and adequate irrigation will leach excess salt from the soil profile, but also factors in varying soil clay content and its potential to hold certain levels of cations. Tables

2-9 – 2-11 compare the CEC values to ratios of soil extract to water quality for both SAR values and CROSS values.

The sites at equilibrium have low ratios for the SAR soil to water ratios. This is in contrast to some of the fairly high CEC values indicating the ability to adsorb significant amounts of cations and potentially have a higher risk of salinity issues. Therefore, the CROSS soil to water ratios are more in line with the expectation of soil values to reach 1.5 – 3 times the water salinity values. Both SAR and CROSS soil values and ratios of soil to water values correlate well with CEC.

Table 2-9. Comparison of CEC and Soil to Water SAR/CROSS Ratios for the Entire Soil Profile for Equilibrium Sites in the Monterey One Water Recycled Water Service Area along the Central Coast of California.

Site/Timeframe	CEC	Soil SAR	Ratio of Soil/Water SAR	Soil CROSS	Ratio of Soil/Water CROSS
M1W Site 2 2010-2019	18.3	2.88	0.76	6.84	1.17
M1W Site 2 2000-2009	21.0	2.37	1.04	6.35	1.80
M1W Site 3A 2010-2019	23.9	3.98	1.06	10.25	1.76
M1W Site 5A 2000-2009	31.3	6.92	1.50	17.24	2.42
Correlation to CEC		**0.95**	**0.98**	**0.97**	**0.94**

Figure 2-6 shows that the CROSS values with high correlation produce a linear trend line with a high R squared value (0.81). The trend line for SAR values had an R squared value of 0.75. The CROSS values are more predictable for determining CROSS values for varying CEC values. Similar to the equilibrium sites, the sites with increasing salinity have low SAR soil to water ratios in comparison to the CEC values and the CROSS soil to water ratios are more consistent with the ratio range of 1.5 – 3. In contrast to equilibrium sites, the increasing sites have higher correlations of soil $CROSS_f$ values to CEC than the SAR soil values.

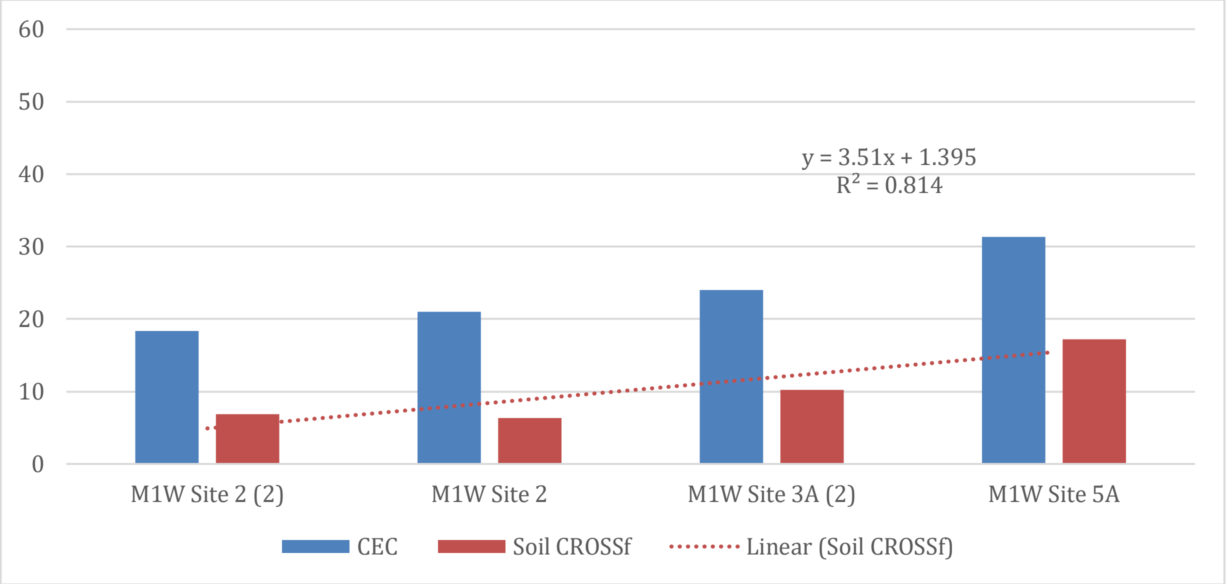


Figure 2-6. Comparison of CEC and CROSS Values Sorted by CEC for Equilibrium Sites in the Monterey One Water Recycled Water Service Area along the Central Coast of California.

Table 2-10. Comparison of CEC, SAR and CROSS Values for the Entire Soil Profile for Increasing Salinity Sites in the Monterey One Water Recycled Water Service Area along the Central Coast of California.

Site/Timeframe	CEC	Soil SAR	Ratio of Soil/Water SAR	Soil CROSS	Ratio of Soil/Water CROSS
M1W Site 4 2000-2009	15.41	2.80	0.98	5.90	1.34
M1W Site 3A 2000-2009	30.87	3.58	0.77	10.68	1.50
M1W Site 7 2000-2009	37.17	6.36	1.34	18.71	2.56
Correlation to CEC		**0.85**	**0.43**	**0.93**	**0.80**

Figure 2-7 shows that the CROSS values with high correlation to CEC produce a linear trend line with a high R squared value of 0.97. The trend line for SAR values also had a high R squared value of 0.90. Similar to the equilibrium and increasing sites, the sites with decreasing salinity have low SAR soil to water ratios. It is important to note that the low ratios are consistent across a wide range of CEC values (15.36 to 57.92). Both SAR and CROSS values correlate well with CEC values. The decreasing sites are the only group to have high correlations of the soil/water ratios with CEC values. Figure 2-8 shows that the CROSS values with high correlation to CEC produce a linear trend line with a high R squared value of 0.85. The trend line for SAR values had a lower R squared value of 0.78.

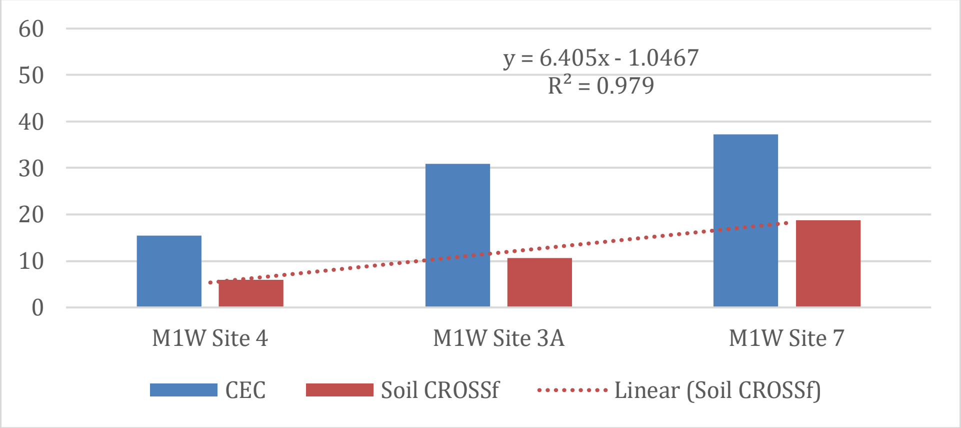


Figure 2-7. Comparison of CEC and CROSS Values Sorted by CEC for Increasing Sites in the Monterey One Water Recycled Water Service Area along the Central Coast of California.

Table 2-11. Comparison of CEC, SAR, and CROSS Values for the Entire Soil Profile for Decreasing Salinity Sites in the Monterey One Water and Pajaro Valley Water Recycled Water Service Area along the Central Coast of California.

Site/Timeframe	CEC	Soil SAR	Ratio of Soil/Water SAR	Soil CROSS	Ratio of Soil/Water CROSS
M1W Site 4 2010-2019	15.36	4.13	1.11	7.59	1.34
M1W Site 5A 2010-2019	22.24	6.05	1.60	12.75	2.16
M1W Site 7 2010-2019	33.64	6.29	1.63	17.47	2.85
PVW Site 3 2009-2019	57.92	13.69	6.22	39.91	10.50
Correlation to CEC		0.97	0.94	0.99	0.96

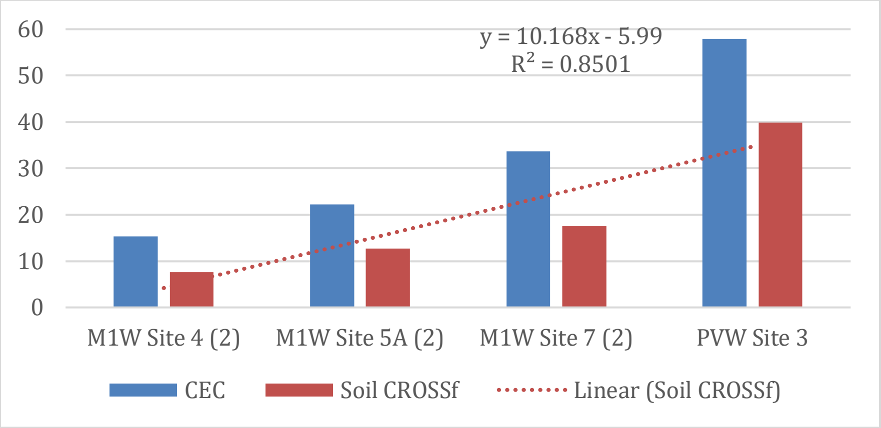


Figure 2-8. Comparison of CEC and CROSS Values Sorted by CEC for Decreasing Sites in the Monterey One Water and Pajaro Valley Water Recycled Water Service Area along the Central Coast of California.

A similar analysis of CEC to SAR and CROSS values was done for the sub-profile values. It is important to note that CEC values are likely to be more correlated with SAR or CROSS values deeper in the soil profile for several reasons. The shallower soil profiles will have decreased CEC due root uptake of the available cations necessary for plant growth. Also, the incorporation of organic matter from rotation crops or organic soil amendments in the shallower profiles improves drainage and cation leaching. Secondly, the deeper soil profiles are likely to have higher CEC values due to cation accumulation when drainage is poor and soil salinity is increasing; the larger number of cations fill all the possible sites on the clay particles.

In Table 2-12 the sub-profile correlations for equilibrium sites, the CROSS values are much more highly correlated with CEC than the SAR values in all sub-profiles and produce linear trend lines with higher R squared values. The highest correlations to CEC values are in the 24-36” sub-profile for both SAR and CROSS values.

Table 2-12. Correlation of CEC and SAR and CROSS Values for Equilibrium Sites in the Monterey One Water Recycled Water Service Area along the Central Coast of California.

Soil Depth	CEC and SAR	SAR Trend Line R Squared	CEC and CROSS	CROSS Trend Line R Squared
1-12”	0.42	0.53	**0.71**	**0.80**
12-24”	0.66	0.67	**0.82**	**0.85**
24-36”	0.94	0.78	**0.97**	**0.84**

Tables 2-13 and 2-14 contain analyses of CEC to SAR and CROSS values for the sub-profile values at increasing and decreasing sites. In the sub-profile correlations, the CROSS values are much more highly correlated with CEC than the SAR values and produce linear trend lines with higher R-squared values. Similar to the equilibrium sites, the highest correlations to CEC values are in the 24-36” sub-profiles.

Table 2-13. Correlation of CEC and SAR and CROSS Values for Increasing Sites in the Monterey One Water Recycled Water Service Area along the Central Coast of California.

Soil Depth	CEC And SAR	SAR Trend Line R Squared	CEC and CROSS	CROSS Trend Line R Squared
1-12”	0.37	0.48	0.82	0.95
12-24”	0.76	0.88	0.90	0.99
24-36”	1.00	0.98	1.00	0.98

Table 2-14. Correlation of CEC and SAR and CROSS Values for Decreasing Sites in the Monterey One Water and Pajaro Valley Water Recycled Water Service Area along the Central Coast of California.

Soil Depth	CEC And SAR	SAR Trend Line R Squared	CEC And CROSS	CROSS Trend Line R Squared
1-12”	0.85	0.68	0.95	0.87
12-24”	0.96	0.75	0.99	0.83
24-36”	0.99	0.85	1.00	0.85

2.6 Trends for Exchangeable Cations in Comparison to SAR and CROSS Values for the Entire Data Set

The consistent and high correlations of CEC with CROSS values for groups with different salinity trends is an important result. Table 2-15 contains the CEC, SAR, and CROSS values for the entire data set sorted by CEC. Similar to prior analyses, greater variability of the CROSS values and the higher ratios for soil extract to water quality were observed. CROSS value correlations are higher than SAR.

Table 2-15. Comparison of CEC, SAR and CROSS Values for the Entire Soil Profile in the Monterey One Water and Pajaro Valley Water Recycled Water Service Area along the Central Coast of California.

Site/Timeframe	CEC	Soil SAR	Ratio of Soil/Water SAR	Soil CROSS	Ratio of Soil/Water CROSS
M1W Site 4 2010-2019	15.36	4.13	1.11	7.59	1.34
M1W Site 4 2000-2009	15.41	2.80	0.98	5.90	1.34
M1W Site 2 2010-2019	18.33	2.88	0.76	6.84	1.17
M1W Site 2 2000-2009	21.00	2.37	1.04	6.35	1.80
M1W Site 5A 2010-2019	22.24	6.05	1.60	12.75	2.16
M1W Site 3A 2010-2019	23.96	3.98	1.06	10.25	1.76
M1W Site 3A 2000-2009	30.87	3.58	0.77	10.68	1.50
M1W Site 5A 2000-2009	31.30	6.92	1.50	17.24	2.42
M1W Site 7 2010-2019	33.64	6.29	1.63	17.47	2.85
M1W Site 7 2000-2009	37.17	6.36	1.34	18.71	2.56
PVW Site 3 2009-2019	57.92	13.69	6.22	39.91	10.50

Figure 2-9 provides a linear model trend line for CROSS values with an r squared of 0.66; the linear trend line for the SAR values has an r squared of 0.55. It is important to note the significant increase in CROSS values when CEC is over 21. Correlations of CEC with Na levels are to be expected as previously discussed; however, the exchangeable amount of Na may be more important in determining salinity risk across a wide variety of soil types. While soils with low CEC’s may not retain high levels of Na, exchangeable Na in excess of 10 % is not a desirable level for salt sensitive plants. Table 2-16 contains an analysis of the variation in % exchangeable cations in comparison to SAR and CROSS values.

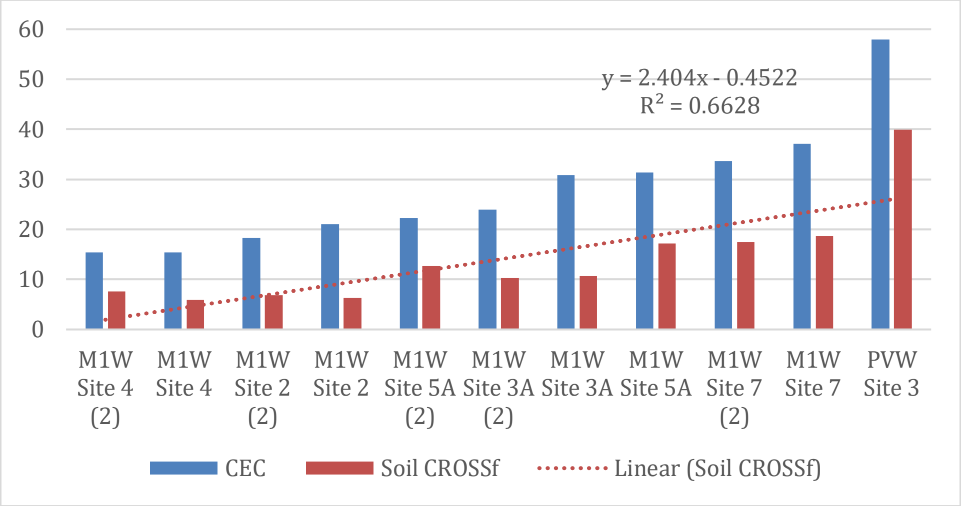


Figure 2-9. Comparison of CEC and CROSS Values Sorted by CEC in the Monterey One Water and Pajaro Valley Water Recycled Water Service Area along the Central Coast of California.

Table 2-16. Comparison of SAR, CROSS and Exchangeable Cation Values for the Entire Soil Profile in the Monterey One Water and Pajaro Valley Water Recycled Water Service Area along the Central Coast of California.

Site/Timeframe	SAR	CROSS	% Exch. Na	% Exch. Ca	% Exch. Mg
M1W Site 2 2000-2009	2.37	6.35	30	41	28
M1W Site 3 2000-2009	3.58	10.68	34	37	27
M1W Site 2 2010-2019	2.88	6.84	37	38	24
M1W Site 4 2000-2009	2.80	5.90	38	36	25
M1W Site 3 2010-2019	3.98	10.25	42	35	21
M1W Site 4 2010-2019	4.13	7.59	50	29	20
M1W Site 7 2000-2009	6.36	18.71	50	29	20
M1W Site 7 2010-2019	6.29	17.47	52	28	18
M1W Site 5A 2000-2009	6.92	17.24	55	24	21
M1W Site 5A 2010-2019	6.05	12.75	57	23	19
PVW Site 3 2009-2019	13.69	39.91	68	12	17

An exchangeable level of Na 50% or greater is where the differences between CROSS and SAR values get larger. Figure 2-10 shows the SAR and CROSS values in comparison to the exchangeable levels of the major cations, Na, Ca and Mg. As the level of % exchangeable Na increased, the team saw decreases in Ca and Mg levels because Na is filling cation exchange sites that held Ca or Mg before salt loading occurred. As % exchangeable Na increases from 40 to 50% the team saw % exchangeable Ca decline to 30% or less and % exchangeable Mg decline to less than 20%. After the major nutrients, Nitrogen (N), Phosphorus (P) and Potassium (K), Ca and Mg are the most critical ions for plant growth for all agricultural species; the Ca and Mg levels observed in this analysis when % exchangeable Na is greater than 50%, are too low and can cause yield and quality reductions (Tisdale, et al., 1993). As % exchangeable Na becomes greater than 50%, CROSS values are 10 or greater and are associated with sites with legacy salt loads and poor drainage. This appears to be an appropriate CROSS threshold level for several reasons: 1) soil Na levels are greater than 10 meq/L, 2) % exchangeable Na is greater than 50% and 3) levels of Ca and Mg are reduced enhancing soil permeability issues as well as potential for reduced crop yields and quality.

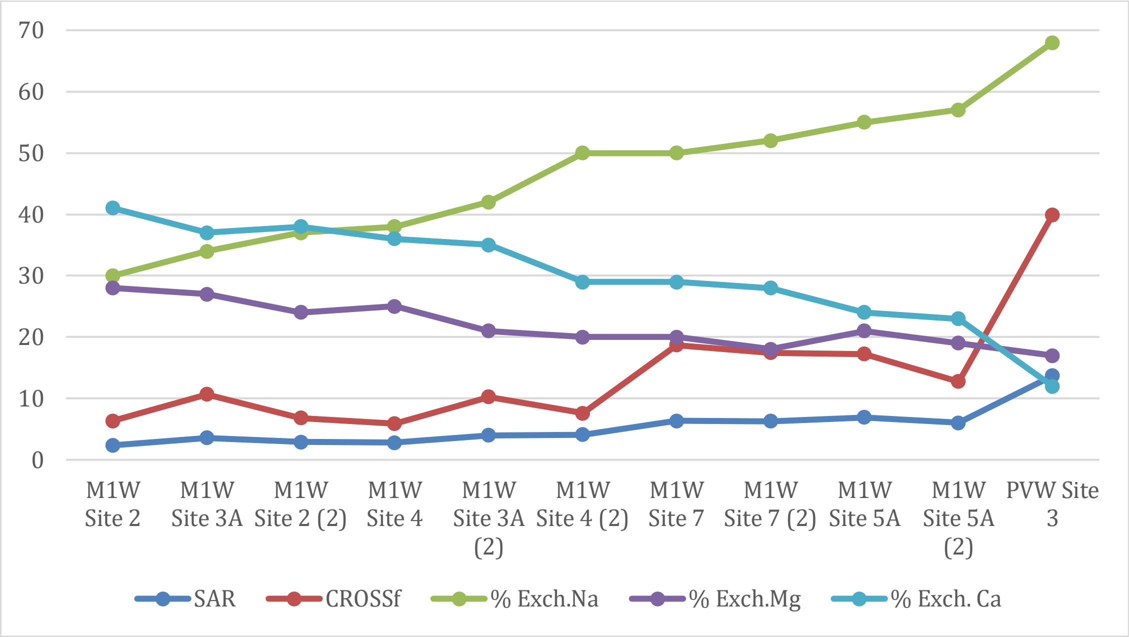


Figure 2-10. Variation of SAR, CROSS and Exchangeable Cations for the Entire Soil Profile in the Monterey One Water and Pajaro Valley Water Recycled Water Service Area along the Central Coast of California.

2.7 Using Alternative Sources of Water for Irrigation

As water reuse strategies are developed in different areas of the world using multiple and different alternative water sources, new methods of evaluating the water quality of reused water need to be developed. Alternative sources of water contain certain salts in concentrations not ordinarily seen in conventional agricultural irrigation water sources (Monterey One Water, 2000). In addition, various soil types and their salt and clay compositions will react differently to these alternative water sources. This section covers water quality assessment for a variety of alternative irrigation water sources, sodicity assessment, and remediation and effect of irrigation methods using recycled water on cropland along the central coast of California.

2.7.1 Evaluation of Recycled Irrigation Water Quality

Water reuse managers and suppliers along the Central Coast of California in the last 20 years have developed systems that take many different sources and types of water and deliver them to agricultural producers. These various water sources have included:

1. Municipal sources, both reclaimed residential and industrial wastewater
2. Surface waters, diverted from rivers or reservoirs
3. Saline groundwater from various sources, some reclaimed by desalination processes

There are multiple challenges to accurately evaluating the water quality delivered to the agricultural producers. These include:

1. Seasonal fluctuations in the salt load in any one source
2. Seasonal fluctuations in the volumes of water from different sources
3. Temporal variations in salt load and amounts of water from different sources

4. Temporal variations in water quality by delivery point depending on water blending strategy

It is standard practice to test well waters for salinity in agricultural production. Rainfall, in most areas, is the purest of water sources and is generally not tested. Many surface waters are also not routinely sampled for salinity or sodicity. Therefore, given the variability of salt concentration and composition levels in alternative water sources, it is important to have a consistent water quality evaluation protocol.

M1W and PVW have developed a basic methodology for evaluating and reporting alternatively delivered water quality results to agricultural producers. This methodology includes the following assessments:

- Consistently sampling each alternative source seasonally or every year
- Sampling the blended delivered water to agricultural producers at appropriate locations
- Deploying various types of salinity monitors (i.e., ECw) to provide real-time data.

The data generated by this approach provides the water producer, or utility, and the agricultural producer with both long-term and real-time data that is generally reported on a monthly or quarterly basis. The frequency of sampling is variable and dependent on the level of variability, source, and quantity of the alternative water sources. The salinity monitors, deployed for real-time measurements, provide a warning system indicating whether sampling frequency needs to be changed. In addition, these sampling protocols can also be leveraged to include food safety data required for various food crops in certain locations.

2.7.1.1 M1W: Irrigation Water Quality

A water producer such as M1W receives municipal residential wastewater and pumps supplemental well water daily. In addition, there are seasonal additions of surface water and occasional inputs of industrial wastewater, municipal storm-drain water and agricultural run-off. The MIW sampling points include:

- Municipal sources of wastewater prior to treatment
- Treated water prior to blending with supplemental well water or surface water
- Supplemental well water at well heads in the delivery system
- Surface water prior to entering the blend pond
- Blending pond and at near delivery point to the system
- Selected sites throughout the delivered water system (Figure 2-1)

Real time salinity sensors monitor water quality both at the input site for wastewater prior to treatment and at the surface water site prior to delivery to the blending pond. The sensors are in-line ECw meters that continuously report EC to data logging systems tracking water volumes entering the treatment facility and the blending pond. These real time monitoring sites were added after several contamination incidents occurred and there was a potential risk from unknown contaminants. Contamination events were the result of an excessive amount of material being dumped into the municipal system or the surface water from the river. One of these events, a massive salt load from an industrial water softening system, led to the development of an alternative site for discarding spent water softening salts.

2.7.1.2 PVW: Irrigation Water Quality

Another water producer, in this case PVW, receives municipal and industrial wastewater and adds supplemental well water continuously throughout daily water delivery. PVW does not have a blending pond or direct surface water source. However, PVW does have a variety of different supplemental wells. Sampling points include:

- Municipal sources of wastewater prior to treatment
- Treated water prior to blending with supplemental water
- Municipal potable water source added to treated water prior to entering the delivery system
- Blend wells, conventional agricultural wells, at well heads in the delivery system
- Recovery wells at well head, shallow wells that receive managed aquifer recharge water from a surface water recharge system
- A variable set of delivery points throughout the delivery system depending on inputs from various water sources.

Real time salinity monitors are deployed at the recycled water facility. These sensors are in-line ECw meters that continuously report EC to data logging systems that track the municipal water volumes entering the treatment facility. These were also deployed after a contamination incident involving an excessive amount of wastewater with an excessive amount of Na and Cl was added to the system by a fish processing facility.

For both water utilities in the examples above, sampling frequency was high in the early years of water deliveries. Long term baseline values were developed and sampling decreased appropriately. However, the different alternative water sources were developed over time and high intensity sampling was conducted until baseline values were developed for new alternative water sources.

2.7.2 Calculating Delivered Recycled Irrigation Water Quality

As previously mentioned, alternative sources of irrigation water may come from several different sources that have variable water quality seasonally as well as annually. Long term analysis has compared the water quality of the samples from the different sources and the samples at delivery points to agricultural producers. This data has shown that simple averages of the water quality of different sources or delivery points is not an accurate representation of the delivered water quality. A weighted average method has been found to be more accurate. This method employs weighting the water quality data by % volume from each source. Two examples are shown below from MIW and PVW.

2.7.2.1 M1W Example

Water producers/utility in 2010 delivered water utilizing 70% recycled municipal wastewater and 30% surface water (Monterey One Water, 2000-2019). Table 2-17 compares the actual water quality data by water source with simple averages, weighted averages and the water quality measured in the blend pond. The weighted averages are extremely close to the actual pond blend analyses, while the simple averages underestimate SAR and CROSS. The weighted averages for each cation can be simply calculated in the following manner; (Na 7.03 meq/L x

0.7) + (Na 4.33 meq/L x 0.3) = 6.2 meq/L. The weighted averages for SAR and CROSSf can be calculated by using the weighted averages for the cations for each equation. In this example, with only two water sources, simple average underestimates the potential for alkalinity expressed as SAR and CROSS since both sources are weighted equally. The contribution of the lower values for SAR/CROSS for the surface water at 30% is overstated with a simple average assuming 50% contribution. In contrast, if the water source with the higher SAR/CROSS values is only 30% of the total, the simple average salinity would be overestimating the salinity. It is interesting to note that the weighted average CROSS value is extremely close to the blend pond CROSS value, while the weighted average SAR value is significantly lower.

In Table 2-17, the amount of cations in meq/L for calculation of SAR and CROSS per methodology used by laboratories analyzing water quality samples for agriculture producers in Monterey One Water and Pajaro Valley Water Management Agency.

Table 2-17. Comparison of Simple and Weighted Average Water Quality by Source for Monterey One Water (MIW) Supplied Water.

Water Source	Na	K	Ca	Mg	SAR[1]	CROSS[2]
Recycled Water	7.03	0.51	2.76	1.27	5	7.26
Surface Water	4.33	0.08	4.11	4.34	2.1	4.37
Simple Average	5.68	0.29	3.43	2.80	3.22	5.78
Weighted Average	6.2	0.4	3.2	2.2	3.8	6.36
Blend pond data	6.2	0.4	2.9	1.6	4.2	6.43

[1] Sodium Adsorption Ratio:

[2] Cation Ratio of Soil Structural Stability

2.7.2.2 PVW Example

Water producer/PVW reports water quality by quarter and has seasonal fluctuations in water quality by water source as shown in in Table 2-18 (Pajaro Valley Water, 2009-2019). Weighted averages are the best indicator of delivered water quality since the producer does not have a blend-pond to sample. Quarterly water quality data are weighted averages since four different sources are used in varying quantities in order to produce enough water to meet demand in the service area shown in Figure 2-2. The annual weighted average sums all of the quarterly water quality data and divides by the total delivered water. In this case the simple annual average from various delivery points in the system overestimates the sodicity potential, while the annual weighted average shows that a much lower amount of salts have been applied in the irrigation water.

Table 2-18. Comparison of Simple and Weighted Averages by Seasonal Variation for PVW Supplied Water.

Timeframe	Na (mg/L)	Cl (mg/L)	TDS	SAR	CROSS
Q1 2019	102	125	690	2.7	4.72
Q2 2019	86	89	571	1.7	3.87
Q3 2019	78	80	955	2.1	3.55
Q4 2019	115	137	1286	2.9	5.19
Annual Simple Average	95	108	876	2.4	4.3
Annual Weighted Average	84	92	558	2.2	3.8

For a given cation, the quarterly weighted average would be calculated as follows:

Q1: (Avg. Na x 5.5%) + (Avg. Na x 0.1%) + (Avg. Na x 94.4%) + (Avg. Na x 0.01%).

Each parenthesis contains the contribution of Na from a different water source. The quarterly weighted averages for each cation are used to calculate SAR and $CROSS_f$ for that quarter.

The annual weighted average calculates the cation weighted averages in the following manner:

Annual: (Avg. Na x 5.1%) + (Avg. Na x 17.4%) + (Avg. Na x 60.1 %) + (Avg. Na x 17.4%)

Similar to the quarterly weighted averages, each parenthesis contains the annual contribution of Na from a different water source. Annual weighted averages of SAR and $CROSS_f$ are calculated using the annual weighted averages of each cation. In this example, with four water sources that vary quarterly in quality and contribution, a simple average may also underestimate or overestimate the salinity and potential for sodicity since all sources are weighted equally. Underestimating would occur if a low salt source is used minimally, but given equal weight in a simple average. Overestimating would occur if a high salt source is used minimally but given equal weight in a simple average.

