12-2010

Effect of Mica Content on Surface Infiltration of Soils in Northwestern Kern County, California

Steven Keyes Stakland
Utah State University

Follow this and additional works at: https://digitalcommons.usu.edu/etd
Part of the Agricultural Science Commons, Agronomy and Crop Sciences Commons, and the Soil Science Commons

Recommended Citation
Stakland, Steven Keyes, "Effect of Mica Content on Surface Infiltration of Soils in Northwestern Kern County, California" (2010). All Graduate Theses and Dissertations. 840.
https://digitalcommons.usu.edu/etd/840

This Thesis is brought to you for free and open access by the Graduate Studies at DigitalCommons@USU. It has been accepted for inclusion in All Graduate Theses and Dissertations by an authorized administrator of DigitalCommons@USU. For more information, please contact rebecca.nelson@usu.edu.
EFFECT OF MICA CONTENT ON SURFACE INFILTRATION OF
SOILS IN NORTHWESTERN KERN COUNTY CALIFORNIA

Steven Keyes Stakland

A thesis submitted in partial fulfillment
of the requirements for the degree

of
MASTER OF SCIENCE

in
Soil Science

Approved:

Dr. V. Philip Rasmussen  Dr. Grant E. Cardon
Major Professor  Committee Member

Dr. Ralph E. Whitesides  Dr. Byron R. Burnham
Committee Member  Dean of Graduate Studies

UTAH STATE UNIVERSITY
Logan, Utah

2010
ABSTRACT

Effect of Mica Content on Surface Infiltration of Soils in Northwestern Kern County, California

By

Steven Keyes Stakland, Master of Science

Utah State University, 2010

Major Professor: Dr. V. Philip Rasmussen
Department: Plants, Soils and Climate

A soils infiltration rate (IR) is the measured rate that soil is able to absorb water, either from precipitation or irrigation. A low IR can cause damage to crops if the necessary amount of water cannot penetrate to the plant roots in the time needed. The damage can be common in permanent plantings such as almond and pistachio orchards where regular tillage is avoided. This indicates a physical aspect to the problem - tillage increases IR. However, there is also an electrochemical side to infiltration problems because certain calcium surfactant treatments can increase IR. Various other methods have been used to increase IR such as using cover crops and increasing organic matter. Despite these different approaches to the problem, the specific cause of low IR is often unknown. This study was conducted to determine what physical properties of soils from a site in California cause low IR. This research shows the relationship of these properties to low IR.
It was assumed that high amounts of mica in the very fine sand and coarse silt fraction of soils in Northwestern Kern County, California may interact with other physical and chemical properties to reduce IR. Fourteen sites were sampled in the area near the towns of Wasco and Shafter. The soils sampled represented the typical agricultural soils of the area and exhibited three levels of infiltration, Good (no amendments), Moderate (requires gypsum), and Poor (gypsum application is insufficient). Mica percentages in the very fine sand and coarse silt were calculated using a petrographic microscope and compared to the overall IR of the fields. Mica was shown to be significant factor at all three levels of IR.
ACKNOWLEDGMENTS

This project was possible due to the generosity and support of Dr. V. Philip Rasmussen, as well as Don Sleight and Paul Genho at AgReserves, Inc. This research would not have been possible without their dedication to furthering the goodness of agriculture and education. I am extremely grateful to them. The farmers and managers of South Valley Farms near Wasco, California have been vital to the success of this project. In particular Jay Payne, Spencer Birch, Stacey Shaw, and Daryl Wilkendorf have answered questions and provided generous assistance in nearly every aspect of this research. California agriculture experts Dr. Brian Marsh, Dr. Charles Burt, and Mr. Hung Le all provided valuable assistance as well.

The Department of Plants, Soils, and Climate at Utah State University has also been essential to the completion of this project. The advice and encouragement of professors and fellow students have been a great boon throughout this entire process. Grant Cardon and Ralph Whitesides from my committee have been excellent sources of inspiration and support. Chod Stevens has been a consistent aid in every aspect of this project. Dr. Janis Boettinger provided valuable advice and equipment. Dr. Paul Grossl gave helpful comments, as did Dr. Teryl Roper. Dr. Astrid Jacobson spent time helping interpret X-ray diffractograms and the soil mineralogy of the experimental area.

My wife has been just the support I needed to finish this project. Her love, patience, and insights have sustained me throughout this complicated and sometimes intense process.

Steven K. Stakland
## CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABSTRACT</td>
<td>iii</td>
</tr>
<tr>
<td>ACKNOWLEDGMENTS</td>
<td>v</td>
</tr>
<tr>
<td>CONTENTS</td>
<td>vi</td>
</tr>
<tr>
<td>LIST OF TABLES</td>
<td>ix</td>
</tr>
<tr>
<td>LIST OF FIGURES</td>
<td>x</td>
</tr>
<tr>
<td>INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>OBJECTIVES</td>
<td>4</td>
</tr>
<tr>
<td>LITERATURE REVIEW</td>
<td>5</td>
</tr>
<tr>
<td><strong>Causes of Low Infiltration</strong></td>
<td>5</td>
</tr>
<tr>
<td>Texture</td>
<td>8</td>
</tr>
<tr>
<td>Clay: Binding of Aggregates and Influence on Crust Formation</td>
<td>11</td>
</tr>
<tr>
<td>Expanding Clays</td>
<td>19</td>
</tr>
<tr>
<td>Soil Structure</td>
<td>24</td>
</tr>
<tr>
<td>Poor Aggregate Stability</td>
<td>25</td>
</tr>
<tr>
<td>Organic Matter</td>
<td>29</td>
</tr>
<tr>
<td>Soil Compaction</td>
<td>31</td>
</tr>
<tr>
<td>Soil Crusts or Seals</td>
<td>33</td>
</tr>
<tr>
<td>Structural Crusts</td>
<td>42</td>
</tr>
<tr>
<td>Erosion Crusts</td>
<td>45</td>
</tr>
<tr>
<td>Depositional Crusts</td>
<td>46</td>
</tr>
<tr>
<td>Saline-Sodic and Sodic Soil Conditions</td>
<td>48</td>
</tr>
<tr>
<td>Fire Induced Water Repellency</td>
<td>49</td>
</tr>
<tr>
<td>Electrolytes, ESP, SAR, and EC</td>
<td>50</td>
</tr>
<tr>
<td><strong>California Infiltration Issues</strong></td>
<td>53</td>
</tr>
<tr>
<td>Sieving Crusts</td>
<td>57</td>
</tr>
<tr>
<td>Smectite Clay Content</td>
<td>57</td>
</tr>
<tr>
<td>Poor Aggregate Stability and Low Organic Matter</td>
<td>58</td>
</tr>
<tr>
<td>Hard Pans</td>
<td>59</td>
</tr>
<tr>
<td><strong>Kern County Infiltration Issues</strong></td>
<td>59</td>
</tr>
</tbody>
</table>
Hard Pans ........................................................................................................ 62  
Soil Crusts ....................................................................................................... 62  
Smectite Clay Content .................................................................................... 64  
Poor Aggregate Stability and Low Organic Matter ........................................ 64  
Mica in the Very Fine Sand and Coarse Silt Fraction of the Soil ..................... 65  

Treatments of Low Infiltration Rate ................................................................. 71  

Water Quality ................................................................................................ 74  
Cover Crops .................................................................................................... 78  
Gypsum ........................................................................................................... 80  
Polyacrylamide ............................................................................................... 85  
Surfactants ....................................................................................................... 94  
Soil Conditioners ............................................................................................ 95  
Tillage ............................................................................................................. 96  

METHODS AND MATERIALS .............................................................................. 98  

Preliminary Investigation ................................................................................ 98  

Two-Tiered Format .......................................................................................... 98  
Evaluation of Sodic and Saline-sodic Soil Conditions .................................... 101  
Water Quality ................................................................................................ 123  
Compaction Issues .......................................................................................... 124  
Texture Evaluation .......................................................................................... 125  
Clay Mineralogy Analysis and Evaluation ..................................................... 149  
Water Retention Curve Constructions and Analysis ........................................ 154  
Mica Determination ........................................................................................ 158  

Validation Study ............................................................................................. 161  

Sampling Areas ............................................................................................... 161  
Sample Collection and Preparation ............................................................... 164  

Methods .......................................................................................................... 166  

Hydrometer Texture Analysis .......................................................................... 166  
Wet Sieving ...................................................................................................... 166  
Petrographic Grain Count of Mica ................................................................... 167  

RESULTS .......................................................................................................... 169  

DISCUSSION .................................................................................................... 172  

Future Research ............................................................................................ 176
Evaluate Sprinkler Application Method ....................................................... 176
Pulsing Pattern of EC, pH and SAR through the Soil Profile ....................... 177
Quantification and Analysis of Other Types of Mica ............................... 178
Examination of Other Size Fractions ....................................................... 179
Additional Validation Studies .................................................................... 180
Verification of Crust Formation ................................................................. 181
Identifying the Mechanism of Reduced Infiltration Rate due to Mica ...... 182

CONCLUSIONS ............................................................................................................ 185

LITERATURE CITED .................................................................................................. 188

APPENDIX .................................................................................................................... 202
# LIST OF TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Average of pH, EC, and SAR of all depths for all five preliminary sampling sites</td>
<td>122</td>
</tr>
<tr>
<td>2. Texture of block 19 for 8 depths</td>
<td>126</td>
</tr>
<tr>
<td>3. Texture of block 18 site 1 for 8 depths</td>
<td>130</td>
</tr>
<tr>
<td>4. Texture of block 18 site 2 for 8 depths</td>
<td>134</td>
</tr>
<tr>
<td>5. Texture of block 17 site 1 for 8 depths</td>
<td>139</td>
</tr>
<tr>
<td>6. Texture of block 17 site 2 for 8 depths</td>
<td>144</td>
</tr>
<tr>
<td>7. Undisturbed soil and disturbed soil bulk densities as well as saturated hydraulic conductivity for blocks 17, 18, and 19</td>
<td>156</td>
</tr>
<tr>
<td>8. Organic matter for three surface depths for the five preliminary sampling sites in blocks 17, 18, and 19</td>
<td>157</td>
</tr>
<tr>
<td>9. Fourteen sites for soil sampling near Wasco and Shafter, California</td>
<td>162</td>
</tr>
<tr>
<td>10. Pairwise means comparison (Scheffe’s Test) for Mica and Infiltration</td>
<td>169</td>
</tr>
<tr>
<td>11. Pairwise means comparison (Scheffe’s Test) for Sand and Infiltration</td>
<td>170</td>
</tr>
<tr>
<td>12. Pairwise means comparison (Scheffe’s Test) for Silt and Infiltration</td>
<td>170</td>
</tr>
<tr>
<td>13. Pairwise means comparison (Scheffe’s Test) for Clay and Infiltration</td>
<td>171</td>
</tr>
<tr>
<td>14. ANOVA for mica significance</td>
<td>171</td>
</tr>
<tr>
<td>15. Confidence intervals for mica, silt, clay, and sand</td>
<td>171</td>
</tr>
<tr>
<td>16. Types of mica and their chemical formulas</td>
<td>178</td>
</tr>
</tbody>
</table>
## LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Picture showing the three preliminary research orchards, their relation to each other and relative IRs</td>
<td>100</td>
</tr>
<tr>
<td>2. Incremental pH values taken every 5cm to a depth of 102cm from block 17 site 1</td>
<td>104</td>
</tr>
<tr>
<td>3. Incremental pH values taken every 5cm to a depth of 102cm from block 17 site 2</td>
<td>105</td>
</tr>
<tr>
<td>4. Incremental EC values taken every 5cm to a depth of 102cm from block 17 site 1</td>
<td>106</td>
</tr>
<tr>
<td>5. Incremental EC values taken every 5cm to a depth of 102cm from block 17 site 2</td>
<td>108</td>
</tr>
<tr>
<td>6. Incremental SAR values taken every 5cm to a depth of 102cm from block 17 site 1</td>
<td>109</td>
</tr>
<tr>
<td>7. Incremental SAR values taken every 5cm to a depth of 102cm from block 17 site 2</td>
<td>110</td>
</tr>
<tr>
<td>8. Incremental pH values taken every 5cm to a depth of 102cm from block 18 site 1</td>
<td>111</td>
</tr>
<tr>
<td>9. Incremental pH values taken every 5cm to a depth of 102cm from block 18 site 2</td>
<td>113</td>
</tr>
<tr>
<td>10. Incremental EC values taken every 5cm to a depth of 102cm from block 18 site 1</td>
<td>114</td>
</tr>
<tr>
<td>11. Incremental EC values taken every 5cm to a depth of 102cm from block 18 site 2</td>
<td>115</td>
</tr>
<tr>
<td>12. Incremental SAR values taken every 5cm to a depth of 102cm from block 18 site 1</td>
<td>117</td>
</tr>
<tr>
<td>13. Incremental SAR values taken every 5cm to a depth of 102cm from block 18 site 2</td>
<td>118</td>
</tr>
<tr>
<td>14. Incremental pH values taken every 5cm to a depth of 102cm from block 19</td>
<td>119</td>
</tr>
</tbody>
</table>
15. Incremental EC values taken every 5cm to a depth of 102cm from block 19 ........ 120
16. Incremental SAR values taken every 5cm to a depth of 102cm from block 19 ..... 121
17. Graph showing the change in sand percentage with depth of the soil at block 19 .. 127
18. Graph showing the change in silt percentage with depth of the soil in block 19 .... 128
19. Graph showing the change in clay percentage with depth of the soil in block 19 ... 129
20. Graph showing the change in sand percentage with depth for the soil at block 18 site 1 ......................................................................................................................... 131
21. Graph showing the change in silt percentage with depth for the soil at block 18 site 1 ......................................................................................................................... 132
22. Graph showing the change in clay percentage with depth for the soil at block 18 site 1 ......................................................................................................................... 133
23. Graph showing the change in sand percentage with depth for the soil at block 18 site 2 ......................................................................................................................... 135
24. Graph showing the change in silt percentage with depth for the soil at block 18 site 2 ......................................................................................................................... 137
25. Graph showing the change in clay percentage with depth for the soil at block 18 site 2 ......................................................................................................................... 138
26. Graph showing the change in sand percentage with depth for the soil at block 17 site 1 ......................................................................................................................... 140
27. Graph showing the change in silt percentage with depth for the soil at block 17 site 1 ......................................................................................................................... 142
28. Graph showing the change in clay percentage with depth for the soil at block 17 site 1 ......................................................................................................................... 143
29. Graph showing the change in sand percentage with depth for the soil at block 17 site 2 ......................................................................................................................... 145
30. Graph showing the change in silt percentage with depth for the soil at block 17 site 2 ......................................................................................................................... 147
31. Graph showing the change in clay percentage with depth for the soil at block 17 site 2 ......................................................................................................................... 148
32. Texture triangle showing the distribution of soil texture results for all five preliminary sampling sites ................................................................. 149

33. X-Ray diffraction graph showing the principal peaks indicating smectite clay content in blocks 17, 18, and 19 ................................................................. 151

34. X-Ray diffraction graph showing the principal peaks indicating smectite clay content in blocks 17, 18, and 19 ................................................................. 152

35. Water retention curves for almond blocks 17, 18, and 19 ................................. 158

36. Map of soil types and sampling sites ................................................................. 163

37. Map showing 12 collection points within sampling sites 17 North West, 17 South West, and 18 North West ................................................................. 165

38. Maps of sampling sites with collection points ............................................. 203-210
INTRODUCTION

Infiltration or, more specifically, infiltration rate (IR) is an important process in the hydrological cycle because it determines the supply of water to the soil profile as well as the amount of runoff and soil erosion (Lado et al., 2005). IR measures the amount of water passing through the soil and is an indication of the total available pore space and pore conductivity. It is important to conserve agricultural water to the maximum extent possible (Howells et al., 1984). It is also essential that crops receive adequate water to be profitable. One significant way to achieve this is by increasing IR, thereby preventing excessive runoff and loss by evaporation from areas of standing water (Howells et al., 1984). Runoff control is important because it is directly related to erosion. The results of Norton et al. (1986) from image analysis and of Le Bissonnais et al. (1989) from mercury porosimetry support a theoretical conclusion that if all of the soil pores are less than 15µm infiltration will cease. As the amount of pore space decreases, the IR decreases until the steady state infiltration of a sealed soil is reached, which will be less than that from reduction in soil water gradient alone (Green et al., 2000).

A distinction between hydraulic conductivity (HC) and IR determinations is essential. HC is usually measured under conditions where the soil surface is not disturbed (Levy and Van Der Watt, 1990). HC is a function of the pore volume, size and geometry, large pores being associated with greater conductivity. Such factors as texture, mineralogy, size and strength of aggregates, and history determine the pore characteristics (Mitchell, 1986). Techniques for measuring IR are cumbersome, consume time, and require special equipment. The results are often difficult to interpret because of the large variability of IR from one place to the next in an irrigated field. Variable soil
types, surface soil textures, water content, chemistries, and traffic patterns all affect IR. The large number of way these factors can interact makes it nearly impossible to measure IR and determine a rate representative of a field (Oster et al., 1992). Oster et al. (1992) does not recommend measuring IR as a diagnosis technique. They indicate that measuring soil water content or soil strength with a penetrometer before and after irrigation is preferable. This is primarily because considerable surface disturbance occurs when IR is measured, especially when precipitation is involved, which leads to crust formation at the soil surface and thus to different water-transmission properties of the crusted layer compared with the underlying soil (Levy and Van Der Watt, 1990). The research done in this thesis does not use IR measurements. Instead observations of how long water takes to infiltrate, the length of time water remains ponded on the surface and the level of chemical treatment required are used to determine three levels of infiltration: Good, Moderate and Poor.

The IR of a naturally porous body depends on its sorptivity and saturated hydraulic conductivity, which in turn is a function of the intrinsic permeability of the medium and the fluidity of the penetrating liquid (Hillel, 1980). At the initial stages of infiltration, soil sorptivity is the primary factor affecting IR; but at prolonged infiltration times, the hydraulic conductivity becomes the controlling factor (Chunye et al., 2003).

The hypothesis of this thesis is that variation in mica content, particularly in the very fine sand and coarse silt fraction of the soil may interact with other soil properties and has an effect on the IR of soils near Wasco, California. The null hypothesis that will be attempted to be proved is that variation in mica content does not interact with other
soil properties to influence hydraulic properties and thus has no effect on surface infiltration.
OBJECTIVES

The primary objective of this research was to determine if mica content in the very fine sand and coarse silt of soil in northwestern Kern County California was a significant factor in the overall IR of the soil. Included in this main objective were five questions:

1. Does an increased amount of mica decrease IR in comparable soils?
2. What effect does the relationship between clay content and mica have on IR?
3. What effect does the relationship between silt content and mica have on IR?
4. What effect does the relationship between sand content and mica have on IR?
5. What are possible ameliorative treatments for soils in Northwestern Kern County that have low IR?
LITERATURE REVIEW

Causes of Low Infiltration

Slow infiltration can develop in sandy loam soils with low organic matter content (Singer and Oster, 1984). Low infiltration in medium and coarse textured soils can be caused by restrictive layers at the surface (crusts, seals) or below the surface (compacted layers, hard pans, fine-textured strata, cemented layers). It can also result from dispersion of the fine particles due to sodicity, or lack of sufficient divalent cations such as calcium (Oster et al., 1992). Many soil properties are known to influence the HC and IR of soils. Organic matter and iron oxides, clay mineralogy, texture, and exchangeable cation composition have all been studied. With regard to the latter, the effect of adsorbed potassium on the hydraulic properties of soil is controversial because results vary or conflict, possibly due to differences in clay mineralogy and sample preparation procedures (Levy and Van Der Watt, 1990). Lado and Ben-Hur (2004) found that examination of the differences in texture, exchangeable sodium percentage (ESP), organic matter and pH of various soils could not explain the differences in the final IR values between the stable and the unstable soil groups. This led to the important conclusion that it was the mineralogy of the clay fraction that was the deciding factor in reduced IR between the soils studied.

Baumhardt et al. (1992) showed that infiltration processes measured in the field are dependent on the soil salinity and sodicity and the salinity of the applied water. This leads to the conclusion that the permeability of a soil to water depends both on its ESP and on the salt concentration of the percolating solution. The permeability tends to
decrease with increasing ESP and decreasing salt concentration (Quirk and Schofield, 1955; McNeal et al., 1968). IR is much more sensitive to the ESP of the soil than is the hydraulic conductivity (Agassi et al., 1981). IR decreases because the clay disperses and clogs the soil pores and aids in sealing the soil.

Another essential soil property affecting IR is the structure of the soil and aggregate stability. These two factors are listed among the most important soil quality indicators in part because of their relation to IR (Doran and Parkin, 1996). Poor soil structure and aggregate stability can lead to a number of problems, most importantly soil sealing or crusting. Green et al. (2000) found that the decrease in IR was due to the formation of a surface seal caused by the physical breakdown of aggregates and clay dispersion. Deterioration in soil structure may take place even when irrigating non-sodic soils with waters of low sodium absorption ratio (SAR) and salinity. Because of crust formation, the resultant IR tends to decrease to a minimum value irrespective of the initial soil moisture content (Abu-Sharar and Salameh, 1995). Lado and Ben-Hur (2004) also found that a decrease in IR at the surface was due to seal formation.

As noted by Feng et al. (2002), water-repellent soils are found throughout the world and their repellency affects IR. They defined a water-repellent soil as one that does not wet spontaneously when a drop of water is placed upon the surface. A positive pressure (water-entry pressure head, hp) must be applied to force water into the soil (Feng et al., 2002). Contreras et al. (2008) emphasized that soil moisture content is also an important factor explaining water repellency. They explained that it would be expected to be higher in aridic or dry soils than in humid soils.
There are also many other factors that can lower IR. Chunye et al. (2003) found that the temperature of infiltrating water is related to IR because its viscosity changes by ~2% per degree Celsius. This leads to an estimated 40% change of IR between summer and winter in arid zones (Chunye et al., 2003). Abu-Sharar and Salameh (1995) emphasized the sensitive nature of IR to any disturbance in surface soil structure. This would include compaction, planting patterns, crop, and cultivation. Mitchell (1986) found that for a clay soil the final IR is not a function of initial IR, indicating that the surface layer is not the zone controlling the IR. This means that the specific properties of the clay mineralogy may change with exposure to water and lower IR – such as a swelling smectite clay.

Low IR can make irrigation more difficult and expensive (Trout et al., 1990). Low infiltration on level surface irrigated fields can result in crop damage due to standing water or inadequate aeration in the root zone, and can result in algae growth on the soil surface that further lowers infiltration. Reducing sprinkler or microirrigation application rates usually increases system costs. Water standing on the soil surface increases evaporation losses (Trout et al., 1990). Oster et al. (1992) explain that in order to reduce the harmful effects of low IR, irrigation should be stopped when ponding or runoff begins. This is aimed to prevent erosion and deep pools that will take even longer to evaporate. If final IR increases, the erodibility factors decrease exponentially due to less runoff (Ben-Hur et al., 1992).

Oster et al. (1992) explain that as a rule all water should infiltrate within 24 to 48 hours. Longer periods of ponding increase the potential for disease and poor aeration. Because infiltration varies from place to place, within a field, more water must be applied
than is needed by the crop to assure adequate irrigation (Oster et al., 1992). Application of about 20% more water than needed by the crop compensates for infiltration variability. However, this increase may cause ponding in areas where IR is lowest. As emphasized by Trout et al. (1990), slow IR can make irrigation more difficult and expensive. This is because IR slower than sprinkler or drip emitter application rates results in water ponding and reduced application uniformity. Water standing on the soil surface can increase evaporation losses. Wet surface soil increases weed growth, changes the weed species mix, and delays access to the field (Ajwa and Trout, 2006).

The remainder of this chapter reviews literature dealing with the major causes of reduced IR. Many of these causes have already been mentioned but each will be described in more detail. Specific emphases will be given to aggregate stability and crust formation as affected by soil and water EC, SAR, and ESP. Next, specific problems with IR in California will be examined. Then the IR problems and causes found in the immediate area where this research took place, Kern County California will be discussed. After this, a chapter on the examination of the various treatments used to increase IR is included. This chapter, the last of the literature review, is a vital portion of this review as it sets the stage for how this research project fits into the overall understanding of reduced IR.

**Texture**

Wakindiki and Ben-Hur (2002) found that soil texture has a substantial effect on aggregate stability and that it therefore influences IR. Thus, texture is similarly relevant with regards to IR in an irrigated cropland. Ben-Hur et al. (1985) reported that the texture of soils also affects the rate of crust formation. Crusts can drastically reduce IR and their
relation to texture is essential. This means that certain soils will not form crusts due to their texture while others will. Indeed, texture can be the factor that determines whether or not a soil will crust. The crusting potential of soils is usually expressed in terms of their silt and clay content. A study by Bielders and Baveye (1995) provides some indication that the textural composition of the sand fraction may play an important role as well. Since soil texture can determine IR, it is also a key factor in erosion (Morgan, 1986).

Texture is determined by the relative percentages of sand, silt and clay. As Eshel et al. (2004) stated, particle-size distribution is one of the most fundamental physical properties of a soil. They emphasized that texture strongly affects many physical and chemical soil properties. Their research also showed that texture, determined from particle-size distribution, can be used to predict the hydraulic properties of the soil.

Ajwa and Trout (2006) raised a concern with high clay content in soils when they found that slow infiltration is commonly associated with fine-textured soils. Typically clay is associated with those soils that have low IR. However, clay is the most important soil texture fraction controlling structural stability (Gollany et al., 1991; Canton et al., 2009). This means that both having too much clay and not enough can result in reduced IR. Bielders and Baveye (1995) showed that the movement of the clay during soil forming processes effects IR. They stated that the intensity of clay illuviation is inversely proportional to sand particle size and is shown to be determined by both rainfall and drop kinetic energy. Thus the amount of rain or irrigation and the force exerted by the impact of the drops are important to both the relation of clay to crust formation and clay movement in clogging soil pores.
Research by Green et al. (2000) shows that soil texture (specifically the clay content) is one of the dominant factors in controlling seal formation. While some soils, such as a Heiden clay, that has a high clay content of 570 g kg\(^{-1}\), also has a strong resistance to seal formation. This is because soils with high clay content have aggregates that are more cemented from clay bonds than soils with lower clay percentages. On the other hand, soils that are very low in clay do not have as much clay to disperse and consequently are less likely to form surface seals and crusts.

Yu et al. (2003) found that the impact of raindrops combined with the absence of electrolytes in the rainwater was enough to form a seal with less than 40 mm of rain. They found that soils which contain 22% clay, 36% silt, and less than 1% organic matter have an unstable structure and are susceptible to sealing (Ben-Hur et al., 1985; Mamedov et al., 2001). Likewise, Ben-Hur et al. (1985) found that a soil with 22% clay and high silt content was more susceptible to sealing than soils with 40% clay. In the same study Loamy soils with 20% clay were found to be the most susceptible to crust formation and to have the lowest final IR with waters of different EC and quality (Ben-Hur et al., 1985). However, in arid areas, where soil organic matter is normally low, sandy loam soils also can develop low infiltration. It can also result from dispersion of the fine particles due to sodicity, or lack of sufficient divalent cations such as calcium. This is the case in some areas of the California San Joaquin Valley (SJV).

The research performed in this thesis project focuses on the importance of a single constituent of a portion of the very fine sand and coarse silt fraction of the soil. Because of its unique properties and abundance in the soils of the SJV of California, mica is being singled out for examination in the very fine sand and coarse silt fraction of the soils.
studied. In relation to texture, Eshel et al. (2004) found that mica slightly affects particle size determination between the various methods. This is because mica tends to have a thin wafer-like shape, especially in the sand and silt fractions of the soil, and is not remotely round as is generally assumed when determining particle size. The shape of mica is important as well as the size of the grains. Le Bissonnais (1996) found accuracy in determining texture depended on the settling velocity of the soil fragments. This settling velocity is closely related to the size of the particles. Vibratory separation methods rely on the shape of mica, but this property is overwhelmed by the effects of relative size. In addition to these concerns with mica and texture classification Harris et al. (1984) found that the engineering properties of coarse-textured soils may be significantly affected by the presence of sand-sized mica. In particular, the ability to compact soils was decreased due to the presence of mica. There will be significantly more to say about the effects of mica on IR, but for now it is important to note the role that it plays in the texture of the soil.

**Clay: Binding of Aggregates and Influence on Crust Formation**

One of the most important aspects of soil clay is its ability to increase aggregate stability (Jacks, 1963). Lado and Ben-Hur (2004) found clay mineralogy to be a dominant factor in controlling aggregate stability. Indeed, aggregate stability increases with increasing clay content (Kemper and Koch, 1966). Green et al. (2000) and Gal et al. (1984) explained that soils with high clay content are cemented together from the clay bonds giving them better stability. According to Gollany et al. (1991) and Canton et al. (2009), clay is the most important fraction controlling structural stability. Le Bissonnais
(1990) has shown that the size and resistance of clay bonds between skeleton grains increases with overall soil clay content. Further research by Le Bissonnais (1996) indicated that the clay volume and the resistance of clay bonds between skeleton grains increase with clay content, so the elementary assemblages of primary particle are bigger. Thus, more clay leads to not only stronger aggregation, but larger soil aggregates. Furthermore, breakdown of soil aggregates by slaking decreases as clay content increases, whereas breakdown by differential swelling increases with increasing clay content. Wakindiki and Ben-Hur (2002) explained that soil mineralogy, i.e. type of clay, and amount of clay have a substantial influence on aggregate stability and, therefore, cause changes in IR. They go on to say that in spite of the dominant affect of soil mineralogy on soil dispersivity and aggregate stability, little is known about its affects on seal formation and micromorphology, runoff and soil loss.

In 1958, McIntyre stated that the nature and significance of some crusting processes are still not fully understood, particularly the formation and dynamics of clay seals. However, Mermut et al. (1995) found that clay content and mineralogy of clay-sized, inorganic particles are among the most significant factors that control the nature and extent of soil seal and crust development. This is because surface soils are essentially clay or mineral-organic complex systems (Theng, 1982). Moldenhauer and Kemper (1969) found that increasing clay content promoted crust formation. In contrast, Le Bissonnais (1990) showed that low clay and organic matter in a soil can indicate a likelihood of crust formation and decreased IR without tilling due to the decrease in aggregate stability of such soils. Thus, it is important to realize that there is no definitive determination as to the exact relationship between the total amount of clay in a soil and
the effect it has on IR. This is because clay can react differently in different conditions. High clay may encourage aggregate stability which when combined with other factors promotes good IR. However, high clay can also lead to soil seals. In contrast low clay can lead to aggregate instability and crust formation. This seeming paradox will be discussed below.