2.7.3 Recommendations for Monitoring Delivered Water Quality

In conclusion, agricultural water users are likely to test the water delivered to their properties. In some cases, this is required by state agencies or by buyers of their agricultural products. It is in the best interest of suppliers of alternative or recycled water sources for agricultural irrigation to have accurate water quality data for their water users. In some cases, the agricultural water users may need to use water quality data from their water supplier for reporting purposes. Depending on the complexity of the acquisition and delivery of alternative water sources various methods of water quality evaluations can be used. However, it is clear that simple averages are not accurate. A comprehensive and accurate water quality sampling protocol, data analysis based on weighted water quality data, and timely reporting system will insure that both the supplier and agricultural producer will be informed about the actual water quality delivered each year. This data will aid both the water supplier and the agricultural producer to make informed and timely decisions about improving delivered water quality and mitigating soil salinity, soil sodicity or food safety issues.

2.8 Factors Affecting Soil Sodicity Assessment

Recycled or other alternative sources of irrigation water contain certain salts in concentrations not ordinarily seen in conventional agricultural irrigation water sources. The most dominant ions present in alternative water sources related to long term soil productivity are Sodium (Na^+), Potassium (K^+), Calcium (Ca^{2+}), Magnesium (Mg^{2+}), Chloride (Cl^-), sulfate (SO_4^{2-}) and bicarbonate (HCO_3^-). The ratio of the cations (Na, K, Ca, and Mg) are critical to soil permeability. The risk of decreasing soil permeability is evaluated by sodicity parameters, the Sodium Adsorption Ration (SAR) and the Cation Ratio of Soil Structural Stability (CROSS) as shown in Equations 2.1 & 2.2. Extremely high concentrations of the anion (Cl^-) can inhibit plant growth and produce toxicity to Cl sensitive crops (Grieve et al., 2012). In Tables 2-19 to 2-21, critical threshold values for SAR and Cl are noted in bold; critical values for CROSS have not been determined at this time. Some authors have suggested that CROSS values can be interpreted in much the same way as SAR (Sposito et al., 2016).

All of the ions listed above also occur in soil amendments and fertilizers used in both conventional and organic agriculture. Similar to agricultural water quality testing, agricultural producers also conduct soil testing. Therefore, it is important to evaluate these ions in the soils over time and evaluate individual agronomic practices that may increase or decrease the quantities or ratios of these ions. The following guidance is to help agricultural producers effectively conduct soil sampling and develop agronomic strategies to optimize long term soil productivity while using alternative or recycled sources of irrigation water.

2.8.1 Frequency and Depth of Soil Sampling for Sodicity Assessments

Agricultural producers do not consistently test soils for salinity and sodicity/alkalinity. While there has been an enormous effort to promote sampling agricultural soils, fairly intensively, for nitrogen and other major nutrients in the U.S., soil sampling for salinity and sodicity is usually conducted as a one-time event or when salinity or sodicity is suspected as being problematic in a particular area. For example, soil salinity and sodicity testing may occur if there is a crop production issue, or upon acquiring a new piece of land, or once a year prior to applying amendments. Because of water quality concerns, two long term projects on the Central Coast of California, Monterey One Water (M1W) and PV Water (PVW) have followed a basic strategy for soil salinity and sodicity sampling within the delivered water zone and evaluating long term trends in soil salinity and sodicity (Monterey One Water, 2000). This strategy includes the following sampling methodology:

- Sampling three times annually, spring, summer and fall, in the same location
- Separate sampling at different depths, 1-12”, 12-24” and 24-36”, in the soil profile in the same location.

Soil sampling three times annually focuses on the temporal variation of soil salinity and sodicity. Moreover, it can aid in quantifying the effects of rainfall and soil amendments. Sampling at different depths focuses on the spatial variation of salinity and sodicity in the soil profile, from the shallow rooting depth of many annual crops to the deeper rooting depth of many perennial crops. It can aid in determining the effects of tillage, leaching and drainage on soil quality.

2.8.2 Evaluating Temporal Variation in Soil Sodicity

On the Central Coast of California, annual winter rainfall has averaged 13.4” (340.63 mm) per year during the last 20 years; dry and wet periods alternate with wet periods receiving over 20” (508 mm) of seasonal rainfall and dry periods receiving less than 10” (254 mm) of seasonal rainfall. Agricultural producers typically apply soil amendments in the fall prior to the rains due to the heavy clay content of the soils and typically avoid spring application of amendments. Spring soil samples will have the lowest salinity due to the leaching effect of the seasonal rains. Soil salinity and/or sodicity increases during the growing season with the use of irrigation and reaches a peak in the fall. Comparing the analytical results from previous fall’s samples to the spring samples allows an agricultural producer to evaluate the effectiveness of seasonal rains or an applied leaching fraction of irrigation water on the effective leaching in the field.

Table 2-19 shows the temporal variation in soil sodicity at two locations for the 1-12” depth. One location has low soil sodicity and good drainage (M1W site 2) and one has high soil sodicity and poor drainage (PVW site 3).

Table 2-19. Temporal Variation in Cations in the Top 1‑12” Soil Depth in Different Farms Receiving Recycled Irrigation Water from Monterey One Water and Pajaro Valley Water Management Agency along the Central Coast of California.

	M1W Site 2			PVW Site 3		
Cation	**Spring**	**Summer**	**Fall**	**Spring**	**Summer**	**Fall**
Na (meq/L)	4.9	6.4	7.1	28.5	25.1	32.3
K (meq/L)	0.3	0.4	0.5	1.1	0.7	1.0
Ca (meq/L)	3.2	5.6	7.4	8.99	4.44	8.64
Mg (meq/L)	1.7	3.1	4.4	8.9	5.0	9.6
Cl (meq/L)	1.7	3.9	5.0	29.9	17.9	33.1
SAR	3.13	3.07	2.92	9.5	11.5	10.7
CROSS	5.02	6.52	7.22	28.7	25.3	32.5

This temporal variation is most pronounced in the soil profile to the depth of 12”. The SAR and CROSS values in Table 2-3 are ratios that indicate the risk of sodicity (or alkalinity) in terms of developing issues with soil permeability. There is a high level of variability for the CROSS values as compared to the SAR values. A SAR level of > 6 is typically indicative of increasing soil permeability issues (Cahn, 1995). Threshold values for the CROSS values have not been determined at this time, although CROSS may be interpreted in much the same way as SAR values. Because of the nature of each equation where K is added to the numerator of CROSS and the contribution of Mg in the denominator is diminished, CROSS values will nearly always be higher than SAR for a water of defined quality. Nevertheless, only sampling once per year can significantly affect the salinity and sodicity values used for making decisions. The timing of fall sampling is critical due to the addition of amendments that may contain the critical ions.

In conclusion, an annual soil sampling program should at least sample one time at the end of the cropping season before any seasonal rains occur and soil amendments are applied. Soil sampling during the growing season, including the beginning of the season, may be helpful in tracking salinity and sodicity concerns if irrigation water quality is poor.

2.8.3 Evaluating Spatial Variation in Soil Sodicity

Using the same sites in Table 2-19, Table 2-20 summarizes the variation by sampling depth for the fall samples. The uniformity of ion concentrations among different soil profiles for the M1W site 2 indicates that the ions in the top 12” are leaching to lower depths due to good drainage below the 36” soil depth. SAR and CROSS values are similar in all three soil profiles for M1W site 2.

Table 2-20. Spatial Variation in Fall Soil Cation, SAR and CROSS Values in the Entire Soil Profile in Different Farms Receiving Recycled Irrigation Water from Monterey One Water and Pajaro Valley Water Management Agency along the Central Coast of California.

	M1W Site 2 — Good Drainage			PVW Site 3 — Poor Drainage		
Cation	**1-12”**	**12-24”**	**24-36”**	**1-12”**	**12-24”**	**24-36”**
Na (meq/L)	7.1	6.4	6.3	32.3	40.0	53.4
K (meq/L)	0.5	0.3	0.2	1.0	1.1	1.2

Ca (meq/L)	7.4	6.6	6.1	8.6	8.1	5.4
Mg (meq/L)	4.4	4.1	5.2	9.6	10.7	10.1
Cl (meq/L)	5.0	5.6	5.5	33.1	39.5	47.9
SAR	2.92	2.77	2.65	10.7	13.1	19.2
CROSS	7.22	6.48	6.34	32.5	40.2	53.6

In contrast, PVW Site 3, where the soil profile is dominated by clay and drainage is poorer, ion concentrations throughout the profile are substantially higher than those at M1W site 2. The critical ions are accumulating at lower depths, particularly Na at the 24-36” depth. This behavior is reflected in the difference in SAR and CROSS values in comparison to those values at the M1W site 2. PVW site 3 is likely to have severe soil permeability issues at 24-36”. Consequently, there is danger when only sampling a shallow 1-12” soil profile as such limited information can significantly affect the salinity and sodicity status of the entire profile used to make decisions.

In conclusion, it is important to sample at different soil depths throughout the profile particularly when soils have a high water-holding capacity, are poorly drained and are being irrigated with poor quality water. While such sampling strategies may not provide very much information for well drained soils using high quality irrigation water, changes in critical ion concentrations with depth can help with many important diagnostic decisions. In addition, since different crops have different root depths and different sensitivities to salinity, collecting samples at different soil depths may aid in crop selection and making decisions about deep tillage, addition of amendments and drainage management.

2.8.4 Evaluating Relationships between Spatial Variation and Deep Tillage

Deep tillage is an important practice to facilitate drainage in agriculture. The use of heavy equipment for several operations such as preparing the soil for planting, fertilizer and pesticide applications, weed control, and harvest compacts the soil and reduces drainage. An old practice is deep plowing which is very effective at incorporating crop residues in the crop root zone to improve the organic matter and facilitate drainage. Deep plowing may turn over the soil profile to a depth of 36” which may bring accumulated salts to the soil surface (1-12”). Table 2-21 summarizes the changes in SAR and CROSS in the shallow soil profile (1-12”) due to a deep plowing event conducted every 5 years between the summer and fall soil samples.

Table 2-21. Variation in Soil Sodicity in the 1‑12” Soil Profile after Deep Plowing in Different Farms Receiving Recycled Irrigation Water from Monterey One Water and Pajaro Valley Water Management Agency along the Central Coast of California.

Cation	PVW Site 4 Summer 2010	PVW Site 4 Fall 2010	PVW Site 4 Summer 2015	PVW Site 4 Fall 2015
Na (meq/L)	8.8	49.0	3.7	44.6
K (meq/L)	1.3	1.8	0.3	0.7
Ca (meq/L)	15.0	5.5	3.3	4.5
Mg (meq/L)	10.0	12.0	2.1	7.9
Cl (meq/L)	9.4	50.0	4.4	47.3
SAR	2.49	16.6	2.2	17.9
CROSS	9.02	49.4	3.8	44.8

The soil characteristics at PVW Site 4 is similar to those at PVW Site 3 with heavy clay soil, poor drainage and a high water-holding capacity. Clearly, the accumulated Na and Cl in the lower portion of the profile were brought to the upper soil profile by the plowing events (Table 2-21). The SAR values in the spring were very good and increased eight-fold by the fall, while the chloride levels were five times the Cl threshold in the fall. It is clear that deep plowing is problematic at this site. After evaluating the data in the table above, an advisory was sent to agricultural producers using alternative water sources to switch to alternative methods of deep tillage if they had heavy clay soils.

The alternate methods of deep tillage that have been developed since the early 1990's do not turn over the soil from deeper in the soil profile. The most common method employs an implement called a deep ripper (Figure 2-11), which breaks through the compacted layers down to 36" without bringing up soil from deeper in the soil profile. It is run across the field multiple times in different directions to break up compaction layers and maximize drainage.

Figure 2-11. The Deep Ripper That Does Not Turn the Soil over Used for Improving Drainage in Clay Soils.
Source: Photo by Belinda Platts.

In conclusion, while deep plowing may be appropriate on well-drained soils using alternative water sources, it is clearly not appropriate for heavy clay soils with poor drainage where salts have accumulated at lower parts of the soil profile. The use of alternative water sources containing high concentrations of Na or Cl for irrigation on heavy clay soils with poor drainage are likely to lead to the formation of high sodicity deep in the profile, which may aggravate soil permeability problems, allow salinity to accumulate and harm Cl sensitive crops, if brought to the soil surface.

2.8.5 Evaluating Soil Amendments under Recycled Water Reuse for Irrigation

Agricultural producers use soil amendments to maintain or improve soil tilth, fertility, pH, soil salinity and sodicity management. Soil amendments include manures, composts, and inorganic materials that provide significant amounts of calcium (e.g., gypsum and lime). Since the use of alternative water sources for irrigation may contain elevated levels of Na and Cl, it is important for agricultural producers to evaluate their amendments for these ions. In addition, evaluation of the amendments for their contribution to decreasing sodicity and increasing water permeability is equally important. Table 2-22 summarizes the ion contributions from various soil amendments at a range of application rates. In certain agricultural settings, these materials may or may not be applied annually. The intensive agricultural production on the Central Coast requires that soil amendments be applied annually; there are two crops grown on each acre of land and the growing season lasts from early January through late November. However, a producer would generally apply only one type of organic material (compost or manure), potash (if deficient), and only one type of inorganic calcium containing product (depending on pH). These amounts of ions are additive to the amount contained in the applied irrigation water.

Table 2-22. Values of Critical Ions Contained in Various Soil Amendments.

Ion	Composts	Manures	Potash (KCl)
Na	0.05 – 0.2%	3.5 – 7%	NA
K	2 – 3 %	19 – 25 %	53 %
Cl	1.5 – 5%	Unknown	47 %
Application rates	500 – 2000 Lbs./Acre/Year	500 – 2000 Lbs./Acre/Year	250 – 500 Lbs./Acre/Year
Lbs./A Na	Up to 4 lbs.	17 – 70	NA
Lbs./A K	10 – 60 lbs.	95 – 250	133 – 265
Lbs./A Cl	7.5 – 100 lbs.	Unknown	118 - 235

Therefore, the data indicate that manures are a significant source of K, composts contribute Cl, and potash can contribute significant amounts of K and Cl. The salt content of manures is fairly well known and expansion of the compost industry and food safety incidents involving manures in California has led most agricultural producers to switch to using fully treated and aged compost only, as an organic amendment. Many of the crops grown on the Central Coast of California have better quality and yields with significant amounts of K; soil samples are routinely deficient with < 0.5 meq/L. One location with heavy clay soils, poor drainage and a history of potash use to improve yields, exhibited significant accumulation of Cl over a 5 year period (soil extract values increasing from 10 to 26 meq/L). This data caused an advisory to be sent to agricultural producers using alternative sources of water to not use potash (KCl) and use fertilizers with higher levels of K (K_2SO_4) to avoid Cl accumulation.

In terms of calcium, the most beneficial cation offsetting increases in sodicity, three materials, gypsum, dolomitic lime and lime ($CaCO_3$), are used in both conventional and organic agriculture. Depending on location and soil pH, agricultural producers will apply one of the materials in Table 2-23 to improve soil tilth, drainage and soil pH, if necessary. Recommendations to use the higher application rates for these materials have been made to agricultural producers using alternative water sources on the Central Coast. Since the alternative water sources on the Central Coast do not have high levels of Ca and Mg, the addition of gypsum to the alternative water sources was investigated, but Ca and Mg amendments to the soil were found to be more cost-effective.

Table 2-23. Values of Critical Ions Contained in Calcium Amendments Commonly Used by California Central Coast Farmers.

Ion	Gypsum	Dolomitic Lime	Lime – $CaCO_3$
Ca	22 – 29%	22%	37 – 40%
Mg	NA	12%	Na
Application rates	500 – 1000 Lbs./Acre/Year	500 – 1000 Lbs./Acre/Year	500 – 1000 Lbs./Acre/Year
Lbs./A Ca	100 - 290	110 – 220	185 - 400

Lbs./A Mg	NA	60 - 120	NA

In addition, the crops grown on the Central Coast remove very small amounts of organic matter; roughly 80 % of all crop biomass is incorporated back into the soil after harvest. Therefore, over time, with minimal crop biomass removal and long-term use of an alternative water source, there is likely to be an accumulation of salts in the soil profile. The use of soil amendments high in Na, K and Cl should be seriously evaluated.

In conclusion, the values listed in Tables 2-22 and 2-23 are only representative of soil amendment salt content and usage for the Central Coast of California. These values were compiled from various brochures, pamphlets, and online sources of soil amendment analyses provided by soil amendment producers. Agricultural producers in other areas must evaluate their soil amendment products and practices in reference to soil needs and irrigation water quality. The examples above provide a methodology for soil amendment assessment.

2.8.6 Evaluating the Effects of Irrigation Methods on Sodicity under Recycled Water Reuse

The use of alternative recycled water sources with elevated levels of Na, K and Cl may affect long term soil sodicity and salinity depending on the volumes required by the irrigation methods. Table 2-24 shows the concentration range of critical ions in the water supplied by M1W from 2000 - 2019. The values vary depending on the amount of each alternative source of water and its quality every year.

Table 2-24. Range of Amounts of Applied Critical Ions in Monterey One Water Delivered Water along the California Central Coast.

Ion	Range of ppm	Range of Lbs./Acre-foot[1]	Range of Lbs./Acre based on water usage[2]
Na	80 - 168	218 - 456	283 – 593
K	1.5 - 1.9	4 – 5	5 – 6
Ca	54 – 58	147- 158	191 – 205
Mg	24 - 25	65 – 68	84 – 88
Cl	120 - 248	326 - 674	424 - 876

[1] One part per million (ppm) in one acre-foot of water weighs 2.72 lbs. (California Fertilizer Association Western Fertilizer Handbook, 1985)

[2] Assuming water usage of 1.3 acre-feet of delivered water per acre per year

Irrigation methods have evolved over time from the application of large volumes of water (flood or furrow irrigation) to the application of smaller amounts of water (drip irrigation) to match crop needs. With the use of alternative sources of irrigation recycled water, the use of low volume microirrigation technologies will reduce the load of negative salt ions (Na, K, Cl) compared to irrigation systems using large volumes of water. This is especially relevant when an agricultural production area using alternative water sources has seasonal rainfall which reduces soil salinity and may offset any increase in soil salinity during a cropping season.

Agricultural producers on the Central Coast use drip irrigation extensively. In fact, M1W water users have reduced the amount of delivered water used by 24 % in the last 10 years (Monterey One Water, 2000-2019). The values based on water usage in Table 2-8 are the reduced amounts applied since 2010. The main reason for the decrease in water application is the cost of the water and the use of drip irrigation. Decreasing the necessary volume of water by 24 % has decreased the likelihood of salt accumulation.

The water projects on the Central Coast have been delivering water for 14 years (from 2009 PVW)-25 years (from 1998 M1W). When the projects were first proposed, there was major concern by both landowners and agricultural producers/utilities about the long-term soil productivity with the use of recycled water. Long-term soil salinity and sodicity studies were initiated to track changes in soil salinity and alkalinity and additional projects were developed to reduce the negative impacts of using recycled water. In addition, with the significant adoption of drip irrigation in the delivery zones of the projects, the projects have seen significant decreases in the volume of delivered water used and no widespread increases in soil salinity. However, more research is still needed to assess the negative impacts on soil from sodicity.

2.9 Summary

SAR and CROSS values were analyzed with a variety of data subsets utilizing different soil profile depths. In addition, correlations and comparisons of SAR and CROSS were made in reference to Na concentrations, CEC values and trends in exchangeable Na, Ca and Mg.

In conclusion the findings from this study confirm that CROSS_f (coefficients of the CROSS equation are derived from the relative flocculating power of K and Mg) was a more robust tool for predicting negative impacts of different recycled water quality compared to SAR. Practitioners should consider using CROSS_f instead of SAR in assessing sodicity impacts. Also, changes in CROSS_f were more indicative of observed differences in recycled water quality delivered to farmers in the Monterey One Water service area along the Central Coast of California. When Na levels are greater than 10 meq/L the increase or decrease in CROSS_f levels were greater than the changes in SAR. CROSSf was also more strongly correlated with CEC compared to SAR.

It is clear that timely and effective soil sampling can help provide agricultural producers, landowners, and water project personnel with data for decision making. Soil sampling that evaluates temporal and spatial variation in salinity and sodicity should be developed that is appropriate to the agricultural production region’s characteristics. A rigorous soil sampling program can identify potential problems with agronomic practices, such as tillage, amendment usage, and water usage and quality. In addition to soil sampling, evaluation of soil amendments and irrigation methods should be conducted. Soil amendment and fertilizer analyses vary substantially by region and crop needs. Evaluation of crop inputs should focus on any supplying Na, K, Ca, Mg and Cl and ascertain the potential amounts applied for crop production. The amount of the critical ions supplied by the alternative sources of water should be evaluated in reference to the crop inputs and the potential water application. It is worth noting that the water projects on the Central Coast have been delivering water for 12 – 23 years. The projects have seen significant decreases in the volume of delivered water to farmers due to adoption of microirrigation and no widespread increases in soil salinity. However, more research is still needed to assess the negative impacts of using alternative water supplies on different qualities on soil sodicity.

CHAPTER 3

Greenhouse and Soil Column Investigations of the Crop, Soil, and Recycled Water Interactions

This chapter has two sections. The first section discusses all the materials and methods for the greenhouse and soil column (Sections 3.1 – 3.2). The second section details the results and conclusions (Sections 3.3 – 3.4)

3.1 Introduction

Most plants grow under unsaturated soil conditions. Oxygen in the root zone is as essential as plant available water. Poorly drained soil media usually causes waterlogging. Macropores between aggregates play an important role in improving soil infiltration, aeration, nutrient uptake, and drainage (Scholl et al., 2014). Besides the impact of the interaction among cationic composition (Na, K, Ca, Mg) of the applied irrigation water on soil structure, plant roots can also improve soil structure by increasing macropores volume. Scholl et al. (2014) studied soil hydraulic properties development due to root growth in soil columns. The study revealed a wide range of pore sizes in the rooted treatment while a narrow range of pore size distribution was observed in the non-rooted columns.

If the soil structure has degraded, the plant growth will be impacted because of poor drainage and waterlogging. The paradox of soil structural degradation on plant growth appears in Farahani et al. (2020) and Chand et al. (2020) studies. Farahani et al. (2020) studied maize growth in pots using loamy soil. The plants were irrigated by capillary rise with different treatments of Na, K, Ca and Mg solutions (with focus on K:Na ratio) with water EC of 3 and 6 dS/m. The study revealed that micropores, plant available water and plant growth increased with increasing dispersible clay. Chand et al. (2020) investigated the use of recycled water, groundwater and mixed water in tomatoes grown in a greenhouse experiment using loamy sand soil. The water was applied using drip irrigation. The authors found that tomato yield and growth were higher in the recycled water treatments, although it had the highest SAR and CROSS values than the other two treatments. The observed high production with the recycled water was attributed to that fact it contained more nutrients than the other treatments. However, this were short term experiments which did not address long term impacts on soil structure and crop production.

Strawberries are one of the crops most widely irrigated with recycled water in California. Strawberries have high sensitivity toward the salinity of the irrigation water. The maximum salinity level of the soil extract (EC_e) should not exceed 4 dS/m (USDA Soil Conservation Service. National Engineering Handbook, 1991). Depending on the irrigation water salinity, a leachate requirement should be applied to avoid salt build-up. On average, strawberry plants require 80 liters/plant/season and soil water content needs to be maintained above 50% field capacity (El-Farhan and Pritts, 1997). Therefore, strawberries were selected for this study since they were expected to respond to soil structure alteration associated with recycled water reuse for irrigation than other crops because they require a high amount of water and well-drained soils (Michael Cahn and Belinda Platts, personal communication, 2020). Strawberry growth and development can be evaluated by the start of blooming, earliest fruit harvested, the number of runners, sweetness, fruit size, shoot biomass, branch crown, leaf area and crown injury (Kadir et al., 2006).

The main goal of this study was to assess strawberry growth and development response to recycled water reuse for irrigation with different cation composition under a greenhouse environment. The specific objectives were to evaluate the effect of recycled water reuse for irrigation on strawberry fruit quality and yield under a controlled greenhouse environment and to evaluate the soil structure and infiltration rate (after removing the plants) at the end of the experiment. A related objective was to evaluate the effect of cation composition on soil permeability in soil columns under laboratory settings. In this study, synthetic recycled water with different cation (Na^+, K^+, Mg^{2+} and Ca^{2+}) composition was used to obtain a wide range of SAR, $CROSS_f$ and $CROSS_{opt}$ values while maintaining soil salinity constant at approximately 1.5 dS/m.

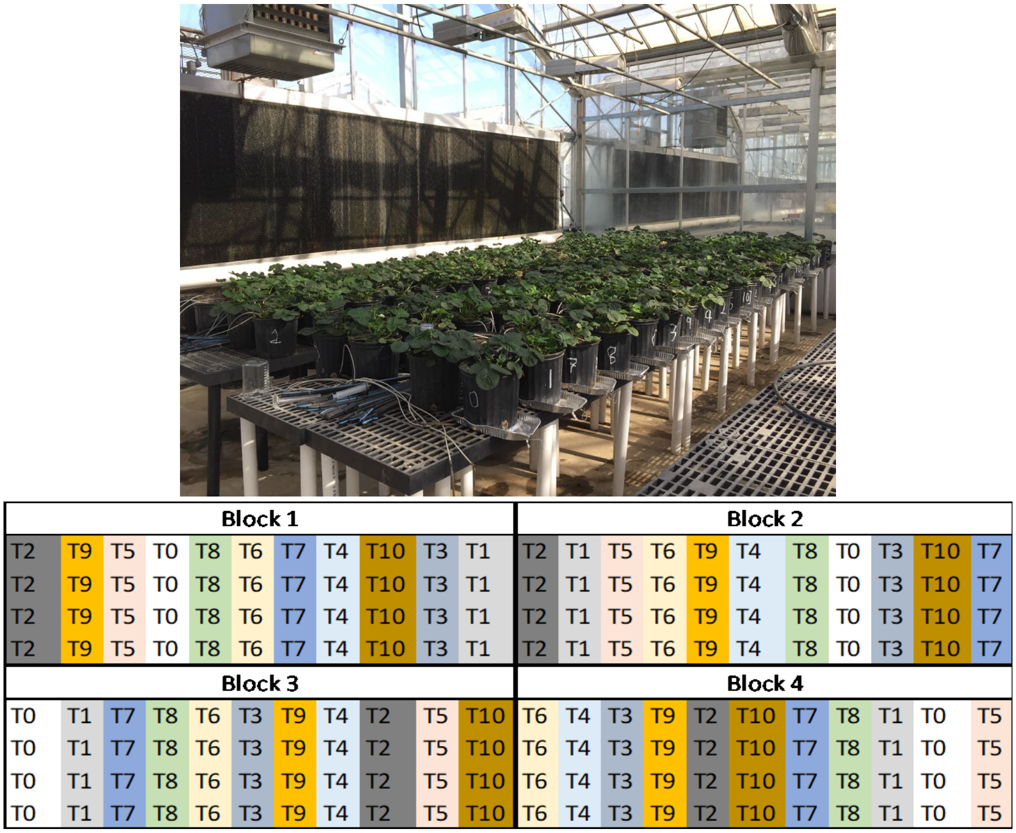
3.2 Materials and Methods

3.2.1 Greenhouse Experiment Setup

A greenhouse experiment was conducted to investigate the effect of specific cation combinations of synthetic recycled water (~1.5 dS/m salinity, Table 3-1) on strawberry growth and development as they affect soil structure and infiltration. The treatment solutions were prepared as concentrates of 100 times as the proposed concentration. The irrigation was provided to the plants using deionized water while injecting the concentrated solution using to MixRite proportional water-driven chemical and fertilizer injector (DEMA Engineering Company, Saint Louis, MO) to have the right concentration as specified in Table 3-1. Only gypsum solution was applied directly as normal concentration to the plants because of the partial salt solubility. A total of 176 pots of size 25 cm top diameter, 20.5 cm bottom diameter, and 23 cm height were used in this study. The pots were filled with Yolo Clay Loam soil collected from the UC Davis Campbell Track Research Farm located near Davis, California. The soil has cation exchange capacity and organic matter content of about 21 meq/100g and 1.3%, respectively. The soil was gently packed through three successive 6 cm layers to achieve an average bulk density of 1.3 g/cm^3 (about 9.0 kg of air-dried soil per pot). A space of 5 cm from the top was left empty to account for the possible ponding of water.

3.2.1.1 Strawberry Production under Greenhouse Environment

One bare root strawberry (Portola variety) was planted in each pot. Each pot received 45 grams of slow-release fertilizer (15N-9P-12K) required to have optimum non-fertilizer limiting strawberry growth conditions. The fertilizer was mixed at the top of the soil surface into a few centimeters of the soil. The experimental design was a randomized complete block design (Figure 3-1) with four replications per treatment and four pots per replication. Recycled irrigation water solutions were applied using spaghetti drippers. The lateral and row spacing between the plants was 30 cm. Because the threshold EC_e is within the range of 1.5-4.0 dS/m for strawberries (USDA-NRCS, 2013), a leaching amount of about 30% was implemented given that the irrigation salinity is about 1.5 dS/m. Hence, the effect of salinity on crop production was diminished.



Block 1											Block 2										
T2	T9	T5	T0	T8	T6	T7	T4	T10	T3	T1	T2	T1	T5	T6	T9	T4	T8	T0	T3	T10	T7
T2	T9	T5	T0	T8	T6	T7	T4	T10	T3	T1	T2	T1	T5	T6	T9	T4	T8	T0	T3	T10	T7
T2	T9	T5	T0	T8	T6	T7	T4	T10	T3	T1	T2	T1	T5	T6	T9	T4	T8	T0	T3	T10	T7
T2	T9	T5	T0	T8	T6	T7	T4	T10	T3	T1	T2	T1	T5	T6	T9	T4	T8	T0	T3	T10	T7
Block 3											Block 4										
T0	T1	T7	T8	T6	T3	T9	T4	T2	T5	T10	T6	T4	T3	T9	T2	T10	T7	T8	T1	T0	T5
T0	T1	T7	T8	T6	T3	T9	T4	T2	T5	T10	T6	T4	T3	T9	T2	T10	T7	T8	T1	T0	T5
T0	T1	T7	T8	T6	T3	T9	T4	T2	T5	T10	T6	T4	T3	T9	T2	T10	T7	T8	T1	T0	T5
T0	T1	T7	T8	T6	T3	T9	T4	T2	T5	T10	T6	T4	T3	T9	T2	T10	T7	T8	T1	T0	T5

Figure 3-1. Greenhouse Experimental Layout (top) and Experimental Design (bottom).

Table 3-1. Synthetic Recycled Water Irrigation Treatments for the Greenhouse Experiment Prepared with Deionized Water.