Research by Fox and Bryan (1992) found that soil crusts are generally thin, less than 0.5 cm thick, and frequently develop on soils with unstable aggregation and low organic contents, particularly when associated with swelling clays and high exchangeable sodium percentages. McNeal and Coleman (1966) suggested that the reduction in the permeability was due to clogging of conducting pores either by in situ mineral swelling or by migration of clay platelets that accumulated and decreased the pore size. Ben-Hur et al. 1985 explained that the formation of a soil crust should be slowed down by an increase in clay content because one of the main factors affecting crust formation is the destructive impact of drops and how wetting affects aggregates. With high clay content the impact damage is lessened as is the damage done by wetting. These effects would slow down or prevent crust formation. According to Morin et al. (1981) the sealing efficiency of the crust is achieved by suction forces that result in the orientation of clay particles into a continuous dense skin.

Lado and Ben-Hur (2004) showed that one important characteristic of clays that controls the aggregate stability is their capacity to disperse. Dispersion of clays occurs when the attractive forces between the clay particles are not strong enough to hold them together under wetting conditions. This dispersion occurs when the electrolyte concentration of the solution decreases below the flocculation value. Indeed, according to
Pupisky and Shainberg (1979), dispersion of the clay particles is possible only when the concentration of the soil solution drops below a threshold concentration at which the clay platelets flocculate. Emerson and Bakker (1973) explained this dispersion process further by suggesting that two conditions favor dispersion and migration of sodium and calcium clays. The first is that the concentration of the soil solution drops quickly below the threshold concentration at which the clay platelets flocculate. The second condition is that a steep salt gradient exists between the dilute solution in the soil pores and the concentrated solution in the micropores inside the aggregate. This salt gradient will cause osmotic water movement into and destruction of the aggregate. At the front of the displacing solution, these two conditions exist and extensive clay dispersion takes place.

Shainberg and Singer (1986) explained that when the electrolyte concentration of the suspension exceeds the flocculation value of the clay, the clay platelets form floculi that settle with a random orientation and open structure. Conversely, when the electrolyte concentration is below the clay flocculation value, the dispersed clay platelets settle into a compact crust with parallel orientation of clay platelets. Some of the clay particles may penetrate slightly into the soil pores beneath the crust and clog these pores (Shainberg and Singer, 1986). Abu-Sharar and Salameh (1995) showed that this process of clay dispersion and the subsequent surface crust formation plays an effective role in the reduction of IR only when electrolyte concentration of the permeating solution drops well below the corresponding critical salt coagulation concentrations (CCC) of the soil-clay.

This means that clay dispersion is a function of a soil’s exchangeable sodium percentage (ESP) (Lentz et al., 1996). Oster and Schroer (1979) showed that IR is very sensitive to the ESP and the salt concentration of the applied water. Thus, clay dispersion
in the soil surface (and crust formation) is enhanced by both the impact of the raindrops and the potential of the soil clays to disperse (Keren and Shainberg, 1981). Green at al. (2000) studied the necessary amounts of clay in the soil to cause a seal and found that soils very low in clay do not have as much clay to disperse and cause a surface seal. Felhendler et al. (1974) found that clay dispersion in soils with low silt content was more pronounced than in soils with similar ESP and clay mineralogy, but with higher silt content. This means that high silt content may interact with clay dispersion to offset its effect of lowering IR by crust formation.

Dispersion of clay also leads to more turbid runoff water. Quirk and Schofield (1955) showed that reduction in HC is due mainly to swelling and dispersion of clay. Lado and Ben-Hur (2004) showed that when the clay fraction at the soil surface is dispersed, the clay percentage in the sediments should be higher than that in the original soil. This is because the clay particles are more easily transported by the overland flow than the bigger silt and sand particles. This means that dispersed clay is most easily eroded and the suspended fine clay particles in the permeating water have the ability to flocculate and clog conducting pores in the soil, when they come out of suspension.

It is evident that clay content has a paradoxical effect on soil IR. There seems to be a delicate balance between having too much clay and not enough. This is particularly evident when it comes to crust formation. For example, if a soil has very low clay content it will not be able to form a crust. However, if it has a little more it will crust much more than a soil with a high clay percentage. This is because a soil with ample clay will have higher aggregate stability and thus will not slake and disperse to form a crust. Ben-Hur et al. (1985) explained this paradox by suggesting that in soils containing more than 20%
clay, the clay fraction acts as a cementing material, stabilizing soil aggregates against the beating action of raindrops and so preventing crust formation. On the other hand, in soils containing less than or right at 20% clay, the clay acts as a substrate for crust formation, decreasing the steady-state HC of the crust (Wakindiki and Ben-Hur, 2002). Ben-Hur et al. (1985) showed that soils with 22% clay and high silt content were more susceptible to sealing than the soils with 40% clay. In their study, Green et al. (2000) determined that the amount at which soils are most susceptible to seal formation from rainfall is when their clay content is 200 g kg⁻¹. They observed a decrease in saturated hydraulic conductivity as clay content increased up to 200 g kg⁻¹ while an increase in clay content above 200 g kg⁻¹ resulted in an increase in saturated HC.

There are some important things to note about the interaction and relationship of mica fragments and clay. Clay is formed from mica and, as Kishk and Barshad (1969) show, clay vermiculite forms by the alteration of biotite, muscovite, or chlorite. Morras (1995) explained that both mica and mica grains undergo a transformation process as do clay particles, clay aggregates, weathered feldspars, silt grains with neoformed fibrous clays and weathered biological silica particles. This transfer of weathered material back and forth between the silt (depending on its mineralogy) and the clay contributes to raising the CEC of silt. Norton (1987) showed that soils which have a substantial amount of water-dispersible clays and 2-10 µm silts have slower final IR than those that are coarser. This is an important study to note since this thesis research seeks to determine if the constituents of the coarse silt (and very fine sand) have an effect on IR. Wakindiki and Ben-Hur (2002) explain that the surface charges of quartz and feldspar, which are the dominant minerals in many soils, are close to zero. By contrast, mica has a negative
surface charge and thus interacts differently than other minerals when exposed to the same materials.

There has already been some discussion of the affect clay mineralogy has on IR. That is, different clay types exhibit different reactions with water that influences their tendency to disperse, swell, crack, and from crusts. The relative amounts of the different types of clays also change the soil’s response to water. As explained by Ben-Hur et al. (1992), soil crust formation depends on clay mineralogy and exchangeable ion composition. Six et al. (2000) studied how mineralogy affected soil stability. Wakindiki and Ben-Hur (2002) showed that the amount of splash which aids in dispersion, erosion and crust formation was about four times greater with a loamy soil, in which smectite, mica, and vermiculite were the dominant clays, than with a silt loam soil, in which vermiculite, mica and kaolinite dominated. These results show the importance of texture and the effects of clay mineralogy. McNeal and Coleman (1966) found that increasing the SAR and decreasing the electrolyte concentration of the percolating solution induced a decrease in soil permeability. Such changes were more pronounced in soils containing expandable 2:1 layer silicates, especially montmorillonite clays, than in soils containing kaolinite or sesquioxides. Velasco-Molina et al. (1971) found that montmorillonitic soils and micaceous soils disperse more in weak salt solutions at low SAR values than do the kaolinitic soils high in iron oxide. Kaolinitic soils are considered to be stable soils that do not disperse easily (McNeal and Coleman, 1966; El-Swaify and Swindale, 1969). Six et al. (2000) showed that in 2:1 clay-dominated soils, soil organic matter (SOM) is a major binding agent because polyvalent metal-organic matter complexes form bridges between the negatively charged 2:1 clay platelets. Furthermore, Lado and Ben-Hur (2004)
reported that the differing morphologies of smectite, illite and kaolinite lead to differing packing of their tactoids, so that they form clay aggregates that differ in their stability. These clay aggregates are the essential components of soil structure and are a key factor in the affect of clay on IR.

Levy and Van Der Watt (1990) showed that an increase in the amount of potassium in the exchangeable phase resulted in a decrease in both the HC and IR of the soils. They explained that the effect of adsorbed potassium on the hydraulic properties of soil is controversial because results vary or conflict, possibly due to differences in clay mineralogy and sample preparation procedures. Relating to the mineralogy of the soils, the effects of potassium were smallest in the kolinitic soils where the iron oxides could have had some overriding stabilizing effect, and biggest in the illitic soil (Levy and Van Der Watt, 1990). They showed that exchangeable potassium cannot be grouped together with either calcium or sodium as ions having similar effects on the hydraulic properties of soils. This is because exchangeable potassium was not as efficient as exchangeable calcium in maintaining high permeability in soil, yet potassium did not have as adverse an effect as exchangeable sodium on the permeability. They concluded that potassium has an intermediate effect on IR and HC, between those of exchangeable calcium and sodium. The more favorable effect of exchangeable potassium on the HC compared with exchangeable sodium was not caused indirectly by a higher EC in the soil solution and hence limited clay dispersion, but was due to a direct positive effect of potassium on stabilizing the soil aggregates. This direct positive effect of potassium may result from lower hydration energy compared with that of sodium, and consequently a reduction of clay dispersion. Their research also emphasized the importance of clay type and amounts.
They found that the presence of a significant amount of smectite (20%) in one of the kaolinitic soils studied may account for the high susceptibility of this soil to crust formation with an increase in exchangeable potassium (Levy and Van Der Watt, 1990).

Shainberg et al. (1987) studied the affect of exchangeable potassium on the HC of smectitic sand mixtures and concluded that the effect of potassium on the HC depended on the charge density of the smectitic clay. They found that the higher the charge density of the clay, the more favorable the effect of exchangeable potassium on the HC. They thus postulated that the low hydration energy of potassium cations coupled with stronger electrostatic attraction forces between the clay platelets, which occur in the smectite with high charge density, account for the inefficiency of exchangeable potassium to disperse smectite. Levy and Van der Watt (1990) explained that the adverse effect of exchangeable potassium on the HC of an illitic soil, compared with the other kolinitic soils, could be attributed to the higher susceptibility of illite to swelling and dispersion compared with kaolinite (McNeal and Coleman 1966; Velasco-Molina et al., 1971).

**Expanding Clays**

Smectite, similar to overall soil clay content, exhibits paradoxical phenomenon when it comes to its affect on IR. This section of the literature review seeks to explain the various studies that have been done on the affect of smectite with regards to IR. The literature does not resolve the issue and there seems to be significant disagreement to the overall affect of smectite on IR.

Typically smectite is thought to lower IR because of its swelling properties. However, it is also a shrinking clay that causes surface cracking when dried, and in turn, greatly increases IR on subsequent wetting. Le Bissonnais (1996) showed that breakdown
by slaking decreases as clay content increases, whereas breakdown by differential swelling increases with increasing clay content. This second effect can be attributed to the clay type. Lado and Ben-Hur (2004) observed from their study that smectite probably decreased aggregate stability. Decreased aggregate stability leads to crust formation and lower IR. They showed that the soil mineralogy affects the size and density of the detached particles, and this leads to increased soil loss in smectitic soils.

Lado and Ben-Hur (2004) explained an important difference in smectite clays as compared to illite clays. The main difference between illite and smectite is in the isomorphic substitutions. In illite, most of the substitutions take place in the tetrahedral sheet, where the Si\(^{4+}\) is substituted by Al\(^{3+}\), leading to a negative charge on the planar surface. They also went on to show that in the smectite group, of which montmorillonite is one of the most common clays, the isomorphic substitutions occur in both the octahedral and the tetrahedral sheets. In this case, water molecules and exchangeable cations can penetrate between adjacent layers (Lado and Ben-Hur, 2004). This penetration of water between the layers of the clay particles gives it the distinctive ability to swell and shrink relative to its exposure to water. Clay mineralogy and smectite determination is essential to defining soils as stable or not (Lado and Ben-Hur, 2004). They went on to suggest that kaolinitic and illitic soils that do not contain any smectite, or in which the smectite level is below the detection threshold, are stable soils that are less susceptible to seal formation. Conversely, soils which contain enough smectite (greater than 5%) and can be clearly detected by X-rays are unstable and are as susceptible to seal formation as the smectitic soils. Due to the instability of smectite soils erosion is typically high as shown by Mermut et al. (1997).
There are some unique attributes to the morphology of smectite clays. Smectite has been found to be unstable in the chemical environment of certain irrigated soils. Apparently, the dissolution of smectite resulted in the formation of kaolinite in some irrigated soils as shown by Lado and Ben-Hur (2004). It was also found that smectite minerals were unstable in the reclaimed sodic/saline soils and were transformed to kaolinite. Thus reclamation of certain soils from saline and sodic conditions may have a secondary effect of making them less susceptible to future infiltration problems due to the transformation of smectite to a stable clay (Amundson and Lund, 1985).

Oster et al. (1992) explained that in California, soils high in silt and sand or low in swelling clays have low shrink-swell properties. Surface crusts that form on these soils do not crack upon drying. Cracks are extremely important for increasing the initial entry of water into dry crusted soils. They increase the total surface area for infiltration 3 to 5 times. The lack of cracks is one reason soils along the east side of the Central Valley have low water intake rates. There, the lack of smectite and the predominance of clay minerals like hydrous mica (illite) and vermiculite (both of which do not swell upon wetting or shrink upon drying) helps to explain why soil crusts in certain regions of California are so effective at lowering IR. In contrast the intensive swelling and shrinking of montmorillonite resulted in many cracks in the crust. Conversely, in vermiculite soil these processes are limited. Thus the clay type will determine the stability of a soil crust (Ben-Hur et al., 1989). This means, as emphasized by Ben-Hur et al. (1989), that it is important to prevent the formation of crusts at the beginning of the irrigation season on soils dominated by non-swelling clays.
A study by Mermut et al. (1995) emphasized, again, that the mineralogy of clay-sized particles is one of the major factors that determine the nature of soil crusting. Wakindiki and Ben-Hur (2002) found that soils in which either kaolinite or illite predominated, but which contained small amounts of smectite, were as susceptible to crust formation as smectitic soils. This means that though shrinking/swelling clays may help to break up crusts, they may not be immune to their formation under certain conditions. For example, highly expansive smectite clay in the soil caused a rapid reduction in the IR despite a high organic C content and the coarse texture of the soil. This factor, the mineralogy of the soil, caused the formation of a crust and outweighed factors that tend to prevent crust formation. This, again, emphasizes the importance of soil mineralogical constituents for crust development (Wakindiki and Ben-Hur, 2002). Crusts formed in smectite soils have been shown to be greater than 0.2 mm thick and included a highly developed washed-in zone (Lado and Ben-Hur, 2004). This means that soil crusts formed on smectite soils have the potential to significantly reduce IR.

Levin et al. (1991) explained that some soils were considered more stable due to high smectitic clay content. Wakindiki and Ben-Hur (2002) showed that montmorillonitic soils had the lowest aggregate stability. The amount of shrinking and swelling clay in a soil has been deemed an important contributing factor to soil stability. Levin et al. (1991) went on to show that cultivated smectitic soils from semiarid regions have an unstable structure that results in poor infiltration and high levels of runoff when exposed to rain. Ajwa and Trout (2006) explained that slow infiltration in medium and coarse-textured soils in California can be caused by swelling of smectite clays with wetting. Thus wetting was the key factor to changing the stable smectite soil to one considered unstable.
Therefore, it seems that soils with smectite, when wetted, exhibit those features that will identify them as being unstable.

As noted by Ben-Hur et al. (1989), it is the intensive swelling and shrinking of montmorillonite that results in many cracks in the surface crusts. Thus, though the swelling of these clays may decrease IR on wetting, their shrinking properties increase IR on drying. Whether or not the one effect outweighs the other has not from my review of the literature been determined. However, Mermut et al. (1995) have shown that drastic reduction in infiltration, especially with high rainstorm intensity (after 7-8 min), was attributed mainly to the swelling of smectite in this soil material. This seems a remarkably fast response to wetting and, given the likelihood that irrigation events and rain storms typically last much longer, it could be assumed that the reduction in IR due to the swelling of smectite clays is greater than the increase of IR due to cracking caused by shrinking after drying since it is only operable for a short period.

Norton et al. (1993) explained that the dispersion of soils by rainwater and subsequent surface sealing is a well know phenomenon in smectitic soils of semiarid regions. Indeed Wakindiki and Ben-Hur (2002) are adamant that smectite soils are the most dispersive of all soils. Lado and Ben-Hur (2004) show that this is because smectite units are held together in tactoids -- face-to-face and/or edge-to-face orientation. In the former orientation, weak Van der Walls’ forces maintain the interactions, and by polyvalent metal ions that form bridges between the negative charged clay platelets. However, the penetration of water between the clay platelets, and the weakness of the edge-to-face interactions in smectite enhance its dispersivity (Lado and Ben-Hur, 2004). Such is the affect of smectite on the dispersive attributes of certain soils it was even
found by Lado and Ben-Hur (2004) that small amounts of smectite may impart dispersive properties in other clay types. This mechanism explains the greater decrease in IR in the soils, which contained smectite than those that did not. This means that in the absence of smectite, the stabilizing effect of kaolinite in reducing seal formation is more pronounced (Lado and Ben-Hur, 2004). Ben-Hur et al. (1985) found that this dispersive mechanism of smectite clay is so strong, due to its decrease of the electrolyte concentration at the soil surface when water is present from rain or irrigation, that it can even lower it enough to produce clay dispersion in calcareous soils. Thus, soils with a high amount of smectite can exhibit reduced IR due to the sealing nature of these soils and the swelling of the clay to fill conducting pores.

**Soil Structure**

Six et al. (2000) state that soil structure determines overall soil porosity and IR. They emphasize that this means soil structure determines water availability to plants and soil erosion susceptibility. As shown above, clay is the most important fraction controlling structural stability (Gollany et al., 1991; Canton et al., 2009). Gillot (1973) showed the importance of soil microstructure and explained that it is a function of water content. Microstructure is relevant when considering the aggregates formed from clusters of clay particles.

Amundson and Lund (1985) emphasized in their work on reclaiming saline-sodic soils in the SJV of California that soil structure has a dominant influence on HC. HC and the infiltration capacity of soils are governed to a large extent by macropores, that is, the macropore volume fraction, diameter distribution, and the continuity and connectivity of the macropore network (Ehlers, 1975; Logsdon et al., 1990; Shipitalo et al., 2000). For
example, Letey (1991) advocated focusing on the arrangement of voids and on the properties that these voids conferred to soils rather than on the solid components of soil structure. Mitchell (1986) goes on to explain that HC is a function of pore volume, pore size, and geometry, and that large pores are associated with greater conductivity. Certain factors relevant to soil structure such as texture, mineralogy, size and strength of aggregates, and history all determine the pore characteristics. With regards to mineralogy Six et al. (2000) found that higher soil stability resulted from the presence of kaolinite and oxides.

**Poor Aggregate Stability**

Le Bissonnais (1996) explained that the main soil properties influencing aggregate stability most often mentioned are soil texture, clay mineralogy, organic matter content, type and concentration of cations, sesquioxide content, and calcium carbonate. He also emphasized that there are multiple interactions between these properties that can modify their individual influences on overall soil aggregate stability. Doran and Parkin (1996) state that aggregate stability is among the most important soil quality indicators. This determination is due to the effect aggregate stability has on the ability to use a soil for agricultural and building purposes. Lado and Ben-Hur (2004) found that the mineralogy was the dominant factor affecting soil aggregate stability. They explained that the surface charges of quartz and feldspar (the dominant minerals in the soils of their study) are close to zero. This means that these minerals cannot act as a cement to hold the particles in the aggregate together. Hence, it is likely that the relatively higher organic matter contents in some of the soils they studied raised the aggregate stability above those of the montmorillonitic soils, but not as high as that of the kaolinitic soil.
Panabokke and Quirk (1957) explained the process of aggregate breakdown in the following way. They said that as the wetting front moves through the dry aggregates, expansion of the wetted portion compared to the non-wetted portion causes shear forces which break a major portion of the bonds between particles and weakens the aggregates’ structure. Slaking also occurs which destroys aggregates on wetting. Akram and Kemper (1979) reported that initial moisture content has a large influence on both aggregate breakdown and erosion. And Le Bissonnais (1996) found that mechanical breakdown of soil aggregates by raindrop impact plays a dominant role on wet soils because the aggregates are weaker when the soil is wetter. Norton (1987) showed that much of the reduction in porosity in the surface horizon of the soil seemed to be due to the breakdown of aggregates by water-drop impact with the residue filling the interstices formed by stable aggregates and primary mineral grains. Green et al. (2000) found the same process in their study and explained how these mechanisms of aggregate breakdown facilitate crust and seal formation. In addition to these studies, Cary and Evans (1974) as well as Wischmeier and Mannering (1969) found that soils with low organic matter and high silt content usually have low aggregate stabilities.

Sodium also causes aggregate breakdown. Agassi et al. (1981) found that the main affect of Na in soils with poor aggregate stability was to enhance the rate of aggregate breakdown. According to their study the presence of exchangeable sodium weakened the soil structure. As a result, IR dropped to low values due to the beating action of the water drops hitting the Na weakened aggregates. However, in contrast, Oster et al. (1992) stated that aggregate stability increases with increasing salinity of the irrigation water or the water in the soil. This is mainly due to the tendency of dispersion
to occur when the applied water has a very low salt content. Pupisky and Shainberg (1979) explained this phenomenon further by saying that at low ESP and very dilute soil solutions, dispersion and clay migration into the conducting pores are the main mechanisms responsible for plugging the soil pores. Dispersion of the clay particles is only possible when the concentration of the soil solution drops below a threshold concentration at which the clay platelets flocculate. Using high salinity water over time will result in poor aggregate stability due to the saline-sodic conditions that can build up if proper irrigation management is not practiced. This is because increasing the ESP of soils weakens the binding forces within the aggregates and increases the tendency of clay to disperse as shown by Ben-Hur et al. (1985).

Crusting and sealing is one of the main effects of poor aggregate stability that lowers IR. In a study by Levin et al (1991), to determine the affect of rain energy and soil amendments on infiltration, one soil was found to be the least susceptible to sealing. This was most likely because of its high smectitic clay content, high specific surface area and high Calcium carbonate content, all of which contributed to stabilizing the structure of the soil. Agassi et al. (1981) and Shainberg and Letey (1984) found that with the breakdown and dispersion of aggregates by raindrop impact, a thin layer like a seal or crust is simultaneously formed on the soil surface. Remley and Bradford (1989) showed that this seal increases the shear strength of the soil surface that, in turn, reduces soil detachment. Reduced soil attachment due to crust formation facilitated by poor aggregate stability is a positive effect. However, the crust also decreases IR, leading to increased runoff volume and its transport capacity (Ben-Hur et al., 1992). These negative effects typically offset the stabilizing benefits of the surface crust. For example, Norton (1987)
showed that a dense layer in surface crusts appears to be the product of reduction in aggregate size and in the frequency and size of packing voids relative to the underlying soil material, which appears to be unaffected by water drop impact. This means that as the crust forms it protects the underlying soil from the aggregate destroying impact of water drops. But as Norton et al. (1993) showed in another study the structural instability which leads to surface sealing reduces infiltration and therefore results in considerable amounts of runoff.

Le Bissonnais (1990) showed that low clay and organic matter in a soil can indicate a likelihood of crust formation and decreased IR without tilling due to the decrease in aggregate stability of such soils. McIntyre (1958) showed that in soils with a stable structure, only the skin seal is effective in decreasing permeability and that the washed-in portion, often identified as a component of a soil crust, is absent. In general, the lower the aggregate stability at the soil surface, the higher the susceptibility of the soil to seal formation (Le Bissonais, 1996). Weak aggregates are by no means the only reason for crust formation. As shown by Wakindiki and Ben-Hur (2002), the aggregate stability of the soil is not the only factor that affects crust formation and IR.

Seybold (1994) explained that the maintenance of stable structural units or aggregates promotes infiltration of water; the physical disintegration of aggregates determines the rate of seal formation and its final permeability (Levin et al., 1991). Green et al. (2000) showed that a decrease in IR was due to the formation of a surface seal caused by the physical breakdown of aggregates and clay dispersion. Abu-Sharar and Salameh (1995) explained that because of crust formation, the resultant IR tends to decrease to a minimum value, irrespective of the initial soil moisture content.
Organic Matter

Theng (1982) emphasized that the clay-humus interaction in soils plays an important and sometimes crucial role in many soil processes, such as mineral cycling and weathering, profile development, and aggregate stabilization. Jacks (1963) states that this interaction is as vital to the continuance of life as, and less understood than, photosynthesis. Six et al. (2000) explains that in 2:1 clay-dominated soils, soil organic matter (SOM or OM) is a major binding agent because polyvalent metal-organic matter complexes form bridges between the negatively charged 2:1 clay platelets. This interaction leads to a greater number of more stable soil aggregates that can increase IR. Thus low OM is typically associated with soils of poor structure and low IR. Guerra (1994) found that an OM content of 3% was a threshold value, below which the aggregates where unstable and the soil erodibility was high. However, Agassi et al. (1981) showed that there is little information on how OM affects the physical disintegration of surface soil aggregates and the physiochemical dispersion of soil clays that form crusts. Lado et al. (2004) made observations of the soil surfaces before and after rainstorm events that indicated that the rainstorm caused more extensive aggregate breakdown in the low-OM as compared to the high-OM soil independent of the initial aggregate size. They concluded that an increase in the OM content of the soil increased the aggregate stability and decreased the soil dispersivity. They also found that the larger the aggregate size, the greater the final IR and the lower the rate of the seal formation.

Greenland et al. (1975) suggested that soils with less than 3.5% organic content have unstable aggregates, but De Ploey and Poesen (1985) indicated that 2% organic matter is a more critical limit. According to Lado et al. (2004) an increase of OM content
from 2.3 to 3.5% limited the aggregate breakdown, soil dispersivity, and the seal formation at the soil surface under raindrop impact conditions. Lado et al. (2004) showed that the cultivation of soils with high OM will be effective because, the larger aggregates will remain stable during the rainy season and will maintain relatively high IR. In contrast, in soils with low OM, the cultivation will have only a short-lived affect because in this soil most of the large aggregates will be broken down and dispersed at the beginning of the rainy season. Guerra (1994) showed that the loss of OM decreases aggregate stability, which increases detachability of particles and encourages crust formation, which in turn increases runoff rates.

Low precipitation and high temperatures reduce OM in many soils. This leads many farmers to regularly add OM to their soils to increase aggregate stability and IR. However, as explained by Fox and Bryan (1992), in many dryland areas adequate quantities of OM are very hard to find. Despite this reality, Andrews et al. (2002) reported clear evidence that indicator properties can be changed through OM building practices in an irrigated, Mediterranean climate such as that of the SJV.

According to Fox and Bryan (1992), crusts develop because of the poor aggregate stability of soils with low OM. In some situations OM in soils has been reported to impede infiltration of water (Allison, 1973). This reduction in IR has been attributed to the blocking of pores by organic matter and/or rendering the surface of soil particles hydrophobic. Such effects have also been observed in some burned areas where the residue is difficult to wet (Singer and Oster, 1984). Jaramillo et al. (2000) tested the hypothesis that OM is the cause of reduced IR in some soils. Their study concluded that climate influences water repellency through the production of OM. Bisdom et al. (1993)
found that micro-aggregates composed of fine organic materials and minerals caused very difficult water absorption and penetration. Contreras et al. (2008) showed that there is a significant exponential relationship between soil organic carbon and water drop penetration time (WDPT). This demonstrates that OM plays an important role in the occurrence of water repellency. Likewise they showed that the quality or nature of the OM (specific organic compounds), and not only the quantity, can play in the severity of the soil water repellency. According to Cammeraat et al. (2002), ants increased water repellent OM which reduced IR. As mentioned previously, soil crusts can catch hydrophobic OM that leads to a crust that can decrease IR to an even greater degree (Contreras, 2008). A number of soil constituents (micro-aggregates, plant fragments with and without coatings, macro-aggregates, speckles, dots, coatings and platy fragments) have been found in water-repellent sieve fractions (Bisdom et al., 1993). Therefore, it has been shown that depending on the type, amount of OM and other soil factors, OM can play a part in reducing IR.

**Soil Compaction**

Ajwa and Trout (2006) emphasized that low IR in medium and coarse-textured soils can be caused by restrictive layers beneath the soil surface such as compacted layers, pans, lenses, fine-textured strata, or cemented layers. Wheel and track traffic is believed to be the largest contributor to soil compaction (Singer and Oster, 1984). According to Oster et al. (1992) soil compaction results when an applied force or pressure rearranges soil particles and increases soil density. With compaction, the total volume of soil pores decreases. Moreover, while it is possible that the number of small
pores increases, the number of large and continuous conducting pores decreases (Singer and Oster, 1984).

Limiting compaction due to traffic in conventional orchards is very difficult to achieve, given the constraints of the tree spacing and the many different equipment operations that take place (Singer and Oster, 1984). Research shows that almost all tillage practices produce compaction (Oster et al., 1992). The bulk density from the soil surface to a foot below where tillage occurs is the most definitive measurement of compaction (Oster et al., 1992). OM, particle size distribution, particle shape, soil mineralogy, and soil water content influence bulk density (Singer and Oster, 1984). Akram and Kemper (1979) show that IR decreases as compacting forces increase. Gomez et al. (2001) showed that, even after nearly two decades of non-tillage, the general compaction of the soil was the main factor reducing saturated HC and subsequent IR. In many locations freezing and thawing is one of the most important factors that loosen compacted soils. However, in areas that do not undergo sustained freezing temperatures, such as California, this natural amelioration of compaction does not occur and thus IR is reduced (Akram and Kemper, 1979).

Ben-Hur et al. (1985) pointed out that compaction caused by raindrops plays a dominant role in crust formation. El-Morsy (1991) found that this impact energy from water drops caused a large reduction in IR independent of water quality. Thus, it was indeed the impact energy that compacted the soil and not the dispersive properties of the water that reduced IR. Hadas and Frenkel (1982) showed that this was due to water drop impact causing soil and clay reorientation that clogged soil voids at or near the soil surface. Thus, compaction from machinery as well as natural forces such as impact
energy from rain drops can contribute to reduced IR since there is subsequent reduction in pore space.