Treatments	EC(dS/m) proposed	NaCl (mmol/L)	KCl (mmol/L)	CaCl2 (mmol/L)	MgCl2 (mmol/L)	CaSO4 (mmol/L)	EC (dS/m) observed	SAR[1]	CROSS_f[2]	CROSS_{opt}[3]
0	1.5	0	0	0	0	<18	~1.5	0	0	0
1	1.5	15	0	0	0	0	1.4	∞	∞	∞
2	1.5	12	0	1.5	0	0	1.4	9.8	9.8	9.8
3	1.5	12	0	0.75	0.75	0	1.3	9.8	11.0	13.4
4	1.5	12	0	0	1.5	0	1.4	9.8	12.7	35.6
5	1.5	6	6	1.5	0	0	1.5	4.9	7.6	6.5
6	1.5	6	6	0.75	0.75	0	1.4	4.9	8.5	8.9
7	1.5	6	6	0	1.5	0	1.5	4.9	9.9	23.8
8	1.5	0	12	1.5	0	0	1.5	0	5.5	3.3
9	1.5	0	12	0.75	0.75	0	1.5	0	6.1	4.5
10	1.5	0	12	0	1.5	0	1.6	0	7.1	11.9

[1] Sodium Adsorption Ratio

[2] Cation ratio of soil structural stability (subscript f represents the fact that the numerical coefficients in the CROSS equation are derived from the relative flocculating power of K and Mg following Rengasamy and Marchuk, 2011)

[3] Cation ratio of soil structural stability (CROSS coefficients determined through optimization).

3.2.1.2 Plant Growth and Development

Plant growth and development were monitored weekly. Canopy cover was collected using the Canopeo mobile application developed by Patrignani and Ochsner, (2015) (Figure 3-2). Strawberry plants produce runners as shown in Figure 3-3. Under field conditions, those runners will find their way into soil and produce new plants. In this experiment, the team removed them to allow the mother plants to direct their energy towards fruit production and maintenance. The team also monitored plants symptoms such as leaf curling, leaf browning, leaf yellowing and leaf dry spots (Figure 3-4). A plant received a value of 1 if the symptom existed otherwise, it receives a value of 0. Yield in the form of the fresh and dry weight of the berries with the following specifications was recorded: 1) marketable fruit i.e., the fresh weight that is at least 10 grams and the fruit is not distorted (Butler et al., 2002). The fruits were dried in the oven at 60oC for 10 days to determine the dry weight. The number of fruits that had a color other than red were also recorded (for example, Figure 3-5a). The number of distorted fruits were recorded (for example, Figure 3-5b). Sugar content was quantified based on Brix (%) using an Anpro Brix Refractometer (Anpro Co. Inc. Ussellville, AR). The Brix% was measured after measuring the fresh weight of the strawberries.

Figure 3-2. Canopy Cover Estimation by Taking Pictures of All Plants at Chest Level Height.

Figure 3-3. Showing Strawberry Runners (Daughter Plants).

Figure 3-4. Observed Symptoms: a) Leaf Curling, b) Leaf Yellowing, c) Leaf Browning, d) Leaf Spots.

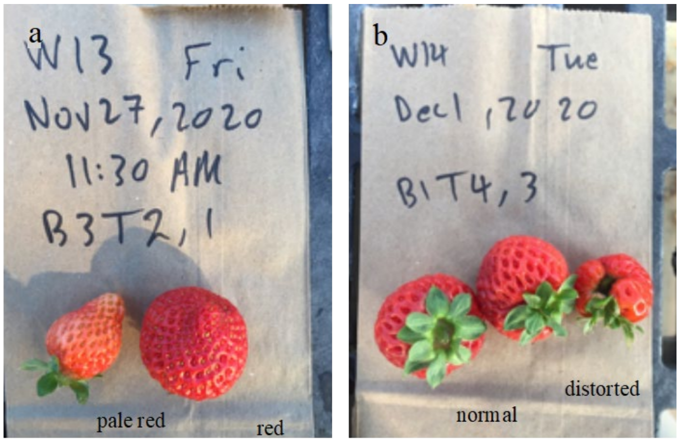


Figure 3-5. Strawberries Fruit Yield Conditions: a) Color (Preferred Fruit Had Bright Red Color), b) Shape (Deformed Fruits Were Not Included in Yield Estimation).

3.2.1.3 Plant Biomass Analyses

At the end of the greenhouse experiment, plants were removed (by cutting the above-ground biomass) from the pots and the fresh weight was recorded. The plants were then oven-dried at 70oC for 72 hours to determine the dry biomass (Kadir et al., 2006). Chemical composition in the plants was analyzed by the UC Davis Analytical Laboratory using ion chromatography. Details on standard operating procedures (SOP) for analysis of plant samples can be found at https://anlab.ucdavis.edu/methods-of-analysis. The following ions were tested in the plant biomass Cl, Mg, K, Na, and Ca.

3.2.1.4 Leachate Analyses

A container was placed below the pots to collect any leachate. Because the threshold ECe was within the range of 1.5-4.0 dS/m for strawberries (USDA-NRCS, 2013), a leaching amount of about 30% was implemented. This was done to mitigate the effect of salinity on crop production and compounding potential sodicity impacts (elevated salinity reduces the effect of sodicity on infiltration). Due to cost, only leachate from selected treatments were analyzed. Treatments 5, 6, and 7 had the most cations in their solutions, therefore they were selected for these analyses. Chemical analysis of the leachate was performed by the UC Davis Analytical Laboratory using Inductively Coupled Plasma Emission Spectrometry (ICP-AES). Chloride concentration in the leachate was analyzed using the Flow Injection Analyzer Method. Detailed information on the UC Davis Analytical SOPs for soil solution analysis can be found in Holstege et al. (2010).

3.2.1.5 Soil Structure Evaluation

At the end of the greenhouse experiment, the impact of recycled water reuse on soil structure and corresponding reduction in infiltration were evaluated by ponding the pots after removing the plants. The team then recorded the percentage of pots that had standing water after several hours ranging from 1.5 to 40 hours. Expressed as the percentage of pots with standing water.

3.2.1.6 Greenhouse Infiltration Experiment Using Wooding Infiltrometer

To determine the effect of recycled water irrigation on soil hydraulic conductivity, the team measured the infiltration rate from each of the 10 treatments at the end of the greenhouse experiments. Three pots were randomly selected from each treatment and the Wooding infiltrometer was placed on top of the pots as shown in Figure 3-6. A total of 33 infiltration tests were conducted. Infiltration rates were then correlated with SAR, $\text{CROSS}_{f,}$ and CROSS_{opt}.

Figure 3-6. Showing Wooding Infiltrometer Placed on Top of Different Treatment Pots at the End of the Strawberry Experiment in a UC Davis Core Facility Greenhouse.

3.2.2 Soil Column Experimental Setup

Soil columns of 15 cm diameter and 60 cm height, made of clear acrylic plastic were used in the experiment. Two tensiometer sensor ports were inserted at a depth of 10 cm and 40 cm from the top of the columns. Each column was filled with Yolo clay loam soil sieved with a 6 mm screen. For homogenization, the soil was collected from a small area at the UC Davis Campbell Tract research farm near Davis California. The soil was packed carefully every 5 cm with a constant bulk density of 1.3 g/cm^3 above a 3-cm layer of glass beads at the bottom of the columns to enhance free flow at the drainage port. The top surface of each layer was disturbed to lessen the boundary compaction. Initial soil physical and chemical properties were evaluated. Electrical conductivity (EC) and pH of the synthetic recycled water was measured in the lab using a Smart Multi-Parameter Tester, (Apera Instruments LLC, PC60-Z). The saturated paste extract of the soil was analyzed for soluble salt content including Na, K, Ca, and Mg by the UC Davis Analytical Lab.

Each soil column received predetermined synthetic recycled water with a salinity of approximately 1.5 dS/m (Table 3-2). The team modified the treatments (by increasing the range of cation composition) in the soil column experiments to have a wide range of treatments among the models for predicting sodicity impacts. Synthetic recycled water was applied from the top using Wooding Infiltrometer (an instrument that uses the Mariotte bottle concept). Therefore, the soil columns were continuously under ponded conditions at the surface, and soil permeability (saturated hydraulic conductivity) was estimated from measurements taken from the soil column setup. The water level in the Mariotte tower was recorded automatically with a pressure transducer connected to CR 1000 Datalogger (Campbell Scientific, Inc., Logan, UT). The saturated hydraulic conductivity (K_S) was estimated as shown in (Figure 3-7) and used the following Equation 3-1 for steady state conditions proposed by Wooding (1968).

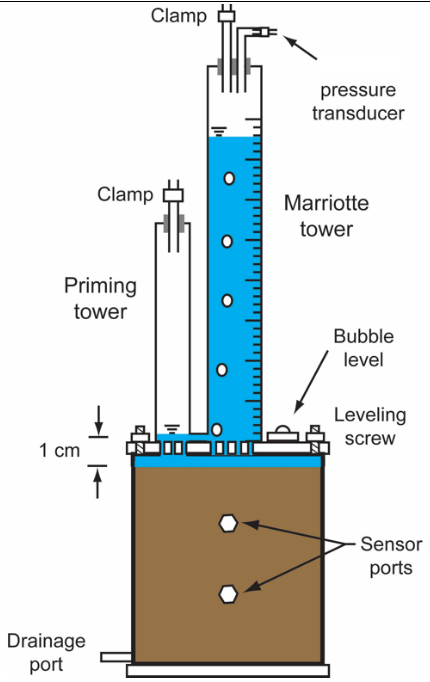
$$q(h_o) = K_S\left(1 + \frac{4}{\pi r_o \alpha_G}\right) exp(\alpha_G h_o) \qquad \text{(Equation 3-1)}$$

Where $q(h_o)$ is the steady-state infiltration rate/water flux density (L T^{-1}), h_o (L) is the tension measurement, and $r_o$is the constant disc radius. The only unknowns in Equation 3-1 are saturated hydraulic conductivity K_S and the fitted parameter α_G, which can be iteratively solved for by making multiple measurements of supply tensions h_o (Angulo-Jaramillo et al., 2000).

Table 3-2. Synthetic Recycled Water Treatments Prepared with Deionized Water for Soil Column Experiment.

Treatments	EC(dS/m) proposed	NaCl (mmol/L)	KCl (mmol/L)	CaCl2 (mmol/L)	MgCl2 (mmol/L)	EC (dS/m) observed	SAR	$CROSS_f$	$CROSS_{opt}$
0	1.5	0	0	8	0	1.4	0	0	0
1	1.5	16	0	0	0	1.4	∞	∞	∞
2	1.5	15	0	0.75	0	1.4	17.3	17.3	17.3
3	1.5	15	0	0.375	0.375	1.4	17.3	19.4	23.6
4	1.5	15	0	0	0.75	1.4	17.3	22.4	62.9
5	1.5	7.5	6	0.75	0	1.5	8.7	12.5	11.0
6	1.5	7.5	6	0.375	0.375	1.5	8.7	14.0	15.0
7	1.5	7.5	6	0	0.75	1.6	8.7	16.2	39.9
8	1.5	0	11	1.5	0	1.6	0	5.0	3.0
9	1.5	0	12	0.375	0.375	1.5	0	8.7	6.3
10	1.5	0	12	0	0.75	1.5	0	10.0	16.9

- Diameter of the soil column was 15 cm and height was 60 cm. The column has two sensor ports for flow cell tensiometers.
- Wooding Infiltrometer has two water towers. The large one (Mariotte) has a diameter of 7.6 and a height of 76 cm. The smaller one (priming tower) has a diameter of 2.54 cm and a height of 50 cm. Both towers were filled with water.
- The infiltrometer was placed on top of the soil column.
- To start the water application, the clamp at the priming tube was opened. Then, the water flowed from the large tower filling the soil with a 1 cm water head.
- The water level dropped inside the Mariotte tower and its level was recorded automatically by connecting the pressure transducer with a datalogger.
- It is assumed that the top 1 cm of soil is fully saturated. Therefore, the saturated hydraulic conductivity (Ks) will equal the final average infiltration rate.



(Adapted from Soil Measurement System)

Figure 3-7. Soil Column Design and Data Analysis Summary.

The pore volume inside the soil column was estimated to be 4.4 L. Each soil column received at least 8 pore volume (PV) of the treatment solution. The saturated hydraulic conductivity measured every pore volume. The drainage water was collected at the bottom of each column into a bucket and the drainage rate was estimated by pore volume. The leachate was analyzed for pH, EC, Na, K, Ca, and Mg content. At the end of the experiment, soil structure changes were evaluated at different depths using the spontaneous dispersible clay estimation method as described in Marchuk et al. (2013b). Soil structure and infiltration rate were then correlated with sodicity hazard prediction models (SAR and CROSS).

3.3 Results

3.3.1 Greenhouse Experiment Results

Before planting, all pots were partially saturated with 2 L of their treatment solutions by applying small doses for 30 min. The bare root strawberries were planted in the pots on August 25, 2020. On September 15, 2020, supplemental lighting was triggered for about 16 hours/day starting at 5 AM if the outdoor light intensity was less than 500 W/m^2. The greenhouse temperature was maintained at about 19^{o}C during the night and 24^{o}C during the day. The blooming was first observed in week 3. By week 5, most plants had bloomed. Figure 3-8 shows the rate of plant growth and development based on the cumulative fresh weight of the harvested fruits. All treatments showed growth with a similar cumulative production rate. Relative yield (i.e., normalized by the control treatment T 0) is shown in Figure 3-9. With the exception of treatments 1, and 4, all the other treatments produced more yield compared to the control/gypsum treatment. These results support observations from commercial open field studies that have shown successful long-term production of strawberries and other crops on the Central Coast of California in the Monterey One and Pajaro Valley service areas under low to moderate irrigation water CROSS and SAR levels.

Sugar content was measured as Brix% and was found to be significantly higher ($P<0.05$) under treatments that had high CROSS (especially treatment 1). Under moderate sodicity levels, plants might actually benefit from slightly high values of CROSS by producing sweeter berries due to the fact that salinity might enhance sugar accumulation in the fruit. The plant growth for treatments irrigated with high SAR/CROSS values will be expected to decrease over time compared to those irrigated with low SAR/CROSS. As shown in Figure 3-10, over time (after 28 weeks) the team observed ponding in some of the treatments with high CROSS. These results indicate that while in the short term if the recycled water has high CROSS its impact on crop production will be minimal however, after continuous application of water with high CROSS infiltration is reduced and poor drainage in the root zone cause anoxic conditions that led to plant death.

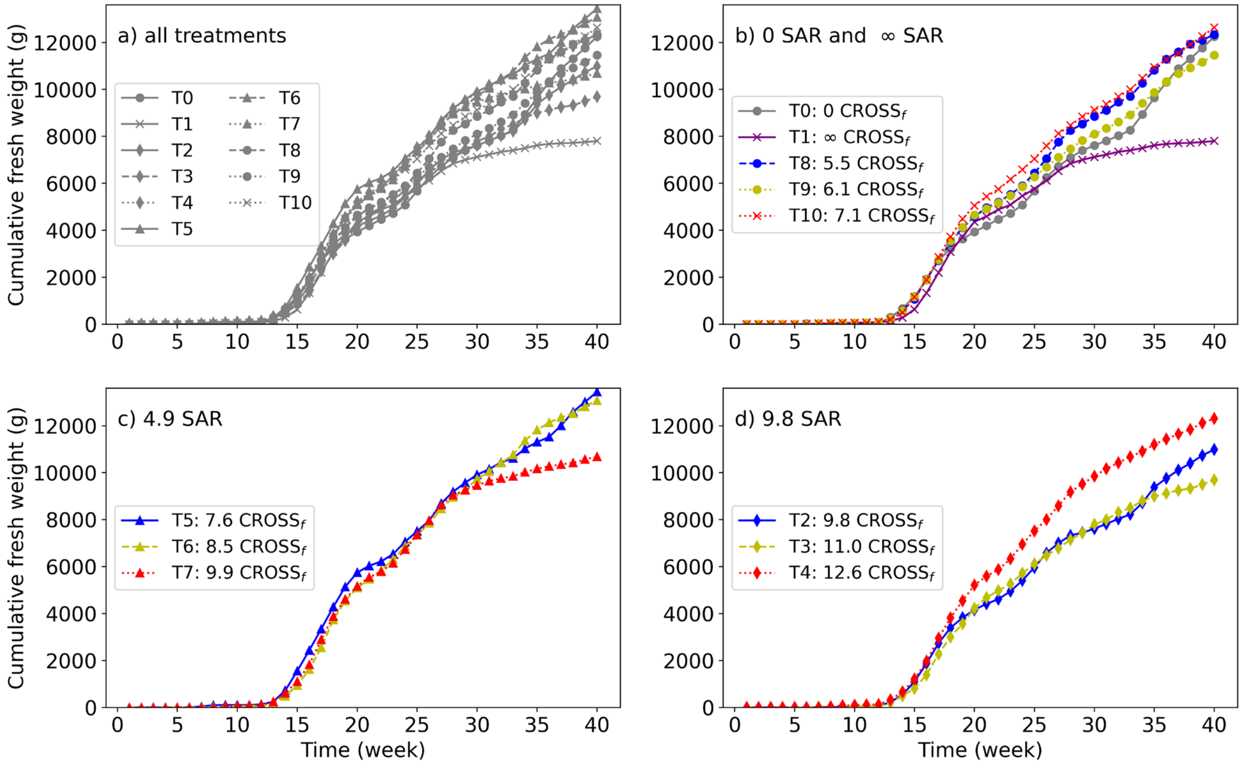


Figure 3-8. Weekly Cumulative Strawberry Yield Based on Fresh Weight (g) from a Green Greenhouse Experiment with Treatments T1 to T10 Mimicking Different Recycled Irrigation Water Qualities and T0 Is the Control (No Sodicity); a) All Treatments, b) 0 SAR Treatments (T0, T8, T9, T10) and T1, c) 4.9 SAR Treatments (T5, T6, T7), d) 9.8 SAR Treatments (T2, T3, T4).

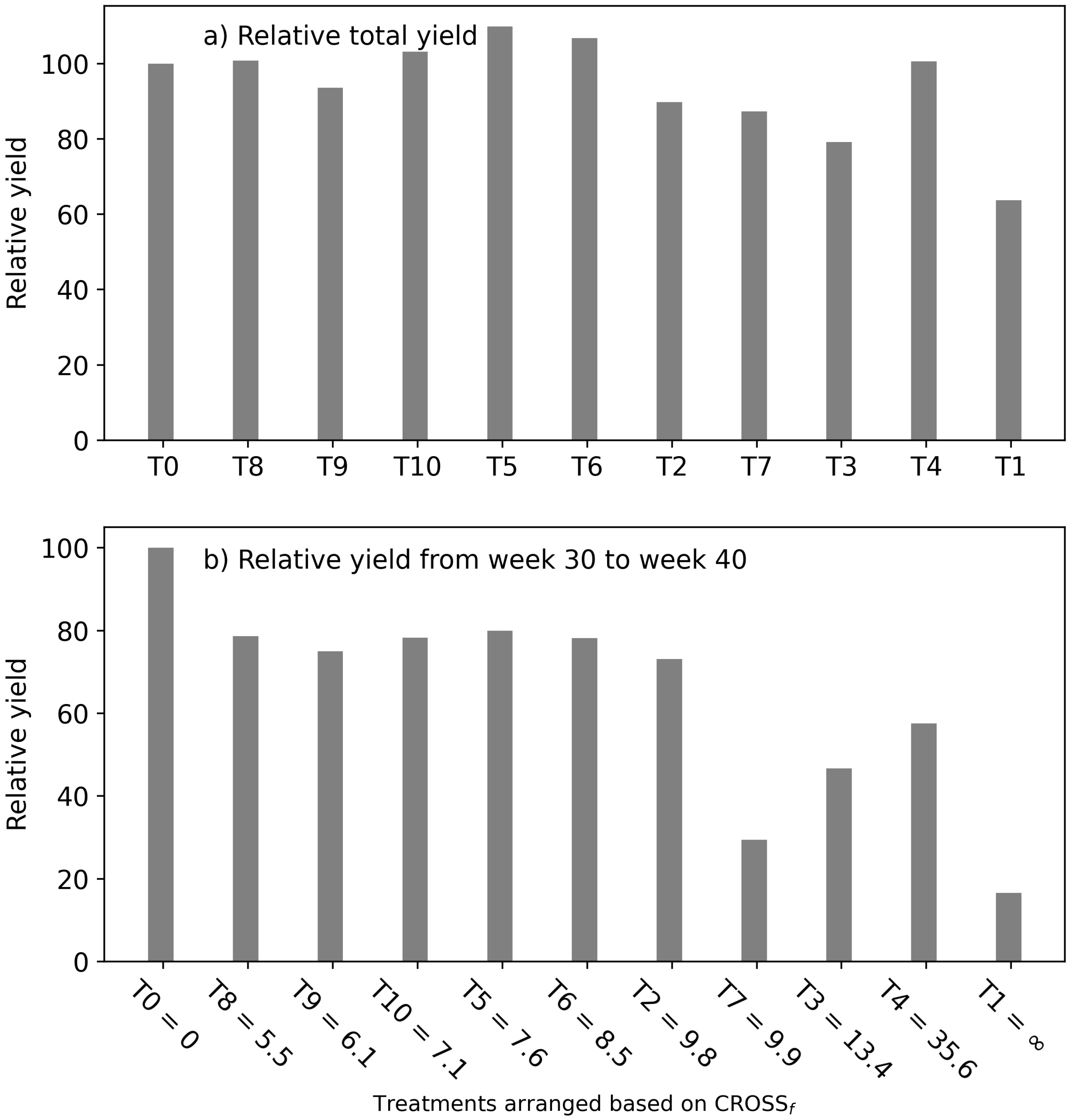


Figure 3-9. Total Production Relative to the Control Treatment (T0) with No Sodicity; a) Relative Yield for the Growing Period, B) Relative Yield from Week 30 to Week 40.

Figure 3-10. Treatments with High CROSS Started to Show Ponding in the Pots and Eventually, the Strawberry Plants Died.

3.3.1.1 Plant and Leachate Analyses

Figure 3-11 shows the results of the average strawberry fresh and dry biomass collected at the end of the greenhouse experiment. The error bars represent the standard deviation of the mean. The correlation between the average plant biomass and cations ratios (SAR, $CROSS_f$, $CROSS_{opt}$) for the different recycled water qualities showed the highest correlation with $CROSS_f$ followed by SAR and the least correlation with $CROSS_{opt}$ (Figure 3-11c&d). It is worth noting that Treatment 1 (with infinity SAR/CROSS, not shown in the correlation graphs) had the lowest average biomass probably due to reduced drainage within the pots affecting oxygen levels (Figure 3-11a&b). Overall, the results indicate that increasing sodicity resulted in reduced strawberry productivity.

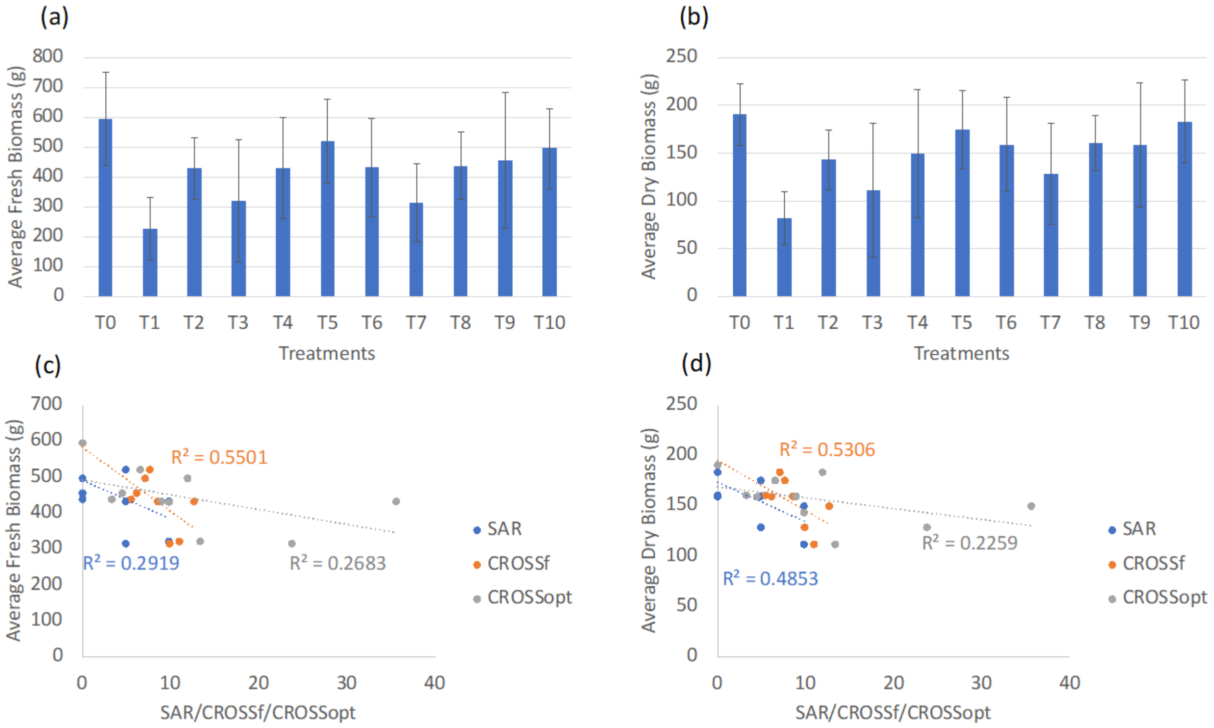


Figure 3–11. Total Strawberry Fresh and Dry Biomass at the End of the Greenhouse Experiment at UC Davis 2021. a) Average fresh biomass in grams (g). b) Average dry biomass (g). c) Correlation between the average fresh biomass and SAR, $CROSS_f$, $CROSS_{opt}$. d) Correlation between the dry biomass and SAR, $CROSS_f$, $CROSS_{opt}$.

Strawberry salt uptake in the form of Cl, Mg, K, Na, and Ca is shown in Figure 3-12. All treatments demonstrated consistency with the cation composition of the applied recycled water. The gypsum treatment (T0) produced plants with no chloride content in the biomass. However, the rest of the treatments had substantial chloride content in the plant tissue because of the chloride-based salts used to create the different treatments of synthetic recycled water. Elevated levels of chloride in strawberries can cause chloride toxicity.

Similarly, for sodium, the team observed that plants irrigated without sodium solutions (T0, T8, T9, T10) had no sodium in their plant tissue. The sodium content in the plant tissues increased with increasing sodium in the recycled water solution until the maximum with treatment 1 (sodium solution infinity SAR and CROSS). The result of the sodium uptake by the plants irrigated with sodium solution only (T1) probably indicates the maximum sodium that strawberry plants can uptake (Figure 3-12).

For potassium, plants that were irrigated with zero potassium in solution (T0-T4) as expected had the lowest potassium content in plant tissues. Therefore, the amount of potassium in the plant tissues must have come from the slow-release fertilizer or residual potassium in the soil. The rest of the plants had higher potassium concentrations in their plant tissues and that extra accumulation must have come from the potassium in the synthetic recycled water solutions. Similar observations (like the potassium observation) were observed with the calcium and magnesium concentrations in the plant tissues.

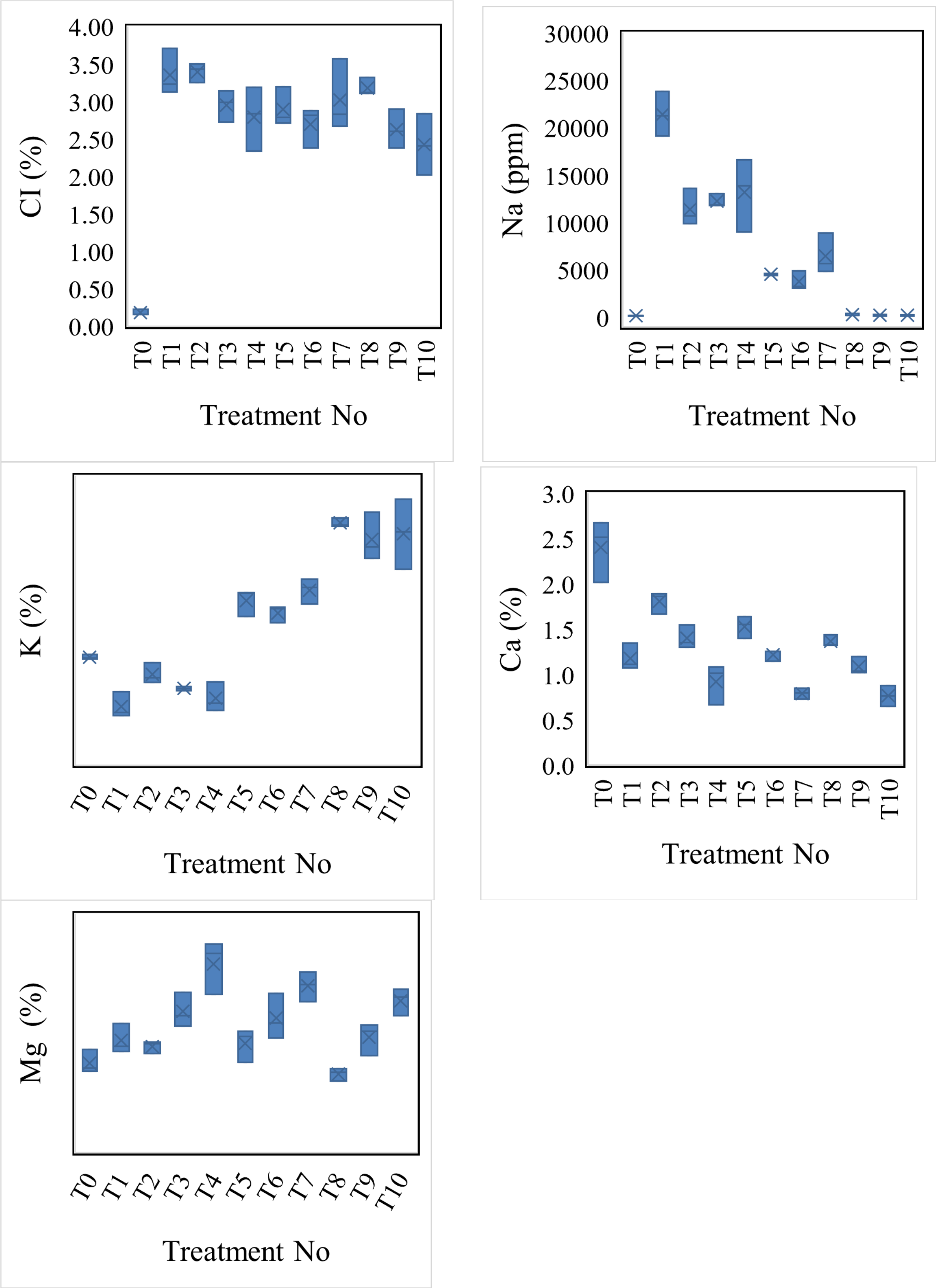


Figure 3-12. Cation Concentration in the Plant Tissues of Various Synthetic Recycled Water Irrigation Treatments (T0 to T10 Defined in Table 3-1).