**Soil Crusts or Seals**

The main cause of crust and seal formation depends on how water encounters the soil. Mitchell (1986) showed that surface irrigation may cause slaking, or crumbling of soil into a structureless mass, which increases the rate of crust formation. Luk et al. (1990) states that surface crusting is a common pedological process in soils of semiarid and arid regions that have a low OM content, high silt content, and low aggregate stability. It has been found in clay soils with high sodium content and other soils as well. Farres (1978) explains that one of the most important responses of the soil surface to intense rainfall is the consolidation of surface particles to form a crust. Soil texture is an important prerequisite for the rate of crust formation (Ben-Hur et al., 1985). As Bielders and Beveye (1995) showed the crusting potential of soils is usually expressed in terms of their silt and clay content. Their study provides some indication that the textural composition of the sand fraction may play an important role as well. Mermut et al. (1995) concluded that the mineralogy of clay sized particles and rainstorm characteristics are among the major factors that determine the nature of soil sealing. Likewise Ben-Hur et al. (1992) showed that seal formation depends on clay mineralogy and the exchangeable ion composition of the soil. Soils with ~20% clay were found to be the most sensitive to crust formation and have the lowest IR. With increasing percentage of clay, the soil structure was more stable and the formation of crust was diminished. In soils with lower clay content (less than 20%), there was a limited amount of clay to disperse and, as a result, undeveloped crust was formed (Ben-Hur et al., 1985). This is because, as noted by Theng
(1982), surface soils are essentially clay or mineral-organic complex systems. This means that the formation of crust should be slowed down by an increase in clay content because one of the main factors affecting crust formation is the destructive impact of drops and how wetting affects aggregates. With high clay content the impact damage is lessened as is the damage done by wetting i.e. slaking (Ben-Hur et al., 1985). For example Ben-Hur et al. (1985) showed that with increase in clay concentration in the range up to 19.2% clay, the rate of the drop in IR increased and the final IR decreased. As the clay percentage increased above 19.2%, the rate at which the IR dropped was lower and the final IR was maintained at higher values compared with the other soils. The clay fraction of the soil has two opposing effects on crust formation. First, the clay is the substrate for crust formation; thus, in soils with low clay content, the rate of crust formation increased and the steady state HC of the crust decreased as the clay content increased. Second, the clay acts as a cementing material, stabilizing the soil aggregates against the beating action of the raindrops. Therefore, increasing the clay content of the soil aggregate prevents their disintegration and eventual crust formation (Ben-Hur et al., 1985).

Oster et al. (1992) explained that surface seals develop as large soil pores are plugged by small soil particles. Levin et al. (1991) showed that surface seals are thin layers less than 2-3 mm and are characterized by greater density, finer pores, and lower saturated conductivity than the underlying soil. Morin et al. (1981) explained that the sealing efficiency of the crust is achieved by suction forces, which result in the orientation of clay particles into a continuous dense skin. Using a scanning electron microscope (SEM), Tarchitzky et al. (1984) observed crusts formed on sandy, sandy-loam and clayey soils and found them to be composed of two layers. The top portion, the
skin, 0.1 mm thick, and a second layer, 2-3 mm thick, with a higher bulk density in which aggregates had been destroyed.

Lado et al. (2004) found that crusts composed of aggregates were much less dense than those made of dispersed materials. They found that the larger the aggregate size, the greater the final IR and the lower the rate of the seal formation. Bielders and Beveye (1995) showed that some of the detached or dispersed clay material that leads to crust and seal formation may be fine enough to be eluviated. However, another portion of this material may be composed of clay micro-aggregates, which can accumulate immediately below the zone of surface eluviation. The portion of the soil losing material in crust formation is known as the washed-out layer. This area is typically sandy and skeletal. The zone of decreased porosity and accumulation is called the washed-in layer (Bielders and Beveye, 1995).

An important characteristic of soil seals and crusts is their relation to time. Crusts can develop over time and their properties can change depending on how long they have been exposed to wet or dry conditions. Indeed the effects of crusts and seals are in large measure determined by their degree of contact with water. Farrell and Larsen (1972) used a model based on a constant soil-water diffusivity to examine, in principle, infiltration through a crust whose properties change exponentially with time. Norton (1987) quantified surface sealing using infiltration measurements. This was an important method because finding the IR of a soil surface has the advantage of being able to monitor the sealing process through time (Norton, 1987).

Crusts or seal formation in soils exposed to rain results from two mechanisms (McIntyre, 1958; Agassi et al., 1981; Chen et al., 1980). The first mechanism is a
physical disintegration of soil aggregates due to impact energy and slaking upon wetting followed by consolidation at the soil surface leading to compaction caused by the impact action of the drops hitting the soil surface. The second mechanism is a physicochemical dispersion of clay particles and their possible movement directly beneath the immediate surface where they lodge and clog conducting pores forming a washed-in region of decreased porosity. Green et al. (2000) emphasized the first aspect of the crust forming mechanism by saying that the impact of the rain and the rapid wetting of the soil cause slaking and dispersion of clays, thus disrupting the integrity of the soil aggregate. Once the soil aggregate has slaked and dispersed into smaller particles, the small particles can clog the pore spaces of the soil matrix. When this occurs, a thin seal develops which, when dry becomes a hardened surface crust. The second stage of crust formation is controlled mainly by the concentration and compositions of the cations in the soil and applied water. The two stages of the mechanism that leads to crust formation act simultaneously, as the first enhances the second (Levin et al., 1991). Zhang et al. (1998) showed that the interaction between the two mechanisms becomes significant when soils with low ESP, low EC, and a dominant 1:1 clay mineralogy are exposed to rain with low EC. Agassi et al. (1981) explained that crust formation is associated with clay dispersion and movement in the soil. Soil surfaces are especially susceptible to the chemistry (electrolyte concentration and cationic composition) of the applied water because of the mechanical action of the falling drops and the relative freedom for particle movement at the soil surface (Agassi et al., 1981).

Levin et al. (1991) put this two part mechanism in a slightly different way by saying that there are two stages of dispersion that lead to crust formation, one a physical
the other a chemical. The physical is caused by impact energy alone and the chemical depends on the soil exchangeable sodium percentage (ESP) and the electrolyte concentration of the applied water (Agassi et al., 1981). Gal et al. (1984) explained that in soils with ESP values above 1.5, chemical dispersion of the soil clays (enhanced by the sodicity of the soil, the low electrolyte concentration in the rain, and the stirring effect of the raindrops) and the downward movement of the clays into the washed in layer clogging the pores is the dominate mechanisms in crust formation. They also note that soils with a washed in layer have a very low IR. Norton (1987) showed that a skin seal was formed due to compaction by waterdrops, and washed-in zone for a subsurface zone of decreased porosity formed from the movement of fine material downward. Evans and Buol (1968) showed that the washed in layer was formed only in soils that were easily dispersed. Their micrographs showed that, in some soils, particles in the layer immediately below the surface skin were oriented, whereas in others, orientation of silt and sand particles occurred in deeper clays of the crust. Thus certain materials, such as mica due to its shape, would be very detrimental in high concentrations because of this orienting aspect of the crust forming mechanism.

As noted by Evans and Buol (1968) there is some debate over the evidence of a washed in layer which depend on the soil properties. For example, Tarchitzky et al. (1984) gave evidence that washing-in was not a major mechanism in soil crusting in the soils used in their study. They suggest that the rapid destruction of soil aggregates with the consequent reduction of pore size and a high concentration of clay eroded in runoff diminishes the probability of washing-in. They support this conclusion with results given by Epstein and Grant (1967, 1973). McIntyre (1958) also supports this conclusion. He
showed that in soils with a stable structure, only the skin seal is effective in decreasing permeability and that the washed-in region could be absent. This debate highlights the complex nature of crusts and seals due to the variability of their genesis and morphology. However, a study by Bielders and Baveye (1995) showed that a washed-out layer forms at the surface of all samples exposed to drop impact. Thus, the washed-in layer may depend on the soil but there is always a washed out layer if there is a soil crust. This highlights the fact that erosion and deposition processes governed to a large extent the development of the crusts (Bielders and Baveye, 1995).

Gal et al. (1984) noted that in soils with ESP below 1.0, and in sodic soils treated with phosphogypsum, aggregate disintegration and crust formation are caused primarily by mechanical action of raindrops’ impact. In soils with higher ESP values, clay dispersion and the formation of a washed in zone is the dominant mechanism. Only in those soils did the IR reach a very low value. Thus, of the two stages of the mechanism, the chemical dispersion has the greatest effect at lowering IR. However, Miller and Scifres (1988) and Shainberg et al. (1989) gave evidence to show that it is more complicated than that. They demonstrated that physical processes predominate when soils with high electrical conductivity or low ESP are exposed to high intensity rains. Otherwise, chemical processes supplement or enhance the physical processes.

Valentin (1986) suggested that a sieving mechanism may be responsible for inducing particle sorting in the washout-out layer of structural crusts. Bielders and Baveye (1995) suggested that clay-band formation is just an extension of the same mechanism. The smallest micro-aggregates forming the clay band are sieved deepest; the depth being controlled only by the maximum depth to which water drops can displace.
particles during impact. In their study Bielders and Beveye (1995) clearly demonstrated that a washed-out layer and a clay-band formation can occur simultaneously in coarse-textured materials exposed to simulated rainfall. During their experiment there was no ponding, thus the washed-out layer and clay-band features are not the result of deposition of runoff water but are direct consequences of drop impact. Seybold (1994) showed that surface sealing occurs from the impact of raindrops or water drops from sprinklers causing soil particle detachment and transportation. Detached particles can clog pores at the soils’ surface resulting in a surface seal (Seybold, 1994). Bresson and Boiffin (1990) explained that the process of soil particle detachment is achieved by various mechanisms. It can be due to a disaggregation by entrapped air compression when moistening i.e. slaking. Particles can become separated due to disaggregation by raindrop impact and/or flow turbulence. Microcracking due to shrinking and swelling clays can set particles free and physico-chemical dispersion also aids in detachment. These mechanisms occur with various intensities depending on the soil composition and moisture status. As a result, the detached particle size distribution varies which may induce significant differences in crust morphology and properties (Bresson and Boiffin, 1990).

Oster and Schroer (1979) showed that the potential for crusting and reduced IR is particularly great where irrigation periodically supplements normal rainfall (or vice versa). This is due to the difference in EC of the infiltrating water. Kemper et al. (1985) and Schamp et al. (1975) showed that soil crusting can occur during a rain or irrigation event, due to soil surface aggregate break down. Rapidly entering rain or irrigation water entraps air in soil aggregates, causing violent disruptive shearing forces upon its release.
Valentin and Bresson (1992) explained that in loamy soils, such as those which predominate this thesis research, crusting always follows the same pattern, sealing of the surface by a structural crust, and development of a depositional crust. The change from the first to the second stage mainly depends on a decrease in IR due to the structural crust properties, which induces microrunoff (Boiffin, 1986).

Although, as Farres (1978) has explained, soil surface crusting stabilizes the soil system by protecting the soil below from drop impact, this causes a myriad of other problems for agriculture. Luk et al. (1990) explained that the development of surface seals and crusts has been known to increase surface runoff and erosion, and to prevent the emergence of seedlings. Wakindiki and Ben-Hur (2002) and Ben-Hur et al. (1992) affirmed that the important effects of soil crust on surface and other phenomena include the reduction of IR. They explained that the IR decreased with increasing cumulative rainfall until a final IR was reached. This decrease of the IR was a result of the crust formation at the soil surface. They also showed that the rates of decrease in IR and the final IR values differed among the various soils used in their study (Wakindiki and Ben-Hur, 2002). One of the main reasons IR is reduced by a soil crust is that there are fewer conducting pores to allow the entry of water. Norton (1987) showed that a change in the percentage of pores in the planar class appears to have a much greater effect on infiltration than the absolute change in total porosity. This means that just a small layer of reduced pores can drastically reduce IR for the entire soil.

Remley and Bradford (1989) showed that the surface crusts increase the shear strength of the soil surface. This has the effect, as shown by Ben-Hur et al. (1990) and Remley and Bradford (1989), of reducing soil detachment. Thus, once a crust is in place
it does not erode. Agassi et al. (1981) also showed that the suction forces at the soil-crust interface are created as a result of the large differences in HC between the crust and the underlying soil. This means that a soil crust is held in place, when exposed to water, due to the difference in HC created by the disparity in conducting pores of the crust and the underlying soil. Surface seals substantially reduce water infiltration because of their low hydraulic conductivity (Zhang et al., 1998). As Mitchell (1986) explained, crusts have smaller macroporosity and lower HC than the soil in general and may act as a “throttle” to determine the infiltration into the entire soil profile. Shainberg and Singer (1986) showed that the resulting HC of a crust formed from dispersed clay particles is an order of magnitude below that of a crust formed from flocculated clay particles. According to Contreras et al. (2008) erosion is also enhanced because of soil crusts. They explain that the tendency of the soil surface to disperse and to form a seal is an important soil property that affects the degree of soil erodibility.

Once crusts are in place they have an enhancing secondary effect according to Contreras et al. (2008). They explain that the presence of crusts could enhance the impact of water repellency. This is because the soil components of the crust (silt, sand, and clay) work together as a net to trap hydrophobic organic compound and chemicals. As these substances build up, the IR of the soil drops even more. Their study found that hydrophobicity is more noticeable in the fine and very fine washed-out sandy sublayer suggesting a hindering effect imposed by the washed-in, massive layer beneath the washed-out layer. This last layer would act as a physical barrier to the redistribution in depth of the organic and hydrophobic compounds and confine them to the surface soil (Contreras et al., 2008).
Bielders et al. (1996) showed that the surface microrelief influenced the spatial distribution of crusts, which explained why certain types of crusts might form in different areas close together. Oster et al. (1992) emphasized that knowing which kind of crust is causing slow water penetration is useful because different treatments depend on the type of crust. Based on their study Valentin and Bresson (1992) argued for three main classes of crusts, each with a subclass: structural, erosion and depositional. All three types of crusts reduce IR (Oster et al., 1992). West et al. (1992) showed that structural crusts result from the destruction of interparticle bonds by wetting or by raindrop impact. Oster et al. (1992) explained that a structural crust has a thick surface crust formed by the beating action of rain and water drops on the soil surface or by the collapse of soil surface structure upon wetting. The soil particles are rearranged with a consequent reduction in the number and size of large pores. Upon drying the crust becomes hard. A depositional crust is a thicker crust formed when sediment-laden water infiltrates into the soil leaving behinds particles that form a crust (Oster et al., 1992). Bresson and Boiffin (1990) showed that crusting followed a general pattern. First, a structural crust seals the surface. Second, the structural crust develops and becomes stronger and thicker. Third, the change from the first to the second stage depended on the hydrodynamic behavior of the soil surface, which was partly controlled by the structural crust development.

**Structural Crusts**

Structural crusts, also known as sieving, slaking, infilling, and coalescing crusts, are formed at the soil surface. Their development involves a sorting and conjoining process caused by water drop impact and the change soil undergoes when moisture decreases soil cohesion (Bresson and Boiffin, 1990). In some soils, wetting leads to
structural instability, which favors surface sealing. As Norton et al. (1993) explained, this process reduces infiltration and therefore results in considerable amounts of runoff. Basically, as rain or sprinkler irrigation water impacts the soil, slaking and dispersion occurs causing structural and depositional seals to develop. The result of these crust developments is a decreasing amount of pores space, which lowers IR (Green et al., 2000).

Valentin and Bresson (1990) showed that structural crusts are characterized by the rearrangement of particles without evidence of lateral movement. These crusts have a thin layer, typically apedal, porous and with weak void interconnection (Valentin and Bresson, 1990). Structural crusts thus maintain pore spaces but manifest a reduced amount of continuous conducting pores. Valentine and Bresson (1990) explained that these crusts are made of a layer of loose skeleton grains overlaying a plasmic layer. The structural crusts advance from this point to have three main layers. The uppermost layer is composed of loose coarse grains, the middle one consists of fine, densely packed grains with vesicular voids. The lower layer (plasmic layer) shows a high content of fine particles with considerably reduced porosity (Valentin, 1991). Lado et al. (2004) supported this three-tiered template for structural crusts. They found that the uppermost layer, from the 0- to 0.1-mm depth, contained particles ~ 0.05 mm in size with no fine materials between them. The middle portion was composed of a transition layer, from the 0.1- to 0.45-mm depth, containing a mixture of ~ 0.05-mm particles and fine materials. The deepest portion of the crust, from 0.45 to 1.1 mm, from visual inspection appeared to be very dense, probably because of the accumulation of dispersed clay that was washed
in from the upper layers (Lado et al., 2004). Structural crusts are generally thick in comparison to the other types of crusts (Valentin and Bresson, 1992).

Le Bissonnais (1996) found that structural crusts are formed by a reorganization of soil particles with little displacement of fragments, and without sorting and sedimentation. They result from the gradual packing and coalescing of particles and small aggregates, which are mainly produced by slaking and microcracking. This is different than the final three-tiered explanation given above. There is no disagreement on the process that causes the formation of a structural crust. Wakindiki and Ben-Hur (2002) explained that structural crusts are due mainly to water-drop impact. In contrast, depositional crusts are formed by translocation of fine particles and their deposition at some distance from their original location. Structural crusts, however, are generally formed during the preponding phase, whereas depositional crusts and erosion are coincident (Le Bissonnais, 1996).

In loamy soils, crusting always follows the same pattern; sealing of the surface by a structural crust, and development of a depositional crust. The change from the first to the second stage mainly depends on a decrease in the IR due to the structural crust properties. This induces microrunoff (Boiffin, 1986). Green et al. (2000) showed that the impact of the rain and the rapid wetting of the soil cause slaking and dispersion of clays, thus disrupting the integrity of the soil aggregate. Once the soil aggregate has slaked and dispersed into smaller particles, the small particles can clog the pore spaces of the soil matrix. When this occurs, a thin seal develops which, when dry, becomes a hardened structural crust (Green et al., 2000).
Wakindiki and Ben-Hur (2002) found that the rearrangement of particles in the crust and the crust’s thickness affect the IR of the soil due to the sealing conditions created by a structural crust. Le Bissonnais (1990) found that the combination of processes causing surface crusts determines the evolution of surface structure, and therefore the evolution of infiltration capacity. Structural crusts had bare silt grains, which clog the interaggregate interstices and form net-like infillings. These bare silt grains are deposited a few millimeters deeper into the interaggregate packing voids, which induces a decrease in IR and an increase in cohesion (Valentin and Bresson, 1992). Although their study did not examine the nature of the silt it is the intent of this research to show that mica flakes in the coarse silt and very fine sand portion of the soil may reduce IR. The potential relevancy of mica content in the silt portion of the soil is shown by their study. The importance of mica will be emphasized in a later section.

**Erosion Crusts**

Valentin and Bresson (1992) showed that erosion crusts consist of only one rigid, thin and smooth surface layer enriched in fine particles. Bielders et al. (1996) explained that these types of crusts form through erosion of the sand layer of structural crusts, following runoff initiation. Basically this means that an erosion crust is what is left over after the top layer of a structural crust has been removed. Le Bissonnais et al. (1989) found that during the second stage of crust formation, between 1.7 and 7 mm of rainfall, the upper layer of aggregates is saturated but no ponding occurs on the surface. Particles mobilized during the previous stage, are moved by raindrop impact and they progressively fill the interaggretate pores. This movement of particles is what leads to the
formation of the erosion crust, although until the sandier surface layer is removed they are not classified as such.

The initial moisture content has a large influence because of its affect on both aggregate breakdown and erosion, which both lead to the formation of erosion crusts (Le Bissonnais, 1996). When the clay fraction at the soil surface is dispersed, the clay percentage in the sediments should be higher than that in the original soil, because the clay particles are more easily transported by the overland flow than the bigger silt sand particles (Lado and Ben-Hur, 2004).

**Depositional Crusts**

Le Bissonnais (1996) explained that depositional crusts, which can also be called sedimentary crusts, result from fragment and particle displacement and sorting under ponding conditions. This is in contrast to structural crusts that are formed during the preponding phase. Depositional crusts and the resulting erosion are coincident with structural crust formation (Le Bissonnais, 1996). Depositional types of crusts are very compact, and characterized by a microbedded layer (Valentin and Bresson, 1992). These microbedded layers most often overlay a structural crust. In the lower part of the crust, the bedding is generally less distinct and particle sorting is poorer. Valentin and Bresson (1992) showed that depositional crusts consist of densely packed and well-sorted particles, the size of which gradual increase with the settling depth. As shown by Bresson and Boiffin (1990) depositional crust formation closely coincides with the appearance of water on the soil surface.

Depositional crusts are formed by the sorting that takes place as materials settle out of suspension in still water. The organization of the crust depends on the settling
velocity of fragments, which is closely related to their size (Le Bissonnais, 1996). Shainberg and Singer (1986) showed that as sediment-containing irrigation water infiltrates, a depositional seal is formed. When the seal dries it forms a depositional crust. Norton (1987) proposed the following sequence of processes for the formation of the depositional crust. First, fine particles were detached by the impact of water drops leading to the destruction of aggregates. These particles were transported in overland flow during the rainfall event and deposited on the erosion surface after overland flow stopped or when the sediment transport capacity was exceeded. This means that either the suspended materials came to rest due to ponding, or, because the water could no longer carry them. This is in contrast to structural crusts, which are formed mainly due to water-drop impact. Depositional crusts, on the other hand, are formed by translocation of fine particles and their deposition at some distance from their original location (Wakindiki and Ben-Hur, 2002).

According to Norton (1987) if turbid water infiltrates into the soil surface a depositional crust can be created that causes a reduction in IR. This is due mainly to a reduction in planar pores. These pores may be thought of as the more continuous openings in the soil that are most likely to conduct water due to their size and geometry (Norton, 1987). Norton found that a change in the percentage of planar pores appears to have a much greater affect on infiltration than the absolute change in total porosity for the whole soil. Green et al. (2000) also found that depositional crust development decreased the amount of pore space at the soil surface. Since the depth of ponding, turbidity of the water and type of material suspended can all change and still yield a crust, the resulting thickness of the depositional crust will vary depending on these factors. Shainberg and
Singer (1986) showed that as the thickness of the depositional crust increases, the IR decreases. They also found that depositional crusts, made of flocculated particles had much higher permeability than depositional crusts made of dispersed clay and silt particles. Flocculated particles were deposited randomly in an open structure, but the dispersed clay particles were deposited in a dense structure oriented parallel to the soil surface (Shainberg and Singer, 1986).

**Saline-Sodic and Sodic Soil Conditions**

Sodic soils are not common. However, it is necessary to consider them since their effects can drastically lower IR. Oster et al. (1992) found that poor infiltration occurs when the SAR of the soil becomes too high for EC of the irrigation water to counteract. This is because, as they showed, salts decrease the affinity of soil particles for water and consequently their tendency to imbibe water.

Oster and Schroer (1979) found that the hydrologic behavior of soils may depend more on the sodium levels at the soil surface than on the chemistry of the remainder of the soil. Agassi et al. (1981) and Kazman et al. (1983) found that the IR was more susceptible to the sodicity of the soil and the electrolyte concentration of the applied water than the permeability of the underlying soil. When distilled water was used for the simulated rainfall, the final IR of a sandy loam soil was maintained at 7.5 mm h⁻¹ as long as the exchangeable sodium percentage of the soil was maintained below 1.0. However, the final IR of the same soil, but with ESP 2.2, 4.6 and 11.6, dropped to 2.3, 0.7, and 0.6 mm h⁻¹, respectively (Agassi et al., 1981; Kazman et al., 1983). The permeability of a soil to water depends both on its exchangeable sodium percentage (ESP) and on the salt concentration of the percolating solution, which tends to decrease with increasing ESP.
and decreasing salt concentration (Quirk and Schofield, 1955; McNeal et al. 1968). Lentz et al. (1996) showed that clay dispersion is also a function of a soil’s ESP. Likewise Baumhardt et al. (1992) found that increased infiltration with continued irrigation indicates that the increasing soil salinity became high enough to counter, in part, the sodic conditions of the soil. And finally, Jacobsen and Adams (1958) spoke of the historical reality of the outcome of sodic-saline soils by examining the example of ancient Mesopotamian societies. They said that as water evaporates and transpires the calcium and magnesium tend to precipitate as carbonates, leaving the sodium ions dominant in the soil solution. Unless they are washed down into the water table, the sodium ions tend to be absorbed by colloidal clay particles, deflocculating them and leaving the resultant structureless soil almost impermeable to water. Thus with increased salinity and sodic conditions IR is drastically lowered.

**Fire Induced Water Repellency**

According to a review by DeBano (1981) it is the organic matter (OM) which induces water repellency in soils by several means, namely by irreversible drying of OM, when OM is heated by fire, by organic substances leached from plant litter, by hydrophobic microbial by-products which coat mineral soil particles, and by intermixing of mineral soil particles with organic matter. Imeson et al. (1992) noted that the main effect of fire is to eliminate the storage of water in the organic horizons (top several cm). This means that at first, for the dry upper organic layer, IR remains high but later decreases as there is a reduction in porosity associated with the heat from the fire because the structure of the OM has been degraded. Their study showed that the porosity of the burnt soils was much less (averaging about 25%). This effect was significant because OM
was only a minor part of the soil. They found that for burnt sites, very much depends on
the structure and texture of the surface soil as well as on the vegetation when determining
the effects of fire on IR. The initial vegetation is important because after a fire the
partially decomposed OM in the macro-pores becomes extremely hydrophilic. Thus
certain plants with lots of resins can induce greater hydrophobicity than others. Based on
their study Imeson et al. (1992) explained that the IR relating to fire induced water
repellency are so complex the relationship cannot be modeled with standard infiltration
equations. A study by Howells et al. (1984) showed that the high water runoff and
amount of material being carried off by water during the first rainy season after a
brushland fire are associated with fire-induced water repellency. Their study showed that
water-repellent areas coincided with the locations of sagebrush burning. In permanent
planting it is common for areas within an orchard to be used to burn the trees after they
are no longer productive. These patches can be quite large and they heat intense. Such
management practices may lead to reduced IR in these areas causing runoff which adds
additional water to other areas and may result in ponding due to the increased amount of
water.

**Electrolytes, ESP, SAR, and EC**

Van Der Watt and Pretoria (1990), as well as Shainberg and Singer (1985), state
that the exchangeable sodium percentage (ESP) and electrical conductivity (EC) of the
soil saturation extract as well as the sodium absorption ratio (SAR) and EC of the
irrigation water play an important role in crust formation.

Abu-Sharar and Salameh (1995) found that IR and HC decreased with decreasing
electrolyte concentration. According to Agassi et al. (1981) one way of limiting seal
formation is to control the chemical clay dispersion by maintaining the electrolyte concentration of the soil solution at the soil surface above the flocculation value of the soil clays. Since rain water or irrigation water from snow melt have such low concentrations of electrolytes they can cause clay dispersion and enhance soil surface sealing. On the other hand an accumulation of electrolytes can lower IR (Baumhardt et al., 1992). Furthermore, water quality is not a constant in all irrigated agriculture. Farmers sometimes blend surface and well sources to meet volume demands, and surface water quality often changes seasonally as snowmelt is displaced by return flows and drainage in surface water sources (Lentz et al., 1996).

Agassi et al. (1981) and Kazman et al. (1983) found that the IR of a soil was more sensitive to the sodicity of the soil and to the electrolyte concentration of the applied water than was the permeability of the underlying soil. As noted in the section on clay, Shainberg and Singer (1986) found that when the electrolyte concentration of the soil suspension exceeds the flocculation value of the clay, the clay platelets form flocculi that settle with a random orientation and open structure. Conversely, when the electrolyte concentration is below the clay flocculation value, the dispersed clay platelets settle into a compact crust with parallel orientation of clay platelets.

Oster and Schroer (1979) state that the hydrologic behavior of soils may depend more on the sodium levels at the soil surface than on the chemistry of the remainder of the soil. The permeability of a soil to water depends both on its ESP and on the salt concentration of the percolating solution (Quirk and Schofield, 1955; McNeal et al., 1968). In a study by Gal et al. (1984) when distilled water was used for simulated rainfall, the final IR of a sandy loam soil was maintained at 7.5 mm h⁻¹ as long as the ESP
of the soil was maintained below 1.0. However, the final IR of the same soil, but with ESP 2.2, 4.6 and 11.6, dropped to 2.3, 0.7, and 0.6 mm h\(^{-1}\), respectively. Agassi et al. (1981) found that the intensity of the chemical dispersion depended on both the soil ESP and electrolyte concentration in the applied water. According to Shainberg et al. (1982) soils that release salt at a rate sufficient to maintain the concentration of soil solution above the flocculation value of the soil clay will not disperse at relatively low ESP. Pupisky and Shainberg (1979) showed that at low ESP and very dilute soil solutions, dispersion and clay migration into the conducting pores are the main mechanisms responsible for plugging the soil pores. Levy and Van Der Watt (1990) explained that the saturated HC of soil decreases with increasing ESP and decreasing salt concentration, due to clay swelling and dispersion. However, high HC values can be maintained even at high ESP levels provided the EC of the percolating water is above a critical (threshold) level (Levy and Van Der Watt, 1990).

Irrigation water composition, through its effect on surface soil conditions, has a greater influence on IR than does the chemistry of the rest of the soil, and the salt concentration of the irrigation water is of at least equal importance to the corrected SAR as a predictor of IR (Oster and Schroer, 1979). El-Morsy et al. (1991) found that the SAR of irrigation water significantly affects water transmission properties of soil. McNeal and Coleman (1966) reported that increasing the SAR and decreasing the electrolyte concentration of the percolating solution induced a decrease in soil permeability. Such changes were more pronounced in soils containing expandable 2:1 layer silicates, especially montmorillonite clays, than in soils containing kaolinite or sesquioxides.
According to El-Morsy et al. (1991) the EC of irrigation water significantly affects the IR of soils. Baumhardt et al. (1992) showed that both the soil and the water EC act to govern IR. They showed that IR declined more rapidly and to a lower value when using reverse-osmosis than well water because of the more dispersive nature of low EC water. The dispersive nature of low EC water contributes to seal formation (Agassi et al., 1981). Their study also found that cumulative infiltration of well water was significantly greater than reverse-osmosis water, regardless of the previous irrigation history. This is because well water typically has more dissolved salts and can penetrate soil better than low EC irrigation water from snow melt or rainfall (Singer and Oster, 1984). As shown by Robbins and Brockway (1978) an increase in EC promotes clay flocculation and settling of suspended sediments in irrigation water. Settling of flocculated particles produces an open, more porous depositional seal than that produced by dispersed systems (Southard et al., 1988). Water quality as a treatment for low IR soils will be discussed further.

California Infiltration Issues

In Storie and Harradine’s 1957 study of the soils of California they explain that the Great Valley of California is more than 644km long and 80km in average width, and is one of the most notable structural valleys in the world. It includes the drainage basins of the Sacramento and San Joaquin rivers, and the Tulare Basin south of the San Joaquin. The Sacramento and San Joaquin rivers have a common outlet into San Francisco Bay; both flow on a low gradient of about 61cm every 1.6km. In reference to the San Joaquin valley they explain that it is about 402km long and 48 to 64km wide, comprising about
5.1 per cent of the state. The lowest part of the valley, at Stockton has an elevation of about sea level; from there, the rise is gradual to about 122m at Bakersfield, which is located at the south end of the valley. Throughout the massive valley of California the soil parent material is a mixed alluvium and natural vegetation consists of water loving grasses (Storie and Harradine, 1957).

As far as the character of the soil in California is concerned, climate, parent material, and time are the three factors which have had the greatest influence (Storie and Harradine, 1957). According to Storie and Harradine (1957) an important aspect of the climatic factor affecting soil development in California is that practically all precipitation occurs during the colder months of the year, and the summer period which follows is long and dry. This results in low OM in most areas and the necessity for massive irrigation projects to make land agriculturally viable (Lado et al., 2005).

Andrews et al. (2002) emphasize the vital importance of California for agriculture by explaining that it is one of the world’s most productive regions. California farmers produce more than one-third of the USA’s annual $3 billion agricultural output, making it the highest revenue-producing location in the USA for farming (California Dep. of Food and Agric., 1997). Despite the high productivity and profitability of California agriculture its lands are subject to significant reductions in IR due to soil and water issues as well as cultural practices.

Low infiltration is commonly associated with fine-textured soils. However, in arid areas, where soil OM is normally low, sandy loam soils also can develop low IR. This is the case in some areas of the California San Joaquin Valley where low IR has been identified as a major problem for crop production (Singer and Oster, 1984). In California
the main factor that controls IR under water-drop impact is the formation of a structural
seal at the soil surface (Morin et al., 1981; Ben-Hur et al., 1985, 1987). Semiarid and arid
regions, which dominate California, are characterized by a long dry season followed by a
short rainy season with high rainfall intensity events, inducing high runoff and erosion
rates.

Letey (2000) explained that even though much of the irrigation water used in
California is low in salts, 1.9 million metric tons of salts are imported each day from
irrigation water and other sources. Letey emphasized that the region is susceptible to salt
concentrations because California soils are derived from alluvium originating from the
coastal mountains. These mountains were once below sea level and uplifted to their
present state, thus the alluvium parent material contains high concentrations of salts and
elements typical of a marine environment. According to Mitchell (1986) many irrigated
soils in the desert Southwest have low HC, which results in substantial economic
consequences (Singer and Oster, 1984). Included in these are problems of inadequate
moisture, inefficient water use, plant injury due to water ponding and salinity (Meek et
al., 1980, 1986). A study by Mukhopadhyay et al. (1997) showed that because of their
poor structural stability the majority of soils in California are susceptible to crust
formation when exposed to rainfall or irrigation which decreases IR.

In their comprehensive infiltration study of California soils Singer and Oster
(1984) found that slow water penetration is a major problem in the production of crops on
over 1 million hectares or more than 20% of the irrigated land in California. Estimated
dollar losses at the time of the study range from $50/ha for irrigated pasture to $1,200/ha
for orchards. After nearly 20 years since their study the problem is just as prevalent if not
more so. Currently, slow infiltration is a multi-million, if not billion, dollar problem in California each year. According to Singer and Oster (1984) the IR problems are most prevalent along the east side of the central valley and southern deserts. From their surveys of county agents, soils of all textures from sandy loams to clays have water penetration problems in California. Some of the main causes that were identified from their study were dense and cemented soil layers which can occur naturally (cemented pans) or can be created by farming practices (plow pans, soil compaction) or by irrigation (soil crusts). Surface crusting (or sealing) is considered a management induced problem because it is not normally a problem on native or uncultivated soils. External factors (rainfall rate, intensity, number and duration of irrigations) which supply energy for soil crusting, and inherent soil characteristics (moisture content, particle size distribution, OM content, exchangeable sodium content, and irrigation water quality), influence crust formation. Soils high in silt and sand or low in swelling clays form crusts readily. Low OM decreases aggregate stability and increases crusting and crust strength. They also noted that abrupt changes in texture across boundaries between neighboring soil layers can reduce water penetration. Compaction was also a major concern. Soil compaction increases soil density, decreases total porosity, and decreases average pore diameter. The decrease in pore volume and size results in slower water penetration and decreased root penetration. Soil properties, particularly OM content, water content, and particle size, determine the degree of soil compaction sustained per compactive effort (Singer and Oster, 1984).
Sieving Crusts

Sieving crusts are likely in California due to the type of soils and their texture. The propensity of the soil to form sieving crusts induces surface water repellency and low IR (Singer and Oster, 1984). Soil water repellency and low IR are associated with; patchy vegetation, concentrations of OM relating to rabbit latrines and ant colonies and the depth of the washed-in layer of sieving crusts. That is, the thickness of the final surface crust formed after a rainstorm or irrigation. This layer of the sieving crusts can be composed of very fine platy mica schist sand particles which can act as a physical barrier restricting the translocation of both organic particles and hydrophobic organic compounds (Contreras et al., 2008). As found by Contreras et al. (2008) soil water repellency reduces the infiltration capacity of soil, promoting a fast runoff response during the early stages of rainfall. Bisdom et al. (1993) found that a number of soil constituents such as micro-aggregates, plant fragments with and without coatings, macro-aggregates, speckles, dots, coatings and platy fragments have been found in water-repellent sieve fractions. Valentin (1986) suggests that a sieving mechanism may be responsible for inducing particle sorting in the washout-out layer of structural crusts. Bielders and Baveye (1995) suggest that a dense clay-band formation in the crust is just an extension of the same mechanism. The smallest micro-aggregates forming the clay band are sieved deepest, the depth being controlled solely by the maximum depth to which water drops can displace particles during impact.

Smectite Clay Content

Smectite soils reduce IR in California agricultural soils because if these soils are maintained wet, as they often are, and have high enough total clay percentage, they will
not form cracks. The cracking of smectite soils is essential for them to maintain sufficient IR (Levin et al., 1991). However, as Norton et al. (1993) explained there is also the problem that even if smectite soils are allowed to dry out they are also highly dispersive and thus are very susceptible to seals and crusts which reduce IR. Based on findings by Lado et al. (2004), it is possible to conclude that smectite in California soils contributes to decreased aggregate stability, which also leads to reduced IR.

**Poor Aggregate Stability and Low Organic Matter**

The same soil properties that influence aggregate stability in all others soils apply to those found in California. That is, soil texture, clay mineralogy, OM content, type and concentration of cations, sesquioxide content, and calcium carbonate content. There are of course various interactions between these properties that can modify their individual influences on aggregate stability (Levin et al., 1991; Le Bissonnais, 1996). Le Bissonnais (1996) explains that aggregate stability influences several aspects of a soil’s physical behavior such as water infiltration. He states that there are two processes of aggregate breakdown: slaking and dispersion. The soil aggregates can resist breakdown with an increase in clay content, which binds the soil constituents together. Although slaking and dispersion are the main cause of aggregate degradation in California where most of the soils are irrigated, mechanical breakdown by raindrop or sprinkler drop impact can destroy aggregates of soils that are already wet. Many agricultural practices keep the soil surface fairly moist, such as under almond canopies where watering can take place several times per week in California. Wet soil is inherently weaker since the particles are lubricated. As the drops strike the surface, significant aggregate breakdown occurs simply from the impact forces of the water drops (Le Bissonnais, 1996).
Aggregation and the proportion of large aggregates decrease with aridity (Lavee et al., 1991; Cerda, 1998). This could be due to low OM, which is a common problem in such climates. Good aggregation is associated with better crop production. Poor aggregation is related to low OM (Singer and Oster, 1984). Mitchell et al. (1999) explained that the intensive production of valuable crops on a vast scale in the SJV of California typically entails intensive tillage and large fertilizer and water inputs but few additions of organic carbon to the soil. Proebsting (1956; 1958) has shown that long-term increases in soil OM content is not possible under California climatic conditions, except under permanent sod. The main issue with OM levels in California soils and its influence on aggregates’ stability is that even though these soils would benefit greatly from regular additions of OM, the availability of adequate quantities is often impossible (Fox and Bryan, 1992).

**Hard Pans**

In California slow infiltration in medium and coarse-textured soils can be caused by restrictive layers at the surface such as crusts or seals, or below the surface such as compacted layers, pans, lenses, fine-textured strata or cemented layers (Oster et al., 1992).

**Kern County Infiltration Issues**

The research for this thesis was done in Northwestern Kern County California near the cities of Wasco and Shafter, 32km north of Bakersfield. Similar to where most crop production occurs in California, the climate is semiarid and Mediterranean with long hot summers (Contreras et al., 2008). Kern County is located in the San Joaquin Valley
(SJV) of California. The SJV is an elongated, northwesterly to southeasterly running, tectonic trough, approximately 80 km wide and 350 km long. It is bounded on the east by the Sierra Nevada and on the west by the Coastal Ranges (Amundson and Lund, 1985). Within the last century, stream diversion and drainage have left much of the SJV and surrounding rim suitable for agriculture (Amundson and Lund, 1985). This area is prone to the same infiltration problems described for California and the general issues facing irrigated soils everywhere. There are additional concerns in this area and certain details relating to the issues already introduced.

The water used for irrigation varies throughout the year and from year to year. Farmers sometimes blend surface and well sources to meet volume demands (Lentz et al., 1996). Depending on the source of the water used, and its quality, IR problems can become severe or non-existent in western Kern County. Studies by Singer and Oster (1984) and Oster et al. (1992) on the east side of the SJV have indicated that irrigation with canal water that contains very low dissolved solids results in dispersion of the soils. These soils also have low salt content even though sodium adsorption ratios are not high.

In 1984, Singer and Oster surveyed Kern County extension agents about the extent of reduced IR. In their study of all counties in California, Kern was reported to have one of the worst IR. Oster found that the estimated acreage suffering from slow IR was 250,000 acres. The type of soils reported to have low IR were sandy loams from granitic parent material. The crops adversely affected by reduced IR were vines, citrus, tree fruits, nut trees, alfalfa and cotton. The reasons thought to be contributing to causes were low salt water, compaction and the lack of tillage. The agents surveyed said that
certain management practices such as early season irrigation to assure deep moisture, gypsum applications annually and cover crops have improved IR in Kern County.

Ajwa and Trout (2006) reported that most of the soils in Kern County are generally on level ground or very low slopes and erosion is not evident. They indicated that surface seal formation is a possible reason for the reduced IR in this area. Contreras et al. (2008) found a similar soil to the one studied in this thesis. The soil they researched in Spain was similar in that it showed little development of pedogenetic horizons in the loamy sands and fine sandy loams. These were all soils with low silt and clay fractions just like the ones found in Kern County California. This is significant because of the IR problems recorded in the Contreras et al. (2008) study. They found that a subsurface layer in the crusts formed on these textures of soils in the same type of climate. This layer consisted of a dense skin of very fine sand and silt that impeded infiltration. Not only did it concentrate particles above it that would reduce IR, but this layer also concentrated hydrophobic organic compounds at the soil surface. If the same mechanism that was studied in Spain occurs in California, and specifically Kern County, it may be strengthened due to the high amount of Biotite mica found in the very fine sand and coarse silt fractions of these soils. The planner shape of these particles and their rich abundance in Kern County could be a major factor in reduced IR.

The particular concern of this study was soils used in permanent plantings. In Kern County, nuts are the most common crop, particularly almonds. These plantings can be in place for over thirty years. As Oster et al. (1992) described, a mature orchard has a higher water requirement than a young orchard. This means that soil or water quality may be sufficient at first, but over time problems can appear that were not originally apparent
in an orchard. Prolonged ponding can result in root diseases (Oster et al., 1992). Gomez et al. (2001) studied the relationship of tillage on IR in an olive orchard. Their work expected IR in orchards to be spatially variable because of tree effects above and below ground. It is likely that the same variable will be found in all long-term permanent plantings. One effect, as Gras and Trocme (1977) observed, is that IR may be higher under the trees than in the rows. They found this to be the case in apple orchards (Gomez et al., 2001).

**Hard Pans**

The IR of a soil is determined by the least permeable layer. Such layers include hard pans, compacted layers, fine-textured strata and cemented layers which are expected in most soils of Kern County. It has become common practice to deep-rip orchards before planting a new crop to remove zones of low IR which can only be affected by deep ripping (Oster et al., 1992).

**Soil Crusts**

Kern County is dominated by soil with a sandy loam texture. Despite the higher percentages of sand in these soils it is possible for crusts to form on these soils (Chen et al., 1980). Ben-Hur et al. (1985) found that loamy soils with 20% clay were the most susceptible to crust formation and that they also had the lowest final IR independent of water quality. This percentage of clay is very typical of soils in Kern County. Busch et al. (1973) showed that crust strength of a sandy loam soil increased with the number of irrigation water applications. They found that low sprinkler rates (3.3mm/h) produced lower strength crusts than high rates (10.9mm/h). Soils high in silt and sand, or low in
swelling clays, have low shrink-swell properties. Kemper and Noonan (1970) found that maximum runoff during rainfall on crust-prone soils occurred when the sand content was between 50-80%. This sand percentage is characteristic of the soils of Northwester Kern County. Surface crusts that form on these soils do not crack upon drying. Cracks are extremely important for increasing the initial IR. The lack of cracks is one reason soils in Kern County have low IR. The predominant clay minerals are hydrous mica and vermiculite that do not swell (Singer and Oster, 1984). Some soils have a clay fraction dominated by smectite, if these soils are maintained moist the smectite remains expanded and the beneficial effects of shrinking such as cracking do not occur. It may even be possible that the swelling of 2:1 clays is what causes particles such as mica to orient and reduce IR. This would explain how soils that would be expected to form cracks do not always. Even if they do, IR is not improved very much (Singer and Oster, 1984). Lemos and Lutz (1957) showed that crusts tended to have a silt content (2 to 3%) and a very fine sand content higher than the underlying soil. In soils with more mica this fraction could be more susceptible to crust formation and a reduction in conducting pores due to particle orientation. Ferry and Olson (1975) proposed that the orientation of clay particles was a critical factor in crust formation and crust properties, particularly strength. As explained by Singer and Oster (1984) the suction forces of the drying soil orients clay particles.

In 2001, Trout and Ajwa found that low permeability crusts or seals were not evident at the soil surface in sandy loam soils of the SJV. While working in an almond orchard with low infiltration problems they carefully removed surface soil layers and replaced them with fine sand prior to irrigation. According to their findings, removing from 1 up to 10 cm of surface soil did not result in increased water penetration. Even if
classical crusts are not found in the soils of Kern County, reduced IR can develop as large soil pores are plugged by small soil particles (Oster et al., 1992). The right conditions are present in this area of California for the formation of both structural and depositional crusts (Oster et al., 1992). Knowing which kind of crust is causing slow water penetration is useful because different remedial procedures apply (Oster et al., 1992).

**Smectite Clay Content**

The clay content and type of clay in Kern County soils is very important when determining if the soil will have IR problems. According to Levin et al. (1991), a soil with a high amount of smectite clay is expected to have better IR due to the cracks that can occur on these soils. Norton et al. (1993) showed that dispersion of soils by rainwater and subsequent surface sealing is a well known phenomenon in smectite soils of semiarid regions. Lado et al. (2004) explained that smectite probably decreases aggregate stability. McNeal and Coleman (1966) found a linear relationship between HC reduction and macroscopic swelling of soil clays. Thus the benefits and harms of smectite in some soils of Kern County may cancel each other.

**Poor Aggregate Stability and Low Organic Matter**

Abu-Sharar and Salameh (1995) found that deterioration in soil structure may take place even when irrigating non-sodic soils with waters of low SAR and salinity. This is primarily due to surface aggregate breakdown and subsequent crust formation. As a result IR tends to decrease to a minimum value irrespective of the initial soil moisture content, water quality or sodium levels in the soil simply due to the destructive action of wetting bare agricultural soils. Oster et al. (1992) stated that aggregates of soil particles
on the soil surface are more sensitive to water quality effects and exchangeable sodium level than those below the surface. They explain that surface aggregates are stirred by the flowing water during surface irrigation and by water drop impact during sprinkler application. The stirring and impacting of aggregates by irrigation water works to destroy surface soil structure. Lavee et al. (1991) and Cerda (1998) found that aggregation and the proportion of large aggregates decrease with aridity. The arid climate of Kern County is thus a limiting factor in soil structure improvement. Cary and Evans (1974) as well as Wischmeier and Mannering (1969) found that soils with low OM and high silt content usually have low aggregate stabilities. It is also possible that mica fragments, very fine sand and silt fraction of the soil could contribute to aggregate instability.

**Mica in the Very Fine Sand and Silt Fraction of the Soil**

Soils along the east side of the San Joaquin valley (SJV) contain a large amount of mica in both the clay size fraction and the larger particles (Singer and Oster, 1984; Storie and Harradine, 1957). A large portion of the soils found in Kern County are Typic Torriorthents which have been found to lie on mica schists (Canton et al., 2009). It has long been assumed that mica grains in the soils of Kern County have caused low IR (Singer and Oster, 1984; Oster et al., 1992). Dr. Charles Burt, an authority on Kern County soils, has maintained this assumption for nearly 30 years (Burt, Personal Communication, 2010). The theory is that these platy particles are able to orient and block water-conducting soil pores, aid in crust formation and collect in dense bands which lower IR.
Singer and Oster (1984) explain that although clay mineralogy is likely to be the most fruitful area of research in finding the causes of reduced IR in California soils, the mineralogy of the silt and sand size fractions will also need to be considered. Singer and Oster (1984) state that mica found in soils may range in size from sand (2-0.05mm) to clay (less than 2 µm), but they are most commonly concentrated in silt (50-2 µm) and coarse clay (2-0.2 µm) fractions. Bielders and Baveye (1995) have pointed out that particles in either very fine sand or silt-sized grains or micro-aggregates of similar size are large enough so that they will not move downward any further in the absence of external energy input. This means a concentration of platy mica is likely to occur at the surface of the soil where such particle sizes tend to accumulate. Such an accumulation would aid in crust formation and reduced IR. Thus, a determination of mica content in the very fine sand and coarse silt fraction of the soil will aid in diagnosing Kern County soils with low IR (Singer and Oster, 1984).

Mica in the sand and coarse silt portion of the soil may affect IR but its presence and relative amounts will also determine clay mineralogy. The clays formed from the weathering of mica can have a profound effect on the soil IR. Oster et al. (1992) found that soils with vermiculite clays will not crack as much and will remain crusted, which will reduce IR. Because vermiculite forms from mica and is platy, the presence of vermiculite in soils on the east side of the Sacramento and SJV indicates there is the potential for serious crusting problems, even in sandy soils. In fact sandy soils, including sandy loams, may be the most at risk. Soils high in silt or VFS and low in swelling clay are among the more troublesome in this regard. Given that mica is found mostly in these
fractions and with swelling clays, due to its affect on clay morphology, soils high in mica typically have low IR (Singer and Oster, 1984).

Road engineers have expressed most of the concern for the amount of mica in the sand and coarse silt portion of the soil. Difficulties, of varying degree, have been attributed to the presence of mica in Ghana, Tanganyika, Angola and the U.S.A. (Hogentogler and Terzaghi, 1929; Anon, 1949; Millard, 1956; Novais, Ferreira and Silva, 1957; Anday, 1960). A survey of 54 countries indicates that micaceous soils are not widespread; but where they do occur, normally in association with mica-bearing rocks, engineers encounter difficulties with the stability of slopes and with the use of micaceous soils in earthworks and pavement construction (Tubey and Bulman, 1964). Also, a high content of free mica particles in the fine aggregates, in both bound and unbound applications, will negatively influence the stability of road construction when exposed to water or moisture. The impact of such mica-water interaction can greatly reduce bearing capacity and influence the hydraulic behavior of road structures (Uthus et al., 2006; Ekblad, 2007). The reason road engineers are particularly concerned with mica content is that it has destabilizing attributes when the soil is compressed. Harris et al. (1984) found that the engineering properties of coarse-textured soils may be significantly affected by the presence of sand-sized mica. Mica minerals are said to have very distinctive characteristics that are important when considering their effect on aggregates and bituminous materials (Kondelchuk and Miskovsky, 2008). The effect of mica on aggregates is to make them weaker.

According to Tubey and Webster (1978) the term mica applies to a family of minerals that are all hydrated silicates of aluminum, but which may also contain small
quantities of other elements such as titanium, iron and magnesium. Micas have a layered structure that imparts a flat, plate-like, shape to their crystals with the ability of successive sheets to part easily in the plane parallel to their larger surfaces (this is known as perfect basal cleavage) and to form very thin flakes. Thus mica typically has a much higher surface area to mass ratio than other mineral particles found in the soil. Mica is also relatively dense (3.0-3.2), in comparison with similar particles of quarts and feldspar (2.6). However, the flocculation rate of mica is much lower (Kondelchuk and Miskovsky, 2008). This means that mica particles tend to cleave together especially after they have dried from a recent exposure to water. This cohesion may be due to the negative charge density of mica since the crystal layers of micas have relatively high permanent negative charge (Singer and Oster, 1984). Canton et al. (2009) found that unstable soil aggregates over 4mm, though not very frequent, might also be explained, apart from the presence of SOM, by the fact that a large percentage of the mineral grains are micas (mainly muscovite, paragonite and biotite) with different degrees of weathering, and therefore have some negative charge, which might contribute to bonding with both SOM and Fe oxihydroxides. Thus, it seems the negative charge of mica attracts certain materials and causes some weak aggregation of mica particles, OM and iron oxides.

Singer and Oster (1984) stated that phyllosilicates (including micas and kaolins) are most frequently implicated in soil permeability problems. Structurally they are characterized by assemblages of tabular or plate-like layers composed of continuous, chemically joined, two-dimensional sheets of silica tetrahedra and alumina, magnesia or iron octahedral. Morras (1995) found that the high CEC of the silt fraction of certain soils may be due to mica grains undergoing a transformation process.
Tubey and Webster (1978) described mica as being an unusually shaped particle. This relates to its resilience under compaction. It is said to be markedly different from the minerals, such as quartz, of which sands are commonly composed primarily because of its shape. The thick plate-like shape of mica contrasts markedly with that of minerals present in most soils, gravels or crushed rocks. These are generally approximately cubical or spherical in shape (Tubey and Webster, 1978). Abu-Sharar and Salameh (1995) comment that the difference in shape extends to the surface of the particles, making them uniquely irregular, depending on the amount and type of weathering.

The larger surface area of mica compared to the more rounded silica means that more water is needed to coat the mica particles and so more water is needed to lubricate the particles for compaction. In addition, the ability of mica to absorb or store water within its lattice enhances this effect (Tubey and Webster, 1978). Kondelchuk and Miskovsky (2008) found that when mica is mixed with limited amounts of water the particles can become plastic. They also noted that as the mica particles absorbed water they expanded because the water filled the spaces between the stacked silicate layers. Tubey and Webster (1978) found that the plastic limit increased in high mica mixes due to mica holding absorbed water.

The most commonly cited phenomena linking mineralogy with slow soil water movement are particle orientation, dispersion and swelling (Singer and Oster, 1984). With regards to mica in the very fine sand and coarse silt fraction of the soil, orientation is the main concern with reduced IR. Singer and Oster (1984) state that phyllosilicate clay and silt particles, with large planar surface in proportion to their mass, are particularly amenable to transport and segregation from rounded or irregular particles.
This means that depositional zones with relatively high concentrations of oriented phyllosilicate minerals are often formed in loessial and alluvial deposits such as those found in Kern County, California. These oriented particle zones generally are of high density and present conducting pores of high tortuosity. Such zones are generally impediments to water percolation (Singer and Oster, 1984). They go on to explain that the tabular habit of the phyllosilicate minerals contributes to their propensity to orient preferentially in a directional plane when allowed to settle freely from suspension or when subjected to directional pressure. A concentration of preferentially oriented mineral materials in more or less continuous zones can reduce IR. Their study found three specific mechanisms that are conducive to particle orientation. First, segregation and deposition of wind and water transported sediments, second application of directional pressure to a soil body (which could be due to flood irrigation flowing in one direction) and third local disturbance and settling of surface soil particles (Singer and Oster, 1984).

Morin et al. (1981) explained that soil crusts are made by suction forces, which result in the orientation of clay particles into a continuous dense skin. This could be analogous to what happens with mica in dispersed soils. According to Gal et al. (1984) the washed in layer of soil crusts was formed only in soils that were easily dispersed. Micrographs by Evans and Buol (1968) show that, in some soils, particles in the layer immediately below the surface skin were oriented, whereas in others orientation of silt and sand particles occurred in deeper clays of the crust. Such orientation would indicate how mica particles could reduce IR by blocking soil pores. A study by Fox et al. (2009) found that aggregate breakdown correlated with low IR soils. They also found a strong relationship between silt content and IR that suggested that silt movement leading to
packing of silt into thin bands with minimal pore space is a key factor behind the low inherent IR in certain soils. This indicates that IR would be reduced if mica is concentrated in the silt fraction, as it is known to be, and if the silt fraction forms bands and the mica orients horizontally to the soil surface.

There is some indication that the effects of mica might be overstated and that mica might actually improve IR. Tubey and Webster (1978) have argued that the distinctive color, luster and flakey-shape of mica renders the presence of even trace quantities very obvious. They explain that many of the difficulties attributed to the presence of mica in the past are more likely to result from other causes such as the overall particle size distribution. In addition to their claim that the harmful effects of mica are exaggerated they say that the mica may, in some way, facilitate water penetration, possibly by increasing the number of capillary-sized pores and larger pore spaces between grains. Furthermore their study showed that the presence of mica particles in the silt and sand portion of the soil reduces compaction. Since compaction is a major cause of reduced IR, their findings indicate that mica might actually alleviate some of the IR reducing effects of compaction in certain soils.

**Treatments of Low Infiltration Rate**

Oster et al. (1992) and Singer and Oster (1984) specifically address how to treat soils with low IR in California and Kern County. Oster et al. (1992) states that, to prevent water infiltration problems or simply to cope with them, changing irrigation practices is the first consideration. They go on to explain that tillage before each irrigation and the use of soil and water amendments are the next alternatives to consider. In consideration
of orchards they argue that changing vegetation management can be an effective alternative to other treatments of low IR. Their prescription for treatments of low IR relies on the fact that IR varies from place to place within a field. According to them this means the application of about 20% more water than needed by the crop compensates for IR variability. Based on their study, irrigation should be stopped when ponding or runoff begins.

Singer and Oster (1984) explained that the first requirement in attempting to solve a specific problem of low IR is to recognize that the phenomenon does not result from a single universal cause. According to them there are many factors that may contribute or be solely responsible for the infiltration problem on any tract of land. This means that solutions to the problem are likely site specific. Despite this explanation for how to approach treatments they claimed that neither adequate diagnostic nor corrective techniques have been developed for all the possible problems and combination of factors that could lead to low IR. In particular they call for a simple, quantitative test to determine the dispersibility of the clay fraction of a particular soil. Such a test would be a valuable tool in diagnosis and prognosis of low IR (Singer and Oster, 1984). Work by Yousaf et al. (1987) and Shanmuganathan and Oades (1982) has made strides towards such a test. Singer and Oster (1984) conclude that there is no universal solution to low IR for all soils and such hopes should be abandoned.

Physical problems reducing IR will need physical solutions such as various forms of tillage and soil agitation. In contrast chemical or physical-chemical problems will normally require chemical solutions (Singer and Oster, 1984). According to Ben-Hur et al. (1989) in the latter case chemical amendments can improve or maintain soil structure
and may be one way of maintaining high IR. It should be noted that there have been, and continue to be many “cures” for slow water penetration available commercially. Many such substances are alleged to have mysterious properties, and the mechanisms by which they function are unknown and are generally unexplainable by soil scientists. No such product has endured very long. Experience indicates that non-fertilizer soil amendments work effectively only for certain conditions, and that the substance must attack the specific cause of the problem however elusive it may be (Singer and Oster, 1984).

Le Souder et al. (1989) studied a hydrophobic mineral conditioner that slows down water entrance into clod pores and thus limits shattering hazards. Such a treatment would be most effective in soil and environmental conditions which are the most favorable to the occurrence of structural slaking crusts namely dry loamy soils subjected to intense rainfall (Valentin and Bresson, 1992). Various surface applied soil ameliorants such as mulches, manure, gypsum and others will combat crusting and improve infiltration (FAO, 1965). According to Zhang et al. (1998) a combination of physical and chemical treatments is the best practice for improving IR.

There are some cultural practices that can improve low IR. For drip or micro-sprinkler systems, the options include decreasing the application rate, increasing irrigation frequency, and increasing the wetted area (Oster et al., 1992). According to Singer and Oster (1984) the irrigation method has no major role in determining IR. They do acknowledge that very slow rates of sprinkling reduce soil sealing by minimizing slaking and reducing the drop impact force. As far as fertilization they are of very little consequence with respect to IR. However, there are well-documented cases where the nitrogen source has caused reduction in IR (Jones et al., 1961). This should alleviate
concerns that potassium fertilization is causing a greater propensity of swelling clays to clog soil pores. Leaving crop residues on the surface can greatly improve IR by improving soil aggregate stability with organic matter, limiting the development of structural sieving crusts and reducing the water drop impact or flowing water shear forces that break down the surface soils (Trout et al., 1990; Oster et al., 1992). In particular, it is better for the soil surface to be as rough as possible. Even slight topographical disturbances aids water entry (Van der Watt and Claassens, 1990). Thus, any treatment that keeps the soil surface rough, such as, gypsum, mulch, tilling etc., aids in preventing crusts.

No-till is also a possible cultural practice that could alleviate low IR induced from compaction. This treatment seems to rely on other factors for its success such as a cover crop. A study by Gomez et al. (2001) showed that even after nearly two decades of no-tillage, the general compaction of the soil seemed to remain the main factor lowering IR.

Singer and Oster (1984) explain that management factors are seldom the sole cause of differences in water intake among soils. Soils in the native condition have had widely varying IR because of differences in texture, structure, cover, alkalinity, and subsoil restricting layers. In most soils, management practices have probably lowered IR from those in the native state. This is due to leaving the soil bare, removing OM, compaction, surface burning and the application of hydrophobic fertilizers, pesticides and fungicides over a long period of time.

**Water Quality**

Oster and Schroer (1979) found that irrigation water composition, through its effect on surface soil conditions, has a greater influence on IR than does the chemistry of
the soil column itself. They showed that the IR is very sensitive to the ESP and the salt concentration of the applied water. Abu-Sharar and Salameh (1995) explained that arid and semiarid soils are characterized by reductions in HC and IR when low salinity/sodicity waters are used. They showed that such reductions are further exacerbated when using turbid water. The permeability of a soil to water depends both on the ESP of the soil and on the salt concentration of the percolating solution. The IR tends to decrease with increasing ESP and decreasing salt concentration (Quirk and Schofield, 1955; McNeal et al., 1968).