Cation concentration (Na, K, Ca, Mg, and Cl) in the leachate is shown in Figure 3-13. Each data point represents the average of three mixed solutions from different pots and replications of the same treatment. Not all treatments were analyzed due to the high cost of the analyses. Treatments 5, 6, and 7 which had the most cations in their solutions were selected for the leachate analyses. From week 9 to week 15, the volume of the leachate solution was not sufficient for laboratory analysis. In week 15, the solution was very little, and it was concentrated as can be seen in Figure 3-13. It appears that a 30% leaching fraction was sufficient to reduce the cation concentration in the leachate over time including sodium. The increase in potassium could be attributed to the effect of the slow-release fertilizer.

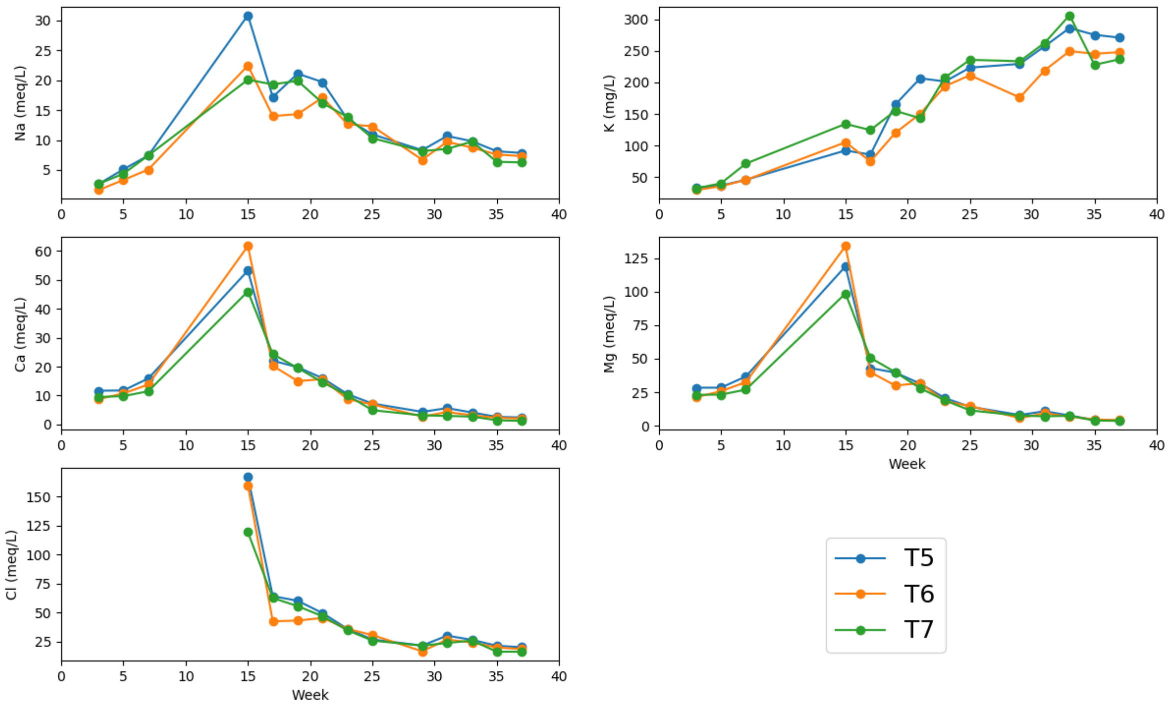


Figure 3-13. Leachate Cation Concentration in Synthetic Recycled Water Treatments 5, 6, and 7 in a Greenhouse Strawberry Experiment.

3.3.1.2 Effect of Recycled Water on Infiltration Rate

Figure 3-14 shows the correlations between cation ratios (SAR, $\mathrm{CROSS_f}$, $\mathrm{CROSS_{opt}}$) and the average infiltration rates measured using a Wooding Infiltrometer in soil pots as shown in Figure 3-6. The average infiltration rate was more highly correlated with $\mathrm{CROSS_f}$ (R^2 0.6) followed by $\mathrm{CROSS_{opt}}$ (R^2 0.4) and least correlated with SAR(R^2 0.2). As expected Treatment 1 (with infinity SAR/CROSS, not shown in the graphs) had the lowest infiltration rate with an average infiltration rate of 0.0138 cm/min and standard deviation ±0.0021 cm/min. These results agreed with the correlation between cation ratios (SAR, $\mathrm{CROSS_f}$, $\mathrm{CROSS_{opt}}$) and average biomass (Figure 3-11). These findings provide evidence that $\mathrm{CROSS_f}$ was a better predictor of reduction in soil infiltration rate as a function of cation concentration in the irrigation recycled water.

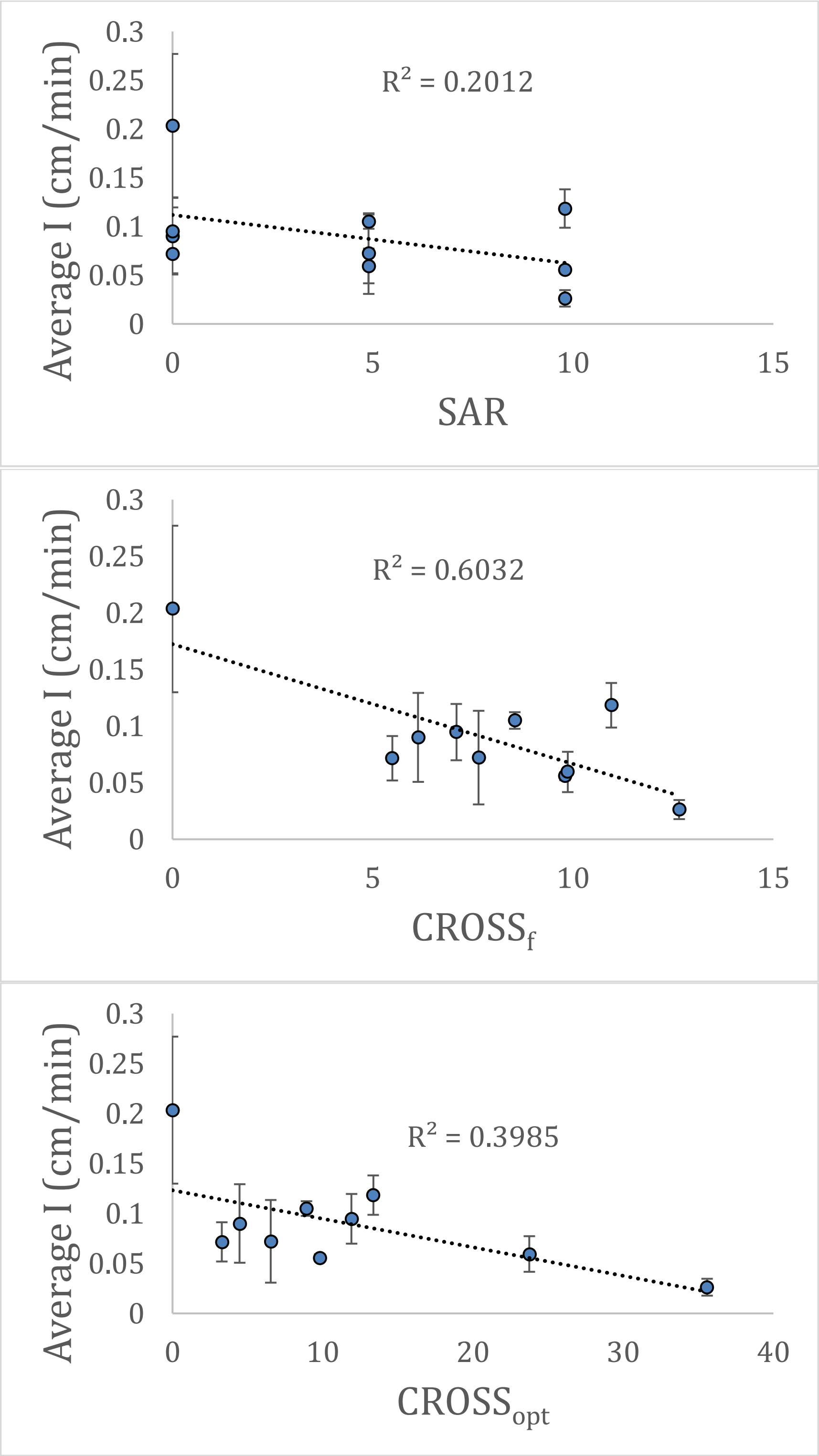


Figure 3-14. Correlation between the Average Infiltration Rates and Cation Ratios (SAR, CROSS$_f$, CROSS$_{opt}$) as Predictors of Reduction in Infiltration Due to Cation Concentration in Recycled Irrigation Water.

3.3.1.3 Soil Moisture Evaluation

Soil moisture was measured using a TDR sensor (Acclima Inc, Meridian Idaho). Figure 3-15 shows the moisture content measured in the pots (after harvesting the whole plants) after 7 days from the termination of the irrigation. Usually, soils that have poor drainage hold more water for longer periods than well-drained structured soils. The correlation results in Figure 3-15 show a higher correlation between $CROSS_f$ and soil moisture (R^2 0.6) compared to SAR and soil moisture (R^2 0.4). These results further confirm the findings of the results presented in Figs 3.11 and 3.14 that CROSS is a better predictor of negative impacts on soil hydrology compared to SAR.

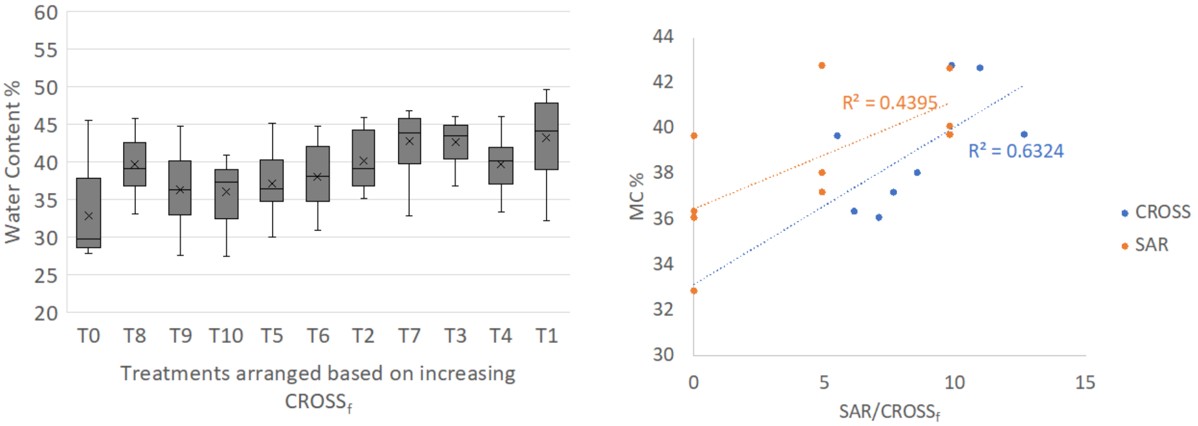


Figure 3-15. Moisture Content Measured in Pots after 7 Days from Terminating the Irrigation (n=13) in Synthetic Recycled Water Treatments Shown in Table 3-1.

3.3.1.4 Dispersed Clay

The dispersed clay estimation was adapted from Marchuk et al. (2013b) method of spontaneous dispersion. In the analysis, 40 g of an oven-dry sample collected from the pots were placed in 250 ml graduated cylinder. Then, 200 ml of deionized water was added and left for 5 hours. After that, the soil was stirred into suspensions and left to stand for 2 hours. The dispersed clay was estimated by pipetting out 10 ml from a depth of 10 cm, and the solution was oven-dried to obtain the weight (mg) using a sensitive scale. The results are shown in figure 3.16. Each data point represents the average of dispersed clay from 4 samples (one sample per block). And each sample was a mix of soil from 4 pots collected from 5 to 10 cm depth. The error bars represent the standard deviation around the mean. Dispersed clay was highly correlated with $CROSS_f$ than SAR and CROSSopt with R^2 of 0.97, 0.63 and 0.55, respectively. Treatment 1 (infinity SAR/CROSS, not shown in the graphs) had the highest dispersed clay on average with 77.4 (±3.3) mg.

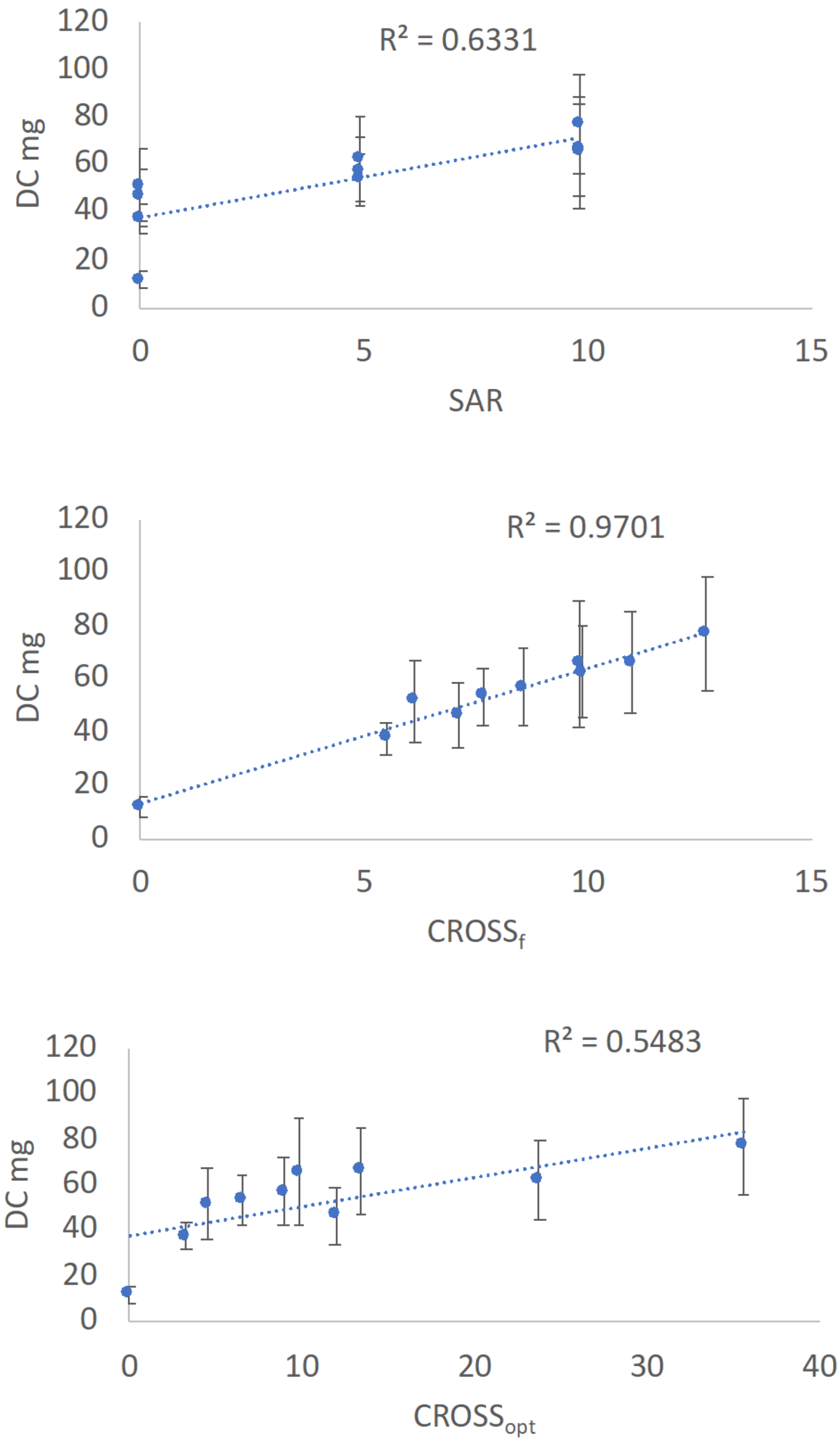


Figure 3-16. Correlation between the Average Dispersed Clay and Cation Ratios (SAR, CROSS_f, CROSS_{opt}).

Table 3-3 is a summary of the linear correlations with and without T0 (gypsum treatment). The summary results show that CROSS_f is a better predictor except for the infiltration correlation excluding T0. However, this might be due to the spread of the treatments in terms of CROSS_f. The difference in the treatments design for the column experiment was to improve the treatments distribution for CROSS_f values.

Table 3-3. Shows Statistical Correlations between Dispersed Clay in Different Recycled Water Treatments and Cation Ratios SAR, $\text{CROSS}_{f,}$ and CROSS_{optm} with and without Including Treatment That Received Gypsum.

	Dispersed Clay		Moisture Content		Fresh Biomass		Dry Biomass		Infiltration		
	R^2 T0 included	R^2 T0 excluded	R^2 T0 included	R^2 T0 excluded	R^2 T0 included	R^2 T0 excluded	R^2 T0 included	R^2 T0 excluded	R^2 T0 included	R^2 T0 excluded	Average
SAR	0.63	0.80	0.44	0.36	0.29	0.19	0.48	0.41	0.20	0.08	0.39
CROSS_f	0.97	0.92	0.63	0.37	0.55	0.26	0.53	0.39	0.60	0.14	0.54
CROSS_d	0.78	0.89	0.51	0.36	0.42	0.24	0.47	0.34	0.40	0.22	0.46
CROSS_{opt}	0.55	0.59	0.31	0.20	0.27	0.14	0.22	0.12	0.40	0.36	0.32

3.3.2 Soil Column Experiment Results

The pressure sensors used in the soil columns were calibrated using a digital manometer. The calibration trendlines are shown in Figure 3-17. Sensors (1-10) connected with tensiometers were calibrated up to 800 (cm H_2O) mbar, while the sensors (11-15) connected with the Wooding infiltrometer water tower were calibrated up to 100 mbar (cm H_2O) because the maximum level of the water inside the water tower is 76 cm. The recorded data uploaded from the data logger (sample data shown in Table 3-4) was converted from negative pressure (vacuum) to soil-water tension (sensors 1-10) and the water level inside the water tower (sensors 11-15).

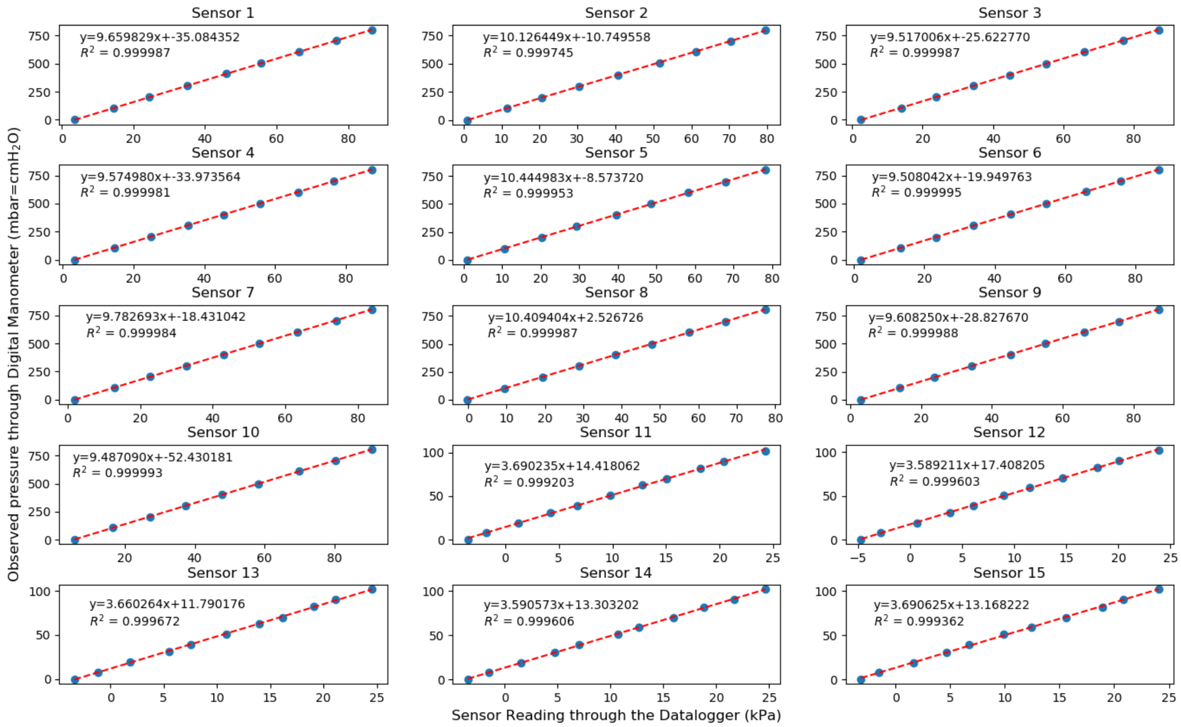


Figure 3-17. Sensor Calibration Trendlines for Sensors 1–10 (Connected to the Tensiometers) and Sensors 11–15 (Connected to the Wooding Infiltrometer Water Tower).

Table 3-4. Sample Datalogger Output for the Tensiometers and Water Tower Readings for Selected Recycled Water Irrigation Treatments.

TIMESTAMP TS		RECORD RN	T0 Sensor 11 -kPa	T1 Sensor 12 -kPa	T2 Sensor 13 -kPa	T3 Sensor 14 -kPa	T4 Sensor 15 -kPa
12/1/21 0:00	2:30:00 PM	2590	16.22	14.55	16.02	15.1	15.86
12/1/21 0:00	2:45:00 PM	2591	15.75	14.54	15.42	14.98	15.11
12/1/21 0:00	3:00:00 PM	2592	14.87	14.29	13.5	14.46	14.04
12/1/21 0:00	3:15:00 PM	2593	14.04	14.01	11.64	13.96	13.05
12/1/21 0:00	3:30:00 PM	2594	13.19	13.7	9.9	13.48	12.04
12/1/21 0:00	3:45:00 PM	2595	12.37	13.38	8.25	12.98	11.05
12/1/21 0:00	4:00:00 PM	2596	11.6	13.06	6.676	12.51	10.11
12/1/21 0:00	4:15:00 PM	2597	10.8	12.74	5.142	12.04	9.16
12/1/21 0:00	4:30:00 PM	2598	9.98	12.17	3.607	11.56	8.23
12/1/21 0:00	4:45:00 PM	2599	9.18	11.81	2.176	11.04	7.254
12/1/21 0:00	5:00:00 PM	2600	8.4	11.51	0.702	10.63	6.392

The experimental set up could fit 5 soil columns at a time. Two sets of soil column experiments were run from treatment 0 to 9. T team had to run the experiment at least 3 times for each treatment to obtain average values for the infiltration rate, drainage rate and clay dispersion. The initial results of the infiltration rate and the drainage rate measured over the applied pore volume of treatment solutions are shown in Figure 3-18.

Both the infiltration rate and the drainage rate were consistent with respect to each treatment over the applied pore volume of water. Treatment T0 (calcium chloride solution) displayed noteworthy statistical significance compared to the other treatments. The application of this treatment solution led to a marked enhancement in the infiltration rate across the entire measurement span. The increasing infiltration rate of treatment T0 allowed it to achieve a 16-pore volume run. The goal was to ascertain the maximum steady state infiltration rate, yet this determination proved elusive even after 16 pore volume applications. The highest observed infiltration attributed to the effect of calcium chloride was also documented by Quirk and Schofield (1955). Treatments T8 and T9 had SAR values of zero and they were both statistically lower than T0. The comparatively slow infiltration rate of the T8 and T9 can primarily be attributed to the influence of potassium on infiltration rate given that these treatments encompassed potassium, calcium and/or magnesium. This confirms the observations of Ahmed et al. (1969); Arienzo et al. (2009); Chand et al. (2020); Chen et al. (1983); Martin and Richards (1959); Quirk and Schofield (1955); Reeve et al. (1954); Rengasamy and Marchuk (2011); and Smith et al. (2015) that potassium has negative impact on soil permeability. Throughout the experiment, T8 maintained a higher average infiltration rate than T9 which could be attributed to calcium's more pronounced effect on aggregate flocculation compared to magnesium, as T8 lacked magnesium in its solution whereas T9 incorporated magnesium. Similarly, Rengasamy and Marchuk (2011) observed that soil saturated with potassium and calcium had higher saturated hydraulic conductivity than soil saturated with potassium and magnesium.

The lowest observed average saturated infiltration rate was associated with treatment T1 although this disparity did not reach statistical significance when compared to treatments T3 and T4. In contrast, treatment T2 exhibited a similar SAR to T3 and T4 demonstrating statistical significance over treatment T1 (Figure 3-18). On average, T2 displayed a higher infiltration rate in comparison to T3 and T4. This divergence may arise from varying degrees of calcium's and magnesium's impact on aggregate flocculation as T2 had calcium alongside sodium cations. Likewise, Rengasamy and Marchuk (2011) observed that soil saturated with sodium and calcium had higher saturated hydraulic conductivity than soil saturated with sodium and magnesium. It is noteworthy that T2 did not reach a constant infiltration rate after applying 10 pore volume of its solution. Despite treatment T3 having a smaller CROSSf value compared to T4, its average infiltration rate from pore volume 5 to pore volume 8 fell below that of T4. Notably, no statistically significant distinctions emerged within the group of treatments featuring an SAR of 8.7 (T5, T6 and T7).

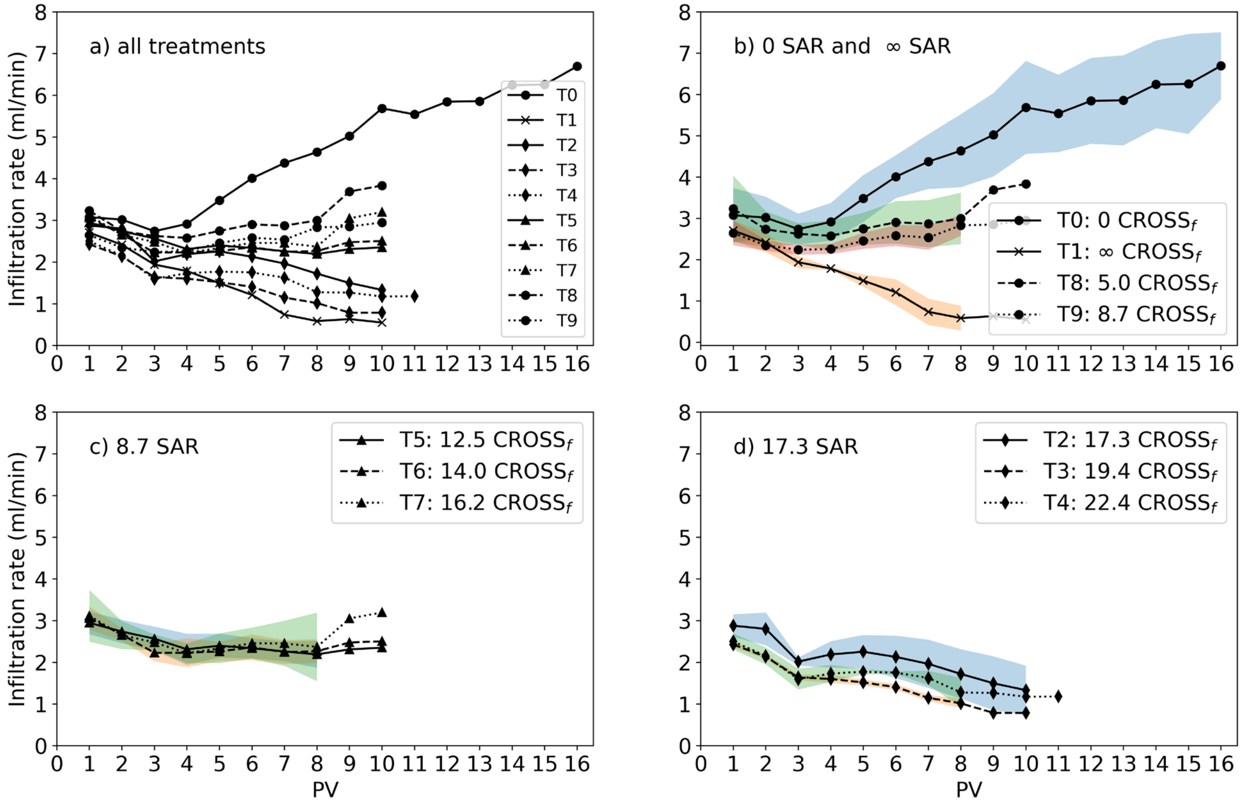


Figure 3-18. Infiltration Rate over Pore Volume for: A) All Treatments, B) Treatments with 0 SAR and T1 with ∞ SAR, c) Treatments with Medium SAR, d) Treatments with High SAR. The Drainage Rate Matched the Infiltration Rate with a Root Mean Square Error (RMSE) of 0.023 ml/min.

The saturated infiltration rate was further analyzed concerning the different cation ratios. The correlation was tested at pore volume 8. Pore volume 8 was chosen to ensure ample time for the cation exchange and to guarantee a minimum of three measurements per treatment. The general trend observed is that the infiltration rate decreases with increasing cation ratios. CROSS$_{opt}$ exhibited the least correlation with an R^2 of 0.41 which could indicate that CROSS$_{opt}$ had a good correlation with the TEC under the specific study conditions outlined in Smith et al. (2015) but may not be generalizable. Conversely, CROSS$_f$ demonstrated a stronger correlation with an R^2 of 0.90 which was also greater than SAR's R^2 (0.75). This finding supports that CROSS$_f$ could be a better model in predicting the reduction in rate of infiltration than SAR. As is widely understood, the SAR-EC chart (Ayers and Westcot, 1985) was developed to predict the reduction in rate of infiltration. Therefore, CROSS$_f$ could be a better replacement for SAR in the y-axis of the chart.

3.4 Summary

The main goal of this study was to assess strawberry growth and development response to recycled water reuse for irrigation with different cation composition under a greenhouse environment. A related objective was to evaluate the effect of cation composition on soil permeability/structure in soil columns under a laboratory setting. Strawberries are one of the crops most widely irrigated with recycled water in California. Strawberries have high sensitivity to the salinity of the irrigation water. Initially all recycled water treatments with a wide range in

SAR and CROSS had minimum impact on strawberry growth and development. However, after 28 weeks the team observed ponding and plant depth in some of the treatments with high CROSS. These results indicate that while in the short term even if the recycled water has high CROSS its impact on crop production will be minimal, but after continuous application of water with high CROSS infiltration is reduced and poor drainage in the root zone causes anoxic conditions that led to plant death. While this was a greenhouse experiment, in the field strawberry crops are grown and harvested for periods of nearly 52 weeks and 28 weeks respectively; additionally, some fields are carried over into the second year of production (Personal Communication, Belinda Platts). This data indicates that the treatments with the most significant ponding would be problematic to growers needing to optimize yields due to factors influencing high growing costs.

Sugar content was measured in the form of Brix (%) and was found to be significantly higher ($P<0.05$) under treatments that had high CROSS. Under moderate sodicity levels, plants might benefit from slightly high values of CROSS by producing sweeter berries. The correlation between the average plant biomass and cations ratios (SAR, $CROSS_f$, $CROSS_{opt}$) for the different recycled water qualities showed the highest correlation with $CROSS_f$ followed by SAR and the least correlation with $CROSS_{opt}$. Overall, the results indicate that increasing sodicity resulted in reduced strawberry productivity. Salt uptake was consistent with the cation composition of the recycled water. The gypsum treatment produced plants with no chloride content in the biomass. However, the rest of the treatments had substantial chloride content in the plant tissue because of the chloride-based salts used to create the different treatments of synthetic recycled water. Chloride can cause ion toxicity in strawberries. The average infiltration rate was more highly correlated with $CROSS_f$ (R^2 0.6) followed by $CROSS_{opt}$ (R^2 0.4) and least correlated with SAR(R^2 0.2). Correlation was also higher between $CROSS_f$ and soil moisture (R^2 0.6) compared to SAR. In addition, dispersed clay was more highly correlated with $CROSS_f$ than SAR and $CROSS_{opt}$. In conclusion, these findings confirm that $CROSS_f$ is a more robust tool for predicting negative impacts of different recycled water quality compared to SAR. Practitioners should consider using $CROSS_f$ instead of SAR in assessing sodicity impacts.

In the soil column experiment, thirty columns were filled with clay loam soil. A comprehensive evaluation was conducted on these columns to examine their soil structure and saturated hydraulic conductivity. The irrigation process involved regular application of water to the soil columns, maintaining a constant water head of 1 cm after pre-saturation. The salinity of the used solution remained constant at 1.5 dS/m. In contrast to SAR, the results revealed a strong association between $CROSS_f$ and saturated hydraulic conductivity. The coefficients of determination for hydraulic conductivity were 0.90 for CROSS and 0.75 for SAR. Finally, both experiments concluded with a consistent finding that $CROSS_f$ could be a better replacement than SAR for assessing the impact of irrigation water quality on soil structure.

CHAPTER 4

Sustainable Reclamation and Management of Sodic Soils

4.1 Effect of Sodicity on Soil Hydrology

Sustainable reclamation of sodium impacted soil requires understanding of how sodium affects soil hydrology. The degree of deterioration in soil physical properties of sodic soils can be assessed using hydraulic conductivity or permeability. Sustainable management of sodium affected soil involves replacing exchangeable Na^+ with Ca^{2+}.Usually the Ca^{2+} comes from the dissolution of Ca-containing minerals in the soil, from amendments such as gypsum or calcium chloride dihydrate, and irrigation water with Ca^{2+} ions (Wallender and Tanji, 2012). Under sustainable management of sodic soils, the goal is to maintain or enhance hydraulic conductivity by providing high electrolyte concentration in the soil solution to counter the influence of exchangeable sodium. Generally, the higher the electrolyte concentration (EC), the higher the exchangeable sodium (E_{Na}) fraction at which a relatively high soil hydraulic conductivity can be maintained (Quirk and Schofield 1955; Wallender and Tanji, 2012). If the EC of the percolating water is adequate to reduce clay swelling, the soil hydraulic conductivity remains high. When low EC water such as rainfall follows high EC irrigation water, high soil hydraulic conductivity can be maintained by adding a source of electrolyte on the surface of a sodium affected soil. The classical criteria for predicting the sodic hazard are the soil ESP (exchangeable sodium percentage), and the sodium adsorption ratio (SAR) of the saturation extract or irrigation water. As discussed in Chapter 2 SAR can be substituted with the cation ratio of structural stability (CROSS).

However, soil sodicity cannot be assessed without information on the EC of the soil solution as noted by Wallender and Tanji (2012). SAR less than 3 causes no harm to soils but if it is higher than 9, it can severely affect soil physical properties and also cause ion toxicity in certain crops (e.g., perennial nut and fruit crops). Irrigation water EC is highly related to SAR. Generally, soil infiltration is not reduced due to high SAR if irrigation water EC is relatively high. Also, a soil is considered to be sodic if the exchangeable sodium percentage (ESP) is more than 6% and highly sodic when the ESP is greater than 15% (Table 4-1). Such soils are characterized by poor structure caused by clay dispersion, low porosity and high bulk density which hinders root growth and crop productivity. Table 4-2 shows empirical relationships between SAR and ESP for different regions of the world. Most of these relationships were developed several decades ago and new research should explore updating these relationships or develop ones. Figure 4-1 adapted from Rengasamy et al. (1984) Shows the relationship between ESP/SAR and irrigation water EC. Increasing EC increases the threshold value of ESP at which soil structure begins to deteriorate resulting in reductions in soil hydraulic conductivity.

Table 4-1. Exchangeable Sodium Percentage (ESP) and Sodicity Hazard.

Source: Adapted from FAO Soils Bulletin 39.

Approx. ESP	Sodicity Hazard	Remarks
< 15	None to slight	The adverse effect of exchangeable sodium on the growth and yield of crops in various classes occurs according to the relative crop tolerance to excess sodicity. Whereas the growth and yield of only sensitive crops are affected at ESP levels below 15, only extremely tolerant native grasses grow at ESP above 70 to 80.
15 - 30	Light to moderate	
30 - 50	Moderate to high	
50 - 70	High to very high	
> 70	Extremely high	

Table 4-2. Relationship between ESP and SAR for Soils from Different Regions of the Word.

Source: Reprinted from Advances in Agronomy 96(2007); by Qadir, M., J. D. Oster, S. Schubert, A.D. Noble, and K.L. Sahrawa; Phytoremediation of Sodic and Saline-Sodic Soils; p. 197-247; Copyright (2007), with permission from Elsevier.

Equations	Sample Size	References
ESP = [100 (-0.0126 + 0.01475 SAR)] / [1 + (-0.0126 + 0.01475 SAR)]	59	US Salinity Laboratory (1954)
ESP = [100 (0.0063 + 0.0124 SAR)] / [1 + (0.0063 + 0.0124 SAR)]	15	Franklin and Schmehl (1973)
ESP = [100 (0.1149 + 0.0109 SAR)] / [1 + (0.1149 + 0.0109 SAR)]	150	Paliwal and Ghandi (1976)
ESP = [100 (-0.0867 + 0.02018 SAR)] / [1 + (-0.0867 + 0.02018 SAR)]	180	Ghafoor *et al*. (1988)
ESP = [100 (-0.0268 + 0.02588 SAR)] 1 / [1 + (-0.0268 + 0.02588 SAR)]	144	Ghafoor *et al*. (1988)

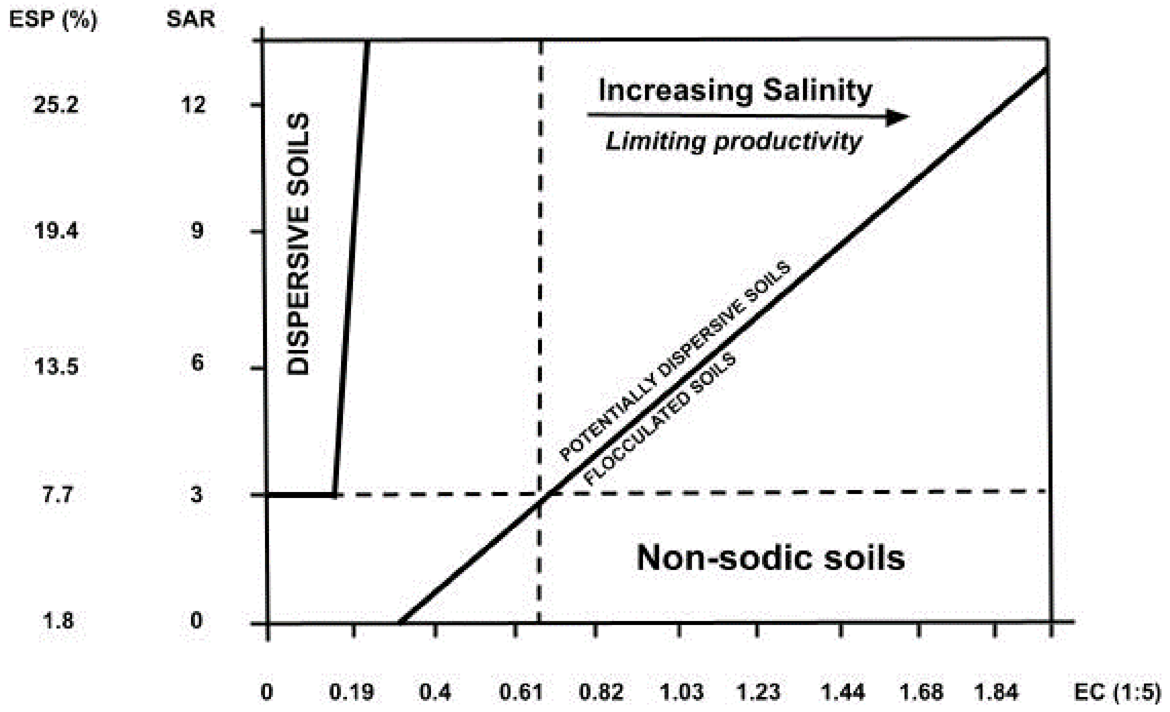


Figure 4-1. Showing the Relationship between ESP/SAR and EC$_{1:5}$, as the Electrolyte Concentration Increases the Threshold ESP/SAR at Which Soil Structure Deteriorates Increases Which Helps to Main Hydraulic Conductivity.

Source: Adapted from Rengasamy et al., 1984.

Where $EC_{1:5}$ refers to the weight to volume soil salinity measurement obtained by taking 1 part by weight (grams) of air-dried soil and mixing it with 5 parts by volume (mL) of distilled water (Slavich and Petterson, 1993). The mixture is agitated and left to sit for 24 hours (low EC soils) or 3 hours (high EC soils). An EC meter is used to measure $EC_{1:5}$ which is then converted to saturated paste extract Ece using conversion factors in Table 4-3 that accounts for differences in soil texture.

Table 4-3. Showing Conversion Factors for $EC_{1:5}$ to Ece for Different Soil Textures.
Source: Adapted from Slavich and Petterson, 1993).

Soil Texture	Multiply Conversion Factor to Get Ece
Sand	15
Sandy loam	12
Loam	10
Clay loam	9
Light–medium clay	8
Heavy clay	6

4.2 Sustainable Management of Sodic Soils Based on Adding Amendments

The first step of reclaiming sodium-affected soils is to determine the ESP of the soil, SAR of the irrigation water and the soil's electrolyte concentration. The target of the reclamation is to maintain high hydraulic conductivity which can be achieved by maintaining relatively high soil-water electrolyte concentration to counter or resist the effect of the exchangeable sodium. The main concept of reclaiming such soil is to replace the exchangeable sodium with calcium to reduce the swelling of the soil due to the high sodium concentration in the diffuse double layer. Therefore, sodic soils and saline-sodic soils can be reclaimed by adding soil amendments such as gypsum and calcium chloride dihydrate. Reclaiming calcareous soils can be achieved by using acidic amendments, for example sulfuric acid, iron sulfate, aluminum sulfate and sulfur, which enhance the conversion of calcium carbonate into gypsum. The most common low-cost amendments are gypsum, sulfuric acid and sulfur.

4.2.1 Gypsum ($CaSO_4$ $2H_2O$)

Gypsum when added to the soil increases soil hydraulic conductivity by raising the soil water solution electrolyte concentration (Shainberg 1982). Gypsum is moderately soluble (~2.0–2.5 g/l at 25 °C), low cost (though cost has recently increased due to demand for other uses), and available, these factors make gypsum the most commonly used amendment for reclaiming Na-affected soil and for reducing the harmful effects of high-Na irrigation waters. Gypsum can be obtained from both mining and as a by-product of the industrial production of fertilizer from phosphate rock. Under the same conditions, the rate of dissolution of industrial gypsum is much higher than that of mined gypsum (Wallender and Tanji, 2012).

Depending on the nature of the sodic soil reclamation, the amount of gypsum to be applied varies. For example, If the electrolyte effect is sufficient to prevent soil clays from dispersing and swelling, then surface application of gypsum is recommended and the mount to be applied depends on the amount of low salt water and dissolution of the gypsum material. On the other hand, if the benefits of applying gypsum derive from cation exchange, the amount of gypsum required depends on the amount of exchangeable Na in the depth of soil to be reclaimed. The amount of exchangeable Na to be replaced during reclamation depends on the initial exchangeable Na fraction (E_{Nai}), soil cation exchange capacity (CEC, mmol/Mg), soil bulk density (ρb) (Mg m^{-3}), the desired final exchangeable sodium fraction (E_{Naf}), and the depth of soil to be reclaimed (*Dr*, m). After these parameters are determined, the amount of exchangeable Na to be replaced per unit of land area (ΔNa) (Na, mol$_c$ ha^{-1}) is calculated following Wallender and Tanji (2012) as:

$$\Delta Na = 10^4\,(D_r)\,(\rho b)\,(CEC)\,E_{Nai} - E_{Naf} \qquad \text{(Equation 4-1)}$$

The value of E_{Naf} depends on the response of infiltration and hydraulic conductivity to gypsum applications and the sodium tolerance of the crop. The gypsum requirement (GR) which refers to the amount of gypsum needed to reclaim a sodium-affected soil, (metric ton ha^{-1}) can be calculated from Equation 4-2:

$$GR = 86.1 * 10^{-6}\,\Delta Na \qquad \text{(Equation 4-2)}$$

Equation 4-2 can also be expressed as equation 5 following Franzen et al. (2019):

$$GR = 086 * F * D * \rho_b * CEC * \left(SAR_i - SAR_f\right) * \frac{100}{Percent\ gypsum\ purity}$$

GR is the gypsum requirement in Mg per hectare (1 Mg/ha = 0.45 tons per acre)
0.86 is derived for the mass of gypsum (CaSO4*2H_2O) required to replace one Na$^+$
F is the Ca to Na exchange efficiency; 1.1 for SAR of 15 or greater, 1.3 for SAR of 5
D is depth of soil to treat in meters
ρ_b is bulk density of soil, grams per cubic centimeter (g/cm3)
CEC is the "real" CEC in mmol$_l$/kg
SAR_i is the initial SAR (%Na)
SAR_f is the goal or final SAR (%Na)

Percent purity is needed for correction to the mass of actual gypsum to be applied.

Table 4-4 shows the amount equivalent of 1 Mg of gypsum for various commonly used soil amendments to reclaim sodic soils. The amount of any amendment to be applied is based on the amount equivalent to that of gypsum (GR) needed to replace sodium from the soil. The efficiency of gypsum in reclaiming sodic and saline-sodic soils depends on a number of factors including; the infiltration characteristics of the soil, level of ESP (greater at higher ESP), and gypsum dissolution properties (higher rates of dissolution are preferred). Gypsum dissolution rate is influenced by surface area of gypsum fragments, soil-water velocity during leaching, and the electrolyte composition of the soil solution (Keren and O'Connor l982). Finer industrial gypsum often has faster dissolution rates compared to mined gypsum. Gypsum is very effective remediating problems such as surface soil crusting (Figure 4-2) and poor infiltration (Figure 4-3) caused soil dispersion in sodic. These problems can cause poor germination, root development and agricultural productivity.

Table 4-4. Equivalent Quantities of Gypsum for Common Amendments for Sodic Soil Reclamation. *Source:* Reprinted from Advances in Agronomy 96(2007); by Qadir, M., J. D. Oster, S. Schubert, A.D. Noble, and K.L. Sahrawa; Phytoremediation of Sodic and Saline-Sodic Soils; p. 197-247; Copyright (2007), with permission from Elsevier.

Amendment	Chemical Composition	Amount Equivalent to 1 Mg of Gypsum
Gypsum	$CaSO_4$, $2H_2O$	1.00
Calcium chloride	$CaCl_2$, $2H_2O$	0.85
Calcium carbonate	$CaCO_3$	0.58
Sulfuric acid	H_2SO_4	0.57
Ferrous sulfate	$FeSO_4$, $7H_2O$	1.61
Ferric sulfate	$Fe_2(SO_4)_3$, $9H_2O$	1.09
Aluminum sulfate	$Al_2(SO_4)_3$, $9H_2O$	1.29

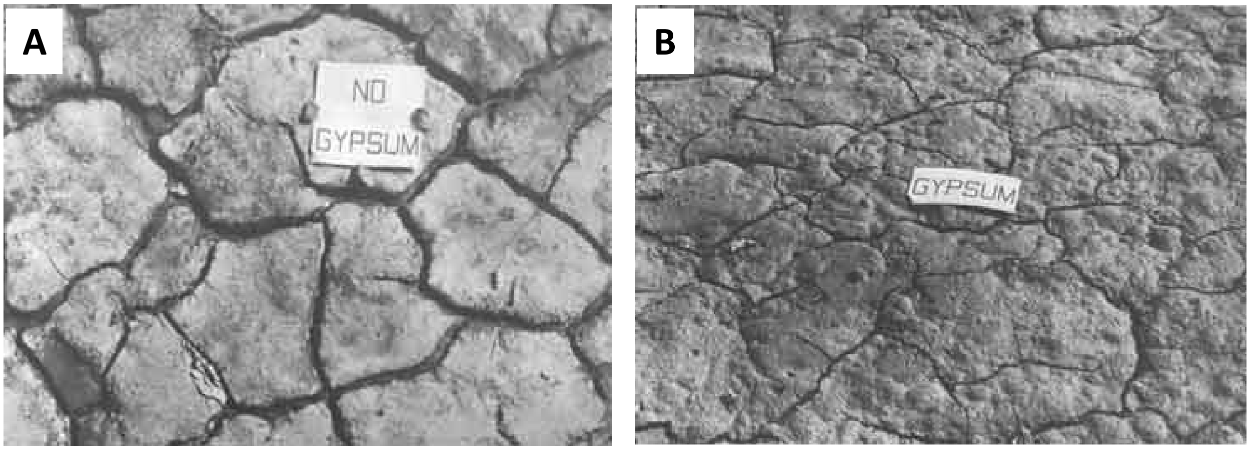


Figure 4-2. Showing Soil Crusting in Sodic Soil Caused by Clay Dispersion (A). In (B) the Soil Has Been Reclaimed Application of Gypsum. Soil Dispersion Causes Soil to Break Up into Individual Particles Resulting in Surface Crusting When the Soil Dries. *Source:* Abrol et al. 1988. Reproduced with permission from Food and Agriculture Organization of the United Nations.

Figure 4-3. Fine Gypsum Was Applied to Soil in the Pajaro Valley of California to Mitigate Poor Infiltration Due to Soil Sodicity.

4.2.2 Calcium Chloride ($CaCl_2$ $2H_2O$)

Compared to gypsum Calcium Chloride dihydrate ($CaCl_2$ $2H_2O$) is more expensive and therefore less commonly used. Where it is available as an industrial by product it is recommended for use as a soil amendment. Calcium Chloride dihydrate requirement (CCR) to achieve a desired sodic soil reclamation is estimated as Equation 4-3:

$$CCR = 75.5 * \ 10^{-6} * \Delta Na \qquad \text{(Equation 4-3)}$$

$CaCl_2$ $2H_2O$ is more soluble compared to gypsum, this makes it a more efficient amendment particularly in soils with high exchangeable sodium fraction. $CaCl_2$ $2H_2O$ produces high levels of electrolyte which rapidly improves soil infiltration and hydraulic conductivity. In non-calcareous soils, in order to prevent reduction in hydraulic conductivity and crust formation, Shainberg et al. (1982) recommended combining $CaCl_2$ $2H_2O$ with gypsum to ensure a constant supply of electrolytes during sodic soil reclamation. The beneficial effect of gypsum in preventing clay dispersion was greatest at the soil surface in the Shainberg et al., (1982) study.

4.2.3 Acids and Sulfur

Sulfuric acid (H_2SO_4) is commonly used as an amendment to reclaim sodium affected soils. The acid reacts with the calcium carbonate in the soil to form gypsum. Hydrochloric acid (HCl) can also be used instead of sulfuric acid. Sulfur is also used as an amendment but requires presence of microbes to oxidize the sulfur to sulfuric acid. Therefore, the success of reclaiming sodic soils using sulfur is characterized by spatiotemporal variability due to presence or absence of microbes. Studies conducted a couple of decades ago revealed that H_2SO_4 increased the penetration of water into calcareous Na-affected soils more effectively than does gypsum (Yahia et al., 1975; Prather et al., 1978). In more recent studies, Mace et al. (2010) also reported that compared to equivalent soil gypsum treatments, H_2SO_4 generally caused (1) lower SAR, (2) more soluble Ca^{2+} and Mg^{2+}, (3) lower pH, and (4) greater EC. They attributed the better performance of H_2SO_4 to gypsum supersaturation, HCO_3- production, lower pH, and higher EC frequently associated with H_2SO_4 reclamation. Also, the concentrated acid applied directly on the surface of the soil results in better distribution, less destruction of soil aggregates, and more efficient leaching of salts. H_2SO_4 can also be directly applied into the ground by chiseling into bands about 45 cm apart (Miyamoto et al. 1975; Wallender and Tanji, 2012). Use of H_2SO_4 as a soil amendment has also been shown to result in improved crop yields compared to gypsum. Sadiq et al. (2007) showed that application of sulfuric acid resulted in higher yield and promoted rapid amelioration of saline-sodic soils. Acids applied at high rates lower the soil's pH in a portion of the rootzone and consequently increase the availability of P, Zn, Mn, and Fe (Miyamoto et al. 1975). This is important in obtaining improved crop responses. However, it is worth noting that H_2SO_4, being highly corrosive should not be added to water that is to be applied through metallic irrigation systems.

4.3 Sustainable Management of Sodic Soils without Adding of Chemical Amendments

Reclamation of sodic soils without addition of chemical amendments requires a soil to have a natural source of Ca^{2+}. Calcium maybe occurs in sodic soils as gypsum or calcite (Herrero and

Porta, 2000) and from silicate minerals (Rhoades, 1968). In situations where a gypsum layer is present close to the soil surface and with good soil permeability and drainage in the soil profile, leaching alone was successful in reclaiming sodic soils (Qadir et al., 2001). Where gypsum is not present in the near surface soil horizon but occurs underlying B or C horizons deep ploughing before leaching was shown to be effective in mixing the gypsum layer with the topsoil (Rasmussen et al., 1972). Qadir et al. (2001) noted that reclamation of sodic and saline-sodic soils using leaching alone was too slow to provide economic benefits.

4.3.1 Dissolution of Calcium Carbonate in Calcareous Soils

Dissolution of $CaCO_3$ depends on a number of factors, including the surface area solution volume ratio, the ionic composition of the solution, the ion composition of the adsorbed phase, the affinity of the clay minerals to cations, the temperature, and the local partial pressure of CO_2 (Wallender and Tanji, 2012). Soil $CaCO_3$ can be dissolved to contribute Ca^{2+} needed in reclaiming sodium-affected soils in situations in which its solubility is enhanced (Oster 1982). In addition, the electrical conductance must be sufficiently high and pH sufficiently low during reclamation to maintain soil structural stability until the SAR decreases to a safe level. With this method there is a risk of significantly reducing hydraulic conductivity earlier in the reclamation process if gypsum was not added Suarez (2001). The reduction in hydraulic conductivity was due to the initial decrease in soil electrolyte concentration while the SAR was relatively high. Reclamation of calcareous soils by dissolution of $CaCO_3$ in the soil profile is feasible and can be enhanced by incorporating fresh organic matter in the soil thereby increasing CO_2 production due to decomposition (Wallender and Tanji, 2012). When soil is kept at near saturation, CO_2 escape to the atmosphere is diminished, elevated CO_2 levels enhance calcite in solution increasing electrolyte concentration and maintain pH with desirable levels. All these factors help to mitigate reductions in hydraulic conductivity.

4.3.2 High Saltwater Dilution Method

This method involves successively diluting a high saltwater containing divalent cations. As discussed earlier, the electrolyte concentration of water applied to reclaim sodic soils is an important factor that influences water transmission rates through the soils during and after the reclamation process. Based on the theory of cation exchange equilibria, it is possible to make use of high-salt waters containing adequate proportions of divalent cations such as Ca^{2+} for the replacement of Na^+ to aid in soil reclamation (Qadir et al., 2001). Initially, the high saltwater method makes use of the effect of high electrolyte concentration of the water on soil hydraulic conductivity and subsequent successive dilutions make use of the `valence dilution' effect principle (Reeve et al., 1954).

In the valence dilution principle, monovalent and divalent cations in solution of the soil water system are in equilibrium with those adsorbed on the cation exchange sites, the equilibrium may or may not be shifted by the addition of water to the system. A change in the equilibrium depends on the valence of the cations involved. However, when the cations of the soil water system and the applied irrigation water are of unequal valence, the adsorbed cations of lower valence, such as Na^+ are replaced by the solution cations of higher valence, such as Ca^{2+} when the solution is diluted (Qadir et al., 2001).

Leaching of sodic soils with saline water can result in large increases in soil hydraulic conductivity without applying any amendment but the *R* ratio of divalent to total cations in the applied water should be at least 0.3 (Reeve and Doering, 1966). The *R* ratio can be computed following (Qadir et al., 2001) as Equation 4-4:

$$R = \left(C_{ca} + C_{Mg}\right)/C_{TC} \qquad \text{(Equation 4-4)}$$

where C_{ca} and C_{Mg} represent concentrations of Ca^{2+} and Mg^{2+} ($mmol_c l^{-1}$), and C_{TC} indicates concentration of total cations ($mmol_c l^{-1}$). C_{TC} is often expressed as a function of the EC of the irrigation water. For irrigation water with EC less than 4 dS/m $C_{TC} = 10(EC)$, for high EC irrigation water (> 4 dS/m) C_{TC} is expressed as $logC_{TC} = 0.99 + 1.055logEC$. Assuming the applied water contains only four principle cations of Ca^{2+},Mg^{2+},$Na^{+}$and K^{+} then Equation 4-4 can also be rewritten as Equation 4-5:

$$R = \left(C_{ca} + C_{Mg}\right)/\left(C_{ca} + C_{Mg} + C_{Na} + C_{K}\right) \qquad \text{(Equation 4-5)}$$

The greater the R value, the lesser the amount of water required for soil reclamation (Doering and Reeve, 1965). Therefore, having divalent cations in sufficient concentrations in the irrigation water is critical for this method. This method of sodic soil reclamation is recommended in situations where the soil under reclamation has smectite type clay minerals, which have extremely low hydraulic conductivities, hydraulic conductivity is so low that the time required for reclamation or the amount of amendment required is excessive, the irrigation water to be used following sodic soil reclamation is so low in electrolyte concentration that hydraulic conductivity would negatively be impacted (Qadir et al., 2003). However, this method also has some limitations, e.g., when there is inadequate concentration of divalent cations in the irrigation water, gypsum might need to be added to increase the R ratio to at least 0.3, cost of the infrastructure required to handle and convey the saline water, need to dispose of saline-sodic drainage water to prevent contamination of groundwater can be a challenge.

4.3.3 Soil Profile Modification through Tillage

In situations where soil with significant quantities of gypsum underlies Na-affected soils, deep plowing can be used to break up and mix the layers while supplying soluble Ca^{2+} needed for sodic soil reclamation. The depth of plowing required varies from 0.5 m to more than 1.0 m, depending on the concentration and depth of the sodic- and Ca-rich layers (Wallender and Tanji, 2012). Deep tillage can result in reduction in soil bulk density, increase in macropores, resulting in an increase in total porosity and plant available water. Tillage practices should be properly operated to avoid soil compaction and should be avoided when soil is wet.

A number of tillage options can be used to modify the soil profile. These options include: i) deep ploughing, ii) subsoiling, iii) sanding, iv) hauling and v) profile inversion (Qadir et al., 2001; Wallender and Tanji, 2012). The goal of methods i) to iii) is to increase soil hydraulic conductivity directly, either by mixing the fine and coarse textured soil layers to obtain a more uniform layer, or by incorporating sand to a fine-textured soil (i.e., sanding). Hauling aims to replace the sodic surface soil with a good soil, while profile inversion covers an undesirable soil layer with a better soil material from a lower layer (Qadir et al., 2001). Presence of a sodic layer with high soil bulky density (1.5 to 1.8Mgm^{-3}) and ESP (15 to 50) with an underlying gypsiferous layer below the sodic layer might manifest itself in the form of a wavy crop growth pattern due to spatial variability in root growth restrictions. Deep tillage of such a soil can result in uniform crop establishment and improved yields. It is recommended that the depth of ploughing not be so shallow that only the A and a part of B horizons are mixed, otherwise improvement in soil physical properties will be short-lived, (McAndrew and Malhi, 1990). However, the high cost of deep ploughing makes it prohibitive for most growers (Grevers and De Jong, 1993).

On the other hand, subsoiling which involves loosening the soil without inverting it, and is used primarily to break and shatter the compact B horizon is much more affordable for most growers. Growers in Monterey One and Pajaro Valley water management districts along the central cost of California use this practice to manage both sodicity and salinity. Subsoiling consists of pulling vertical strips of steel or iron, called knives, shanks or tines, through the soil to open channels to improve soil hydraulic conductivity and macro porosity. A powerful tractor is used to pull a subsoiler (Figure 3-1) and the effects of subsoiling may continue for several years if the compacted layer is shattered completely, otherwise the effect may persist for only one season (Qadir et al., 2001). Subsoiling using implements such as a slip plow (Figure 4-4) is also commonly practiced by nut and fruit growers who use it to shutter compacted layers before establishing a new orchard. Sometimes gypsum is applied at rates of 2 to 4 Mg ha^{-1} either before or after tillage, depending on a far’er's experience with gypsum on a particular field or on soil test analysis (Oster et al., 1999; Qadir et al., 2001).