Oster et al. (1992) explained the important distinction between having salty irrigation water and water high in Sodium. Water quality determines the extent to which soil particles remain together. When soil particles separate, the small particles plug the large soil pores through which most of the water flows. The higher the salt content of irrigation water the more likely soil particles will remain together and the less likely soil particle will adsorb water and become separated. The higher the sodicity, or sodium content, of irrigation water, the higher the ESP in the soil and the more likely soil particles will adsorb water and become separated (Oster et al., 1992; Agassi et al., 1981). Ben-Hur et al. (1985) found in their study that when saline water was used instead of distilled water the final IR is higher. This means that the ideal water quality is one with enough salts to keep soil particles from dispersing but not too much. It is important to avoid water that contains high levels of sodium containing salts.

Where poor water penetration is a problem, salinity and sodicity of the soil water are often greater than those of the irrigation water (Oster et al., 1992). Typically the soil water is a greater concentrated version of the applied water. As Letey (2000) explained,
even though the salt concentrations in the imported water in the SJV are relatively low, 1.9 million metric tons of salts are imported each day. This continual addition of salts causes an increased concentration of salts in the soil solution. Without appropriate management, salt levels will build up in irrigated arid soils despite the low salt levels of the applied water. Shainberg and Singer (1986) explain the effect of the different salt concentrations of the irrigation water and soil solution. When the electrolyte concentration of the soil solution mixed with the irrigation water exceeds the flocculation value of the clay, the clay platelets form flocculi that settle with a random orientation and open structure. This is what happens when irrigation water is sufficiently salty to prevent dispersion. When the electrolyte concentration of the irrigation water mixed with the soil solution is below the clay flocculation value, the clay disperses. The dispersed clay platelets settle into a compact crust with parallel orientation of clay platelets. The dispersed clay may be carried down by gravity deeper into the soil and further block conducting pores (Ben-Hur et al., 1985).

According to Singer and Oster (1984), well water is salty and leads to lower IR in CA soils. Field tests by Trout and Ajwa (2001) confirm this claim. Their study showed that IR with well water (1.2 dS m⁻¹) was generally higher than with canal water. Oster and Schroer (1979) showed that the potential for crusting and reduced IR can be strongly affected by changes in water sources from regular irrigation to normal rainfall or vice versa. Trout and Ajwa (2001) explained that the mountain runoff water, found in many of the irrigation canals of Kern County has extremely low levels of dissolved solids and electrical conductivity of about 0.02 dS/m. This low EC water may result in soil dispersion.
Lado et al. (2005) found that irrigation with effluent caused increased seal formation and soil loss on sandy soils, whereas in the clay soil the effect was negligible. In the sandy soil, seal formation was mainly influenced by clay dispersion in the soil surface and clogging of the pores in the washed-in zone. Effluent irrigation enhanced clay dispersion due to the increase of the SAR of the soil solution, and therefore a less permeable seal was formed in the effluent than in the fresh water irrigated soil. Consequently, IR was reduced in the effluent-irrigated sandy soil, independently of its initial condition. In contrast, seal formation in a dry calcareous clay soil was mainly affected by slaking of the aggregates, reducing the impact on clay dispersion due to effluent irrigation.

Water with high SAR reduces the soil structure stability because of consequent clay dispersion swelling and reorientation (Chen and Banin, 1975; Frenkel et al., 1978). According to Abu-Sharar and Salameh (1995), irrigation water at a given SAR causes IR to decrease with decreasing electrolyte concentrations of the permeating solution. Oster et al. (1992) explained that at an SAR between 0 and 3, irrigation water with ECw less than 0.3 dS/m are likely to cause water penetration problems whereas those with ECw greater than 0.7 dS/m are not. Similarly those with an SAR between 3.1 and 6 are likely to cause infiltration problems if the ECw is less than 0.4 dS/m, but not if the ECw is greater than 1 dS/m. El-Morsy et al. (1991) showed that soils which have been irrigated with water of high SAR are particularly susceptible to physical disruption leading to low IR when exposed to water of low electrolyte concentration such as precipitation.

Singer and Oster (1984) explain that irrigating with water high in electrolytes decreases smectite clay swelling which increases IR. Keren and Shainberg (1981) found
that clay dispersion in the soil surface (and crust formation) is enhanced by both the impact of raindrops and the potential of the soil clays to disperse. The effectiveness of amendments designed to improve IR, such as PAM, depend on the quality of irrigation water (Seybold, 1994; Ajwa and Trout, 2006). Water with a high amount of suspended particles and low salinity can also reduce IR. Abu-Sharar and Salameh (1995) showed that turbid water full of suspended fine clay particles flocculated in the soil conducting pores causing their clogging. This dirty water caused crust formations, substantial reductions in IR, water ponding on soil surface, poor seedling emergence, and extensive soil erosion. To counteract this effect, turbid waters need to have clay particles flocculated before irrigation use (Abu-Sharar and Salameh, 1995). Shainberg and Singer (1986) showed that as irrigation water containing sediment infiltrates, a depositional crust forms when dried. Thus, turbid water should be avoided in all irrigation systems.

Chunye et al. (2003) showed that the temperature of irrigation water affects its viscosity. Their study showed significant seasonal differences in IR based on temperature differences of the infiltrating water. Water viscosity changes by ~2% per degree Celsius, leading to an estimated 40% change of IR between summer and winter in arid zones. Thus, when determining potential IR for a field it may be important to take into consideration the temperature of the water.

**Cover Crops**

Oster et al. (1992) have conducted a careful review of cover crop use in California soils to improve IR. According to them, both research data and farmer experiences have established that cover crops improve IR. They state that careful vegetation management is often the best way to prevent slow water penetration. This is because vegetation
management is the only practical means of supplying sufficient OM to maintain or improve soil structure (Oster et al., 1992). Good soil structure is the key to sufficient IR. Cover crops protect the soil surface from the mixing and sorting action of water flow or water drop impact. They also increase OM, which improves soil structure. The net effect is to reduce the formation of a thin, compact soil layer at the surface which reduces IR, increases macroporosity through root channeling, and enhances biological activity (Oster et al., 1992; Trout et al., 1995; Gomez et al., 2001). A study by Grimes et al. (1991) measured the effects of cover crops on cumulative infiltration in a vineyard on Hanford sandy loam soil at the Kearny Agricultural Center. Cumulative infiltration was greatest in the brome grass continuous cover, intermediate in the cover/herbicide-treated, and lowest in clean no-till treatments. Differences increased considerably the second year. Using annual cover crops that are dead during the summer months reduces water requirements and competition for nutrition of mature trees and vines. It also is convenient for nut crops that are harvested from the ground and for tree crops with closed canopies during the summer months (Oster et al., 1992). Zuzel et al. (1990) found that maintaining high fertility and leaving crop residue on the soil surface was more important for maintaining high IR than choice of tillage and reduction of compaction caused by equipment traffic. According to Fox and Bryan (1992), certain amendment application treatments designed to improve IR are dramatically improved when combined with cover crops. Singer and Oster (1984) explain that to make up for the lack of sufficient OM, laboratory research indicate that to be highly effective physically, most organic amendments must occupy over half the volume of the amended soil so that the amendment becomes the matrix. This is a tremendous amount of material to be added if soils are to be maintained bare of
cover crops. They go on to explain that where the surface is the limiting layer, as it most often is in California soils, residues may be more effective if not incorporated too deeply.

There are some disadvantages to maintaining a cover crop. It requires the same management as harvested crops. This management involves extra costs for meeting the cover crop’s water and nutritional needs (Gomez et al., 2001) as well as costs of changing the timing of farm operation to accommodate the cover crop. Sowing an annual cover crop in the fall, followed by cultivation the following spring or summer, has been used to minimize these disadvantages (Oster et al., 1992). The cover crop can harbor insects or diseases, and crop residues can interfere with harvesting nut crops (Oster et al., 1992). Singer and Oster (1984) state that cover crops grown only during the winter do not contribute much to water infiltration. This means that for the best results cover crops must be alive and growing throughout the year. It has been found that clean cultivation produced the lowest IR but the highest yields (Saayman and van Huyssteen, 1983). Gomez et al. (2001) explained that periodic droughts make cover corps a high-risk option in permanent plantings. Therefore, although cover crops can contribute significant advantages to permanent plantings there benefits should be weighed against their costs and the priorities of the farm.

Gypsum

Baumhardt et al. (1992) found that increasing the EC_w of infiltrating water with surface applied gypsum reduces chemical dispersion and seal development in soil column experiments. Warrington et al. (1989) showed that when gypsum was spread over sandy loam soils exposed to distilled water, it dissolved and prevented clay dispersion, tripled the permeability of the soil, and decreased the runoff depth and the soil loss. Keren and
Shainberg (1981) showed that gypsum acted as a slow releasing salt, supplying sufficient electrolytes to the rainwater and preventing clay dispersion. Agassi et al. (1981) explained that one way of limiting soil seal formation is to control the chemical clay dispersion by maintaining the electrolyte concentration of the soil solution at the soil surface above the flocculation value of the soil clays. This can be achieved by spreading phosphogypsum (PG) at the soil surface (Agassi et al., 1981; Kazman et al., 1983; Lado and Ben-Hur, 2004). According to Levin et al. (1991) the electrolyte concentration of a saturated PG solution is 25 mmol(+) L\(^{-1}\), which is above the flocculation value of the soil clays in arable lands.

Oster et al. (1992) explained that gypsum decreases the Exchangeable Sodium Percentages (ESP) and increases soil salinity, resulting in higher infiltration rates. Kazman et al. (1983) showed that it is evident that gypsum is effective even in soils with ESP of 1.0, indicating that some chemical dispersion takes place even at low ESP values. Sodium adsorption ratios (SAR) of the soil or the irrigation water greater than 5 further increase the likelihood that surface-applied gypsum would be beneficial. They explained that because of the instantaneous effect of gypsum and its high efficiency, it seems that gypsum operates mainly by dissolution, with a resulting increase in electrolyte concentration of the rainwater or irrigation water. In a study by Keren and Shainberg (1981) they found that the main effect of the gypsum is its influence on the chemistry of the soil surface. Lado and Ben-Hur (2004) confirmed that indeed gypsum affects the soils surface to improve infiltration by preventing clay dispersion.

Baumhardt et al. (1992) found that not all field applications of gypsum resulted in increased IR. This may be due to factors beyond what gypsum can influence such as
particle orientation and the texture of the soil. Both of these factors are studied in this thesis as they relate to soils treated with gypsum but which still exhibited low IR.

The effectiveness of gypsum as an amendment to improve IR depends on its dissolution properties (Keren and Shainberg, 1981; Baumhardt et al., 1992). Kazman et al. (1983) found that phosphogypsum (industrial gypsum), a by-product of the phosphate fertilizer industry, is available in huge quantities, and it dissolves at a much higher rate than mined gypsum.

The amount of gypsum applied will depend on many factors such as soil type, water quality, climate, crop, etc. Baumhardt et al. (1992) recommends a minimum rate of 5 Mg ha\(^{-1}\) of gypsum since 3 Mg ha\(^{-1}\) rate was within one standard deviation of the 0 Mg ha\(^{-1}\) rate. For a silty loam soil, Keren et al. (1983) showed that applying 2 and 4 Mg Ha\(^{-1}\) (200 and 400 g m\(^{-2}\), respectively) gypsum increased the final IR of the silty loam by 50 and 100%, respectively. Ben-Hur et al. (1992) used 5 Mg PG ha\(^{-1}\) on the soil surface, which decreased the soil loss sharply from dispersive soils and moderately from nondispersive soils. Ajwa and Trout (2006) showed that applications of 1 to 2 tons per acre of gypsum to the tilled surface can reduce crusting if the salinity of the irrigation water is less than 0.5 dS/m. Their findings show the importance of the quality of water being applied and the interaction between gypsum and tillage to improve IR.

The addition of calcium salts to irrigation canal water often results in improved IR in arid soils. A common practice for growers using canal water in areas where soils have low IR is to add gypsum to the irrigation waters (Ajwa and Trout, 2006). It has been shown by Trout and Ajwa (2001) that mountain runoff water used for irrigation has extremely low levels of dissolved solids and electrical conductivity of about 0.02 dS/m.
Because the low EC water may result in soil dispersion, finely ground gypsum can be added to the canal water to achieve calcium concentration of approximately 3 meq/L and EC levels of 0.3 dS/m. Past studies have shown this level of dissolved Calcium is sufficient to avoid soil dispersion and improve infiltration in these soils (Trout and Ajwa, 2001).

Past studies on the east side of the SJV have indicated that, irrigation with canal water with very low dissolved solids results in dispersion of the soils, which also have low salt content, even though SAR are not high (Singer and Oster, 1984; Oster et al., 1992), and that additions of Calcium to the canal water results in improved infiltration. In field tests (Trout and Ajwa, 2001), infiltration with well water (1.2 dS m\(^{-1}\)) was generally higher than with canal water, and infiltration using canal water improved with the addition of 3 mmolc Calcium L\(^{-1}\) as gypsum.

Ajwa and Trout (2006) found that powdered gypsum did not affect the infiltration amount where the soil surface was undisturbed. Baumhardt et al. (1992) explained that this could be due to an interaction with tillage, probably because of existing crusts that were broken by tillage or compaction treatments. The effectiveness of gypsum in increasing IR by reducing seal development may depend on the soil’s physical condition as affected by tillage (Baumhardt et al., 1992). They found that infiltration increased with tillage and the application of gypsum even on compacted soils. The interaction between tillage and gypsum indicates that the increase in IR due to gypsum depends on tillage, resulting in no increase in infiltration when gypsum was applied to an undisturbed soil. These data suggest that the effect of surface applied gypsum to increase IR would be short lived, as noted by Freebairn et al. (1988). Results from some field studies (Hadas
and Frenkel, 1982) indicate that gypsum increases the IR in both cultivated and crusted soils. Gypsum increased IR to a similar degree regardless of tillage or compaction treatment, but not when the soil was undisturbed. Thus, gypsum is most effective when combined with some sort of tillage or compaction/crust reducing physical treatment.

A 1977 study by Carter et al. showed a synergistic effect, whereby the solubility and penetration of gypsum is enhanced by ammonium nitrate. Zhang et al. (1998) found that gypsum and PAM prevented clay dispersion and reduced runoff. Yu et al. (2003) found that gypsum added to the erosion benefits of PAM by increasing IR and decreasing runoff. They explained that the PAM plus gypsum treatment was more effective in preventing seal formation than in preventing soil detachment. Stabilization of aggregates at the soil surface by the PAM plus gypsum treatment prevents seal formation, but was less effective in preventing particle detachment (Yu et al., 2003).

A rough soil surface is ideal for IR. Van der Watt and Claassens (1990) found that the smoothness of crusts on soils not treated with gypsum is in strong contrast to the microstructure and roughness that can be seen on the crusts formed on gypsum treated soils. They also found that cross-sectional views of the upper 0-2mm of crusts showed structural differences between gypsum treated and untreated soils. A greater degree of compaction is evident in the case of untreated soil. This increased compaction is due to dispersed clay filling in voids and increasing bulk density. Van der Watt and Claassens (1990) also showed that gypsum applications counter acts crust formation. Keren and Shainberg (1981) explained that the high rate of dissolution of phosphogypsum (PG) and the maintenance of high electrolyte concentration in the soil solution explain the effectiveness of PG in preventing clay dispersion and crust formation.
The stripping of clay skins from sand grains speeds crust formation and decreases IR. According to Gal et al. (1984), PG applications prevented clay stripping from sand grains but the water drop impact still lowered IR. They showed that only when low electrolyte water is used does the washed in layer of soil crusts develop. The intensity of the clay movement and the development of the washed in layer increase with an increase in the ESP of the soil. When gypsum is applied, and the concentration of electrolytes in the soil solution is high this prevents clay dispersion and movement. The washed in layer characteristic of strong crusts is not developed because no clay has been dispersed and only a thin compacted layer, at the soil surface is formed by the mechanical impact of the raindrops (Gal et al., 1984).

Van der Watt and Claassens (1990) explain that the displacement of exchangeable nutrient cations such as Mg and K by the high solution concentration of Ca is a factor to be considered when using gypsum as an ameliorant to improve IR. They state that it is evident that regular applications of 2 t/ha PG can replace fertilizer Phosphorus.

**Polyacrylamide**

Maintenance of stable structural units or aggregates promotes infiltration of water and resistance to erosive forces (Seybold, 1994). Levin et al. (1991) showed that a way of limiting seal formation and improving aggregate stability at the soil surface is the use of organic polymers. Mitchell (1986) explained that reducing the ability of a soil to disperse will decrease crust formation and improve water infiltration.

Seybold (1994) explained that polymers were first used in the early 1940s to stabilize temporary roads and runways constructed during wartime. This use led to the subsequent research for engineering and agricultural applications. These polymers, for
the most part, interact with the clay fraction of soils. The degree of interaction depends on both the properties of the polymer and properties of the soil. Polymer properties that are important are type and amount of surface charge, polymer configuration, molecular weight, and molecular size. Important soil properties are type and amount of clay, soil solution ionic strength, type of ions in soil solution, and pH (Seybold, 1994; Theng, 1982).

Ajwa and Trout (2006) explained that polyacrylamide (PAM) is a non-Newtonian fluid whose viscosity is not constant. According to Seybold (1994), PAM is a water-soluble, high molecular weight synthetic organic polymer. It is effective in stabilizing soil aggregates, reducing soil erosion, and increasing water infiltration, and also has an indirect significant impact upon crop growth and yield. For the most part, PAM is resistant to microbial attack, and its degradation is mainly through physical breakdown. PAM adsorbs to soils through linkages between its anionic groups and the negatively charged soil constituents by exchangeable cation bridges. Once adsorbed in soils, it is irreversibly bonded (Seybold, 1994).

According to Cook and Nelson (1986), soil aggregate failure or destruction is the prime cause of crusting. To prevent crusting and maintain sufficient IR interest in developing amendments that will stabilize soil aggregates has been carried. Their study showed that treatment with PAM kept soil aggregates stable throughout seven irrigation events and reduced penetrometer resistance in soils with different initial physical conditions. They found that neither liquid nor solid PAM created new aggregates, but soil aggregates treated with liquid PAM were preserved in the physical form existing at the time of application. Their comparison of granular PAM with liquid applications showed
that granular did not improve emergence. This was due to inadequate dispersion and coating of aggregates. Liquid PAM helped soil aggregates remain more stable, and they did not slake or break down after 7 days and exposure to surface watering. Their study concluded that PAM stabilizes soils in their original conditions, but preserved them rather than improving them (Seybold, 1994). Kijne (1967) stated that PAM applied to several soils was found to increase aggregate stability and water permeability. According to Trout and Ajwa (2001), PAM does not increase soil permeability; it prevents the decline in permeability due to aggregate breakdown and seal formation. Thus a soil must be in good physical condition before PAM is applied (Cook and Nelson, 1986).

Seybold (1994) showed that PAM treatments on plant growth and yield are affected by the improved physical condition of the soil; aeration and water movement are increased, and surface crusting or sealing is abated. He showed that the impact of PAM on infiltration depended on the charge density (CD) and application sequence (Lentz and Sojka, 2000).

Green et al. (2000) proposed that understanding the interaction between PAMs of different molecular formulations and soils of varying physicochemical properties will enable soil managers to select the most effective PAM product for the their specific soil properties and conditions. They explained that increasing the molecular weight (MW) increases the length of the polymer chain and the viscosity of the PAM solution. The chain length of the PAM polymer in dilute solutions may reach 0.1 to 0.2 mm (Barvenik, 1994). The polymer is then adsorbed on the external surfaces of the aggregates (Ben-Hur and Keren, 1997) and binds soil particles together that are far apart, thereby increasing their resistance to splash by raindrop impact and detachment by runoff (Smith et al.,
Green et al. (2000) hypothesized that sandy soils will likely need a greater MW PAM than clayey soils as there are fewer adsorption sites on sandy soils. They also hypothesized that lower MW polymers may be able to penetrate soil aggregates slightly more than higher MW polymers, but higher MW polymers are able to bridge longer distances. Thus a medium-size MW PAM may be necessary for optimum performance. They found that for sandy loam soils, MW not CD was the major factor in controlling soil sealing. Their study also found that full air-drying resulted in a more permanent binding of PAM to the soil. They concluded that different soils had varying optimum molecular formulations of PAM for effective protection. No single PAM performed better than all of the others. A MW of 12 Mg mol$^{-1}$ is highly effective for sandy soils (Green et al., 2000).

Mitchell (1986) showed that PAM weakens the rupture strength of the soils causing several smaller cracks as the soil dries and shrinks. This relates to soil moisture and increases IR. His study also found that PAM as a dilute solution in the irrigation water keeps the soil macropores open and is effective where the water contacts the soil.

PAM can also be used to improve irrigation water. Seybold (1994) showed that in suspensions of fine particles, additions of PAM of high molecular weight causes the particles to flocculate and drop out of suspension. Ajwa and Trout (2006) explain that PAM is used as a flocculent in wastewater and potable water.

The effectiveness of PAM on preventing surfacing sealing and improving IR is linked to how it is applied. Ben-Hur et al. (1989) found that spraying PAM on the surface was slightly but significantly less effective than the application of PAM in water with a rain simulator in maintaining IR during subsequent water applications. The authors
theorized that spraying produces a thin layer on the soil surface and application through sprinkler irrigation promoted deeper penetration. Misra (1996) proposed that at low concentration, the polymers dissolved in water with fully extended conformations and therefore have more reaction points. If the PAM was applied in a concentrated solution, the polymers dissolved with coiled formations. This reduces the ability of the PAM to adsorb to the soils.

Ben-Hur et al. (1989) showed that the application sequence of PAM changed its effect on IR. Seybold (1994) found that the length of efficacy of PAM treatments depend upon the rate of application, depth of application, weathering of soil and tillage operation. His study showed that high IR on sprinkler-irrigated soils was maintained with low concentrations of PAM in irrigation water. Bjorneberg and Aase (2000) showed that both single and multiple PAM applications reduced runoff and soil loss, but multiple applications more effectively controlled runoff longer than a single application. Their study found that multiple PAM applications reduced cumulative runoff 50% compared to the control. Thirty-four percent of the total water applied during four irrigations ran off the control treatment compared to just 23% for single application and 17% for multiple applications.

Ajwa and Trout (2006) reported that although the chemical composition of water can affect IR and HC of soils, limited information is available on the interaction between PAM and salts in irrigation water on IR. They found that the beneficial effects of the polymer were greater in soils treated with water that has high EC values and concluded that the impact of PAM on IR was primarily due to the concentration and viscosity effect
in the infiltration water. They also found that there might be some residual effect from previous PAM applications.

The effectiveness of PAM on stabilizing soils has been shown to improve with the addition of phosphogypsum (PG) or by increasing the electrolyte concentration in solution (Seybold, 1994). In addition, it was reported that the combined application of a polymer and PG had a more pronounced effect than that of either one separately in improving infiltration (Shainberg et al., 1990; Smith et al., 1990). Yu et al. (2003) found that gypsum added to the erosion benefits of PAM by increasing infiltration and decreasing runoff. El-Morsy et al. (1991) found that the beneficial effects of PAM tended to be greater with increasing EC and/or decreasing SAR. Zhang et al. (1998) showed that gypsum and PAM prevented clay dispersion and reduced runoff.

Since gypsum raises the electrolyte concentration of the soil solution, Shainberg et al. (1990) suggested that if the concentration of electrolytes exceeds the flocculation value of the clay, the cementing action of PAM polymers is more effective. Barvenik (1994) explained that with an increase in electrolyte concentration in the soil solution, the repulsion forces between the negative sites on the anionic polymer diminishes, and the dissolved PAM exists as coiled and short chains whose effect on the polymer’s solution viscosity diminishes. Therefore, the short PAM chains are ineffective in clogging the conducting pores, but effective in stabilizing the surface aggregates and preventing seal formation (Yu et al., 2003).

Ajwa and Trout (2006) found that the reduction in IR when PAM was applied with water containing calcium salt was less than with distilled water or water containing sodium. They concluded that Ca in the water reduced the impact of PAM on viscosity.
and infiltration. Yu et al. (2003) explained that in high electrolyte concentration such as applying PAM dry with gypsum, the polymer chains are shorter and less efficient in binding together soil particles that are far apart. Thus, in the presence of electrolytes, the efficiency of the polymers in decreasing soil losses was reduced. Yu et al. (2003) concluded that the PAM plus gypsum treatment was more effective in preventing seal formation than in preventing soil detachment. Stabilization of aggregates at the soil surface by the PAM plus gypsum treatment prevents seal formation, but is less effective in preventing particle detachment. Ajwa and Trout (2006) showed that 300 mg Ca L$^{-1}$ (15 mmol$_c$ Ca L$^{-1}$) was sufficient to diminish the negative impact of 10 mg PAM L$^{-1}$ on water infiltration into sandy loam soils. The effect of PAM on final IR was negligible 48 h after PAM application, indicating diminished viscosity effect.

The use of PAM as an amendment to treat low IR poses some problems. Seybold (1994) expressed concern that with high levels of PAM in soil (5%), a condition of low phosphorous could result. However, this PAM content is orders of magnitude higher than what would be used for agricultural purposes. Mitchell (1986) explained that applying PAM in the irrigation water to an effective concentration greatly increases the waters’ viscosity, which reduces HC, because conductivity is inversely proportions to viscosity (Hillel, 1971). Work by Trout and Ajwa (2001) in the SJV showed that PAM does not reduce aggregate breakdown and surface seal formation. This may be due to the already poor condition of the soil surface. Ajwa and Trout (2006) found that PAM addition to irrigation water slightly decreased IR. They explain that PAM at high concentrations (>100 mg L$^{-1}$) could reduce IR in coarse-textured soils, mainly by increasing the viscosity of the infiltrating water. A similar product to PAM studied by Hemyari and Nofziger
Ajwa and Trout (2006) showed that the effect of PAM on preserving aggregate structure and reducing sediment deposition and thus maintaining pore structure at the surface of sandy loam soils was not adequate to compensate for the viscosity effect. In a silt loam soil, Trout et al. (1995) measured a 30% increase in infiltration with PAM. Thus, in erodible soils with sufficient fine-textured particles to form surface seals, it is feasible that soil structural changes can more than compensate for the PAM effect on viscosity. Ajwa and Trout (2006) concluded that PAM applied in irrigation water will reduce infiltration unless the material improves surface soil aggregate structure and sustains pores sufficient to mask the effect of solution viscosity (Ajwa and Trout, 1999; Trout and Ajwa, 2001). But as shown previously, PAM does not improve structure it only maintains the structure and aggregate stability that is present at the time of its application.

Mitchell (1986) showed that PAM molecules attached to the surface particles and do not penetrate far into the soil matrix. This means that the PAM will concentrate at the surface and may reduce the number and size of conducting pores (Malik and Letey, 1992; Letey, 1996). Allowing the soil to dry for 48 hours after application of PAM eliminated the PAM effect on pores. Yu et al. (2003) states that the labor and water needed for PAM dissolution and spraying makes its application in dryland farming uneconomical.

Clay is the primary soil material that PAM bonds to. Laird (1997) explained that charge neutralization is the primary bonding mechanism between cationic polymers and mineral surfaces. Theng (1982) stated that the adsorption of polymers, especially of high molecular weight species, is largely an entropy driven process, as they connect to clay minerals. Deng et al. (2006) explained that for smectite clays and other expandable
minerals, PAM might access the interlayer gallery. According to their study, if the intercalation can occur, the interlayer polymers may have different conformation from those adsorbed on the external surfaces. The interlayer surface properties of smectite could be altered (Deng et al., 2006).

The increased aggregate stability caused by PAM is due to coagulation of clay particles. Coagulation occurs when polymers neutralize charge sites on particle surfaces, compressing the diffuse double layers (Laird, 1997). Green et al. (2000) explained that anionic PAM, being negatively charged like the clay surface, would be expected to experience repulsion from the negatively charged clay sites. Counter intuitively, it does bind to some of the negative sites, primarily through a process called cation bridging (Green et al., 2000). They emphasize that the presence of divalent cations, either in the PAM solution or on the clay surface, is imperative for effective soil stabilization. In a study by Mitchell (1986) on soils with a high fraction of swelling clays the final IR and total water infiltrated were not increased by PAM application. This indicates that soil seals and crusts are not the limiting factor to permeability of such soils.

Ajwa and Trout (2006) found that high PAM concentration and surfactants may affect IR. They found that applying 10 mg PAM L\(^{-1}\) plus anionic surfactant to silt loam and sandy loam soils reduced saturated hydraulic conductivity by up to 70% relative to the same PAM concentration without surfactant.

Green et al. (2000) stated that in the arid and Mediterranean climates of the world, anionic PAM of high molecular weight and low charge density is being used quite effectively to stabilize soil structure. This leads to increased infiltration. Ajwa and Trout (2006) used soils from a 25-year-old vineyard in Parlier, CA. They found that the
decrease in final IR caused by PAM application to Chualar and Wasco soils were 10 to 20% less than those found in another California soil, i.e. Hanford. In soil column tests of Hanford and Wasco sandy loams, the reduction in infiltration with increasing PAM concentration was consistent and predictable (Ajwa and Trout, 1999). Their study (2006) showed that infiltration reduction was greater at high PAM concentrations, when PAM was applied continuously throughout the irrigation period, and in water with low salt or high sodium content. They concluded that PAM-treated water could reduce IR in the San Joaquin Valley sandy loam soils by more than 50%. Thus, PAM is not recommended as a treatment of the soils in this study unless their structure is improved first with tillage or extensive organic carbon amendments.

**Surfactants**

Surfactants are noted for their ability to reduce surface tension, thereby diminishing the solid/liquid interfacial forces (Zartman and Bartsch, 1990). Nonionic surfactants have merit for improving IR, and they could increase crop growth (Howells et al., 1984). Feng et al. (2002) found that applying a surfactant to water and lowering its surface tension would have a positive effect on infiltration in a water-repellent soil but could have a positive or negative effect on infiltration in a soil that is not water repellent. They explain that one of the major benefits of using surfactants to overcome water repellency is the rewet properties after treating and drying the soil material. Surfactants can convert a water repellent soil material to a wettable soil material. They are most beneficial when the water repellency is associated with the surface layer and the depth of water repellency is not great. Their study concluded that the quantitative effects of surfactants in changing the surface tension of applied water has relatively little value in
predicting the IR of a surfactant solution. All of the surfactant concentration used in their study had identical liquid surface tension. Nevertheless, different IR were observed for the different surfactant concentrations. Howells et al. (1984) found that for different soil types the maximum increase in IR occurred at different times after the nonionic surfactant was applied. This means soils will react at different times to surfactant applications and to different degrees.