Figure 4-4. Showing Slip Plow Used to Loosen Deep Soil Layers.

Source: Regents of the University of California.

4.3.4 Electromelioration

Electromelioration also known as electro-reclamation of sodic soils is an old technique that refers to treating soils with electric current in order to remove exchangeable sodium. The application of electric current increases the solubility of calcite in sodic soils which supplies Ca^{2+} needed for reclamation of such soils. Vadyunina et al. (1968) successfully reclaimed a saline-sodic soil by apply $2mA/cm^2$ followed by leaching with 500 mm of water. The increase in stable aggregates was attributed to the increase in Ca^{2+} ion at the exchange complex. Abdel-Fattah (2014) reduced both the EC and SAR of a saline-sodic soil by treating the soil with a direct current of 9 volts followed by intermittent leaching. They concluded that electromelioration was an affective technique of reclaiming saline sodic soils and required less time than leaching alone. Although this technique has been shown to be effective under research settings, it has not been widely adopted by farmers for several reasons e.g., i) lack of a well-defined standard for application and management of electric current to the soil, ii) safety issues during electro-reclamation, iii) economic considerations associated with the cost of energy. Qadir et al. (2001) estimated energy requirements of 736,560 KWh ha^{-1} (assuming $0.18\ mA/cm^2$ for a month) to remove over 90% of exchangeable Na+ in the top 0.58 m of a sodic soil profile. At an average cost of $0.104 per KWh in the United States in 2022, electromelioration per hectare would cost $76,602 which is economically prohibitive. However, advances in solar energy technology and practices such as agrivoltaic could make this technique of sodic soil reclamation plausible.

4.3.5 Phytoremediation

Phytoremediation is a type of remediation of sodic soils that involves using plants to increase the dissolution of calcite ($CaCO_3$) in the soil, thereby resulting in enhanced levels of Ca^{2+} in the soil pore water solution which replaces Na^+ at the cation exchange complex (Qadir et al., 2007). Phytoremediation has been demonstrated to effectively ameliorate sodic soils. There are many factors that have made phytoremediation attractive to farmers and resource managers in parts of the world affected by sodic soils e.g., i) lower initial costs compared to chemical reclamation, ii) financial benefits from sell of crops grown during the reclamation, iii) improvements in soil physical and hydraulic properties such as soil aggregate stability, macropores, and reduction in soil bulky density due to better root proliferation, iv) better nutrient cycling in phytoremediated soils compared to chemical reclamation, v) larger soil depth is reclaimed compared to other methods, vi) improved soil organic matter (Qadir et al., 2007). All these advantages in totality imply phytoremediation would be preferred if improving soil health was a secondary goal of the remediation. However, to achieve the benefits of phytoremediation requires understanding the processes that boost phytoremediation e.g., suitable plant species. Many sodic soils contain calcite at varying levels within the soil layers either as part of parent material or from precipitation as coating on soil particles. But due to its low solubility of 0.14 mmol $liter^{-1}$ it does not provide sufficient Ca^{2+} to replace Na^+ at the cation exchange complex. Hence the need for plants whose roots can increase the dissolution rate of calcite. Qadir et al. (2007) summarized the factors that contribute to dissolution of calcite at the root soil interface using Equation 4-6:

$$Phyto_{Sodic} = R_{PCO_2} + R_H + R_{Phy} + S_{Na^+} \qquad \text{(Equation 4-6)}$$

where $Phyto_{Sodic}$ is phytoremediation of sodic soils, R_{PCO_2} refers to increased partial pressure of CO$_2$ within the root zone, R_H refers to proton production in the root zone produced by some plants e.g., legumes, R_{Phy} refers to physical effects of roots in improving soil aggregation and soil physical properties and S_{Na^+} refers to Na+ of the above ground biomass which is removed through harvest.

Dissolution kinetics of calcite is governed by the chemical processes in the rhizosphere according to the equations below:

$$CaCO_3 + CO_2 + H_2O \Leftrightarrow Ca^{2+} + 2HCO_3^- \qquad \text{(Equation 4-7)}$$

$$CaCO_3 + H_2CO_3 \Leftrightarrow Ca^{2+} + 2HCO_3^- \qquad \text{(Equation 4-8)}$$

$$CaCO_3 + H^+ \Leftrightarrow Ca^{2+} + HCO_3^- \qquad \text{(Equation 4-9)}$$

$$CaCO_3 + H_2O \Leftrightarrow Ca^{2+} + CO_3^{2-} + H_2O \qquad \text{(Equation 4-10)}$$

The above equations summarize three processes which occur concurrently i) conversion of CO_2 into H_2CO_3 and its reaction with calcite, ii) dissociation of carbonic acid into H^+ and bicarbonate and the reaction of H^+ with calcium carbonate, and iii) finally dissolution of calcium carbonate into Ca^{2+} and CO_3^{2-}. Increases in production of Ca^{2+} are affected by several factors e.g., presence of anerobic conditions, respiration from roots, oxidation of plant root exudates, and production of organic acids by soil microorganisms (Van den Berg and Loch, 2000, Qadir et al. 1996). Some studies have found that reclamation of sodic soils based on increasing partial pressure of CO$_2$ requires a longer time and twice the amount of water required to reclaim the same soil with gypsum (Suarez, 2001).

The release of protons by N$_2$-fixing plants e.g., annual legumes and perennial legumes such as alfalfa in the root zone of sodic soils enhances calcite dissolution producing Ca^{2+} and HCO_3^-. The chemical reactions are similar to those discussed under enhanced R_{PCO_2}. Plant roots play a critical role in phytoremediation e.g., they improve soil porosity through creation of micropores, they improve soil structure through in-situ production of polysaccharides (Tisdall, 1991), some plant roots also act as biological tillage tools by growing through compacted soil layers. This leads to improved macroporosity in the compacted soil layers. The improvement in soil structure and hydraulic properties enhances leaching of Na$^+$ replaced from the cation exchange complex. While some plant species such as halophytes can accumulate a lot of salts that is removed through harvest, their contribution to remediation of sodic soils is minimum because the removed salts are a very small fraction of the total amount salts in the soil. The primary mechanism of sodicity decrease in sodic soils is through leaching of Na$^+$ replaced from the cation exchange complex. Table A-1 in the appendix lists examples of crops that can be used in phytoremediation as a function of their potential to tolerate sodic conditions.

4.3.5.1 Soil Health Benefits of Phytoremediation of Soils

Prior studies have reported improved nutrient dynamics following phytoremediation. Qadir et al. (1997) reported increases in phosphorus (P), zinc (Zn), and copper (Cu) availability in the phytoremediation research plots planted with sesbania, sordan, or Kallar grasses compared to non-planted plots that only received gypsum. This increased nutrient availability was attributed to production of root exudates and dissolution of nutrients coated on calcite. Ghai et al. (1988) reported increased availability of nitrogen for rice crops following growing of sesbania crops in a sodic soil. Conversely when sodic soils are reclaimed through chemical treatments, nitrogen is often lost through leaching. Phytoremediation has also been reported to increase soil microbial activity. Soil microbial activity is commonly measured using the Dehydrogenase activity (DHA) index which is related to soil microbial populations, respiration activity, and soil organic matter (Qadir et al., 2007). Batra et al. (1997) observed greater levels of DHA 80hytoremediatedted soils compared to gypsum treated soils.

4.3.5.2 Environmental Benefits of Phytoremediation

Typically, sodic soils and saline sodic soils lose a significant amount of their soil organic carbon pool. The soil carbon pool is not only important for agricultural productivity but also critical for global carbon cycling which has an effect on mitigating greenhouse gas emissions (Lal, 2004; Kaur et al., 2002). Increases in soil C of up to 34.2 Mg C ha^{-1} in 7 years, and 54.3 Mg C ha^{-1} in 30 years after phytoremediation were reported by Bhojvaid and Timmer (1998). When phytoremediation is used to reclaim sodic soil, -HCO3 are leached as part of the process. The leaching of -HCO3 by irrigation water through the soil profile provides a pathway for sequestration of soil inorganic carbon (Sahrawat, 2003). The rate at which soil C is sequestered through this pathway has been reported to range between 0.25 and 1.0 Mg C ha^{-1} year^{-1} (Wilding, 1999)

4.4 Summary

Sustainable management of sodic soils is critical for agricultural productivity, environmental resource conservation, and climate resilience. Successful sodic soil remediation requires the availability of Ca^{2+} to replace Na^+ followed by leaching with sufficient amounts of irrigation water. The amount of fresh water allocated to agriculture will continue to decrease and the proportion of recycled water use for irrigation is projected to increase. The most widely used method for reclamation of sodic soils and saline-sodic soils has been the application of chemicals amendments e.g., gypsum to provide Ca^{2+} to replace Na^+ at the exchange complex. Increasing costs due to demand of gypsum from other industries has led to shortages which has stimulated interest in other reclamation practices such as soil profile modification through tillage operations and phytoremediation. Deep ploughing and sub soiling have been used to breakup shallow sodic clay pans. The high cost of deep tillage has influenced high adoption of this practice. In some cases, the benefits of tillage have been short lived. Phytoremediation has been proven through various research studies to be an effective low-cost method of reclaiming sodic soils. Phytoremediation is more effective when used to reclaim moderately sodic soils and saline-sodic soils. However, it is worth noting that phytoremediation has the disadvantages of reducing sodicity more slowly compared to chemical approaches and requires calcite to be present in the soil. Adoption of other methods such as electromelioration has been limited due to cost, safety, and lack of standardization for implementing the practice. These various methods of reclamation of sodic soils could be used in combination e.g., application of chemical amendment plus soil profile modification, or phytoremediation plus gypsum application. This might allow for speeding up and improving the efficiency of the sodic soil remediation.

APPENDIX A

A.1 Ranges of ESP in Soils Indicating about 50% of the Yield Potential Yield of Different Crops

Source: Reprinted from Advances in Agronomy 96(2007); by Qadir, M., J. D. Oster, S. Schubert, A.D. Noble, and K.L. Sahrawa; Phytoremediation of Sodic and Saline-Sodic Soils; p. 197-247; Copyright (2007), with permission from Elsevier.

ESP Range	**CropS**	
	Common Name	**Botanical Name**
10-15	Safflower	*Carthamus tinctorius* L.
	Mash	*Vigna mungo* (L.) Hepper
	Pea	*Pisum sativum* L.
	Lentil	*Lens culinaris* Medik
	Pigeon pea	*Cajanus cajan* (L.) Millsp
	Urd-bean	*Phaseolus mungo* L.
16-20	Bengal gram	*Cicer arietinum* L.
	Soybean	*Glycine max* (L.) Merr
20-25	Groundnut	*Apios americana* Medik
	Cowpea	*Vigna unguiculata* (L.) Walp
	Onion	*Allium cepa* L.
	Pear millet	*Pennisetum glaucum* (L.) R. Br.
25-30	Linseed	*Linum usitatissimun* L.
	Garlic	*Allium sativum* L.
	Guar	*Cyamopsis tertagonoloba* (L.) Taub
30-50	Indian mustard	*Brassica juncea* (L.) Czern
	Wheat	*Triticum aestivum* L.
	Sunflower	*Helianthus annuus* L.
	Guinea grass	*Panicum maximum* Jacq
50-60	Barely	*Hordeum vulgare* L.
	Sesbania	*Sesbania bispinosa* (Jacq.) W. Wight
60-70	Rice	*Oryza sativa* L.
	Para grass	*Brachiaria mutica* (Forssk.) Stapf
70+	Bermuda grass	*Cynodon dactylon* (L.) Pers
	Kallar/Karnal grass	*Leptochloa fusca* (L.) Kunth
	Rhodes grass	*Chloris gayana* Kunth

A.2 Tolerance of Various Crops to Exchangeable Sodium (ESP) under Non-saline Conditions

Source: Pearson 1960.

Tolerance, to ESP and Range at Which Affected	Crops	Growth Response under Field Conditions
Extremely sensitive (ESP = 2-10)	Deciduous fruits	Sodium toxicity symptoms even at low ESP values.
	Nuts	
	Citrus (**Citrus** spp.)	
	Avocado (**Persea americana** Mill.)	
Sensitive (ESP - 10-20)	Beans (**Phaseolus vulgaris** L.)	Stunted growth at these ESP values even though the physical condition of the soil may be good.
Moderately tolerant (ESP - 20-40)	Clover (**Trifolium** spp.)	Stunted growth due to both nutritional factors and adverse soil conditions.
	Oats (**Avena saliva** L.)	
	Tall fescue (**Festuca arundinacea** Schreb.)	
	Rice (**Oryza saliva** L.)	
	Dallisgrass (**Paspalum dilatum** Poir.)	
Tolerant (ESP - 40-60)	Wheat (**Triticum aestivum** L.)	Stunted growth usually due to adverse physical conditions of soil.
	Cotton (**Gossypium hirsutum** L.)	
	Alfalfa (**Medicago sativa** L.)	
	Barley (**Hordeum vulgare** L.)	
	Tomatoes (**Lycopersicon esculentum** Mill.)	
	Beet, garden (**Beta vulgaris** L.)	
Most tolerant (ESP more than 60)	Crested and Fairway wheatgrass (**Agropyron** spp.)	Stunted growth usually due to adverse physical conditions of soil.
	Tall wheatgrass (**Agropyron elongatum** Host Beau.)	
	Rhodes grass (**Chloris gayana** Kunth)	

A.3 Site Descriptions, Delivered Recycled Water Quality and Mann-Kendall Statistical Results

Figure A-1. M1W Site 2.

M1W Site 2 is a flat and well drained field in the Monterey One Water (M1W) recycled water delivery zone. It has a Clear Lake Clay soil layer that is 18-24” in depth underlain by a silt loam to fine sand layer (USDA, 1978). This soil has an available water capacity of 8-10”. The Cation Exchange Capacity (CEC) ranges from 18-20. The site has no history of seawater intrusion affecting its well water. It received very high-quality irrigation water from 2000-2009 due to its proximity to a high quality supplemental well water source. Water quality declined after changes were made to M1W’s system in late 2009 that included additional sources of water and changes in the blending of different sources before recycled water delivery. From 2010-2019, M1W Site 2 received water with larger amounts of Na and Cl, but it was still of very acceptable quality for agricultural production.

Table A-1. Delivered Water Quality for M1W Site 2.

Note: Cations are reported in meq/L.

	2000-2009	2010-2019	Difference
ECw	0.75	1.44	0.69
Sodium	3.50	6.24	**2.74**
Potassium	0.02	0.05	0.03
Calcium	1.36	2.98	1.62
Magnesium	0.84	2.04	1.20
Chloride	3.39	5.83	**2.44**
SAR	3.33	3.94	0.61
CROSSf	3.51	6.26	**2.75**

M1W Site 2 shows no trends in soil sodicity for SAR or CROSSf values over the 10 year periods with differences in delivered water quality.

Table A-2. Mann-Kendall Statistics for CROSSf soil values at M1W Site 2.

Note: alpha = 0.10

	2000-2009	2010-2019
Mk-stat	17	-3
S.E.	11.18	11.18
z-stat	1.43	-0.17
p-value	0.15	0.85
Trend	No	No

Figure A-2. M1W Site 3A.

M1W Site 3A is a low lying and poorly drained field in the Monterey One Water (M1W) recycled water delivery zone. It has a Pacheco Clay Loam soil layer that is 22" thick underlain by a sandy loam 35" thick (USDA, 1978). This soil has an available water capacity of 10-12". The Cation Exchange Capacity (CEC) ranges from 24-31. The site has a history of seawater intrusion affecting its well water and a legacy salt load deep in the soil profile. It received poor quality irrigation water from 2000-2009 due to its source of water being undiluted by supplemental well water. Improvement in the water quality occurred after changes were made to M1W's system in late 2009 that included additional sources of water and changes in the blending of different sources before recycled water delivery. From 2010-2019, M1W Site 3A received water with reduced amounts of Na and Cl and the water quality was significantly improved.

Table A-3. Delivered Water Quality for M1W Site 3A.

Note: Cations are reported in meq/L.

	2000-2009	2010-2019	Difference
ECw	1.52	1.42	-0.10
Sodium	7.14	6.18	**-0.96**
Potassium	0.05	0.05	0
Calcium	2.78	2.95	0.17
Magnesium	1.72	2.02	0.30
Chloride	6.88	5.77	**-1.11**
SAR	4.76	3.92	-0.84
CROSSf	7.16	6.19	-0.97

M1W Site 3A shows trends of increasing soil sodicity for SAR or CROSSf values during 2000-2009, but no trend for CROSSf values for 2010-2019.

Table A-4. Mann-Kendall Statistics for CROSSf Soil Values at M1W Site 3A.
Note: alpha = 0.10.

	2000-2009	2010-2019
Mk-stat	27	17
S.E.	11.18	11.18
z-stat	2.32	1.43
p-value	0.02	0.15
Trend	Yes	No

Figure A-3. M1W Site 4.

M1W Site 4 is a field with rolling ground and good drainage due to slopes of 0-15%. It is typical of the eastern edge of the Monterey One Water (M1W) recycled water delivery zone. It has an Antioch Fine Sandy Loam soil layer that is 15” thick underlain by a sandy loam and clay loam layer 67” thick (USDA, 1978). This soil has an available water capacity of 4-5”. The Cation Exchange Capacity (CEC) ranges from 15-16. The site has no history of seawater intrusion affecting its well water. It received high quality irrigation water from 2000-2009 due to its proximity to a high quality supplemental well water source. Water quality declined after changes were made to M1W’s system in late 2009 that included additional sources of water and changes in the blending of different sources before recycled water delivery. From 2010-2019, M1W Site 4 received water with larger amounts of Na and Cl, but it was still of very acceptable quality for agricultural production.

Table A-5. Delivered Water Quality for M1W Site 4.

Note: Cations are reported in meq/L.

	2000-2009	2010-2019	Difference
ECw	0.94	1.39	0.45
Sodium	4.41	6.05	1.64
Potassium	0.03	0.05	0.02
Calcium	1.72	2.88	1.16
Magnesium	1.06	1.98	0.92
Chloride	4.25	5.65	1.40
SAR	3.74	3.88	0.14
CROSSf	4.42	6.06	1.64

M1W Site 4 shows two different trends in soil sodicity for SAR or CROSSf values over the 10 year periods with differences in delivered water quality. It has an increasing trend in sodicity from 2000-2009 and a decreasing trend from 2010-2019.

Table A-6. Mann-Kendall Statistics for CROSSf Soil Values at M1W Site 4.

Note: alpha = 0.10.

	2000-2009	2010-2019
Mk-stat	33	-25
S.E.	11.18	11.18
z-stat	2.86	-2.14
p-value	0.004	0.03
Trend	Yes	Yes

Figure A-4. M1W Site 5A.

M1W Site 5A is a flat and poorly drained field in the Monterey One Water (M1W) recycled water delivery zone. It has a Pacheco Clay Loam soil layer that is 22" thick underlain by a sandy loam 35" thick (USDA, 1978). This soil has an available water capacity of 10-12". The Cation Exchange Capacity (CEC) ranges from 22-31. The site has a history of seawater intrusion affecting its well water and a legacy salt load deep in the soil profile. It received poor quality irrigation water from 2000-2009 due to its source of water being undiluted by supplemental well water. Improvement in the water quality occurred after changes were made to M1W's system in late 2009 that included additional sources of water and changes in the blending of different sources before recycled water delivery. From 2010-2019, M1W Site 5A received water with reduced amounts of Na and Cl and the water quality was improved.

Table A-7. Delivered Water Quality for M1W Site 5A.
Note: Cations are reported in meq/L.

	2000-2009	2010-2019	Difference
ECw	1.56	1.45	-0.11
Sodium	7.07	6.31	-0.76
Potassium	0.05	0.05	0
Calcium	2.75	3.01	0.26
Magnesium	1.70	2.07	0.37
Chloride	7.05	5.89	-1.16
SAR	4.74	3.96	-0.78
CROSSf	7.09	6.32	-0.77

M1W Site 5A shows no trend for soil sodicity for SAR or CROSSf values during 2000-2009, but a decreasing trend for CROSSf values for 2010-2019.

Table A-8. Mann-Kendall Statistics for CROSSf Soil Values at M1W Site 5A.
Note: alpha = 0.10.

	2000-2009	2010-2019
Mk-stat	5	-19
S.E.	11.18	11.18
z-stat	0.35	-1.60
p-value	0.72	0.10
Trend	No	Yes

Figure A-5. M1W Site 7.

M1W Site 7 is a low lying and poorly drained field in the Monterey One Water (M1W) recycled water delivery zone. It has a mixture of soil types including Alviso Silty Clay Loam, Clear Lake Clay and Alviso Silty Clay with a clay content of 35% (USDA, 1978). The drainage is extremely poor and water is always present at 24” deep in the soil profile. The Cation Exchange Capacity (CEC) ranges from 34-37. The site has a history of seawater intrusion affecting its well water and a legacy salt load deep in the soil profile. It received poor quality irrigation water from 2000-2009 due to its source of water being undiluted by supplemental well water. Improvement in the water quality occurred after changes were made to M1W's system in late 2009 that included additional sources of water and changes in the blending of different sources before recycled water delivery. From 2010-2019, M1W Site 3A received water with reduced amounts of Na and Cl and the water quality was significantly improved.

Table A-9. Delivered Water Quality for M1W Site 7.

Note: Cations are reported in meq/L.

	2000-2009	2010-2019	Difference
ECw	1.56	1.53	-0.03
Sodium	7.30	6.57	**-0.73**
Potassium	0.05	0.05	0
Calcium	2.84	3.13	0.29
Magnesium	1.76	2.15	0.39
Chloride	7.05	6.14	**-0.91**
SAR	4.81	4.04	-0.77
CROSSf	7.32	6.58	**-0.74**

M1W Site 7 shows two trends for soil sodicity for SAR and CROSSf values. There is an increasing trend for CROSSf values during 2000-2009, but a decreasing trend for SAR and CROSSf values for 2010-2019.

Table A-10. Mann-Kendall Statistics for CROSSf Soil Values at M1W Site 7.

Note: alpha = 0.10.

	2000-2009	2010-2019
Mk-stat	21	-35
S.E.	11.18	11.18
z-stat	1.78	-3.04
p-value	0.07	0.002
Trend	Yes	Yes

Figure A-6. PVW Site 3.

PVW Site 3 is a low lying and poorly drained field in the PV Water (PVW) recycled water delivery zone. It has a several layers of Clear Lake soils. There is a surface layer of alkaline clay 44” in depth, underlain by a secondary clay layer 62” thick (USDA, 1980). This soil has an available water capacity of 9-15”. In addition, the water table is very high and is present at 40-60” in depth. The Cation Exchange Capacity (CEC) ranges from 33-58. The site has a history of seawater intrusion affecting its well water and a legacy salt load deep in the soil profile. In the picture above a cover crop has been planted and will be incorporated into the soil. This is a mitigation strategy to reduce sodicity and improve drainage. It has received very high-quality irrigation water from 2009-2019.

Table A-11. Delivered Water Quality for PVW Site 3.

Note: Cations are reported in meq/L.

	2009-2019
ECw	1.00
Sodium	4.0
Potassium	0.5
Calcium	2.6
Magnesium	2.5
Chloride	2.59
SAR	2.53
CROSSf	4.20

PVW Site 3 shows a decreasing trend for soil sodicity for SAR and CROSSf values during 2009-2019.

Table A-12. Mann-Kendall Statistics for CROSSf Soil Values at PVW Site 3.

Note: alpha = 0.10.

	2009-2019
Mk-stat	-34
S.E.	14.54
z-stat	-2.26
p-value	0.02
Trend	Yes

A.4 Annual Soil Sampling Values for All Sites and Timeframes

Note: Unless noted all cation values are in meq/L. Exchangeable cation values and Cation Exchange Capacity are based only on alkaline cations since all soil pH values are ≥ 7.

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M1W Test Site 2 Summary by Year and Depth

	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	10 yr. Average	Meq/L	% Exch.
EC 1-12"	1.22	1.17	2.17	2.14	1.64	2.57	1.98	2.97	2.32	1.47	EC 1-12"	1.96	
Ca 1-12"	4.27	4.80	8.63	8.10	6.87	11.27	11.17	15.00	10.97	6.33	Ca 1-12"	8.74	43%
Mg 1-12"	3.00	2.60	5.87	5.57	3.27	7.40	4.07	8.33	5.97	3.37	Mg 1-12"	4.94	25%
Na 1-12"	4.63	3.87	6.80	7.33	5.70	7.97	5.10	7.10	6.40	5.10	Na 1-12"	6.00	30%
K 1-12"	0.30	0.37	0.40	0.40	0.40	0.47	0.37	0.50	0.53	0.37	K 1-12"	0.41	2%
Cl 1-12"	1.80	2.07	4.10	4.03	5.20	6.93	3.30	4.74	4.40	4.87	Cl 1-12"	4.14	
											Total Meq		20.09
SAR 1-12"	2.56	2.04	2.57	2.82	2.73	2.57	1.87	2.08	2.26	2.34	SAR 1-12"	2.38	
CROSSf 1-12"	4.75	3.98	6.89	7.43	5.80	8.06	5.18	7.19	6.52	5.20	CROSSf 1-12"	6.09	
CROSSopt 1-12"	4.71	3.94	6.86	7.40	5.77	8.03	5.15	7.16	6.48	5.17	CROSSopt 1-12"	6.06	
EC 12-24"	1.66	1.58	1.87	2.96	1.63	2.09	1.67	2.38	2.45	3.15	EC 12-24"	2.14	
Ca 12-24"	6.00	6.33	7.33	11.40	6.37	7.53	8.23	11.00	11.03	13.80	Ca 12-24"	8.90	40%
Mg 12-24"	4.60	4.67	5.00	8.40	3.60	6.87	3.07	7.27	7.07	9.07	Mg 12-24"	5.96	27%
Na 12-24"	5.30	4.53	6.03	9.43	6.20	7.20	5.83	6.40	6.87	10.60	Na 12-24"	6.84	31%
K 12-24"	0.67	0.30	0.33	0.37	0.33	0.30	0.23	0.33	0.40	0.53	K 12-24"	0.38	2%
Cl 12-24"	2.17	2.33	4.73	6.00	5.50	7.50	2.97	5.00	6.77	6.90	Cl 12-24"	4.98	
											Total Meq		22.08
SAR 12-24"	2.36	1.94	2.44	2.94	2.85	2.81	2.45	2.11	2.29	2.99	SAR 12-24"	2.51	
CROSSf 12-24"	5.46	4.61	6.12	9.51	6.30	7.28	5.89	6.47	6.95	10.69	CROSSf 12-24"	6.92	
CROSSopt 12-24"	5.42	4.59	6.09	9.48	6.27	7.26	5.87	6.45	6.92	10.66	CROSSopt 12-24"	6.90	
EC 24-36"	2.09	1.56	2.06	2.89	1.97	1.76	1.65	2.08	2.03	2.40	EC 24-36"	2.05	
Ca 24-36"	7.67	6.13	7.63	10.97	7.90	5.93	8.30	8.40	8.07	9.07	Ca 24-36"	8.00	38%
Mg 24-36"	7.27	5.43	7.23	9.73	5.83	5.43	3.13	6.93	7.10	8.40	Mg 24-36"	6.65	32%
Na 24-36"	5.43	3.80	5.43	7.97	6.23	6.57	5.63	5.93	5.67	7.17	Na 24-36"	5.98	29%
K 24-36"	0.47	0.30	0.30	0.23	0.17	0.23	0.23	0.20	0.30	0.27	K 24-36"	0.27	1%
Cl 24-36"	2.43	1.77	4.37	7.70	7.20	6.87	4.10	4.47	4.47	6.53	Cl 24-36"	4.99	
											Total Meq		20.91
SAR 24-36"	1.99	1.58	2.02	2.39	2.35	2.78	2.37	2.15	2.06	2.41	SAR 24-36"	2.21	
CROSSf 24-36"	5.54	3.88	5.51	8.01	6.27	6.63	5.69	5.98	5.73	7.22	CROSSf 24-36"	6.04	
CROSSopt 24-36"	5.51	3.86	5.49	8.00	6.26	6.61	5.67	5.97	5.72	7.21	CROSSopt 24-36"	6.02	

M1W Test Site 2 Summary by Year and Entire Profile

	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	10 yr. Average	Meq/L	% Exch.
EC 1-36"	1.65	1.43	2.03	2.66	1.74	2.14	1.76	2.47	2.26	2.34	EC 1-36"	2.05	
Ca 1-36"	5.97	5.75	7.86	10.15	7.04	8.24	9.23	11.46	10.02	9.73	Ca 1-36"	8.55	41%
Mg 1-36"	4.95	4.23	6.03	7.90	4.23	6.56	3.42	7.51	6.71	6.94	Mg 1-36"	5.85	28%
Na 1-36"	5.12	4.06	6.08	8.24	6.04	7.24	5.52	6.47	6.31	7.62	Na 1-36"	6.27	30%
K 1-36"	0.47	0.32	0.34	0.33	0.30	0.33	0.27	0.34	0.41	0.38	K 1-36"	0.35	2%
											Total Meq		21.03
Cl 1-36"	2.13	2.05	4.40	5.91	5.96	7.10	3.45	4.73	5.21	6.10	Cl 1-36"	4.70	
Cl ppm	75.73	72.97	156.20	209.84	211.81	252.05	122.67	168.15	184.99	216.55	Cl ppm	167.09	
SAR 1-36"	2.30	1.85	2.34	2.71	2.64	2.71	2.23	2.11	2.20	2.58	SAR 1-36"	2.37	
CROSSf 1-36"	5.25	4.15	6.17	8.31	6.12	7.32	5.58	6.54	6.39	7.70	CROSSf 1-36"	6.35	
CROSSopt 1-36"	5.21	4.12	6.14	8.29	6.09	7.29	5.56	6.52	6.37	7.67	CROSSopt 1-36"	6.33	