One product that is effective in increasing IR in soils that still pond after gypsum application is PeneCal. This is a soil surfactant which combines reacted calcium and tensioactive Ethoxylated Co-Polymers composed of 22% surfactant and 10% calcium. It is used to increase IR and strengthen soil aggregates and is designed to alleviate problems associated with air and water ratios in the soil (PeneCal, 2010). It is said to improve water penetration speed, increases ideal volumetric soil moisture levels and improves soil structure by delivering water and calcium to soil capillary pore space the recommend rate of application is 0.25-1 gal/acre every 30-45 days (PeneCal, 2010).

**Soil Conditioners**

A soil conditioner is defined as any synthetic organic chemical or chemically modified natural substance that stabilizes soil aggregates, and/or favorably modifies the soils’ structural or physical properties (Seybold, 1994). Mukhopadhyay et al. (1997) found that the application of soil conditioner improved IR and substantially reduced runoff and soil loss on a loamy sand soil. Fox and Bryan (1992) showed that the conditioner application combined with raking inhibited crust development and improved IR, but long-term effects of conditioners depended on a combination with cover crops.
They concluded that the conditioner enhanced infiltration by altering the diffuse double layer around clay particles.

**Tillage**

Low clay and organic matter in a soil can indicate a likelihood of crust formation and decreased IR without tilling due to the decrease in aggregate stability of such soils (Le Bissonnais, 1990). Lado et al. (2004) explained that cultivation of soil with high OM will be effective because the large aggregates will remain stable during the rainy season and will maintain relatively high IR. In contrast, they found that in soils with low OM, the cultivation will have only a short effect because in this soil most of the large aggregates will be broken down and dispersed at the beginning of the rainy season. Baumhardt et al. (1992) explained that tilling is effective at increasing IR by reducing soil bulk density. Tilling improves the effectiveness of amendments used to treat low IR such as gypsum, PAM and soil conditioners (Baumhardt et al., 1992; Fox and Bryan, 1992).

Oster et al. (1992) explained that some soils need to be tilled in order to get a significant amount of water to enter the soil and to disrupt surface crusts. Soils high in silt or very fine sand and low in swelling clay are the most troublesome with respect to surface sealing and crusts. Water repellency is confined to the surface or upper soil layers, generally in the top 10cm of the soil (Contreras et al., 2008) so tillage mixes and breaks up the hydrophobic materials that concentrate in this zone with more adsorbent material. Singer and Oster (1984) explain that for some soils, tillage is necessary to break up crusts. However, this also contributes to a further structural deterioration. Cultivation and wheel traffic increase the tendency of soils to form seals, so tillage used to reduce
crusting can result in only a temporary increase in IR, usually for just one irrigation (Singer and Oster, 1984). Tillage that breaks soil crusts leavening the surface rough and plant residue on top, have the greatest chance of maintaining increased infiltration throughout an irrigation and until the next irrigation. Fox and Bryan (1992) showed that complete disturbance of the crust by raking significantly increased final IR. Shallow cultivations were as effective in increasing the IR of the control plots as was the addition of gypsum on untilled plots. Thus, frequent shallow tillage with light equipment may be the best management for soils with low OM and low clay such as those found in Northwestern Kern County.

Singer and Oster (1984) explained that deep ripping more deeply than 1 m is not necessary if tillage pans and equipment induced compaction is the only problem being corrected. However, if there are natural layers, such as stratification, claypans, and hardpans that limit either deep water percolation or root growth, deeper ripping or slip plowing may be beneficial.

In tree nut production, nontillage is desirable to provide a smooth clod-free surface from which to pick the nuts (Singer and Oster, 1984). However, in a long-term study by Schlesselman et al. (1986) of almonds in California, poor water penetration in untilled soil reduced almond yields while moderate cultivation did not reduce yields. Gomez et al. (2001) recorded that some orchards have reverted to conventional or to minimum tillage because of real or perceived problems of reduced IR caused by no-tillage.
METHODS AND MATERIALS

Preliminary Investigation

Two-Tiered Format

The methods section of this thesis is divided into two portions. The first section will recount the preliminary research that the main investigation of this study is based on. The second section details the research that was found to be most insightful into determining the IR of soils in northwestern Kern County. This second portion outlines procedures that may be replicated by anyone trying to duplicate the results of this study.

This thesis research was based on preliminary investigations that took place from October 2008 through May of 2010. This initial work was conducted on South Valley Farms (SVF) land in northwestern Kern County California near the city of Shafter. SVF provided major funding for this thesis, as such all findings had to be relevant to this farm. Thus, the initial research delved into the reduced IR on SVF almond orchards.

The preliminary research explored pursuing numerous feasible explanations for reduced IR on SVF land. It was hypothesized that sodic or saline-sodic soil conditions were the cause of reduced IR in SVF permanent plantings. Clay mineralogy was also assumed to be a factor which would distinguish different levels of IR. However, most of the experiments, lab work and research were dead ends. Despite the failure of many of the early hypotheses in explaining the IR problems of the soils in this region, a description of these is necessary to make a clear accounting of all of the work that led up to the results of the validation study presented in this thesis. The reason for such an accounting is twofold. First of all, a full explication of the preliminary investigation
unites the methods, results and discussion sections of this thesis with the literature review. Secondly, presenting the certain failures of this research will inform those who will continue to do further IR research in this area of California. That is, including the preliminary investigation that formed the foundation of this thesis at the beginning of the methods section will help others avoid repeating unnecessary experiments and lab work, wasting time and money. It should be clear that these preliminary studies are not part of the findings of the validation study set up in the second section of this methods section. Therefore, it is not necessary to repeat the preliminary experiments in order to perform the mica quantification experiment.

The rest of this first section of the methods portion of the thesis contains all of the preliminary research that went into this thesis. Each step in the initial investigation will be presented with reasoning as to why it was thought necessary and the results of the experiment. Each section will conclude with a discussion as to the relevancy or usefulness of the results. As stated above most of the early theories ended in negative results. However, some did not. Two were selected for the validation study. The reasoning behind this selection will be explained as the preliminary investigation is presented.

The land that was used for the initial study area was located on three adjacent almond orchards at SVF. From east to west these almond orchards were designated as blocks 19, 18, and 17. As shown in Figure 1, these three orchards are relatively close together. From the western edge of block 17 to the eastern edge of block 19 is only 3.7km. The reason these three orchards were chosen is because each demonstrated a distinct level of infiltration
The IR levels Good, Moderate, and Poor, for each of the three almond orchards on SVF, were determined in the following way. Block 19 required no amendments for it to have a sufficient IR. Due to the lack of any required treatments by block 19 it was designated as having Good IR. Block 18 required gypsum to maintain the soil at a level that was sufficient for good almond production. Because of the use of gypsum, block 18 was designated as having Moderate IR. Block 17 was similar to block 18 except that gypsum applications did not ameliorate the low IR of this soil. This was especially true along its western edge. Gypsum was insufficient to maintain the soil of block 17 at an IR suitable for almond production. Therefore, additional amendments were required. Because more expensive and powerful treatments were used, specifically a calcium
surfactant solution called *Penecal* (Penecal, 2010), the western watering set of block 17 was designated a Poor IR soil.

It should be observed that all references to the application of gypsum in this study are to gypsum being applied in the irrigation water. Likewise, all of the soils in this research were irrigated with micro-sprinklers. In addition to this similarity, all three almond orchards were composed of the same soil type, a Wasco Sandy Loam (Typic Torriorthent). All three plots received the same irrigation water and cultural practices relating to harvesting and care.

**Evaluation of Sodic and Saline-sodic Soil Conditions**

The variation between the three almond blocks was first hypothesized to be related to sodic or saline-sodic soil conditions. As discussed in the literature review this is a relatively rare problem for most soils in the world. For irrigated soils of the western United States it can be a problem. The main cause for sodic or saline-sodic conditions in irrigated agriculture is due to the quality of the water applied.

There was no visual evidence that indicated that any of these three plots had sodic or saline-sodic soils. Evidence of this would have a typical gray color of a sodic soil, salt crusts, or the very sticky mud from the dispersed clay of a sodic or saline-sodic soil. In order to determine if sodic or saline-sodic conditions were a factor all three of the initial study orchards were sampled and tested to determine the electrical conductivity (EC), sodium absorption ratio (SAR) and pH of the soil solution. Although it was not assumed that block 19 had sodic or saline-sodic conditions it was sampled and tested so that it could be compared to the other two blocks. Thus, from the very beginning of this study it
can be seen that a comparative method was sought in order to characterize soils in northwestern Kern County as having Good, Moderate, or Poor IR.

There were five random undisturbed soil profile samples taken from the three blocks. There were two sampling locations in blocks 17 and 18 and one in block 19. Sample sites were recorded with GPS coordinates. The second site in block 17 is where the lowest infiltration was reported by SVF. The rest of block 17 is very similar to the IR of block 18. Thus, throughout the results presented below it is important to notice the difference, if any, between the second site in block 17 and the first. Soil samples were collected with a 5 cm probe every 5 cm to a depth of 102 cm. Samples were delivered to the Utah State University Analytical Soils Laboratory for analysis of EC, SAR and pH. These tests were done to determine if sodic or saline-sodic soil conditions were a factor influencing the variation in IR between the three orchards.

The results of the three tests are given in the following figures. The figures show pH, EC, and SAR separately in graphs. The results of the lab analysis are shown every 5 cm to a depth of 102 cm. The figures for each of the three orchards are grouped together. The first collection of results is for the two sites in block 17, which is comprised of figures 1 through 6. The second group, figures 7 through 12, shows the results for block 18. The final set, figures 13 through 15, is for the one site in block 19. For each group the results of pH are shown first followed by EC and then SAR.

The presentation of these results includes commentary. The reason for this is to highlight the significance of each graph. In addition, due to the number of figures, it will be easier for the reader to follow which graph is which. There will be a concluding paragraph discussing what was determined as far as potential sodic conditions in all three
almond orchards. Also, it is important to understand the criteria used to evaluate these results. For a soil to be considered sodic it must have an EC of less than 4 dS/m, a pH greater than 8.5 and an SAR greater than or equal to 13. For a soil to be considered saline-sodic it must have an EC greater than 4 dS/m, a pH less than 8.5 and an SAR greater than or equal to 13. The third designation for salt affected soils, those with saline soil conditions, is not a concern for this research. Saline soils normally have good water penetration. However, these results could be used to determine if almond yields in these orchards are being influenced by saline soil conditions.

Figure 2 shows the pH results from the soil sampled at the first site in block 17. The points show increasing pH with depth. The pH shown in this figure does not give any evidence for sodic conditions in this soil. However, since the pH is less than 8.5, there is some evidence for saline-sodic conditions in this soil but it cannot be determined from the pH alone.

Figure 3 shows pH results for the second site in block 17. This site is where the lowest IR was reported. The results show a zigzag pattern of pH with increasing depth. This zig-zag pattern is exhibited in a number of the following figures showing the results of the EC, pH and SAR analysis. The zigzagging pattern will be discussed more below. The results for pH in the second site of block 17 are distributed throughout a consistent range. The results show no indication of sodic conditions. There is some evidence for saline-sodic conditions since all pH results are below 8.5. However, to determine if the soil is indeed saline-sodic depends on the results of the EC and SAR tests.

Figure 4 shows the EC values versus depth for the first site in block 17. These results show a significant upward trend in EC with increase in depth. This change in EC
Figure 2. Incremental pH values taken every 5cm to a depth of 102cm from block 17 site 1.
Figure 3. Incremental pH values taken every 5cm to a depth of 102cm from block 17 site 2.
Figure 4. Incremental EC values taken every 5cm to a depth of 102cm from block 17 site 1.
from the surface samples of the soil to the deeper samples shows a gradual trend towards saline-sodic conditions. That is, from about 56cm down the soil is in the EC range for saline-sodic conditions. Thus, it will be very important what the SAR results of these samples are to determine if this soil is indeed a saline-sodic soil. There is also some evidence for sodic soil conditions particularly in the surface soil where about half the results are below an EC of 4 dS/m.

Figure 5 shows the results for EC at the second site in block 17. The EC does not trend up as it did in the first site of block 17. Even though the range of all the points may be the same the very high EC reading taken at 89cm may be an outlier (a contaminated sample). This high EC at 89cm gives some evidence for saline-sodic conditions in this soil since it is above 4 dS/m. However, analysis of the SAR results of these samples shows that saline-sodic conditions do not exist. There is also some evidence for sodic soil conditions since most of the results are below an EC of 4 dS/m.

Figure 6 shows SAR results from the first site in block 17. There is a fairly steady increase in SAR with depth in this soil but there is also some zigzagging as SAR increases. The results do not show evidence for sodic or saline-sodic conditions in this soil since they are well below 13 mol/L.

Figure 7 shows the results for SAR analysis at the second site in block 17. The results show an increase in SAR with depth though the final five samples show the greatest increase in SAR with depth. The results do not indicate any evidence for sodic or saline-sodic conditions since the SAR values are all well below 13 mol/L.

Figure 8 shows the results for pH at the first site in block 18. The results show a sharp drop in pH followed by a gradual increase with depth. The lowest sample has a pH
Figure 5. Incremental EC values taken every 5cm to a depth of 102cm from block 17 site 2.
Figure 6. Incremental SAR values taken every 5cm to a depth of 102cm from block 17 site 1.
Figure 7. Incremental SAR values taken every 5cm to a depth of 102cm from block 17 site 2.
Figure 8. Incremental pH values taken every 5cm to a depth of 102cm from block 18 site 1.
only slightly greater than the surface sample. These results give no evidence for sodic conditions in this soil. However, since the pH values are all below 8.5 there is some indication that saline-sodic conditions are present in this soil. However, combined with the EC and SAR data these conditions are not an issue.

Figure 9 shows results for pH from the second site in block 18. Though the pH values are slightly higher than for the first site in block 18 the change is only slight. What is more significant is the steadiness of pH with depth. There is much less zigzagging in these pH results than those found at the first site in block 18. It is unknown what influence this pattern has on IR. These results show no evidence for sodic conditions in this soil since they are all below 8.5. There is some indication that this soil might be saline-sodic since all of the pH results are below 8.5. A full classification will depend on the EC and SAR results.

Figure 10 shows the EC results for the first sampling site in block 18. The EC results exhibit a curious zigzag pattern that is quite extreme with almost every 5cm change in depth. The EC results for this soil show some evidence for both sodic and saline-sodic soil conditions since there are results both above and below an EC of 4 dS/m. To conclusively diagnose this soil it will depend on the pH and SAR results.

Figure 11 shows the results for EC at the second site in block 18. These results show a similar zigzag pattern as the soil samples taken from the first site in block 18, but the range is not as consistent. The EC values fluctuate a great deal and there is one sample that is very high. These results show evidence for both sodic and saline-sodic conditions since there are EC values both above and below 4 dS/m. The surface soil and depths below 71cm show evidence for sodic conditions and the middle samples for
Figure 9. Incremental pH values taken every 5cm to a depth of 102cm from block 18 site 2.
Figure 10. Incremental EC values taken every 5cm to a depth of 102cm from block 18 site 1.
Figure 11. Incremental EC values taken every 5cm to a depth of 102cm from block 18 site 2.
saline-sodic conditions. However, full determination of the salt condition of the soil will depend on the pH and SAR results for this soil.

Figure 12 shows the results for SAR samples taken from the first site in block 18. There is a general trend upward in SAR from the surface soil down but the SAR values are all very low and show no evidence for sodic or saline-sodic soil conditions.

Figure 13 shows the SAR results from samples taken at the second site in block 18. There is a consistent zigzag pattern from the surface of the soil to greater depth with a trend towards greater values of SAR the deeper the samples were taken. None of these results are remotely close to showing any evidence for sodic or saline-sodic soil conditions in this soil.

Figure 14 shows the pH results of block 19. The results show a consistent trend of increasing pH with depth and only a few zigzags. There is no evidence from these pH results that sodic soil conditions are present in this soil. These results show some evidence for saline-sodic conditions since they are all below 8.5. A complete diagnosis will depend on the EC and SAR results from this soil.

Figure 15 shows the results of the EC test on block 19. The surface samples show an EC indicative of saline-sodic soil conditions but these results drop down to sodic soil conditions with depth. With increased depth of the samples the EC rises again to slightly higher than the soil surface before dropping off once again. Thus, these results show some evidence for both sodic and saline-sodic soil conditions. A full diagnosis will depend on pH and SAR for this soil.

Figure 16 shows the SAR results for block 19. The results show a gradual zigzag pattern with a slight increase in SAR with depth from the soil surface. The SAR trend
Figure 12. Incremental SAR values taken every 5cm to a depth of 102cm for block 18 site 1.
Figure 13. Incremental SAR values taken every 5cm to a depth of 102cm from block 18 site 2.
Figure 14. Incremental pH values taken every 5cm to a depth of 102cm from block 19.
Figure 15. Incremental EC values taken every 5 cm to a depth of 102 cm from block 19.
Figure 16. Incremental SAR values taken every 5cm to a depth of 102cm from block 19.
ends up with an SAR lower than that found at the surface. The SAR results from the
samples taken from block 19 are the highest of the five sites. This is consistent with the
fact that no gypsum is applied to block 19 and thus the sodium has not been leached and
replaced by calcium in the sampling area as much as it has in the other four sites. None of
the SAR results for block 19 show any evidence for sodic or saline-sodic condition in this
soil.

Table 1 presents the average pH for all depths as well as the EC and SAR. This
table is useful for comparing the three blocks and their respective IR levels. It is
interesting that the second site in block 17, the lowest IR area, had the lowest average
EC. It is not clear what relationship EC has to IR. If a connection can be found between
EC and IR than there may be a simple in situ technique for determining IR of a field
without sampling by using various electromagnetic reflection devices such as the EM-38.
This would provide a means to use remote sensing to evaluate land for permanent

<table>
<thead>
<tr>
<th>Site</th>
<th>pH</th>
<th>EC</th>
<th>SAR</th>
</tr>
</thead>
<tbody>
<tr>
<td>19-1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average</td>
<td>7.28</td>
<td>3.96</td>
<td>6.22</td>
</tr>
<tr>
<td>STDV</td>
<td>0.56</td>
<td>1.90</td>
<td>1.04</td>
</tr>
<tr>
<td>18-2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average</td>
<td>7.48</td>
<td>3.98</td>
<td>2.52</td>
</tr>
<tr>
<td>STDV</td>
<td>0.55</td>
<td>4.62</td>
<td>0.41</td>
</tr>
<tr>
<td>18-1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average</td>
<td>6.83</td>
<td>3.85</td>
<td>2.70</td>
</tr>
<tr>
<td>STDV</td>
<td>0.30</td>
<td>2.62</td>
<td>0.68</td>
</tr>
<tr>
<td>17-2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average</td>
<td>6.58</td>
<td>1.22</td>
<td>2.75</td>
</tr>
<tr>
<td>STDV</td>
<td>0.31</td>
<td>1.43</td>
<td>0.86</td>
</tr>
<tr>
<td>17-1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average</td>
<td>6.67</td>
<td>2.76</td>
<td>3.62</td>
</tr>
<tr>
<td>STDV</td>
<td>0.62</td>
<td>1.99</td>
<td>1.05</td>
</tr>
</tbody>
</table>
planting based on potential IR.

Based on the results of the EC, pH, and SAR tests for the five sites in the three orchards it can be concluded that there are no sodic or saline-sodic soils present. Despite EC and pH results that showed that sodic or saline-sodic soils might be a concern, the SAR values eliminated any such possibility.

The curious zigzag pattern found in the results could be due to the use of irrigation water with gypsum followed by irrigation without. The low EC irrigation water would flush salts to lower depths and subsequent irrigations with gypsum would increase EC and pH at more shallow depths. However, it is not clear exactly why this pattern exists. It is also unclear as to how this pattern may influence IR.

The SAR results all show an increase in value with depth. This is consistent with what would be expected in a soil which receives continual gypsum applications. The calcium replaces the sodium bound in the soil as the gypsum is applied. The sodium is then leached to greater and greater soil depths as it is replaced by calcium.

**Water Quality**

As noted above all three almond orchards receive the same water. It is high quality irrigation water with very low EC derived mainly from snow melt originating in the Sierra Nevada Mountains. This water is delivered to the almond orchards by a large concrete lined irrigation canal. Smaller, dirt canals branch off of the main line and service the three orchards in question (Figure 15). This high quality water is supplemented throughout the year with additions of water from wells in or near the almond orchards. This well water typically has a higher EC than the canal water. This complex interaction
of consistent canal water with a variable mix of well water throughout the year means that the water quality changes. Since all three orchards are relatively close, any wells that might be near them are also near to each other which means the well water quality being added to the canals should be fairly consistent between the three orchards.

**Compaction Issues**

In addition to sodic or saline-sodic soils, it was thought that a variation in the amount of compaction between the three almond orchards might be the cause of the variation in IR levels. It was observed that compaction is an issue for these three orchards but only in the traffic area between the trees. That is, the soil is most compacted where harvesting, spraying and irrigation vehicles drive. The tree rows remain relatively uncompacted. That is, between the trees and about one to two meters on either side of the row. The increased compaction of the traffic area has been thought to have little influence on IR since no water is applied to this area. This is because the sprinkler application area is within the area that vehicles do not drive on. Thus, if water ponds on the traffic area, the IR is significantly reduced due to increased compaction.

Compaction was measured using a handheld penetrometer (Spectrum Technologies SC900). There was relatively little difference in compaction among the three blocks. The measurements that did show a difference between the blocks are not reliable for determining the amount of compaction in each block. This is because the handheld penetrometer is highly variable. One area where the penetrometer was used might be just a short distance from an area of greater or lesser compaction. More importantly, the penetrometer is not an adequate device for measuring soil compaction
because variations in soil water content can dramatically influence the compaction data. Thus, the data gathered using the penetrometer is only a rough estimate of what the compaction is like in these three almond orchards and cannot be relied on to give an accurate determination of the amount of compaction in each orchard. For this reason it is not included in this explication of the preliminary investigation nor was it used in the validation study.

**Texture Evaluation**

The initial research determined that the difference in texture may contribute to the variability in IR among these three almond orchards. Texture analyses was performed using the hydrometer method on soil core samples taken every 15.24cm to a depth of 1.23m from the five random sampling sites located in each of blocks 17, 18 and 19. Each 15.24cm section of soil was gathered using a 10.16 soil collection auger. These samples were dried, ground and passed through a 2mm sieve before being mixed with water and measured with a hydrometer.

Table 2 shows the texture of the soil for the sampling site in block 19. Data are presented for each 15.24cm section and the percentages of sand, silt and clay for each depth are presented. This soil was a found to be a loam at all depths. This is important because previous analysis indicated that the soil in block 19 had a sandy loam texture. The IR type for this soil is Good.

Figure 17 shows how the amount of sand in the soil at the sampling site in block 19 decreases with depth. The amount of sand in this soil is high in the surface soil comprising almost half until at about 50cm depth it falls sharply from to only 30%.
Table 2. Texture of block 19 for 8 depths.

<table>
<thead>
<tr>
<th>Block</th>
<th>Site</th>
<th>Depth (cm)</th>
<th>Sand%</th>
<th>Silt%</th>
<th>Clay%</th>
<th>Texture</th>
</tr>
</thead>
<tbody>
<tr>
<td>19</td>
<td>1</td>
<td>-15.24</td>
<td>49</td>
<td>29</td>
<td>22</td>
<td>Loam</td>
</tr>
<tr>
<td>19</td>
<td>1</td>
<td>-30.48</td>
<td>47</td>
<td>29</td>
<td>25</td>
<td>Loam</td>
</tr>
<tr>
<td>19</td>
<td>1</td>
<td>-45.72</td>
<td>47</td>
<td>35</td>
<td>19</td>
<td>Loam</td>
</tr>
<tr>
<td>19</td>
<td>1</td>
<td>-60.96</td>
<td>46</td>
<td>38</td>
<td>16</td>
<td>Loam</td>
</tr>
<tr>
<td>19</td>
<td>1</td>
<td>-76.2</td>
<td>39</td>
<td>41</td>
<td>20</td>
<td>Loam</td>
</tr>
<tr>
<td>19</td>
<td>1</td>
<td>-91.44</td>
<td>35</td>
<td>46</td>
<td>19</td>
<td>Loam</td>
</tr>
<tr>
<td>19</td>
<td>1</td>
<td>-106.68</td>
<td>36</td>
<td>48</td>
<td>16</td>
<td>Loam</td>
</tr>
<tr>
<td>19</td>
<td>1</td>
<td>-121.92</td>
<td>36</td>
<td>45</td>
<td>18</td>
<td>Loam</td>
</tr>
</tbody>
</table>

Figure 18 shows how the amount of silt in the site in block 19 increases with depth. The silt percentage changes from about 30% in the surface soil to about 50% at the lower depths. This is a dramatic increase in silt content and may greatly contribute to more developed soil structure. A more developed soil structure would increase IR levels. Thus, a possible explanation for the Good IR of block 19 over 18 and 17 is due to soil structure.

Figure 19 shows how the amount of clay in the site in block 19 changed with depth. The clay percentage fluctuated with depth but showed an overall decrease. In conjunction with figures 17 and 16 it can be understood that as the clay percentage and sand amount decreased silt content increased.

Table 3 shows the texture found for every 15.24cm sample at block 18 site 1. It is important to notice that the surface of this soil had a sandy clay loam texture. Previously it was thought that the surface soil was a sandy loam. However, the hydrometer analysis shows that an increased amount of clay in the surface as well as a higher silt content make the surface of this soil a sandy clay loam rather than a sandy loam. The amount of clay shown in the surface of this soil could act as a substrate for crust formation. With
Figure 17. Graph showing the change in sand percentage with depth of the soil at block 19.
Figure 18. Graph showing the change in silt percentage with depth of the soil in block 19.
Figure 19. Graph showing the change in clay percentage with depth of the soil in block 19.
increased depth the soil has a sandy loam texture with a brief return to sandy clay loam texture at 91 cm due to an increase in clay. The IR type for this soil is Moderate.

Figure 20 shows how the amount of sand changed with depth of the soil sampled at block 18 site 1. The percentage of sand increased with depth with a large jump from about 30.48 cm to 45.72 cm. The sand amounts at the greater depths constituted almost two thirds of the soil material. With such high sand amounts it could be expected that this was a soil with a high IR.

Figure 21 shows the change in silt content with depth in block 18 site 1. The amount of silt decreases with depth in this soil with a slight increase at the greatest depth. Since silt is most responsible for soil structure it is important to note that in this soil with Moderate IR even when silt content is the highest at around 23% it is still less than the least amount of silt found in block 19 which has an IR level of Good. This may indicate a difference in structure between the two soils which relates to the difference in IR.

Figure 22 shows the change in clay content with depth for block 18 site 1. There is an increase in clay content by a few percentages in the surface soil before the amount

<table>
<thead>
<tr>
<th>Block</th>
<th>Site</th>
<th>Depth (cm)</th>
<th>Sand</th>
<th>Silt</th>
<th>Clay</th>
<th>Texture</th>
</tr>
</thead>
<tbody>
<tr>
<td>18</td>
<td>1</td>
<td>-15.24</td>
<td>56</td>
<td>23</td>
<td>21</td>
<td>SCL</td>
</tr>
<tr>
<td>18</td>
<td>1</td>
<td>-30.48</td>
<td>55</td>
<td>21</td>
<td>24</td>
<td>SCL</td>
</tr>
<tr>
<td>18</td>
<td>1</td>
<td>-45.72</td>
<td>63</td>
<td>18</td>
<td>19</td>
<td>SL</td>
</tr>
<tr>
<td>18</td>
<td>1</td>
<td>-60.96</td>
<td>62</td>
<td>19</td>
<td>19</td>
<td>SL</td>
</tr>
<tr>
<td>18</td>
<td>1</td>
<td>-76.2</td>
<td>64</td>
<td>18</td>
<td>18</td>
<td>SL</td>
</tr>
<tr>
<td>18</td>
<td>1</td>
<td>-91.44</td>
<td>66</td>
<td>16</td>
<td>18</td>
<td>SL</td>
</tr>
<tr>
<td>18</td>
<td>1</td>
<td>-106.68</td>
<td>63</td>
<td>17</td>
<td>20</td>
<td>SCL</td>
</tr>
<tr>
<td>18</td>
<td>1</td>
<td>-121.92</td>
<td>64</td>
<td>18</td>
<td>18</td>
<td>SL</td>
</tr>
</tbody>
</table>
Figure 20. Graph showing the change in sand percentage with depth for the soil at block 18 site 1.
Figure 21. Graph showing the change in silt percentage with depth for the soil at block 18 site 1.
Figure 22. Graph showing the change in clay percentage with depth for the soil at block 18 site 1.
drops down again and remains fairly steady to the greater depths. The total fluctuation in clay content is only 6% from the least amount to the greatest.

Table 4 shows the texture results for all eight depths of the second site in block 18. This soil was a sandy clay loam for all depths except the deepest sample taken. This is important because previous to this sampling the soil in block 18 was considered a sandy loam. The increased amount of clay found in this soil may indicate a possible reason the IR type of this soil being Moderate and that it thus requires gypsum to maintain sufficient IR levels.

Figure 23 shows an increase in sand content for the soil at the second site in block 18. The range in sand increase is from about 46% at the surface to 67% at the greatest depth. Such a high amount of sand and an increase of over 20% with depth may be one reason this soil has Moderate IR as opposed to Poor. However, it could be expected that with such a high sand content IR would be at the Good level. The Moderate level of IR found in this soil could be due to a less well developed soil structure such as the one possibly found in block 19 due to increased silt and less sand.

Table 4. Texture of block 18 site 2 for 8 depths.

<table>
<thead>
<tr>
<th>Block</th>
<th>Site</th>
<th>Depth (cm)</th>
<th>Sand</th>
<th>Silt</th>
<th>Clay</th>
<th>Texture</th>
</tr>
</thead>
<tbody>
<tr>
<td>18</td>
<td>2</td>
<td>-15.24</td>
<td>48</td>
<td>25</td>
<td>27</td>
<td>SCL</td>
</tr>
<tr>
<td>18</td>
<td>2</td>
<td>-30.48</td>
<td>50</td>
<td>26</td>
<td>25</td>
<td>SCL</td>
</tr>
<tr>
<td>18</td>
<td>2</td>
<td>-45.72</td>
<td>50</td>
<td>22</td>
<td>28</td>
<td>SCL</td>
</tr>
<tr>
<td>18</td>
<td>2</td>
<td>-60.96</td>
<td>47</td>
<td>20</td>
<td>33</td>
<td>SCL</td>
</tr>
<tr>
<td>18</td>
<td>2</td>
<td>-76.2</td>
<td>52</td>
<td>19</td>
<td>29</td>
<td>SCL</td>
</tr>
<tr>
<td>18</td>
<td>2</td>
<td>-91.44</td>
<td>57</td>
<td>16</td>
<td>27</td>
<td>SCL</td>
</tr>
<tr>
<td>18</td>
<td>2</td>
<td>-106.68</td>
<td>65</td>
<td>12</td>
<td>23</td>
<td>SCL</td>
</tr>
<tr>
<td>18</td>
<td>2</td>
<td>-121.92</td>
<td>67</td>
<td>14</td>
<td>19</td>
<td>SL</td>
</tr>
</tbody>
</table>
Figure 23. Graph showing the change in sand percentage with depth for the soil at block 18 site 2.
Figure 24 shows a significant decrease in the amount of silt found in the soil at the second site in block 18. This decrease of 10 to 15% in silt coupled with the increase in sand content may indicate a less well developed soil structure. A less defined soil structure due to lower silt content could contribute to lower IR.

Figure 25 shows the change in clay content with depth for the soil sampled at the second site in block 18. Clay starts out at the surface at a fairly high level for soils in this area as indicated by the sandy clay loam texture of this soil. Clay content increases with depth until about 61 cm depth, then it begins to gradually decrease with depth to about 19% clay. These levels of clay are enough to cause IR problems in the soil. The clay amount at the surface may be a particular problem since it can act as a substrate for crust formation.

Table 5 shows the texture determination for each 15.24 cm soil sample. The surface soil is a loam and all of the deeper samples are sandy clay loams except the deepest sample which is a sandy loam. Previous to this texture analysis the soil found in block 17 was assumed to be a sandy loam. It is clear that there is more clay and sand in this soil than previously thought. The clay content found in this soil can be just the right amount for crust formation. The IR type is Moderate for this soil.

Figure 26 shows the increase in sand content with depth for the soil sampled at the first site in block 17. The sand amount starts at a fairly high percentage and drops slightly with depth before continuing to increase. With sand content above 50% for most of the soil and nearing 60% at the greater depths this soil would be expected to have a sufficient IR. However, this soil exhibited an IR similar to the soils sampled in block 18 e.g. a Moderate IR level.
Figure 24. Graph showing the change in silt percentage with depth for the soil at block 18 site 2.
Figure 25. Graph showing the change in clay percentage with depth for the soil at block 18 site 2.
Table 5. Texture of block 17 site 1 for 8 depths.

<table>
<thead>
<tr>
<th>Block</th>
<th>Site</th>
<th>Depth (cm)</th>
<th>Sand</th>
<th>Silt</th>
<th>Clay</th>
<th>Texture</th>
</tr>
</thead>
<tbody>
<tr>
<td>17</td>
<td>1</td>
<td>-15.24</td>
<td>50</td>
<td>28</td>
<td>22</td>
<td>Loam</td>
</tr>
<tr>
<td>17</td>
<td>1</td>
<td>-30.48</td>
<td>51</td>
<td>25</td>
<td>23</td>
<td>SCL</td>
</tr>
<tr>
<td>17</td>
<td>1</td>
<td>-45.72</td>
<td>50</td>
<td>27</td>
<td>23</td>
<td>SCL</td>
</tr>
<tr>
<td>17</td>
<td>1</td>
<td>-60.96</td>
<td>50</td>
<td>27</td>
<td>23</td>
<td>SCL</td>
</tr>
<tr>
<td>17</td>
<td>1</td>
<td>-76.2</td>
<td>51</td>
<td>26</td>
<td>23</td>
<td>SCL</td>
</tr>
<tr>
<td>17</td>
<td>1</td>
<td>-91.44</td>
<td>54</td>
<td>22</td>
<td>24</td>
<td>SCL</td>
</tr>
<tr>
<td>17</td>
<td>1</td>
<td>-106.68</td>
<td>55</td>
<td>24</td>
<td>21</td>
<td>SCL</td>
</tr>
<tr>
<td>17</td>
<td>1</td>
<td>-121.92</td>
<td>57</td>
<td>24</td>
<td>19</td>
<td>SL</td>
</tr>
</tbody>
</table>
Figure 26. Graph showing the change in sand percentage with depth for the soil at block 17 site 1.
Figure 27 shows the change in silt content with depth for the soil sampled at the first site in block 17. The range in silt varies only about 6%. At the surface silt is the highest and followed by a trend towards decreased silt with increased depth.

Figure 28 shows the change in the amount of clay found in the soil sampled at the first site in block 17. The clay content is fairly consistent until about 91cm. At this depth there is a slight increase followed by a drop of 6% over the remaining sampling depths. Typically clay would be expected to accumulate in the deeper soil depths. However, given the poor developments of these Entisols such clay migration does not necessarily occur. The amount of clay found in this soil is in the range of which can cause crusting. These percentages of clay, particularly in the surface soil are ideal for forming the substrate layer of soil crusts. Any crust formation on this soil could contribute to a lower IR.

Table 6 shows the texture results for the soil sampled at the second site in block 17. This was the soil with the lowest IR sampled during the preliminary investigation. It had an IR level of Poor. The texture was a sandy clay loam for all depths. This finding is different than what was assumed before this research was done. Previously the soil was considered a sandy loam. The amount of clay in this soil is much higher than previously thought. It may be that this amount of clay throughout the soil column is a factor in the Poor IR of this soil. There is remarkable consistence in all three size fractions of this soil. The variation with depth for sand, silt and clay is only a few percent.

Figure 29 shows the slight change in sand content with depth for the soil sampled at the second site in block 17. The sand content remains consistent with depth with only a slight drop before returning to about the same amount of sand as found on the surface.
Figure 27. Graph showing the change in silt percentage with depth for the soil at block 17 site 1.
Figure 28. Graph showing the change in clay percentage with depth for the soil at block 17 site 1.
Table 6. Texture of block 17 site 2 for 8 depths.

<table>
<thead>
<tr>
<th>Block</th>
<th>Site</th>
<th>Depth (cm)</th>
<th>Sand</th>
<th>Silt</th>
<th>Clay</th>
<th>Texture</th>
</tr>
</thead>
<tbody>
<tr>
<td>17</td>
<td>2</td>
<td>-15.24</td>
<td>49</td>
<td>26</td>
<td>25</td>
<td>SCL</td>
</tr>
<tr>
<td>17</td>
<td>2</td>
<td>-30.48</td>
<td>49</td>
<td>26</td>
<td>26</td>
<td>SCL</td>
</tr>
<tr>
<td>17</td>
<td>2</td>
<td>-45.72</td>
<td>48</td>
<td>25</td>
<td>27</td>
<td>SCL</td>
</tr>
<tr>
<td>17</td>
<td>2</td>
<td>-60.96</td>
<td>47</td>
<td>26</td>
<td>26</td>
<td>SCL</td>
</tr>
<tr>
<td>17</td>
<td>2</td>
<td>-76.2</td>
<td>49</td>
<td>25</td>
<td>26</td>
<td>SCL</td>
</tr>
<tr>
<td>17</td>
<td>2</td>
<td>-91.44</td>
<td>49</td>
<td>26</td>
<td>25</td>
<td>SCL</td>
</tr>
<tr>
<td>17</td>
<td>2</td>
<td>-106.68</td>
<td>49</td>
<td>26</td>
<td>25</td>
<td>SCL</td>
</tr>
<tr>
<td>17</td>
<td>2</td>
<td>-121.92</td>
<td>48</td>
<td>27</td>
<td>25</td>
<td>SCL</td>
</tr>
</tbody>
</table>
Figure 29. Graph showing the change in sand percentage with depth for the soil at block 17 site 2.
This consistency in sand is fairly different than what was found at the other preliminary sampling sites. Given that this soil has the lowest IR one wonders if this consistency in any way aids in reduced infiltration.

Figure 30 shows the slight change in silt content with depth for the soil sampled at the second site in block 17. The range of silt content is only 2% for all of the samples taken showing a consistent amount of silt in this soil. The amount of silt is not particularly high especially when compared with the amount of silt found in block 19.

Figure 31 shows the slight change in clay content for the soil sampled at the second site in block 17. The range of clay content only varies 2% throughout all depth changes. This is a remarkably consistent amount of clay. This particular amount of clay between the ranges of 25 and 27% is higher than what would be expected from this soil. That is, this soil is commonly considered to be too sandy to have so much clay. The clay content of this soil is ideal for acting as a substrate for crust formation which could reduce IR. The mineralogy of this clay content may also play an important part in the IR level of this soil.

Figure 32 shows the graphical distribution of textures for all five of the preliminary sampling sites (SSSA Texture Triangle). This shows that the range in textural difference is slight. However, the difference from the Good IR level to Poor is quite significant.

Silt is the soil size fraction most responsible for structure. It can reasonably be assumed that, due to the increased silt content with depth in block 19, soil structure is more stable with greater depth in this soil than in the other preliminary sampling sites. The other two blocks do not have as high an amount of silt nor do they exhibit an
Figure 30. Graph showing the change in silt percentage with depth for the soil at block 17 site 2.
Figure 31. Graph showing the change in clay percentage with depth for the soil at block 17 site 2.
increasing amount with depth. The soil sampled in block 19 shows the greatest amount of silt and the increasing trend with depth supports the conclusion that texture determination is relevant for differentiating the three blocks and their respective IRs. This is because texture can give information relevant to factors influences IR. Thus, in order to determine potential IR of a soil texture classification is necessary. Thus, texture determination using the hydrometer method was performed on all samples of the validation study.

Clay Mineralogy Analysis and Evaluation

In the preliminary study, after no evidence for sodic or saline-sodic soils was found clay mineralogy was the next major hypothesis as to why IR varied between these three almond orchards. It was assumed that a variation in the amount of clay in combination with the types of clays found in the soil could be used to distinguish the
differences in IR levels. To determine the influence of clay mineralogy, directed samples were taken of each area representing the three levels of IR. 21 samples were taken from each of the three orchards. The samples in block 17 were concentrated along the western edge were the lowest IR was found. In blocks 18 and 19 the samples were randomly directed throughout the entire orchards. The samples were collected using a soil auger probe. Samples were taken only of the surface soil to a depth of 7cm. For each block the samples were aggregated together to form composite samples. These samples were ground and air dried and delivered to UC Riverside for X-Ray diffraction analysis by Dr. Robert Graham (Klute, 1986).

Figures 33 and 34 show the results of the X-Ray diffraction analysis for smectite and kaolinite clays. In block 17 smectite is indicated by a 17Å peak for the Mg-ethylene glycol solvation treatment, a 15 Å peak when the clay sample is only Mg-saturated, and progressive collapse of the mineral structure when the clay is potassium saturated and heated. The progressive collapse is shown by the shoulder to the left of the10Å peak that moves to the right (lower d value) as the temperature is raised. At 550 °C the smectite has collapsed to a 10Å d-space. Mica is indicated by the 10Å peak that is constant, regardless of treatment. The peak at 4.96 Å is a second order peak from mica, and a 3rd order mica peak contributes to the peak at 3.34 (along with quartz). Kaolin is indicated by the peak at approximately 7Å that disappears upon heating to 550°C (mineral structure decomposed). The peak at 3.57 is a second order peak from kaolin. Quartz is indicated by peaks at 4.25 and 3.34 Å. Feldspar is indicated by small peaks to the right of 3.34 Å.
Figure 33. X-Ray diffraction graph showing the principal peaks indicating smectite clay content in blocks 17, 18, and 19.
Figure 34. X-Ray diffraction graph showing the principal peaks indicating smectite clay content in blocks 17, 18, and 19.
For block 18 there are the same mineralogical components as those found in block 17. However, smectite may be a little less expansive. In block 19 there are the same clay mineralogical components as those in 18, but smectite may be a little more expansive. Thus, the smectite found in these soils is most similar between blocks 17 and 19. This is curious since 19 had a Good level of IR and 17 had a Poor level of IR. From figure 32 it is evident that there is qualitatively more smectite in block 17 than in 19, but 18 has the least amount of all. This is shown by the nearly flat line of block 18 in figure 32 and the two peaks for 19 and 17, each progressively greater. Block 17 also has the most amount of kaolinite clay over blocks 19 and 18, respectively.

From this X-ray diffraction analysis it can be determined that the block with the most shrink-swell clay is 17. This is not a quantitative value merely a qualitative assessment of the relative amounts of smectite in each block. Block 17 having the highest amount of shrink-swell clay fits with the assumption that high amounts of smectite can lower IR. The problem is that in block 18, where IR is at a Moderate level, there is very little smectite. And in block 19 where there is Good IR smectite is present. Thus, it is hard to characterize, with these results, the exact correlation that shrink-swell clay has with IR.

Given the expense and difficulty of performing X-ray diffraction clay analysis, it was not used in the validation study. As well as the prohibitive cost and lack of experienced technicians the results were insignificant with respect to the mineralogy of 19 as compared with those of both 17 and 18. If a distinct difference were found between the clay types of 19 with those of 17 and 18 then further X-ray diffraction could have been justified in the validation portion of this research. Without the significant difference
it was concluded that the clay mineralogy may be important but only in conjunction with total clay content given that both blocks 17 and 19 had smectite clay. Thus, it was concluded that texture analysis would be done in the validation study with the hope that some simpler technique than X-ray diffraction could be used to determine the presence of shrink-swell clays in the validation samples.

**Water Retention Curve Constructions and Analysis**

After clay analysis the next assumption was that there must be a variation in the hydraulic properties of the soils in the three almond orchards. It was also thought that perhaps block 19 had a higher amount of organic matter (OM). Higher OM would lead to greater soil aggregation and better structure which would cause higher infiltration.

There is a considerable amount of theory behind the use of the Van Genuchten fitting model used in this research to graph the soil water retention curve for each of the three soils. The equation used is: \( \theta_e = \left[1+ (\alpha|\psi|)^n\right]^{-m} \) (Porebska et al., 2006). Estimation of VG parameters from experimental data requires: (i) sufficient data points, at least 5 to 8 \( \psi_m-\theta_V \) pairs; and (ii) a program for performing nonlinear Regression (Or et al., 2008; van Genuchten, 1980). This means that due to the complexity of calculating soil water retention curves, considerable assumptions must be made. These assumptions have been proven effective in modeling soil water retention using the van Genuchten model.

The soil used to determine water retention curves was from left over soil from the same samples used for the X-ray diffraction analysis. The soil used for the OM analysis came from the same soils used to determine soil texture. These samples were taken every 15.24cm. For the OM determination only the top three samples were used to find surface OM (Klute, 1986). The saturated hydraulic conductivity was calculated from undisturbed
surface core samples taken at the same time and location of the five preliminary sampling sites. These cores were collected in acetate sleeves 15.24 cm long.

The method for determining the individual water retention curves was as follows (Klute, 1986). The curves were constructed using data from Tempe cells, pressure plate, and WP4-T dewpoint meter (Decagon Devices, Pullman, WA). Tempe cells were filled with loose, air-dried soil from each block. The soils were saturated and then sealed. Three pressure levels were applied -- first, one meter of air, then 4 meters and finally 8 meters. Water loss was measured at each interval. An ideal bulk density of 1.33 g/cm³ was assumed for initial calculations. After the pressure was converted to meters of head, then graphed against volumetric water content and fit to a van Genuchten model.

Saturated hydraulic conductivity was calculated from undisturbed soil columns using the constant head method (Klute, 1986). The caps for the columns were modified with spigots at each end and sealed with abundant amounts of vacuum grease and tape. Marriot siphons were used to slowly saturate the columns and create flow through the soils.

Bulk density was calculated from both the disturbed samples used in the Tempe cells and from the undisturbed columns used to find saturated hydraulic conductivity. The bulk densities of undisturbed and disturbed soils from all three almond blocks as well as saturated hydraulic conductivity (Klute, 1986) can be found in Table 7. Block 17 has the highest undisturbed and disturbed bulk densities as well as the lowest saturated hydraulic conductivity (Ks). Block 19 has a higher undisturbed bulk density than block 18. Block 19 had a slightly lower disturbed bulk density than 18. The soil from block 18 had the highest Ks followed by block 19 which was about half of 18.
Table 7. Undisturbed soil and disturbed soil bulk densities as well as saturated hydraulic conductivity for blocks 17, 18, and 19.

<table>
<thead>
<tr>
<th></th>
<th>Block 17</th>
<th>Block 18</th>
<th>Block 19</th>
</tr>
</thead>
<tbody>
<tr>
<td>Undisturbed Bulk Density</td>
<td>1.76 g/cm³</td>
<td>1.14 g/cm³</td>
<td>1.54 g/cm³</td>
</tr>
<tr>
<td>Disturbed Bulk Density</td>
<td>1.45 g/cm³</td>
<td>1.27 g/cm³</td>
<td>1.22 g/cm³</td>
</tr>
<tr>
<td>Ks</td>
<td>2.14 cm/day</td>
<td>35.71 cm/day</td>
<td>16.85 cm/day</td>
</tr>
</tbody>
</table>

Table 7 also shows that bulk density does not explain why block 19 has the highest IR. The Ks data also does not correlate to the assumption that block 19 should have the highest IR. There may be some experimental error involved but aside from that these tests did not distinguish 19 from the other soils. However, there is some indication as to why block 17 would have the lowest IR. It is the densest soil and had by far the lowest Ks. These tests were not deemed necessary to be applied to the validation study because they did not show enough noticeable difference between the three infiltration regimes, Good, Moderate, and Poor.

Table 8 displays OM percentages for all three soils, five sites, to a depth of 46 cm. OM is very low in all five sites. There is slightly more OM in block 19. It is not evident that the difference alone is enough to explain the great variation in IR between these three almond orchards. Due to the slight difference in OM this test was not performed in the validation study. It was assumed that all of the soil sampled would have very low OM and it would not be a major factor influencing IR.

Figure 35 shows the soil water retention curve for each soil. The soils have very similar shaped curves. It is interesting that the three curves are in order of their respective IR. 17 is on top but ends first. Then comes 18, which ends next, followed by 19 on the bottom which ends last. Based on this graph 19 would appear to be the most permeable.
Table 8. Organic matter for three surface depths for the five preliminary sampling sites in blocks 17, 18 and 19.

<table>
<thead>
<tr>
<th>Block 17 site 1</th>
<th>Depth (cm)</th>
<th>% Organic Matter</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>-15.24</td>
<td>0.7</td>
</tr>
<tr>
<td></td>
<td>-30.48</td>
<td>0.6</td>
</tr>
<tr>
<td></td>
<td>-45.72</td>
<td>0.6</td>
</tr>
<tr>
<td></td>
<td>Average</td>
<td>0.633</td>
</tr>
<tr>
<td>Block 17 site 2</td>
<td>-15.24</td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td>-30.48</td>
<td>0.6</td>
</tr>
<tr>
<td></td>
<td>-45.72</td>
<td>0.7</td>
</tr>
<tr>
<td></td>
<td>Average</td>
<td>0.800</td>
</tr>
<tr>
<td>Block 18 site 1</td>
<td>-15.24</td>
<td>0.7</td>
</tr>
<tr>
<td></td>
<td>-30.48</td>
<td>0.4</td>
</tr>
<tr>
<td></td>
<td>-45.72</td>
<td>0.4</td>
</tr>
<tr>
<td></td>
<td>Average</td>
<td>0.500</td>
</tr>
<tr>
<td>Block 18 site 2</td>
<td>-15.24</td>
<td>0.6</td>
</tr>
<tr>
<td></td>
<td>-30.48</td>
<td>0.3</td>
</tr>
<tr>
<td></td>
<td>-45.72</td>
<td>0.3</td>
</tr>
<tr>
<td></td>
<td>Average</td>
<td>0.400</td>
</tr>
<tr>
<td>Block 19</td>
<td>-15.24</td>
<td>1.2</td>
</tr>
<tr>
<td></td>
<td>-30.48</td>
<td>0.7</td>
</tr>
<tr>
<td></td>
<td>-45.72</td>
<td>0.7</td>
</tr>
<tr>
<td></td>
<td>Average</td>
<td>0.867</td>
</tr>
</tbody>
</table>

The soil in block 19 has Ks sufficient to keep up with current irrigation practices and does not need to be treated with any chemicals in order to stay productive. Although this soil showed a tendency to have more expansive clay, which could facilitate the formation of crust and soil sealing problems causing low IR, it has a low bulk density in relation to its texture. The soil in 18 has Ks twice what it needs to keep up with irrigation, but this Ks may be because this field has been treated with gypsum for years. This soil had a less expansive clay which could explain why it does not have as severe a problem with water ponding and a better response to chemical treatments. Block 17 has a very low Ks that is insufficient to keep up with irrigation, despite the soil having been treated with gypsum. The bulk density of 17 is much higher than the other two soils and surprisingly
soil 18 has the lowest bulk density even though it has had a history of ponding problems before treatments.

**Mica Determination**

Mica quantification was focused on as a potential cause of the difference in IR between the three preliminary sampling sites. This focus was due to the opinion of area experts such as Dr. Grant Cardon, Dr. Brian Marsh, and Dr. Charles Burt and numerous citations in the literature (Singer and Oster, 1984). It was thought that mica content determination would be easy to perform, relatively cheap compared to the other tests (such as clay mineralogy) and very little research had quantified mica in the soil.

Preliminary grain counts comparing the soils in blocks 17, 18 and 19 showed that the soils in block 17 contained over 10% more mica than those in block 19. The soils in block 18 also contained more mica than those in 19. Because of this verifiable difference

Figure 35. Water retention curves for almond blocks 17, 18, and 19.
in mica content between the three soils, mica quantification became the focus of the validation portion of this research.

The initial determination of mica content in the soil used a petrographic microscope. Grain counts were made and the percentage of mica was calculated. In addition to this method a vibration separation technique was employed. This method was attempted because it was assumed to be the simplest method of mica quantification possible and thus would be the most readily accessible for those attempting to replicate this study. One of the objectives of this thesis was to provide farmers and land owners with a method for evaluating land for permanent plantings. Because of this goal the simplest and most cost effective tests were sought.

The idea behind the vibration separation method of mica is that if vibration is applied to an inclined surface on which a granular material rests, the material can be conveyed over the surface, and of a given type, amplitude and frequency of vibration, its rate of movement depends upon its particle size and shape (Tubey and Bulman, 1964). Since mica is generally flakier than other material in the sand fraction of the soil it is possible to separate it out with vibration. To use this technique it is essential to break down soil aggregates. For some soils this requires removing all of the iron oxides and washing with acetone. Other soils may require the removal of all of the organic matter. Soil is then separated by sieving into texture classes for treatment. Tubey and Bulman (1964) called for a sieving at the number 14 B.S. scale, but sand fractionation also works. It is not possible to examine mica content of the clay fraction using this method.

Good separation of mica is likely to be obtained with a slope of the vibration tray at 11 degrees to the horizontal and with amplitude obtained with a vibrator current of 0.3
ampere (Tubey and Bulman, 1964). The process begins by spreading about half a gram of the desired texture of the soil in a band at the top of the inclined table. The sample must be oven dried and free of aggregates, since the mica is most easily lost, all losses are ascribed to the mica fraction. That is, the mica percentage is equivalent to the percentage lost from the sample after the process is complete. To calculate this the material that comes off during vibration is collected and weighed. The amount lost is attributed to mica. This method can be verified using the petrographic microscope. When such verification is done, up to 98% of all mica is removed from the sample (Tubey and Bulman, 1964).

Despite the research that indicated that vibratory separation of mica was possible, the preliminary research found no correlation between the amount of mica lost during vibration (including what stayed on the pan) and what was counted from the same sample under the microscope. A possible reason for this is that the size of the mica flakes is just as important as their shape. That is, mica tended to leave the vibration pan with the other sand material that had a common size. It is true that the sand particles left the pan faster due to their spherical shape but mica was often mixed with these particles or close behind. This method may be effective in the larger sand sizes but this research needed to determine the mica content in the finest sand fraction possible. In addition to the ineffectiveness of this method at separating mica, it was also found to be just as complicated as using the petrographic microscope technique. Delicate weighing was required as well as precise tuning of the vibrator. The time it took to do enough samples to have a statistically viable estimate of the mica content of the soil took much longer than the microscope method. Thus, the vibration method was deemed unnecessary and
insufficient for the validation portion of this research. Therefore, the petrographic microscope technique was relied on exclusively during the validation portion of the study.

**Validation Study**

**Sampling Areas**

The validation study took place in farms near the towns of Wasco and Shafter in northwestern Kern County, California. Fourteen sites were sampled. Most of the sites were in almond orchards of various ages. These sites were chosen because they represent the typical soils of the San Joaquin Valley and exhibited the various levels of infiltration that farmers throughout the valley experience. Table 9 provides details about each site. According to the NRCS database, the soil taxonomy for the types sampled are; Wasco Sandy Loam is a Coarse-loamy, mixed, superactive, nonacid, thermic Typic Torriorthent. A Buttonwillow Clay is classified as a clayey over loamy, smectitic, nonacid, thermic Vertic Torrifluvents. The McFarland Loam is a Fine-loamy, mixed, superactive, nonacid, thermic Typic Torriorthents. And the Lewkalb Sandy Loam is a Coarse-loamy, mixed, superactive, calcareous, thermic Duric Torriorthent. Figure 36 is a map showing the locations of sampling sites in relation to the cities of Wasco and Shafter and soil types.

The soils from the 14 sites are categorized into six different soil types. As shown in Table 9 two sites were taken from locations that overlapped with two soils. All of these soils are formed from granitic alluvium and considered to be well drained or excessively well drained except for the Buttonwillow.
Table 9. Fourteen sites for soil sampling near Wasco and Shafter, California.

<table>
<thead>
<tr>
<th>Site Name</th>
<th>Soil Type</th>
<th>Infiltration Level</th>
<th>Lat</th>
<th>Long</th>
</tr>
</thead>
<tbody>
<tr>
<td>17 South West</td>
<td>Wasco Sandy Loam</td>
<td>Poor</td>
<td>35°</td>
<td>-119°</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>33.816°'</td>
<td>14.679°</td>
</tr>
<tr>
<td>17 North West</td>
<td>Wasco Sandy Loam</td>
<td>Poor</td>
<td>35°</td>
<td>-119°</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>34.176°'</td>
<td>14.695°</td>
</tr>
<tr>
<td>18 North West</td>
<td>Wasco Sandy Loam</td>
<td>Moderate</td>
<td>35°</td>
<td>-119°</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>34.276°'</td>
<td>13.706°</td>
</tr>
<tr>
<td>Shafter Research</td>
<td>Wasco Sandy Loam</td>
<td>Poor</td>
<td>35°</td>
<td>-119°</td>
</tr>
<tr>
<td>North West</td>
<td></td>
<td></td>
<td>32.181°'</td>
<td>16.853°</td>
</tr>
<tr>
<td>Shafter Research</td>
<td>Wasco Sandy Loam</td>
<td>Moderate</td>
<td>35°</td>
<td>-119°</td>
</tr>
<tr>
<td>North</td>
<td></td>
<td></td>
<td>32.073°'</td>
<td>16.764°</td>
</tr>
<tr>
<td>15 West</td>
<td>Wasco Sandy Loam</td>
<td>Moderate</td>
<td>35°</td>
<td>-119°</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>34.743°'</td>
<td>14.69°</td>
</tr>
<tr>
<td>Paramount North</td>
<td>Buttonwillow Clay &amp; McFarland Loam</td>
<td>Poor</td>
<td>35°</td>
<td>-119°</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>40.532°'</td>
<td>22.537°</td>
</tr>
<tr>
<td>19 North East</td>
<td>Wasco Sandy Loam &amp; Lewkalb Sandy Loam</td>
<td>Good</td>
<td>35°</td>
<td>-119°</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>34.089°'</td>
<td>12.524°</td>
</tr>
<tr>
<td>Shafter Research</td>
<td>Wasco Sandy Loam</td>
<td>Good</td>
<td>35°</td>
<td>-119°</td>
</tr>
<tr>
<td>South</td>
<td></td>
<td></td>
<td>31.506°'</td>
<td>17.236°</td>
</tr>
<tr>
<td>20 South East</td>
<td>Lewkalb Sandy Loam</td>
<td>Good</td>
<td>35°</td>
<td>-119°</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>34.444°'</td>
<td>12.431°</td>
</tr>
<tr>
<td>20 North West</td>
<td>Delano Sandy Loam</td>
<td>Good</td>
<td>35°</td>
<td>-119°</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>35.393°'</td>
<td>12.783°</td>
</tr>
<tr>
<td>11 South</td>
<td>Cajon Loamy Sand</td>
<td>Good</td>
<td>35°</td>
<td>-119°</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>35.324°'</td>
<td>15.837°</td>
</tr>
<tr>
<td>3</td>
<td>Wasco Sandy Loam</td>
<td>Good</td>
<td>35°</td>
<td>-119°</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>39.539°'</td>
<td>17.791°</td>
</tr>
<tr>
<td>19 South West</td>
<td>Wasco Sandy Loam</td>
<td>Good</td>
<td>35°</td>
<td>-119°</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>33.651°'</td>
<td>12.891°</td>
</tr>
</tbody>
</table>
Figure 36. Map of soil types and sampling sites.
Sample Collection and Preparation

The fourteen sites were divided into three infiltration level groups. Soils that needed no amendments to achieve sufficient IR were considered to have no infiltration problems. The second group was soils with Moderate IR. These needed regular gypsum applications in order to grow crops. The third group was considered to have Poor infiltration problems. This level was defined by gypsum applications being insufficient to ameliorate the problem highlighted by water ponding lasting 48 hours or more. The reason for the three groups was to represent the various degrees of infiltration management encountered in this area of California. That is, farmers must correct for low IR or not and sometimes what they do, normally applying gypsum, is not sufficient and more expensive amendments are required.

Directional sampling was conducted within each of the 14 sites. Figure 37 is a map showing three sampling plots. Within each plot there were 12 collection points where soil was collected. See the Appendix for maps of all sampling sites. The method for directional sampling within a plot was based on how samples were taken from the lowest IR plots. That is, in a Poor IR plot the area with the lowest IR was sampled. In the other plots the same general distribution and pattern of sampling was followed.

Rather than multiplying sampling sites more samples were taken from each of the 14 sites. This was done in order to give good statistical significance of factors within each site. Twelve samples were collected from each of the fourteen sites. Samples were collected using a three inch diameter soil probe. Soil was gathered from only the top seven centimeters. GPS coordinates were taken for each samples site for repeatability of
Figure 37. Map showing 12 collection points within sampling sites 17 North West, 17 South West, and 18 North West.

the experiment. Samples were air dried (less than 1% moisture), and ground to pass a 2 mm sieve to allow for easier dispersion.
Methods

Hydrometer Texture Analysis

The hydrometer method was used to determine texture (Klute, 1986). This method was used because it is simple and easily reproducible. As noted in the literature review, there has been some concern that the assumptions of Stokes Law might make texture determinations of soils with high amounts of mica difficult. However, no discrepancies were found between the texture determined by hydrometers in this experiment and the soil textures recorded by the USDA-NRCS. It seems that the assumptions of Stokes Law are satisfied as long as the settling time is not shortened. Shortening the settling time after the first agitation may not allow for the planar shaped mica grains in the sand fraction to fall out of suspension. This would cause the sand and silt percentages to be skewed.