M1W Test Site 3A Summary by Year and Depth

	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	10 yr. Average	Meq/L	% Exch.
EC 1-12"	2.69	4.32	5.41	4.97	2.36	2.33	1.86	3.30	3.53	2.82	EC 1-12"	3.35	
Ca 1-12"	12.50	20.97	26.97	22.30	11.43	11.35	8.65	14.73	14.70	12.00	Ca 1-12"	15.56	44%
Mg 1-12"	7.70	12.67	18.63	15.35	8.67	4.35	2.40	9.03	9.13	6.27	Mg 1-12"	9.42	27%
Na 1-12"	6.00	8.60	10.57	11.03	9.47	7.35	7.25	12.03	12.57	10.47	Na 1-12"	9.53	27%
K 1-12"	0.70	0.93	1.13	1.07	0.40	0.40	0.50	0.77	0.80	0.67	K 1-12"	0.73	2%
Cl 1-12"	2.05	3.10	7.07	8.47	9.37	10.70	6.05	11.50	11.67	10.80	Cl 1-12"	8.07	
											Total Meq		35.25
SAR 1-12"	1.87	2.11	2.21	2.55	2.99	2.57	3.10	3.51	3.62	3.82	SAR 1-12"	2.83	
CROSSf 1-12"	6.15	8.74	10.71	11.18	9.55	7.43	7.38	12.17	12.71	10.61	CROSSf 1-12"	9.66	
CROSSopt 1-12"	6.10	8.69	10.67	11.14	9.52	7.41	7.33	12.13	12.66	10.57	CROSSopt 1-12"	9.62	
EC 12-24"	1.80	2.92	3.39	3.94	2.82	2.95	2.93	3.00	3.61	2.94	EC 12-24"	3.03	
Ca 12-24"	5.75	10.93	14.00	14.83	10.60	10.45	10.85	11.93	13.90	10.60	Ca 12-24"	11.38	37%
Mg 12-24"	4.68	9.03	10.87	11.70	8.47	9.80	6.15	9.27	9.87	7.73	Mg 12-24"	8.75	28%
Na 12-24"	7.30	8.63	8.63	12.30	9.87	10.50	11.55	11.67	13.37	11.70	Na 12-24"	10.55	34%
K 12-24"	0.28	0.53	0.43	0.57	0.37	0.40	0.35	0.40	0.50	0.47	K 12-24"	0.42	1%
Cl 12-24"	2.95	2.93	5.57	9.50	11.13	12.95	13.05	14.10	15.47	12.03	Cl 12-24"	9.96	
											Total Meq		31.12
SAR 12-24"	3.23	2.76	2.47	3.37	3.24	3.31	3.95	3.58	3.89	3.87	SAR 12-24"	3.36	
CROSSf 12-24"	7.37	8.74	8.71	12.40	9.94	10.58	11.62	11.74	13.46	11.79	CROSSf 12-24"	10.63	
CROSSopt 12-24"	7.35	8.71	8.69	12.37	9.92	10.56	11.60	11.72	13.43	11.77	CROSSopt 12-24"	10.61	
EC 24-36"	1.30	2.01	2.99	3.69	2.28	2.78	2.44	2.24	2.93	2.54	EC 24-36"	2.51	
Ca 24-36"	3.05	4.43	8.43	10.07	10.77	7.25	8.20	6.30	8.37	8.20	Ca 24-36"	7.50	29%
Mg 24-36"	2.48	4.93	9.50	10.33	6.90	7.60	4.30	6.37	8.40	6.43	Mg 24-36"	6.72	26%
Na 24-36"	7.30	10.40	11.63	16.07	9.90	13.15	12.50	11.53	12.80	11.57	Na 24-36"	11.68	45%
K 24-36"	0.18	0.33	0.27	0.43	0.37	0.35	0.35	0.27	0.47	0.30	K 24-36"	0.33	1%
Cl 24-36"	3.08	3.97	7.57	9.97	7.73	10.45	10.40	9.13	12.00	11.80	Cl 24-36"	8.60	
											Total Meq		26.25
SAR 24-36"	5.00	4.88	3.90	4.96	3.43	4.82	5.00	4.58	4.42	4.38	SAR 24-36"	4.53	
CROSSf 24-36"	7.37	10.50	11.69	16.15	9.97	13.23	12.58	11.60	12.90	11.63	CROSSf 24-36"	11.76	
CROSSopt 24-36"	7.36	10.47	11.67	16.13	9.95	13.21	12.56	11.58	12.87	11.62	CROSSopt 24-36"	11.74	

M1W Test Site 3A Summary by Year and Entire Profile

	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	10 yr. Average	Meq/L	% Exch.
EC 1-36"	1.93	3.08	3.93	4.20	2.49	2.69	2.41	2.85	3.35	2.77	EC 1-36"	2.96	
Ca 1-36"	7.10	12.11	16.47	15.73	10.93	9.68	9.23	10.99	12.32	10.27	Ca 1-36"	11.48	37%
Mg 1-36"	4.95	8.88	13.00	12.46	8.01	7.25	4.28	8.22	9.13	6.81	Mg 1-36"	8.30	27%
Na 1-36"	6.87	9.21	10.28	13.13	9.74	10.33	10.43	11.74	12.91	11.24	Na 1-36"	10.59	34%
K 1-36"	0.38	0.60	0.61	0.69	0.38	0.38	0.40	0.48	0.59	0.48	K 1-36"	0.49	2%
											Total Meq		30.87
Cl 1-36"	2.69	3.33	6.73	9.31	9.41	11.37	9.83	11.58	13.04	11.54	Cl 1-36"	8.88	
Cl ppm	95.55	118.33	239.03	330.54	334.09	403.51	349.08	411.01	463.07	409.82	Cl ppm	315.40	
SAR 1-36"	3.37	3.25	2.86	3.63	3.22	3.57	4.02	3.89	3.98	4.02	SAR 1-36"	3.58	
CROSSf 1-36"	6.97	9.32	10.37	13.24	9.82	10.41	10.53	11.84	13.02	11.35	CROSSf 1-36"	10.68	
CROSSopt 1-36"	6.94	9.29	10.34	13.21	9.80	10.39	10.50	11.81	12.99	11.32	CROSSopt 1-36"	10.65	

M1W Test Site 4 Summary by Year and Depth

	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	10 yr. Average	Meq/L	% Exch.
EC 1-12"	1.02	1.40	1.50	2.99	1.24	1.23	1.74	1.62	1.60	1.21	EC 1-12"	1.55	
Ca 1-12"	3.77	5.03	5.90	7.00	4.37	3.90	6.50	7.00	5.37	3.63	Ca 1-12"	5.24	36%
Mg 1-12"	1.87	3.07	2.87	3.07	2.17	1.95	2.10	3.83	3.03	1.80	Mg 1-12"	2.57	17%
Na 1-12"	4.37	5.57	5.90	8.07	6.00	6.50	8.90	6.60	7.33	7.27	Na 1-12"	6.65	45%
K 1-12"	0.23	0.33	0.30	0.23	0.20	0.15	0.27	0.27	0.27	0.20	K 1-12"	0.24	2%
Cl 1-12"	1.93	2.17	2.83	4.90	3.90	7.10	5.83	4.10	5.17	6.10	Cl 1-12"	4.40	
											Total Meq		14.72
SAR 1-12"	2.61	2.79	2.84	3.55	3.33	3.76	4.83	2.85	3.57	4.29	SAR 1-12"	3.44	
CROSSf 1-12"	4.45	5.67	5.98	8.13	6.07	6.55	8.98	6.67	7.41	7.34	CROSSf 1-12"	6.72	
CROSSopt 1-12"	4.42	5.64	5.95	8.11	6.04	6.53	8.95	6.65	7.39	7.32	CROSSopt 1-12"	6.70	
EC 12-24"	1.38	1.22	1.12	3.71	1.34	1.15	1.90	1.74	1.76	1.27	EC 12-24"	1.65	
Ca 12-24"	5.13	4.63	3.97	7.00	4.63	3.60	6.73	7.60	6.43	3.60	Ca 12-24"	5.33	35%
Mg 12-24"	4.47	3.70	2.80	5.53	3.50	2.80	2.90	4.70	4.17	2.63	Mg 12-24"	3.72	25%
Na 12-24"	4.03	3.70	4.27	6.20	5.47	5.50	9.30	6.87	6.97	6.87	Na 12-24"	5.91	39%
K 12-24"	0.13	0.20	0.10	0.23	0.13	0.10	0.17	0.13	0.13	0.10	K 12-24"	0.14	1%
Cl 12-24"	1.73	1.47	2.57	6.30	6.60	5.90	7.63	6.10	5.47	6.20	Cl 12-24"	4.99	
											Total Meq		15.11
SAR 12-24"	1.90	1.82	2.35	2.49	2.74	3.11	4.49	2.77	3.12	3.87	SAR 12-24"	2.86	
CROSSf 12-24"	4.07	3.76	4.30	6.26	5.51	5.54	9.35	6.90	7.00	6.91	CROSSf 12-24"	5.95	
CROSSopt 12-24"	4.06	3.74	4.29	6.24	5.50	5.53	9.33	6.89	6.99	6.89	CROSSopt 12-24"	5.94	
EC 24-36"	1.36	1.18	1.41	3.28	1.50	1.62	1.70	1.69	1.76	1.61	EC 24-36"	1.71	
Ca 24-36"	4.60	4.23	6.23	7.43	6.00	6.75	6.83	7.40	6.23	5.27	Ca 24-36"	6.09	37%
Mg 24-36"	5.40	4.20	4.20	6.97	5.37	6.05	3.80	5.30	5.17	5.20	Mg 24-36"	5.16	32%
Na 24-36"	3.53	3.23	3.53	5.43	4.50	5.45	6.10	5.40	6.03	6.67	Na 24-36"	4.98	30%
K 24-36"	0.10	0.17	0.13	0.20	0.10	0.15	0.17	0.10	0.13	0.10	K 24-36"	0.13	1%
Cl 24-36"	1.77	1.33	2.30	7.47	6.57	8.85	8.43	6.57	5.77	7.10	Cl 24-36"	5.61	
											Total Meq		16.39
SAR 12-24"	1.58	1.57	1.55	2.02	1.89	2.17	2.64	2.15	2.57	2.91	SAR 24-36"	2.10	
CROSSf 24-36"	3.56	3.28	3.57	5.48	4.53	5.49	6.14	5.42	6.07	6.69	CROSSf 24-36"	5.02	
CROSSopt 24-36"	3.55	3.27	3.56	5.47	4.52	5.48	6.13	5.42	6.06	6.69	CROSSopt 24-36"	5.01	

M1W Test Site 4 Summary by Year and Entire Profile

	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	10 yr. Average	Meq/L	% Exch.
EC 1-36"	1.25	1.27	1.34	3.33	1.36	1.33	1.78	1.69	1.70	1.36	EC 1-36"	1.64	
Ca 1-36"	4.50	4.63	5.37	7.14	5.00	4.75	6.69	7.33	6.01	4.17	Ca 1-36"	5.55	36%
Mg 1-36"	3.91	3.66	3.29	5.19	3.68	3.60	2.93	4.61	4.12	3.21	Mg 1-36"	3.82	25%
Na 1-36"	3.98	4.17	4.57	6.57	5.32	5.82	8.10	6.29	6.78	6.93	Na 1-36"	5.85	38%
K 1-36"	0.16	0.23	0.18	0.22	0.14	0.13	0.20	0.17	0.18	0.13	K 1-36"	0.17	1%
											Total Meq		15.41
Cl 1-36"	1.81	1.66	2.57	6.22	5.69	7.28	7.30	5.59	5.47	6.47	Cl 1-36"	5.00	
Cl ppm	64.29	58.77	91.11	220.88	201.95	258.55	259.15	198.40	194.06	229.56	Cl ppm	177.67	
SAR 1-36"	2.03	2.06	2.25	2.68	2.65	3.01	3.99	2.59	3.08	3.69	SAR 1-36"	2.80	
CROSSf 1-36"	4.03	4.24	4.62	6.62	5.37	5.86	8.16	6.33	6.83	6.98	CROSSf 1-36"	5.90	
CROSSopt 1-36"	4.01	4.22	4.60	6.61	5.35	5.85	8.14	6.32	6.81	6.97	CROSSopt 1-36"	5.88	

M1W Test Site 5A Summary by Year and Depth

	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	10 yr. Average	Meq/L	% Exch.
EC 1-12"	2.31	1.76	4.74	2.71	2.12	3.83	3.26	2.99	3.00	3.07	EC 1-12"	2.97	
Ca 1-12"	3.93	5.53	14.33	7.70	6.17	13.47	13.23	11.77	10.67	12.30	Ca 1-12"	9.91	32%
Mg 1-12"	4.27	4.00	10.17	5.93	4.10	9.33	5.50	6.57	6.40	5.97	Mg 1-12"	6.22	20%
Na 1-12"	14.80	10.50	22.30	13.20	11.87	16.87	14.50	14.03	14.00	14.53	Na 1-12"	14.66	47%
K 1-12"	0.17	0.27	0.60	0.30	0.17	0.27	0.27	0.33	0.33	0.30	K 1-12"	0.30	1%
Cl 1-12"	4.40	3.13	6.27	8.17	8.53	9.83	7.07	8.97	8.30	8.10	Cl 1-12"	7.27	
											Total Meq		31.09
SAR 1-12"	7.82	4.87	6.24	5.09	5.29	5.02	4.91	4.67	4.89	4.87	SAR 1-12"	5.36	
CROSSf 1-12"	14.86	10.57	22.40	13.27	11.91	16.91	14.55	14.10	14.07	14.60	CROSSf 1-12"	14.72	
CROSSopt 1-12"	14.84	10.55	22.37	13.25	11.90	16.90	14.53	14.08	14.05	14.58	CROSSopt 1-12"	14.70	
EC 12-24"	2.45	1.90	4.19	3.44	2.71	2.54	2.62	3.32	3.30	3.09	EC 12-24"	2.95	
Ca 12-24"	2.67	4.50	9.03	7.83	6.93	5.57	6.33	9.27	7.97	8.33	Ca 12-24"	6.84	22%
Mg 12-24"	4.50	5.70	10.10	9.33	7.17	6.67	5.23	10.67	8.97	7.47	Mg 12-24"	7.58	24%
Na 12-24"	17.13	12.37	22.50	17.03	15.30	14.03	15.10	16.40	17.40	17.43	Na 12-24"	16.47	53%
K 12-24"	0.13	0.20	0.27	0.20	0.13	0.13	0.10	0.17	0.23	0.20	K 12-24"	0.17	1%
Cl 12-24"	5.37	3.37	6.73	11.57	13.67	10.20	8.10	11.47	11.70	11.97	Cl 12-24"	9.41	
											Total Meq		31.07
SAR 12-24"	9.02	5.52	7.09	5.83	5.77	5.68	6.39	5.31	6.13	6.20	SAR 12-24"	6.29	
CROSSf 12-24"	17.18	12.42	22.55	17.08	15.33	14.07	15.13	16.43	17.45	17.48	CROSSf 12-24"	16.51	
CROSSopt 12-24"	17.17	12.41	22.54	17.06	15.32	14.06	15.12	16.42	17.44	17.46	CROSSopt 12-24"	16.50	
EC 24-36"	3.83	2.37	3.64	2.71	2.93	2.99	2.53	2.81	2.97	3.90	EC 24-36"	3.06	
Ca 24-36"	9.90	2.80	4.97	4.27	5.40	4.63	4.27	5.63	5.00	6.27	Ca 24-36"	5.31	17%
Mg 24-36"	6.40	4.10	4.23	4.30	5.73	6.33	2.97	7.60	6.00	9.97	Mg 24-36"	5.76	18%
Na 24-36"	21.57	18.30	26.90	18.37	18.30	20.17	18.33	17.67	19.60	25.23	Na 24-36"	20.44	64%
K 24-36"	0.43	0.27	0.23	0.20	0.17	0.20	0.10	0.17	0.23	0.17	K 24-36"	0.21	1%
Cl 24-36"	7.50	5.00	7.50	16.00	16.83	14.00	10.93	12.13	11.30	15.33	Cl 24-36"	11.65	
											Total Meq		31.74
SAR 12-24"	9.98	9.96	12.04	8.78	7.82	8.65	9.63	7.03	8.40	8.84	SAR 24-36"	9.11	
CROSSf 24-36"	21.66	18.39	26.97	18.43	18.34	20.22	18.37	17.71	19.67	25.27	CROSSf 24-36"	20.50	
CROSSopt 24-36"	21.64	18.37	26.95	18.42	18.33	20.21	18.36	17.70	19.65	25.26	CROSSopt 24-36"	20.48	

M1W Test Site 5A Summary by Year and Entire Profile

	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	10 yr. Average	Meq/L	% Exch.
EC 1-36"	2.86	2.01	4.19	2.95	2.59	3.12	2.80	3.04	3.09	3.35	EC 1-36"	3.00	
Ca 1-36"	5.50	4.28	9.44	6.60	6.17	7.89	7.94	8.89	7.88	8.97	Ca 1-36"	7.35	24%
Mg 1-36"	5.06	4.60	8.17	6.52	5.67	7.44	4.57	8.28	7.12	7.80	Mg 1-36"	6.52	21%
Na 1-36"	17.83	13.72	23.90	16.20	15.16	17.02	15.98	16.03	17.00	19.07	Na 1-36"	17.19	55%
K 1-36"	0.24	0.24	0.37	0.23	0.16	0.20	0.16	0.22	0.27	0.22	K 1-36"	0.23	1%
											Total Meq		31.30
Cl 1-36"	5.76	3.83	6.83	11.91	13.01	11.34	8.70	10.86	10.43	11.80	Cl 1-36"	9.44	
	204.3	136.0	242.5	422.8	461.8	402.7	308.8	385.3	370.3	418.9			
Cl ppm	2	8	8	4	9	3	5	7	8	0	Cl ppm	335.36	
SAR 1-36"	8.94	6.78	8.46	6.57	6.30	6.45	6.98	5.67	6.47	6.64	SAR 1-36"	6.92	
CROSSf 1-36"	17.90	13.79	23.97	16.26	15.20	17.07	16.01	16.08	17.06	19.12	CROSSf 1-36"	17.24	
CROSSopt 1-36"	17.88	13.78	23.95	16.24	15.18	17.06	16.00	16.07	17.05	19.10	CROSSopt 1-36"	17.23	

M1W Test Site 7 Summary by Year and Depth

	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	10 yr. Average	Meq/L	% Exch.
EC 1-12"	2.15	2.18	2.42	3.44	3.07	2.34	4.31	5.72	4.96	6.21	EC 1-12"	3.67	
Ca 1-12"	5.90	6.37	7.53	12.60	11.23	8.60	17.63	22.67	17.20	25.20	Ca 1-12"	13.49	35%
Mg 1-12"	4.50	4.57	5.47	8.30	7.47	5.20	7.17	15.23	10.97	14.77	Mg 1-12"	8.36	22%
Na 1-12"	10.70	10.33	10.73	14.57	12.70	10.03	19.17	23.97	22.40	27.70	Na 1-12"	16.23	42%
K 1-12"	0.40	0.50	0.50	0.63	0.63	0.53	0.87	1.53	0.93	1.03	K 1-12"	0.75	2%
Cl 1-12"	3.30	3.27	7.30	10.23	10.80	9.63	20.50	25.10	21.53	32.87	Cl 1-12"	14.45	
											Total Meq		38.84
SAR 1-12"	4.69	4.57	4.39	4.59	4.20	3.81	5.46	5.52	5.95	6.20	SAR 1-12"	4.93	
CROSSf 1-12"	10.81	10.47	10.85	14.69	12.83	10.16	19.32	24.18	22.55	27.85	CROSSf 1-12"	16.36	
CROSSopt 1-12"	10.78	10.43	10.82	14.65	12.79	10.12	19.26	24.11	22.50	27.80	CROSSopt 1-12"	16.32	
EC 12-24"	3.27	2.97	2.98	3.06	2.67	2.62	2.74	3.36	4.56	5.20	EC 12-24"	3.34	
Ca 12-24"	7.90	8.63	7.97	8.27	7.50	8.53	9.63	11.50	15.17	17.10	Ca 12-24"	10.22	30%
Mg 12-24"	6.40	6.37	6.37	6.33	5.50	4.93	3.73	8.10	10.73	11.33	Mg 12-24"	6.98	20%
Na 12-24"	17.90	14.13	14.93	15.47	13.63	13.20	14.53	16.80	22.33	25.17	Na 12-24"	16.81	49%
K 12-24"	0.50	0.57	0.50	1.07	0.43	0.40	0.53	0.60	0.67	0.67	K 12-24"	0.59	2%
Cl 12-24"	2.90	4.30	8.57	7.13	9.63	11.67	13.83	16.33	22.43	27.00	Cl 12-24"	12.38	
											Total Meq		34.60
SAR 12-24"	6.69	5.22	5.58	5.62	5.40	5.14	5.63	5.41	6.24	6.68	SAR 12-24"	5.76	
CROSSf 12-24"	18.02	14.26	15.05	15.67	13.74	13.29	14.66	16.92	22.45	25.28	CROSSf 12-24"	16.93	
CROSSopt 12-24"	17.98	14.22	15.02	15.61	13.71	13.26	14.61	16.88	22.41	25.24	CROSSopt 12-24"	16.89	
EC 24-36"	4.08	3.66	4.35	4.76	2.95	2.81	2.87	3.09	3.49	4.25	EC 24-36"	3.63	
Ca 24-36"	7.00	8.10	8.97	12.80	7.33	7.83	6.93	7.50	7.87	9.53	Ca 24-36"	8.38	22%
Mg 24-36"	6.90	7.03	7.60	9.27	5.50	3.90	3.07	6.00	6.90	8.00	Mg 24-36"	6.41	17%
Na 24-36"	26.30	21.07	26.37	28.70	20.00	17.93	19.40	19.80	21.33	26.30	Na 24-36"	22.72	60%
K 24-36"	0.50	0.63	0.57	0.60	0.50	0.40	0.47	0.57	0.57	0.60	K 24-36"	0.54	1%
Cl 24-36"	3.50	5.30	12.93	10.37	10.23	9.70	10.43	11.47	13.93	18.00	Cl 24-36"	10.58	
											Total Meq		38.06
SAR 24-36"	9.98	7.83	9.13	8.55	7.88	7.43	8.71	7.62	7.93	8.83	SAR 24-36"	8.38	
CROSSf 24-36"	26.42	21.21	26.49	28.81	20.12	18.03	19.52	19.93	21.46	26.42	CROSSf 24-36"	22.84	
CROSSopt 24-36"	26.39	21.17	26.45	28.78	20.09	18.00	19.48	19.90	21.43	26.39	CROSSopt 24-36"	22.80	

M1W Test Site 7 Summary by Year and Entire Profile

	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	10 yr. Average	Meq/L	% Exch.
EC 1-36"	3.17	2.94	3.25	3.75	2.90	2.59	3.31	4.06	4.34	5.22	EC 1-36"	3.55	
Ca 1-36"	6.93	7.70	8.16	11.22	8.69	8.32	11.40	13.89	13.41	17.28	Ca 1-36"	10.70	29%
Mg 1-36"	5.93	5.99	6.48	7.97	6.16	4.68	4.66	9.78	9.53	11.37	Mg 1-36"	7.25	20%
Na 1-36"	18.30	15.18	17.34	19.58	15.44	13.72	17.70	20.19	22.02	26.39	Na 1-36"	18.58	50%
K 1-36"	0.47	0.57	0.52	0.77	0.52	0.44	0.62	0.90	0.72	0.77	K 1-36"	0.63	2%
											Total Meq		37.17
Cl 1-36"	3.23	4.29	9.60	9.24	10.22	10.33	14.92	17.63	19.30	25.96	Cl 1-36"	12.47	
Cl ppm	114.78	152.26	340.80	328.18	362.89	366.83	529.74	625.98	685.15	921.42	Cl ppm	442.80	
SAR 1-36"	7.12	5.87	6.37	6.25	5.83	5.46	6.60	6.18	6.71	7.24	SAR 1-36"	6.36	
CROSSf 1-36"	18.41	15.31	17.46	19.72	15.56	13.83	17.83	20.34	22.16	26.52	CROSSf 1-36"	18.71	
CROSSopt 1-36"	18.38	15.27	17.43	19.68	15.53	13.79	17.79	20.30	22.12	26.48	CROSSopt 1-36"	18.67	

M1W Test Site 2 Summary by Year and Depth

	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	10 yr. Average	Meq/L	% Exch.
EC 1-12"	1.68	1.92	2.15	2.20	1.70	1.48	1.83	1.42	1.53	1.77	EC 1-12"	1.76	
Ca 1-12"	6.70	8.13	8.67	9.30	6.70	5.87	7.20	5.40	5.60	6.60	Ca 1-12"	7.01	39%
Mg 1-12"	3.27	4.47	4.97	4.83	3.47	3.10	4.03	3.07	2.93	3.53	Mg 1-12"	3.76	21%
Na 1-12"	6.97	7.00	7.23	7.47	6.23	5.60	7.07	6.13	6.73	7.40	Na 1-12"	6.78	38%
K 1-12"	0.43	0.43	0.47	0.50	0.40	0.43	0.43	0.40	0.33	0.40	K 1-12"	0.42	2%
Cl 1-12"	5.13	6.10	5.13	4.10	2.63	3.20	5.87	3.53	4.77	3.20	Cl 1-12"	4.36	
											Total Meq		17.99
SAR 1-12"	3.13	2.82	2.91	2.88	2.81	2.68	2.97	3.04	3.26	3.29	SAR 1-12"	2.97	
CROSSf 1-12"	7.08	7.10	7.34	7.58	6.34	5.73	7.18	6.25	6.83	7.51	CROSSf 1-12"	6.89	
CROSSopt 1-12"	7.04	7.07	7.31	7.54	6.30	5.69	7.14	6.21	6.80	7.47	CROSSopt 1-12"	6.85	
EC 12-24"	2.20	1.82	1.84	1.95	1.94	1.68	1.53	1.44	1.96	1.79	EC 12-24"	1.81	
Ca 12-24"	9.77	7.33	6.67	7.57	7.83	6.47	5.80	5.23	7.57	6.53	Ca 12-24"	7.07	38%
Mg 12-24"	5.03	4.33	4.33	4.63	4.37	3.90	3.33	3.17	4.57	3.83	Mg 12-24"	4.15	22%
Na 12-24"	8.00	6.97	6.47	6.77	6.77	6.47	6.33	6.23	7.97	7.63	Na 12-24"	6.96	38%
K 12-24"	0.40	0.37	0.33	0.33	0.37	0.33	0.33	0.30	0.33	0.30	K 12-24"	0.34	2%
Cl 12-24"	7.10	6.13	5.53	4.63	3.70	4.03	3.57	4.20	7.07	4.77	Cl 12-24"	5.07	
											Total Meq		18.53
SAR 12-24"	2.99	2.88	2.80	2.77	2.74	2.84	2.96	3.08	3.24	3.36	SAR 12-24"	2.96	
CROSSf 12-24"	8.09	7.06	6.56	6.85	6.86	6.55	6.43	6.32	8.05	7.71	CROSSf 12-24"	7.04	
CROSSopt 12-24"	8.06	7.03	6.53	6.82	6.83	6.53	6.40	6.29	8.02	7.69	CROSSopt 12-24"	7.02	
EC 24-36"	2.16	1.85	1.89	2.01	1.76	1.74	1.59	1.64	1.72	1.71	EC 24-36"	1.80	
Ca 24-36"	8.20	7.03	6.80	7.27	6.47	6.47	6.00	5.83	6.27	5.93	Ca 24-36"	6.62	36%
Mg 24-36"	6.57	5.63	5.30	6.03	4.47	4.83	4.43	4.53	4.63	4.23	Mg 24-36"	5.06	27%
Na 24-36"	7.67	6.40	6.17	6.60	5.90	6.07	6.03	6.60	6.83	6.90	Na 24-36"	6.51	35%
K 24-36"	0.33	0.27	0.27	0.27	0.27	0.30	0.23	0.23	0.27	0.30	K 24-36"	0.27	1%
Cl 24-36"	7.13	6.33	5.60	5.57	3.10	4.20	3.90	4.83	6.07	5.33	Cl 24-36"	5.20	
											Total Meq		18.48
SAR 24-36"	2.84	2.55	2.54	2.55	2.51	2.55	2.64	2.91	2.92	3.06	SAR 24-36"	2.70	
CROSSf 24-36"	7.74	6.47	6.23	6.66	5.97	6.15	6.10	6.66	6.90	6.98	CROSSf 24-36"	6.58	
CROSSopt 24-36"	7.72	6.45	6.21	6.65	5.95	6.12	6.08	6.64	6.88	6.96	CROSSopt 24-36"	6.56	

M1W Test Site 2 Summary by Year and Entire Profile

	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	10 yr. Average	Meq/L	% Exch.
EC 1-36"	2.012	1.861	1.96	2.05	1.80	1.63	1.65	1.50	1.74	1.76	EC 1-36"	1.79	
Ca 1-36"	8.222	7.500	7.38	8.04	7.00	6.27	6.33	5.49	6.48	6.36	Ca 1-36"	6.90	38%
Mg 1-36"	4.956	4.811	4.87	5.17	4.10	3.94	3.93	3.59	4.04	3.87	Mg 1-36"	4.32	24%
Na 1-36"	7.544	6.789	6.62	6.94	6.30	6.04	6.48	6.32	7.18	7.31	Na 1-36"	6.75	37%
K 1-36"	0.389	0.356	0.36	0.37	0.34	0.36	0.33	0.31	0.31	0.33	K 1-36"	0.34	2%
											Total Meq		18.33
Cl 1-36"	6.456	6.189	5.42	4.77	3.14	3.81	4.44	4.19	5.97	4.43	Cl 1-36"	4.88	
Cl ppm	229.17	219.71	192.49	169.22	111.63	135.29	157.78	148.71	211.82	157.38	Cl ppm	173.31	
SAR 1-36"	2.987	2.749	2.75	2.73	2.69	2.69	2.86	3.01	3.14	3.24	SAR 1-36"	2.88	
CROSSf 1-36"	7.640	6.876	6.71	7.03	6.39	6.14	6.57	6.41	7.26	7.40	CROSSf 1-36"	6.84	
CROSSopt 1-36"	7.609	6.848	6.68	7.00	6.36	6.11	6.54	6.38	7.23	7.37	CROSSopt 1-36"	6.81	