Wet Sieving

In order to calculate the percentage of mica in a soil sample it was necessary to isolate a certain size fraction for study. Since large mice flakes would likely not be the source of significant reduction in IR (as shown above by Tubey and Webster (1978), coarse mica increased IR) the smallest sized mica that could be observed under a petrographic microscope was targeted. This fraction included the very fine sand (VFS) and coarse silt (from 0.1 to 0.02mm covering the USDA definition for VFS and coarse silt). Roughly 10g of soil was weighed out and dispersed using sodium hexametaphosphate (brand name Calgon) and agitated for two hours. The exact amount of soil was not important so long as it was a representative amount small enough that it
did not clog the sieve too much and dramatically increase the amount of sieving time. For each sample all material greater than and including fine sand was removed with a USA standard test sieve number 140 (0.104 mm). Wet sieving was completed using a number 635 (20µm) in conjunction with a VFS sized sieve (number 325, 45µm). These two sieves collected all of the VFS and coarse silt. The final step in sieving was to use water to transfer the material on the VFS sieve to the coarse silt sieve for a final rinse. This removed any clay and finer silt that still might be in the sample and to mix the coarse silt and VFS. Samples were oven dried to remove the water used to transfer them to glass jars. Glass jars are important to use because of the stickiness of mica. After drying samples were tumbled briefly with ceramic beads to break surface crusts formed during drying. From visual inspection it was clear that the crusts that form during drying are composed mostly of mica. Because mica takes a little bit longer to settle more mica ends up on the surface. When all of the water has evaporated, the mica sticks together in a crust. It was thought that these surface crusts might disrupt the percentages of mica measured in the samples. Even though this was not found to be the case crusts were still destroyed as good as possible just in case. Each dried and sieved sample was weighed so that if necessary its percentage of the total sample could be determined.

**Petrographic Grain Count of Mica**

The microscope used was an Olympus BH-2. Preparation for petrographic microscope analysis used a series A, certified refractive index liquid of 1.5400 (Cargille Labs, Cedar Grove, NJ 07009 USA). This refractive liquid was necessary to identify mica grains. Extreme care was used in transferring the mixed VFS and coarse silt to the slides because dispersed, dry mica grains are very sticky; due to static electricity the particles
adhere to all surface but non-reactive ones. They also attach readily to each other. Non-reactive utensils were used to transfer a small amount of the sieved material to the slides (2-3 thousand grains). A double handheld click counter was used to record non-mica grains and mica grains. Dust and anything that was clearly organic in nature was not counted. At least a total of 300 grains were counted in order to determine the percentage of mica for each sample (Klute, 1986; Boettinger, Personal Communication, 2010). For example, 243 grains of non-mica may have been counted and 76 mica grains for a total of 319 grains and a mica percentage of ~24%.
RESULTS

The primary objective of this research was to determine whether high mica content in the very fine sand and coarse silt fraction of various soils located near Wasco and Shafter California corresponded to reduced IR in comparable soils. Texture was also examined to see what interactions there might be between the sand, silt and clay, and mica which might be a factor in the level of IR. Statistical analysis of the textural and mica data compared to the severity of Poor infiltration was run using Analysis of Variance (ANOVA) in SAS (SAS Institute, 2010). The following tables (Tables 10-13) are the pairwise means comparisons of mica, sand, silt, and clay with regard to infiltration severity at three levels, Good, Moderate and Poor.

Table 10 shows that mica is a significant factor between Good infiltration and both Moderate and Poor infiltration regimes. Mica was not a significant factor differentiating Moderate and Poor infiltrations.

<table>
<thead>
<tr>
<th>Infiltration Comparison</th>
<th>Difference Between Means</th>
<th>Simultaneous 95% Confidence Limits</th>
<th>Significant at the 0.05 Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Poor – Moderate</td>
<td>2.161</td>
<td>-1.505 – 5.826</td>
<td>*</td>
</tr>
<tr>
<td>Poor – Good</td>
<td>6.365</td>
<td>3.327 – 9.403</td>
<td>*</td>
</tr>
<tr>
<td>Moderate – Poor</td>
<td>-2.161</td>
<td>-5.826 – 1.505</td>
<td>*</td>
</tr>
<tr>
<td>Moderate – Good</td>
<td>4.205</td>
<td>0.914 – 7.495</td>
<td>*</td>
</tr>
<tr>
<td>Good – Poor</td>
<td>-6.365</td>
<td>-9.403 – -3.327</td>
<td>*</td>
</tr>
<tr>
<td>Good – Moderate</td>
<td>-4.205</td>
<td>-7.495 – -0.914</td>
<td>*</td>
</tr>
</tbody>
</table>

Table 11 shows that sand was significant in differentiating Good IR with those from soils with Poor infiltration problems. Table 3 also indicates that sand was not a
significant factor differentiating Good and Moderate infiltrations or Moderate and Poor infiltrations.

Table 11. Pairwise means comparison (Scheffe’s Test) for Sand and Infiltration.

<table>
<thead>
<tr>
<th>Infiltration Comparison</th>
<th>Difference Between Means</th>
<th>Simultaneous 95% Confidence Limits</th>
<th>Significant at the 0.05 Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Good – Moderate</td>
<td>2.728</td>
<td>-2.217</td>
<td></td>
</tr>
<tr>
<td>Good – Poor</td>
<td>7.815</td>
<td>3.250</td>
<td>12.380</td>
</tr>
<tr>
<td>Moderate – Good</td>
<td>-2.728</td>
<td>-7.673</td>
<td>2.217</td>
</tr>
<tr>
<td>Moderate – Poor</td>
<td>5.087</td>
<td>-0.421</td>
<td>10.595</td>
</tr>
<tr>
<td>Poor – Good</td>
<td>-7.815</td>
<td>-12.380</td>
<td>-3.250</td>
</tr>
<tr>
<td>Poor – Moderate</td>
<td>-5.087</td>
<td>-10.595</td>
<td>0.421</td>
</tr>
</tbody>
</table>

Table 12 shows that silt is the only factor that was significant for Moderate and Poor levels of infiltration. Table 4 also shows that silt was also a significant factor between Poor and Good infiltration regimes. Silt was not a significant factor differentiating Good and Moderate infiltrations.

Table 12. Pairwise means comparison (Scheffe’s Test) for Silt and Infiltration.

<table>
<thead>
<tr>
<th>Infiltration Comparison</th>
<th>Difference Between Means</th>
<th>Simultaneous 95% Confidence Limits</th>
<th>Significant at the 0.05 Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Poor – Good</td>
<td>3.9644</td>
<td>1.2114</td>
<td>6.7175</td>
</tr>
<tr>
<td>Poor – Moderate</td>
<td>4.1115</td>
<td>0.7898</td>
<td>7.4331</td>
</tr>
<tr>
<td>Good – Poor</td>
<td>-3.9644</td>
<td>-6.7175</td>
<td>-1.2114</td>
</tr>
<tr>
<td>Good – Moderate</td>
<td>0.1470</td>
<td>-2.8350</td>
<td>3.1291</td>
</tr>
<tr>
<td>Moderate – Poor</td>
<td>-4.1115</td>
<td>-7.4331</td>
<td>-0.7898</td>
</tr>
<tr>
<td>Moderate - Good</td>
<td>-0.1470</td>
<td>-3.1291</td>
<td>2.8350</td>
</tr>
</tbody>
</table>

Table 13 shows that clay is a significant factor for the same infiltrations regimes as mica. It is a significant factor between Good infiltration and both Moderate and Poor infiltration regimes. Table 5 also shows by the lack of asterisks in the appropriate cell that clay was not a significant factor differentiating Moderate and Poor infiltrations.
Table 13. Pairwise means comparison (Scheffe’s Test) for Clay and Infiltration.

<table>
<thead>
<tr>
<th>Infiltration Comparison</th>
<th>Difference Between Means</th>
<th>Simultaneous 95% Confidence Limits</th>
<th>Significant at the 0.05 Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Poor – Moderate</td>
<td>0.9755</td>
<td>-1.8978 - 3.8489</td>
<td>*</td>
</tr>
<tr>
<td>Poor – Good</td>
<td>3.8508</td>
<td>1.4693 - 6.2323</td>
<td>*</td>
</tr>
<tr>
<td>Moderate – Poor</td>
<td>-0.9755</td>
<td>-3.8489 - 1.8978</td>
<td>*</td>
</tr>
<tr>
<td>Moderate – Good</td>
<td>2.8752</td>
<td>0.2957 - 5.4548</td>
<td>*</td>
</tr>
<tr>
<td>Good – Poor</td>
<td>-3.8508</td>
<td>-6.2323 - 1.4693</td>
<td>*</td>
</tr>
<tr>
<td>Good - Moderate</td>
<td>-2.8752</td>
<td>-5.4548 - 0.2957</td>
<td>*</td>
</tr>
</tbody>
</table>

An analysis of variance was computed for mica. Table 14 shows that mica is a significant factor for all three levels of infiltration.

Table 14. ANOVA for Mica Significance.

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>Sum of Squares</th>
<th>Means Square</th>
<th>F Value</th>
<th>Pr &gt; F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>2</td>
<td>1327.496030</td>
<td>663.748015</td>
<td>14.56</td>
<td>&lt; 0.0001</td>
</tr>
<tr>
<td>Error</td>
<td>165</td>
<td>7521.778379</td>
<td>45.586536</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Corrected Total</td>
<td>167</td>
<td>8849.274409</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 15 shows the confidence intervals for all four factors. For the ranges of mica, silt, clay and sand ranges are given which correspond to the level of infiltration.

Table 15. Confidence Intervals for Mica, Silt, Clay and Sand.

<table>
<thead>
<tr>
<th>IR Level</th>
<th>Mica %</th>
<th>Silt %</th>
<th>Clay %</th>
<th>Sand %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Poor</td>
<td>24.5 – 28.5</td>
<td>&gt; 25</td>
<td>18.5 – 21.5</td>
<td>50 – 56</td>
</tr>
<tr>
<td>Moderate</td>
<td>22 – 26.5</td>
<td>12 – 25</td>
<td>17 – 20.5</td>
<td>55 – 62</td>
</tr>
<tr>
<td>Good</td>
<td>&lt; 21.5</td>
<td>21.5 – 24</td>
<td>15 – 17</td>
<td>59 – 63</td>
</tr>
</tbody>
</table>
DISCUSSION

The reduced IR of permanent plantings in Kern County, California seems to be a complex interaction of many soil variables both physical and chemical. Some of these variables include texture and mica content. The objective of this research was to establish whether mica content in the VFS and coarse silt fraction of the soil was a significant factor in the IR of soils in northwestern Kern County, California. It was assumed that high amounts of mica in this fraction of the soil may interact with other physical and chemical properties to reduce IR. Based on the findings of this study it seems that mica percentage and texture would be necessary to evaluate land in northwestern Kern County for its future need for infiltration amendments under typical permanent planting practices.

For landowners contemplating establishing permanent plantings in northwestern Kern County, California, a mica and texture analysis will inform them of how suitable the land will be. As shown in Table 7, if the range of mica is discovered to be between 24.5 – 28.5%, silt greater than 25%, clay between 18.5 – 21.5%, and sand between 50 – 56%, then the IR can be estimated with 95% confidence to be in at the Poor level. This means that the soil will require more than gypsum, as a treatment, in order to keep the soil at a Good level of IR for permanent plantings. A potential soil will need gypsum to grow permanent planting sustainably if it is found to have a mica content range of 22 – 26.5%, silt between 21 – 25%, clay between 17 – 20.5% and sand content between 55 – 62%. And finally, if a soil is found to have mica content less than 21.5%, silt between 21.5 – 24%, clay content between 15 – 17% and sand between 59 – 63% than the soil will likely not need any amendments.
The results show that if a soil in this area of California has a high percentage of mica it will likely have reduced IR if it is used for permanent plantings. The low IR of such soils can be ameliorated for permanent plantings by the use of amendments such as gypsum, calcium and surfactants as well as tillage and cover crops. However, having the mica percentage of the soil before purchase can inform a farmer as to the degree of potential IR problems a new field may have.

The results showed that mica in the silt fraction was the only factor out of mica, sand, silt and clay that was significant between Moderate and Poor IR. This is important because the assumption of this study was that mica was a significant factor between all levels of IR. The results show that it was only between Good and Poor IR as well as Good and Moderate IR. These results indicate that the percentage of mica is significant for each level but not for the change between the two lowest IR levels. Since the results show silt as the only significant factor between Moderate and Poor levels of IR an explanation is required.

It could be that since only the coarse silt was measured the rest of the silt fraction is actually the size fraction most responsible for reduced IR due to mica content. That is, most of the IR lowering mica is in the silt size finer than coarse silt. Comments by Dr. Grant Cardon support this assumption (Cardon, Personal Communication, 2010). It would be interesting to determine the amount of mica in the rest of the silt size fraction. However, the reason silt is a significant factor between Moderate and Poor levels of IR has to do with the sampling sites used in this study.

The SAS program outlier test showed no significance for the silt variable. However, the most Poor IR site sampled in this project, Paramount North, had average
silt contents of 37% (Standard deviation 6.24, and median of 37) for twelve sample locations. Thus, this one site, out of the fourteen, may have, with its twelve samples, forced silt content into the significance range between Moderate and Poor IR because, not only was it a Poor IR site, it was also a high silt soil. This means that if further study was done only on variable IR levels in Wasco Sandy Loam soils (or similar soils) then mica may indeed show up, as we originally assumed, as a significant factor between all levels of IR. As is, this study includes a Buttonwillow Clay soil that is rare in this area of California and one which exhibits extremely low IR in permanent plantings. Therefore, when using this research to determine potential usability of a field for permanent plantings, texture determination, particularly silt percentage, as well as mica percentage in the VFS and coarse silt content must be quantified.

It is also important to note how the levels of IR are defined in this study. Since direct IR readings were not taken, the three IR levels are defined on the historical use of the plots and how they have been amended for successful permanent plantings. That is, the degree of difference in IR between the three levels of IR is characterized in this study by the chemical treatments used to provide adequate IR. Thus, the levels of Moderate and Poor IR differ only in that Moderate is ameliorated to the level of Good IR by the consistent application of gypsum and Poor IR is generally ameliorated to the level of Good by the application of calcium and surfactants. The main distinction in the definition of the levels of IR in this study is between the use of no amendments, as in the case of Good infiltration, and the other two levels which both require amendments. However, some of the sites sampled are not improved to the level of Good IR even with the most extreme amendments (calcium and surfactants). The Buttonwillow Clay soil is one such
site. Despite efforts by the owner, water tends to pool for up to three days after an irrigation. Thus, it is possible to conclude that within the level of the worst IR in this study, Poor, there are degrees of IR. The worst IR soils may contribute to the lack of the significance of mica between all IR levels. For the same reason, silt may be the only factor significant between Moderate and Poor IR. Thus, it is important to emphasize that the most important discovery of this research is showing that mica content is a significant factor between soils that require no amendments and those that do. This means that when using the mica results to evaluate land for permanent plantings a farmer may discover if amendments will be required or not, but never how much and if amendments will completely ameliorate low IR. Based on these findings, only with the added information of texture, taxonomy and historical use can the IR be fully estimated.

A more comprehensive quantification of soil mica could be done to determine its influence on IR. This study only quantified biotite mica in the VFS and coarse silt fraction of the soil. This was the smallest soil fraction that could be looked at using a petrographic microscope, a cheap and effective method. The size of these particles was closest to those thought to be the most damaging to IR. However, the mica percentage of the very coarse, coarse, medium and fine sand as well as the fine silt and clay was not quantified. The mica in the other sand fractions would be relatively easy to quantify, but it is not likely that larger sand mica is much of a factor in reducing IR. Quantifying mica in the clay and fine silt would be much more difficult and expensive especially for the number of samples used in this study. Quantification of other types of mica which have the same physical characteristics, particularly muscovite mica, might also help to show that mica is a significant factor between all levels of IR.
Future Research

There is significant future work that can be done to better understand IR in the soils of Northwestern Kern County California. Additional research into several key aspects illuminated by this thesis would be insightful into the implications found here. Some of these areas of continued work are as follows: A full evaluation of the influence that various water application methods have on the soils of this region, a comprehensive quantification and study of all soil mica, additional validation research, i.e. more samples, and further investigations and theoretical exploration into the mechanism that would cause platy particles to orient in the soil in such a way as to reduce IR. Each of these areas of future work will be explicated in more detail below. However, it is important to keep in mind the complex variability of soil factors, conditions and treatments which may influence IR in a given location. These areas of future work will all rely on rigorous statistical testing in order to more fully understand the IR problems in these soils.

Evaluate Sprinkler Application Method

A vital area of continued IR research in the soil of northwestern Kern County California is the influence various water applications methods can have on changing the IR of the soil. For example, in the preliminary research the primary objective was to determine what made the block 19 almond orchard have a Good IR when two orchards nearby and of the same soil type had Moderate and Poor IR. Even though all three block received the same quality water block 19 used different sprinklers. In blocks 17 and 18 there are two sprinklers per tree. In block 19 there is only one. The sprinklers are further
apart in block 19 and they have a much higher application rate than those used in the other two blocks.

Detailed evaluation of these different water application methods is required. For example, one way of testing whether or not the sprinklers and their number per tree makes a difference is to duplicate the arrangement in 19 in the lowest IR areas of 17. After a certain amount of time it should become evident if this arrangement can ameliorate the low IR of block 17, particularly along the western edge.

One of the main reasons such a sprinkler configuration may provide higher IR is because there is little overlap in water application with only one sprinkler per tree. The overlap of water may cause reduced IR simply because the soil cannot absorb the amount of water being applied. One sprinkler may apply the rate or water suitable to the soils ability to absorb. However, two sprinklers distributing water in the same area would overwhelm the IR of the soil.

**Pulsing Pattern of EC, pH and SAR Through the Soil Profile**

A fruitful area of research would be to investigate the reason for the curious zigzagging pattern found in the salt evaluation of the preliminary research. A before and after study of an untreated soil irrigated with water containing no amendments followed by water with gypsum could verify the cause of this pattern. Different levels of EC in the applied water could also be done to determine if the effect is separate from the gypsum application and instead has to do with seasonal variability in the water quality due to the use of well water or pure canal water. As the relationship of EC to IR becomes clearer
these future investigations may be important to understanding the reduced IR in permanent plantings throughout the San Joaquin Valley.

**Quantification and Analysis of Other Types of Mica**

A more comprehensive quantification of soil mica could be done to determine its influence on IR. This study only quantified biotite mica in the VFS and coarse silt fraction of the soil. This was the smallest soil fraction that could be looked at using a petrographic microscope, a cheap and effective method. The size of these particles was closest to those thought to be the most damaging to IR. However, the mica percentage of the very coarse, coarse, medium and fine sand as well as the fine silt and clay was not quantified.

<table>
<thead>
<tr>
<th>Table 16. Types of mica and their chemical formulas.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Type of Mica</strong></td>
</tr>
<tr>
<td>Biotite</td>
</tr>
<tr>
<td>Phlogopite</td>
</tr>
<tr>
<td>Zinnwaldite</td>
</tr>
<tr>
<td>Lepidolite</td>
</tr>
<tr>
<td>Muscovite</td>
</tr>
<tr>
<td>Clintonite</td>
</tr>
</tbody>
</table>

There are several other types of mica that can be found in the soil in addition to biotite mica. The primary micas found in the soil are muscovite, phlogopite, zinnwaldite, lepidolite and clintonite as shown in table 16. Muscovite and lepidolite have been known to be found in California. It is unlikely that all types are found in the area of this study but they could be sought using various petrographic techniques.

The primary assumption that biotite mica content in the soil can cause reduced IR is based on biotite’s shape. Due to their flat structure, particles of mica behave differently
than other soil particles. These differences in behavior are conducive to causing conditions of reduced IR. All of these other types of mica also have the same shape as biotite. Thus, their presence in the soil could also lead to reduced IR. A more complete quantification of soil mica would include these types of mica. They may require a different refractive index liquid in order to be identified and quantified. This would add another step in the methods of mica quantification, but would give a more accurate account for the amount of platy particles contain in a soil.

It is important to note, as shown in table 6, that these other micas contain different elements in their chemical structure. It is not evident to what degree the variation in composition of these micas may influence their power over IR. It seems possible that a variation in the internal compositions of these micas could lead to a variation in the electro-chemical properties of each. It could be that certain micas, such as biotite, have more of the constituents and charge that allow a process in the soil to orient such particles. It is also possible that due to the ions composing some of these micas they actually increase IR in the soil. For example it has been found that mica in the larger sand sizes decreases compaction. Less compaction results in higher IR. Thus, perhaps due to their makeup, some of these other types of mica do not break down as readily into smaller sizes as do others. Thus, these stronger micas would aid in keeping IR levels high since they reduce compaction.

**Examination of Other Size Fractions**

A more comprehensive quantification of mica percentages in all size fractions of the soil is also possible to more fully characterize the influence this mineral has on soil IR. In the larger sand sizes such as the coarse, medium and fine sand mica can be
expected to reduce compaction. However, these sizes can also contribute to sieving crusts. Due to their size it is also possible that the mechanism that orients mica particles in the soil to cause reduced IR does not operate as well. It is also possible that the orienting mechanism works more effectively on these sizes of mica. Thus, quantifying these sizes of mica would be a future project that could use the same methods of this study, the petrographic microscope, and give added information on the statistical significance of larger sized mica to various IR levels.

The finer silt (less than coarse silt) and clay mica could also be quantified in order to determine the influence these sizes of mica might have on the soil. The orientation of clay sized mica was discussed in the literature review above. Quantifying mica in the clay and fine silt would be much more difficult and expensive because it would require X-Ray diffraction or similar methods. These techniques are not only difficult to perform the equipment used is expensive.

It could be that since only the coarse silt was measured in this study the silt most responsible for reduced IR was not quantified. It is possible that the finer silt is the size fraction most responsible for reduced IR due to mica content. This could be because the mechanism that orients platy particles operates best on the silt sized mica. That is, it could be that most of the IR lowering mica is in the silt size finer than coarse silt. Comments by Dr. Grant Cardon support this assumption (Cardon, Personal Communication, 2010).

**Additional Validation Studies**

Additional validation studies could be performed to strengthen the evidence of the influence mica has on the IR of soils in the San Joaquin Valley. Future studies could be
designed to sample only the same soil type such as Wasco Sandy Loam soils. These studies could be based on soil survey maps of the area. Wasco Sandy Loam soils exhibited all three levels of IR: Good, Moderate and Poor. By taking validation samples from only one soil, potential significant differences in the soils can be illuminated.

In contrast to this method of study, other validation work could be designed to sample from a wide variety of soil types. The advantage of such a study would be that the results could be more widely applicable. That is, the findings might be relevant to areas outside of the region of northwestern Kern County California.

Any additional studies could increase the number of plots sampled. The amount of plots described as either having Good, Moderate or Poor IR could be increased proportionally. For example, in this study seven sampling plots were untreated and considered to have Good IR. The other seven plots received amendments and were either Moderate or Poor IR. Of these plots that received amendments, four were considered Poor IR areas and three were considered Moderate. This unequal sampling of plots could be illuminated in future studies. The amount of samples taken from each plot could also be increased. The increase in the number of plots and samples would strengthen the argument that mica is a factor in reducing IR by giving it greater statistical weight.

**Verification of Crust Formation**

In continued research, one of the very first observations that are imperative to make is identification of a surface crust in the soils sampled. To do this intact surface peds must be sampled and thin sections prepared for microscopic observations. Thin sections should show any evidence for crust formation. This type of sampling would also help to identify whether or not mica is a constituent of such crusts. These observations
would be very important in understanding how IR is reduced in these soils and if mica is a contributing factor to crust formation. This type of sampling and preparation would be somewhat expensive, time consuming and would require experience. There are labs that will prepare thin sections for a reasonable price but evaluating the samples for crust formation would also require experience. However, such observations of crusts in these soils is vital to continued IR research in this area.

Identifying the Mechanism of Reduced Infiltration Rate due to Mica

Having identified that mica is a significant factor in various levels of infiltration is important for beginning to understand what kind of mechanism may be functioning in the soil that would cause orientation and reduced IR. Due to its flat shape, high density and high cation exchange capacity, it is likely that mica is interacting with some forces in the soil which cause it to reduce IR.

One possible explanation for the tendency of mica to orient in the soil is due to clay mineralogy. If clays that swell when wet and shrink when dry are found in the soil in sufficient quantities, they may be part of what causes horizontal mica orientation. Mica dispersed throughout such a clay, and exposed to this swelling and shrinking action, may become horizontally oriented within in the soil matrix. This would explain how IR could be reduced in a high mica soil in northwestern Kern County California when no evidence for crusting is found. Therefore, in future research evaluation of the clay fraction needs to be evaluated. As stated above, X-Ray diffraction is expensive and requires expert knowledge and access to rare equipment. Thus, simpler test to evaluate the clay fraction of the soil to see if it is a shrink-swell clay should be employed. Such methods might
include separating out as much of the fine soil fraction as possible and placing it in graduated cylinders with a Marriott siphon to wet from the bottom and observe if swelling occurs and by what percentage. This is a rough estimate but some sort of evaluation as to whether these types of clay are present in the soil need to be made before further investigation into this hypothesis for the mechanism of particle orientation is evaluated.

Once shrink-swell clays are identified in a soil, observations of the mechanism at work should be made. One possible way of doing this would be to take intact ped samples from the surface of a new field where shrink-swell clays have been identified and mica is present. A new field would be one that has not yet been used for permanent plantings or has been extensively tilled and prepared for a new orchard planting. From these peds thin sections would be prepared and detailed observations made, i.e. photographs should be taken. Next, another group of these peds would be gently wetted. This may be difficult given the high sand content in these soils since exposure to water may cause the peds to fall apart. Nevertheless, this should be attempted and once wetted these peds should be allowed to dry. From these wetted and dried peds thin sections should be prepared and observations made. Various replications of this wetting and drying treatment may be needed to be done before any observation of mica orientation can be identified in the thin sections. Indeed no observation may be found. However, such a study would be similar to what is occurring in the field under irrigation conditions and would be a good place to start when evaluating the potential for shrink-swell clays to be involved in the particle orientation that is assumed to be happening and leading to reduced IR.
Another way to evaluate if mica orientation is occurring is to do a three-dimensional rotational signal intensification study. This study could be done in conjunction with the ped wetting research above. That is, at each level of wetting whether none, once, twice or more signal intensification could be used to potentially create a three-dimensional image or determination of particle orientation. Such analysis could be calibrated to identify specific particle sizes and could give evidence for particle orientation due to shrink-swell clays. This same method could be used on soils without testing for shrink-swell clays. That is, if a soil in an orchard has low IR intact peds could be collected and evaluated using this method to see if particle orientation has already occurred.
CONCLUSIONS

The results of this study do not contradict any previous scientific findings. However, Tubey and Webster (1978) showed that since mica reduced compaction it helped to maintain IR at higher levels. In his study, Tubey was referring to coarser mica than was measured in this research. Thus, these results do not disprove his findings.

Several authors have argued that low IR may be due to particle orientation particularly in the clay size fraction of the soil (Gal et al., 1984; Singer and Oster, 1984; Shainberg and Singer, 1986). The results of this research give support for these studies due to the properties of mica (see below). This is the first study to quantify mica in the VFS and coarse silt size and determine whether it is a factor in IR. The results are new and, thus, the findings are provocative and relevant to further infiltration research.

There are several possible explanations for why mica might reduce IR. Due to its planar shape, mica tends to orient parallel to the surface of the soil. This preferential orientation maximizes its ability to present a solid surface to incoming water. If there is a large enough amount of such horizontally oriented mica flakes total pores available for water entry can be greatly reduced. Mica also has the tendency to stick together with other mica flakes. This cohesiveness aids in crust formation and crust strength. These two properties of mica, its tendency to orient and stick together, are facilitated by the slow settling velocity of mica flakes.

Because of its perfect basal cleavage, mica particles are typically very thin and wide as opposed to most other soil constituents of the same size which assume a spherical shape. Thus, when moving water picks up soil the last particles to settle out in each size fraction down to clay are the wide flat mica particles. This means that if there is a high
amount of mica in the soil over time more and more of it will end up on the surface of the soil where it can facilitate crust formation, clog the soil matrix, and reduce IR.

The variations in mica content that are found throughout Kern County California could be attributed first to the pattern of alluvial deposits of the soil parent material that occurred millennium ago. Ancient rivers wound through this valley for thousands of years depositing the sediment that contained the parent material for the current soils found in this region. Slow bends in the river may have been likely areas of mica deposits as well as wide shallow sections. More recently, in the last 150 years, massive earth moving projects have been undertaken to level the land for agriculture. These projects may have concentrated mica that had settled on the surfaces of hills to one edge or portion of a current field. It is also possible that the extensive flood irrigation that used to be more common in this region carried mica flakes to certain areas. For example, one of the areas sampled in this study used to be flood irrigated from many years. The water would enter from the east and collect on the west side. It is assumed that this consistent directional flow of the water in an area that already had high mica percentages may have led to very low IR in no-tilled almond orchards along the west edge of this land.

Mica content in the VFS and coarse silt fraction of soils from the northwestern region of Kern County California is a significant factor in IR. Since there is no treatment to remove mica the application of this research would be to test soil for mica content, texture and taxonomy before using them for future or continued permanent plantings. Based on the results it could be determined the similarity of the new land to the three levels of IR in this study, Good, Moderate, and Poor. Depending on the similarity of the
characteristics of the new soil with the soils studied a more complete cost evaluation of the land could be made.
LITERATURE CITED


Kondelchuk, D., and K. Miskovsky. 2008. Determination of the test methods sensitive to free mica content in aggregate fine fractions. Luleå University of Technology Department of Civil, Mining and Environmental Engineering Division of Mining and Geotechnical Engineering.


APPENDIX
Soil Types
- SoilSamplePoints

Soil Taxonomy
- Other Soil Types

Sampled Soil Areas
- 123 - Buttonwillow Clay
- 125 - Cajon Loamy Sand
- 138 - Delano Sandy Loam
- 184 - Lewkow Sandy Loam
- 192 - McFarland Loam
- 243 - Wasco Sandy Loam

SVF - 15 West
Figure 38. Maps of sampling sites with collection points.