M1W Test Site 3A Summary by Year and Depth

	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	10 yr. Average	Meq/L	% Exch.
EC 1-12"	1.74	2.23	4.20	1.68	2.63	2.50	1.72	2.07	2.47	2.74	EC 1-12"	2.39	
Ca 1-12"	6.47	9.10	16.47	5.87	9.47	9.10	5.93	7.47	9.10	9.53	Ca 1-12"	8.85	37%
Mg 1-12"	3.27	4.13	8.23	2.83	4.53	4.60	3.07	3.90	4.90	4.67	Mg 1-12"	4.41	18%
Na 1-12"	7.70	9.60	13.83	7.77	10.83	9.47	8.40	9.57	11.70	12.80	Na 1-12"	10.16	42%
K 1-12"	0.50	0.63	0.97	0.47	0.70	0.57	0.50	0.63	0.57	0.67	K 1-12"	0.62	3%
Cl 1-12"	5.93	7.73	10.13	5.30	6.77	5.13	5.73	5.20	7.20	7.43	Cl 1-12"	6.65	
											Total Meq		24.05
SAR 1-12"	3.49	3.78	3.94	3.79	4.21	3.63	4.02	4.17	4.63	4.81	SAR 1-12"	4.04	
CROSSf 1-12"	7.84	9.75	14.00	7.90	10.99	9.60	8.55	9.73	11.83	12.95	CROSSf 1-12"	10.31	
CROSSopt 1-12"	7.79	9.70	13.94	7.86	10.94	9.55	8.50	9.67	11.79	12.90	CROSSopt 1-12"	10.26	
EC 12-24"	2.31	2.48	2.42	2.17	2.53	2.22	2.51	2.34	2.44	2.52	EC 12-24"	2.39	
Ca 12-24"	9.37	9.87	8.77	7.73	8.90	7.73	9.43	7.97	8.30	8.67	Ca 12-24"	8.67	36%
Mg 12-24"	4.73	5.10	4.97	4.50	4.77	4.23	5.40	4.67	4.97	4.67	Mg 12-24"	4.80	20%
Na 12-24"	9.50	10.30	9.60	9.57	10.43	9.00	11.10	11.17	11.63	11.97	Na 12-24"	10.42	43%
K 12-24"	0.47	0.57	0.57	0.47	0.53	0.40	0.50	0.57	0.43	0.57	K 12-24"	0.50	2%
Cl 12-24"	9.33	11.33	8.80	10.57	7.33	5.23	9.33	8.37	8.83	8.30	Cl 12-24"	8.74	
											Total Meq		24.41
SAR 12-24"	3.54	3.82	3.68	3.88	4.02	3.66	4.10	4.46	4.57	4.63	SAR 12-24"	4.03	
CROSSf 12-24"	9.60	10.42	9.73	9.68	10.56	9.10	11.21	11.30	11.73	12.10	CROSSf 12-24"	10.54	
CROSSopt 12-24"	9.57	10.38	9.69	9.64	10.52	9.07	11.18	11.26	11.70	12.06	CROSSopt 12-24"	10.50	
EC 24-36"	2.78	2.66	2.23	1.95	1.88	1.84	1.94	2.49	2.68	2.20	EC 24-36"	2.26	
Ca 24-36"	10.90	10.07	7.13	6.37	6.23	6.00	6.13	8.23	7.03	6.60	Ca 24-36"	7.47	32%
Mg 24-36"	7.83	7.23	5.37	4.83	4.57	4.37	4.80	6.33	6.27	4.80	Mg 24-36"	5.64	24%
Na 24-36"	10.17	10.30	9.10	8.17	8.47	7.57	8.87	11.10	13.90	10.13	Na 24-36"	9.77	42%
K 24-36"	0.53	0.67	0.57	0.50	0.47	0.33	0.50	0.63	0.53	0.53	K 24-36"	0.52	2%
Cl 24-36"	12.80	11.50	8.90	10.20	6.67	3.87	8.40	9.17	10.93	7.30	Cl 24-36"	8.97	
											Total Meq		23.41
SAR 24-36"	3.26	3.52	3.64	3.45	3.66	3.32	3.80	4.16	5.66	4.25	SAR 24-36"	3.87	
CROSSf 24-36"	10.27	10.44	9.24	8.30	8.59	7.66	9.00	11.25	14.02	10.27	CROSSf 24-36"	9.90	
CROSSopt 24-36"	10.24	10.40	9.20	8.26	8.55	7.63	8.96	11.20	13.99	10.23	CROSSopt 24-36"	9.86	

M1W Test Site 3A Summary by Year and Entire Profile

	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	10 yr. Average	Meq/L	% Exch.
EC 1-36"	2.28	2.46	2.95	1.93	2.35	2.19	2.06	2.30	2.53	2.49	EC 1-36"	2.35	
Ca 1-36"	8.91	9.68	10.79	6.66	8.20	7.61	7.17	7.89	8.14	8.27	Ca 1-36"	8.33	35%
Mg 1-36"	5.28	5.49	6.19	4.06	4.62	4.40	4.42	4.97	5.38	4.71	Mg 1-36"	4.95	21%
Na 1-36"	9.12	10.07	10.84	8.50	9.91	8.68	9.46	10.61	12.41	11.63	Na 1-36"	10.12	42%
K 1-36"	0.50	0.62	0.70	0.48	0.57	0.43	0.50	0.61	0.51	0.59	K 1-36"	0.55	2%
											Total Meq		23.96
Cl 1-36"	9.36	10.19	9.28	8.69	6.92	4.74	7.82	7.58	8.99	7.68	Cl 1-36"	8.12	
	332.1	361.7	329.3	308.4	245.7	168.4	277.6	269.0	319.1	272.5			
Cl ppm	2	0	6	5	3	2	8	1	0	6	Cl ppm	288.4	
SAR 1-36"	3.43	3.71	3.75	3.71	3.96	3.54	3.97	4.26	4.95	4.57	SAR 1-36"	3.98	
CROSSf 1-36"	9.24	10.20	10.99	8.63	10.05	8.78	9.59	10.76	12.53	11.77	CROSS 1-36"	10.25	
CROSSopt 1-36"	9.20	10.16	10.94	8.59	10.00	8.75	9.54	10.71	12.49	11.73	ESP 1-36"	10.21	

M1W Test Site 4 Summary by Year and Depth

	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	10 yr. Average	Meq/L	% Exch.
EC 1-12"	1.81	1.95	2.22	1.83	1.67	1.80	0.94	0.95	1.26	0.71	EC 1-12"	1.51	
Ca 1-12"	6.10	7.20	6.37	5.63	4.63	5.30	2.43	2.57	4.40	1.67	Ca 1-12"	4.63	31%
Mg 1-12"	2.60	3.73	3.57	2.90	2.40	3.10	1.43	1.43	2.20	0.90	Mg 1-12"	2.42	16%
Na 1-12"	9.37	8.93	9.23	9.57	8.93	9.30	5.57	5.93	6.37	4.30	Na 1-12"	7.75	51%
K 1-12"	0.27	0.37	0.37	0.27	0.27	0.30	0.17	0.17	0.17	0.10	K 1-12"	0.24	2%
Cl 1-12"	8.80	5.40	5.50	5.60	5.80	4.05	2.13	2.50	3.40	1.33	Cl 1-12"	4.45	
											Total Meq		15.05
SAR 1-12"	4.39	3.95	4.29	4.68	4.78	4.54	4.10	4.29	3.70	3.81	SAR 1-12"	4.25	
CROSSf 1-12"	9.44	9.03	9.33	9.64	9.02	9.39	5.64	6.00	6.42	4.35	CROSSf 1-12"	7.82	
CROSSopt 1-12"	9.42	9.00	9.30	9.62	8.99	9.36	5.61	5.98	6.40	4.34	CROSSopt 1-12"	7.80	
EC 12-24"	1.66	1.69	1.69	2.08	2.16	1.54	0.97	1.05	1.25	1.07	EC 12-24"	1.51	
Ca 12-24"	5.17	5.80	4.60	5.67	6.43	4.45	2.27	2.97	3.83	2.30	Ca 12-24"	4.34	29%
Mg 12-24"	3.20	3.97	3.20	4.33	4.47	2.90	1.47	1.87	2.27	1.50	Mg 12-24"	2.91	19%
Na 12-24"	8.10	7.77	7.93	11.00	9.57	7.55	5.87	6.47	6.33	6.57	Na 12-24"	7.71	51%
K 12-24"	0.10	0.17	0.17	0.17	0.13	0.15	0.10	0.13	0.13	0.10	K 12-24"	0.13	1%
Cl 12-24"	6.20	6.47	5.63	10.23	7.93	3.90	2.30	2.20	3.47	2.97	Cl 12-24"	5.13	
											Total Meq		15.12
SAR 12-24"	3.96	3.65	4.06	4.90	4.10	3.94	4.31	4.31	3.77	4.79	SAR 12-24"	4.17	
CROSSf 12-24"	8.13	7.81	7.98	11.05	9.60	7.60	5.91	6.52	6.38	6.61	CROSSf 12-24"	7.76	
CROSSopt 12-24"	8.12	7.80	7.97	11.03	9.59	7.58	5.90	6.50	6.36	6.60	CROSSopt 12-24"	7.74	
EC 24-36"	1.66	1.71	1.58	2.16	2.07	1.77	1.42	0.99	1.23	1.15	EC 24-36"	1.57	
Ca 24-36"	4.90	6.00	4.67	4.33	6.43	5.10	4.10	1.93	3.47	2.67	Ca 24-36"	4.36	27%
Mg 24-36"	4.70	4.57	4.07	4.77	5.30	4.50	3.53	1.47	2.53	2.30	Mg 24-36"	3.77	24%
Na 24-36"	7.13	7.13	7.30	12.57	8.20	7.70	6.73	6.70	6.57	6.67	Na 24-36"	7.67	48%
K 24-36"	0.10	0.13	0.13	0.13	0.13	0.15	0.10	0.10	0.10	0.10	K 24-36"	0.11	1%
Cl 24-36"	5.27	6.23	4.93	9.17	7.33	4.95	3.43	2.00	3.57	3.33	Cl 24-36"	5.02	
											Total Meq		15.92
SAR 24-36"	3.24	3.12	3.50	5.68	3.37	3.52	3.45	5.28	3.82	4.23	SAR 24-36"	3.92	
CROSSf 24-36"	7.16	7.17	7.34	12.61	8.23	7.74	6.77	6.75	6.60	6.71	CROSSf 24-36"	7.70	
CROSSopt 24-36"	7.15	7.16	7.33	12.60	8.22	7.73	6.76	6.73	6.59	6.69	CROSSopt 24-36"	7.69	

M1W Test Site 4 Summary by Year and Entire Profile

	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	10 yr. Average	Meq/L	% Exch.
EC 1-36"	1.71	1.78	1.83	2.03	1.96	1.70	1.11	1.00	1.25	0.98	EC 1-36"	1.53	
Ca 1-36"	5.39	6.33	5.21	5.21	5.83	4.95	2.93	2.49	3.90	2.21	Ca 1-36"	4.44	29%
Mg 1-36"	3.50	4.09	3.61	4.00	4.06	3.50	2.14	1.59	2.33	1.57	Mg 1-36"	3.03	20%
Na 1-36"	8.20	7.94	8.16	11.04	8.90	8.18	6.06	6.37	6.42	5.84	Na 1-36"	7.71	50%
K 1-36"	0.16	0.22	0.22	0.19	0.18	0.20	0.12	0.13	0.13	0.10	K 1-36"	0.16	1%
											Total Meq		15.36
Cl 1-36"	6.76	6.03	5.36	8.33	7.02	4.30	2.62	2.23	3.48	2.54	Cl 1-36"	4.86	
Cl ppm	239.8	214.2	190.1	295.8	249.3	152.7	93.1	79.3	123.5	90.3	Cl ppm	172.86	
SAR 1-36"	3.86	3.57	3.95	5.09	4.08	4.13	3.95	4.63	3.76	4.28	SAR 1-36"	4.13	
CROSSf 1-36"	8.25	8.00	8.22	11.10	8.95	6.51	6.10	6.42	6.47	5.89	CROSSf 1-36"	7.59	
CROSSopt 1-36"	8.23	7.98	8.20	11.08	8.94	6.49	6.09	6.41	6.45	5.88	CROSSopt 1-36"	7.57	

M1W Test Site 5A Summary by Year and Depth

	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	10 yr. Average	Meq/L	% Exch.
EC 1-12"	2.68	2.03	1.64	1.56	2.12	1.42	1.58	2.25	2.35	1.64	EC 1-12"	1.93	
Ca 1-12"	9.50	7.27	4.87	4.43	6.50	3.43	4.30	7.17	8.40	4.50	Ca 1-12"	6.04	30%
Mg 1-12"	5.37	3.83	2.80	2.40	3.43	2.00	2.57	4.63	4.60	2.80	Mg 1-12"	3.44	17%
Na 1-12"	14.57	9.40	8.10	8.43	12.23	8.77	8.73	11.53	11.27	9.63	Na 1-12"	10.27	51%
K 1-12"	0.33	0.27	0.17	0.23	0.27	0.23	0.20	0.33	0.53	0.20	K 1-12"	0.28	1%
Cl 1-12"	7.27	6.57	4.83	5.87	8.90	4.23	4.10	5.47	4.83	6.50	Cl 1-12"	5.86	
											Total Meq		20.02
SAR 1-12"	5.30	4.25	4.14	4.59	5.49	5.35	4.82	4.86	4.76	5.06	SAR 1-12"	4.86	
CROSSf 1-12"	14.64	9.47	8.16	8.51	12.31	8.85	8.80	11.62	11.39	9.70	CROSSf 1-12"	10.34	
CROSSopt 1-12"	14.62	9.45	8.14	8.48	12.28	8.83	8.78	11.59	11.35	9.68	CROSSopt 1-12"	10.32	
EC 12-24"	3.11	2.33	2.76	1.59	2.26	1.46	1.49	1.83	2.46	1.49	EC 12-24"	2.08	
Ca 12-24"	6.73	6.33	5.37	3.80	4.60	3.23	3.50	3.77	7.27	3.43	Ca 12-24"	4.80	23%
Mg 12-24"	7.23	5.03	5.60	2.63	4.50	2.67	2.63	3.47	5.20	2.53	Mg 12-24"	4.15	20%
Na 12-24"	18.20	12.57	14.17	8.93	14.40	8.73	8.73	11.80	12.70	9.30	Na 12-24"	11.95	57%
K 12-24"	0.10	0.13	0.20	0.13	0.13	0.13	0.10	0.20	0.33	0.13	K 12-24"	0.16	1%
Cl 12-24"	11.43	6.93	9.17	5.83	9.63	4.80	5.10	4.70	7.93	5.30	Cl 12-24"	7.08	
											Total Meq		21.07
SAR 12-24"	6.89	5.60	6.03	4.99	6.78	5.12	5.12	6.26	5.33	5.39	SAR 12-24"	5.75	
CROSSf 12-24"	18.22	12.60	14.22	8.98	14.44	8.78	8.77	11.87	12.77	9.35	CROSSf 12-24"	12.00	
CROSSopt 12-24"	18.22	12.59	14.21	8.97	14.43	8.77	8.76	11.85	12.75	9.33	CROSSopt 12-24"	11.99	
EC 24-36"	4.35	2.94	3.65	2.44	2.67	1.88	2.44	1.37	2.35	1.47	EC 24-36"	2.56	
Ca 24-36"	7.93	6.10	4.47	3.80	3.27	2.90	5.63	2.23	5.00	1.97	Ca 24-36"	4.33	17%
Mg 24-36"	9.10	7.10	7.17	5.17	4.60	4.07	5.53	2.33	4.77	2.63	Mg 24-36"	5.25	20%
Na 24-36"	27.57	16.10	22.13	14.87	18.00	12.17	13.40	9.83	14.17	10.37	Na 24-36"	15.86	62%
K 24-36"	0.20	0.20	0.23	0.17	0.20	0.17	0.13	0.10	0.37	0.10	K 24-36"	0.19	1%
Cl 24-36"	17.40	8.97	9.53	9.50	7.23	5.83	8.27	3.90	8.23	4.53	Cl 24-36"	8.34	
											Total Meq		25.62
SAR 24-36"	9.53	6.83	9.35	7.00	9.07	6.54	6.45	6.48	7.22	6.84	SAR 24-36"	7.53	
CROSSf 24-36"	27.61	16.15	22.20	14.91	18.06	12.22	13.44	9.88	14.26	10.41	CROSSf 24-36"	15.91	
CROSSopt 24-36"	27.60	16.14	22.18	14.90	18.05	12.21	13.43	9.86	14.24	10.40	CROSSopt 24-36"	15.90	

M1W Test Site 5A Summary by Year and Entire Profile

	2010	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**10 yr. Average**	**Meq/L**	**% Exch.**
EC 1-36"	3.38	2.43	2.68	1.86	2.35	1.59	1.83	1.82	2.38	1.53	EC 1-36"	2.19	
Ca 1-36"	8.06	6.57	4.90	4.01	4.79	3.19	4.48	4.39	6.89	3.30	Ca 1-36"	5.06	23%
Mg 1-36"	7.23	5.32	5.19	3.40	4.18	2.91	3.58	3.48	4.86	2.66	Mg 1-36"	4.28	19%
Na 1-36"	20.11	12.69	14.80	10.74	14.88	9.89	10.29	11.06	12.71	9.77	Na 1-36"	12.69	57%
K 1-36"	0.21	0.20	0.20	0.18	0.20	0.18	0.14	0.21	0.41	0.14	K 1-36"	0.21	1%
											Total Meq		22.24
Cl 1-36"	12.03	7.49	7.84	7.07	8.59	4.96	5.82	4.69	7.00	5.44	Cl 1-36"	7.09	
Cl ppm	427.18	265.86	278.48	250.87	304.91	175.92	206.69	166.46	248.50	193.28	Cl ppm	251.81	
SAR 1-36"	7.24	5.56	6.51	5.53	7.11	5.67	5.47	5.86	5.77	5.76	SAR 1-36"	6.05	
CROSSf 1-36"	20.16	12.74	14.86	10.80	14.94	9.95	10.34	11.12	12.81	9.82	CROSSf 1-36"	12.75	
CROSSopt 1-36"	20.14	12.72	14.84	10.78	14.92	9.93	10.32	11.10	12.78	9.80	CROSSopt 1-36"	12.74	

M1W Test Site 7 Summary by Year and Depth

	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	10 yr. Average	Meq/L	% Exch.
EC 1-12"	4.35	5.50	6.66	3.10	2.72	2.36	2.17	1.58	2.23	1.56	EC 1-12"	3.22	
Ca 1-12"	18.10	21.35	22.07	10.30	8.30	6.93	7.67	5.57	8.20	5.23	Ca 1-12"	11.37	34%
Mg 1-12"	9.80	12.45	13.57	5.83	4.43	3.90	4.33	3.13	4.47	2.80	Mg 1-12"	6.47	20%
Na 1-12"	19.10	22.85	27.43	15.10	14.20	11.27	9.93	7.03	10.13	7.30	Na 1-12"	14.44	44%
K 1-12"	0.95	1.20	1.03	0.63	0.67	0.47	0.60	0.57	0.57	0.37	K 1-12"	0.71	2%
Cl 1-12"	13.90	17.35	24.53	12.73	5.63	6.07	6.57	5.50	8.73	4.00	Cl 1-12"	10.50	
											Total Meq		32.98
SAR 1-12"	5.12	5.58	6.46	5.30	5.63	4.90	4.27	3.37	4.03	3.84	SAR 1-12"	4.85	
CROSSf 1-12"	19.25	23.03	27.58	15.24	14.36	11.39	10.08	7.20	10.27	7.42	CROSSf 1-12"	14.58	
CROSSopt 1-12"	19.20	22.97	27.54	15.19	14.31	11.35	10.04	7.14	10.23	7.38	CROSSopt 1-12"	14.53	
EC 12-24"	4.82	4.69	4.77	4.21	3.47	2.81	2.01	1.48	1.93	1.51	EC 12-24"	3.17	
Ca 12-24"	16.35	14.95	13.10	13.07	10.57	7.13	5.23	4.63	5.10	4.37	Ca 12-24"	9.45	29%
Mg 12-24"	10.55	10.20	9.30	8.80	6.57	4.80	3.30	2.67	3.33	2.50	Mg 12-24"	6.20	19%
Na 12-24"	24.55	24.15	22.17	21.17	18.27	14.27	11.70	7.73	11.17	8.07	Na 12-24"	16.32	50%
K 12-24"	0.70	1.00	0.73	0.73	0.63	0.47	0.47	0.47	0.47	0.33	K 12-24"	0.60	2%
Cl 12-24"	24.90	18.75	18.97	19.07	7.20	8.75	5.57	5.33	7.43	4.23	Cl 12-24"	12.02	
											Total Meq		32.58
SAR 12-24"	6.71	6.82	6.62	6.38	6.27	5.85	5.71	4.07	5.40	4.35	SAR 12-24"	5.82	
CROSSf 12-24"	24.67	24.32	22.30	21.30	18.40	14.38	11.84	7.88	11.30	8.18	CROSSf 12-24"	16.46	
CROSSopt 12-24"	24.63	24.27	22.26	21.26	18.36	14.35	11.80	7.83	11.26	8.14	CROSSopt 12-24"	16.42	
EC 24-36"	5.05	3.89	4.05	3.67	3.73	4.16	2.78	2.21	2.82	2.37	EC 24-36"	3.47	
Ca 24-36"	12.75	8.20	7.10	8.77	8.73	8.60	5.73	4.90	5.40	5.43	Ca 24-36"	7.56	21%
Mg 24-36"	9.60	6.75	6.17	6.97	6.43	7.33	4.60	3.47	4.30	3.83	Mg 24-36"	5.95	17%
Na 24-36"	29.35	25.20	24.00	21.33	22.47	24.30	17.77	14.40	18.97	14.60	Na 24-36"	21.24	60%
K 24-36"	0.70	0.85	0.67	0.67	0.70	0.70	0.57	0.50	0.50	0.43	K 24-36"	0.63	2%
Cl 24-36"	23.45	14.65	15.67	16.90	19.75	11.93	8.20	6.03	9.17	6.20	Cl 24-36"	13.20	
											Total Meq		35.37
SAR 24-36"	8.77	9.27	9.33	7.61	8.18	8.67	7.79	7.09	8.61	6.87	SAR 24-36"	8.22	
CROSSf 24-36"	29.48	25.39	24.16	21.48	22.62	24.45	17.92	14.55	19.11	14.72	CROSSf 24-36"	21.39	
CROSSopt 24-36"	29.44	25.34	24.11	21.44	22.58	24.41	17.88	14.50	19.06	14.69	CROSSopt 24-36"	21.34	

M1W Test Site 7 Summary by Year and Entire Profile

	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	10 yr. Average	Meq/L	% Exch.
EC 1-36"	4.74	4.69	5.16	3.66	3.30	3.11	2.32	1.75	2.32	1.81	EC 1-36"	3.29	
Ca 1-36"	15.73	14.83	14.09	10.71	9.20	7.56	6.21	5.03	6.23	5.01	Ca 1-36"	9.46	28%
Mg 1-36"	9.98	9.80	9.68	7.20	5.81	5.34	4.08	3.09	4.03	3.04	Mg 1-36"	6.21	18%
Na 1-36"	24.33	24.07	24.53	19.20	18.31	16.61	13.13	9.72	13.42	9.99	Na 1-36"	17.33	52%
K 1-36"	0.78	1.02	0.81	0.68	0.67	0.54	0.54	0.51	0.51	0.38	K 1-36"	0.64	2%
											Total Meq		33.64
Cl 1-36"	20.75	16.92	19.72	16.23	9.75	8.92	6.78	5.62	8.44	4.81	Cl 1-36"	11.79	
Cl ppm	736.63	600.54	700.14	576.28	346.13	316.54	240.61	199.59	299.78	170.79	Cl ppm	418.70	
SAR 1-36"	6.86	7.22	7.47	6.43	6.69	6.47	5.92	4.84	6.01	5.02	SAR 1-36"	6.29	
CROSSf 1-36"	24.47	24.25	24.68	19.34	18.46	16.74	13.28	9.88	13.56	10.10	CROSSf 1-36"	17.48	
CROSSopt 1-36"	24.42	24.19	24.64	19.30	18.41	16.70	13.24	9.83	13.52	10.07	CROSSopt 1-36"	17.43	

PVW Site 3 Summary by Year and Depth

	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	10 yr. Average	Meq/L	% Exch.
EC 1-12"	5.15	3.77	2.53	3.63	4.65	4.96	3.30	3.72	4.25	4.06	4.18	EC 1-12"	4.02	
Na 1-12"	35.50	25.67	17.55	26.00	33.26	33.15	23.90	22.69	28.65	26.98	30.40	Na 1-12"	27.61	0.63
K 1-12"	2.06	1.30	0.74	0.85	0.95	0.84	0.63	0.71	0.94	0.75	0.84	K 1-12"	0.96	0.02
Ca 1-12"	13.50	5.50	3.00	5.50	8.89	10.11	5.01	4.37	7.36	6.91	8.16	Ca 1-12"	7.12	0.16
Mg 1-12"	15.10	6.60	3.70	6.43	10.15	11.40	5.35	4.97	7.86	7.72	9.50	Mg 1-12"	8.07	0.18
Cl 1-12"	33.00	22.00	8.27	17.67	34.90	37.45	19.93	18.15	27.00	29.70	35.75	Cl 1-12"	25.80	
												Total Meq		43.77
SAR 1-12"	11.04	10.17	9.63	10.55	10.76	10.51	10.58	10.69	10.59	10.22	9.69	SAR 1-12"	10.40	
CROSSf 1-12"	35.85	26.00	17.80	26.22	33.46	33.32	24.08	22.90	28.87	27.16	30.58	CROSSf 1-12"	27.84	
CROSSopt 1-12"	35.76	25.92	17.74	26.16	33.41	33.27	24.03	22.85	28.81	27.12	30.53	CROSSopt 1-12"	27.78	
EC 12-24"	5.60	6.20	5.33	5.27	4.89	5.62	3.58	4.13	5.80	5.70	4.95	EC 12-24"	5.19	
Na 12-24"	43.50	46.00	43.04	42.67	36.50	41.31	28.41	31.00	37.99	37.95	38.80	Na 12-24"	38.83	0.67
K 12-24"	2.49	2.22	1.13	1.03	0.95	1.03	0.75	0.85	1.15	0.91	0.94	K 12-24"	1.22	0.02
Ca 12-24"	13.75	8.87	5.70	6.37	7.26	8.79	5.28	4.99	9.52	7.64	6.48	Ca 12-24"	7.69	0.13
Mg 12-24"	16.50	13.67	8.83	9.60	9.48	12.80	6.73	6.81	11.35	10.40	8.98	Mg 12-24"	10.47	0.18
Cl 12-24"	43.50	45.67	28.97	40.33	35.94	46.91	25.89	26.47	39.92	42.20	41.34	Cl 12-24"	37.92	
												Total Meq		58.22
SAR 12-24"	11.74	13.69	16.18	15.14	13.03	12.56	11.76	12.86	11.99	13.08	13.10	SAR 12-24"	13.19	
CROSSf 12-24"	43.90	46.43	43.32	42.90	36.71	41.51	28.60	31.22	38.22	38.15	39.01	CROSSf 12-24"	39.09	
CROSSopt 12-24"	43.80	46.33	43.26	42.85	36.66	41.46	28.56	31.17	38.16	38.10	38.96	CROSSopt 12-24"	39.03	
EC 24-36"	8.90	6.60	7.00	6.17	6.33	5.91	4.60	5.27	6.20	7.21	5.85	EC 24-36"	6.37	
Na 24-36"	78.00	49.80	63.44	56.33	53.48	49.32	36.74	41.96	45.43	53.24	50.06	Na 24-36"	52.53	0.72
K 24-36"	2.77	2.25	1.34	0.98	1.14	0.93	0.70	0.83	1.18	0.97	0.95	K 24-36"	1.28	0.02
Ca 24-36"	12.25	10.27	7.10	5.67	8.12	5.40	3.65	4.30	7.68	5.81	5.67	Ca 24-36"	6.90	0.10
Mg 24-36"	22.50	15.03	13.37	11.03	13.29	9.83	6.26	7.78	10.63	10.83	9.52	Mg 24-36"	11.82	0.16
Cl 24-36"	79.00	52.83	37.90	51.33	51.06	46.71	33.21	36.78	43.93	57.06	51.66	Cl 24-36"	49.23	
												Total Meq		72.53
SAR 24-36"	19.27	12.86	20.09	19.38	17.38	18.02	16.83	17.34	15.45	18.64	17.06	SAR 24-36"	17.48	
CROSSf 24-36"	78.43	50.19	63.72	56.55	53.71	49.55	36.94	42.18	45.68	53.47	50.27	CROSSf 24-36"	52.79	
CROSSopt 24-36"	78.35	50.11	63.67	56.51	53.67	49.50	36.90	42.14	45.63	53.43	50.23	CROSSopt 24-36"	52.74	

PVW Site 3 Summary by Year and Entire Profile

	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	10 yr. Average	Meq/L	% Exch.
EC 1-36"	6.55	5.52	4.96	5.02	5.29	5.50	3.83	4.37	5.42	5.66	4.99	EC 1-36"	5.19	
Na 1-36"	52.33	40.49	41.34	41.67	41.08	41.26	29.68	31.88	37.36	39.39	39.75	Na 1-36"	39.66	68%
K 1-36"	2.44	1.92	1.07	0.95	1.01	0.93	0.69	0.80	1.09	0.88	0.91	K 1-36"	0.90	2%
Ca 1-36"	13.17	8.21	5.27	5.84	8.09	8.10	4.65	4.55	8.18	6.79	6.77	Ca 1-36"	7.24	12%
Mg 1-36"	18.03	11.77	8.63	9.02	10.97	11.34	6.11	6.52	9.95	9.65	9.33	Mg 1-36"	10.12	17%
												Total Meq		57.92
Cl 1-36"	51.83	40.17	25.04	36.44	40.63	43.69	26.34	27.13	36.95	42.99	42.92	Cl 1-36"	37.65	
Cl ppm	1840.0	1425.9	889.07	1293.7	1442.4	1551	935.1	963.1	1311.7	1526.0	1523.5	Cl ppm	1336.55	
SAR 1-36"	14.02	12.24	15.30	15.02	13.72	13.70	13.06	13.63	12.68	13.98	13.28	SAR 1-36"	13.69	
CROSSf 1-36"	52.73	40.87	41.62	41.89	41.29	41.46	29.88	32.10	37.59	39.59	39.95	CROSSf 1-36"	39.91	
CROSSopt 1-36"	52.64	40.79	41.56	41.84	41.25	41.41	29.83	32.05	37.53	39.55	39.91	CROSSopt 1-36"	39.85	

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