TEMPORAL AND SPATIAL VARIABILITY OF AGRICULTURAL IRRIGATION WATER SALINITY AND EFFECTS OF IRRIGATION AND DRAINAGE PRACTICES ON SOIL SALINITY IN NORTHEAST FLORIDA

By

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To Abraham Yarney and Dr. Benjamin Campion
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<td>BEBR</td>
<td>Bureau of Economic and Business Research</td>
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<td>BMAP</td>
<td>Basin Management Action Plan</td>
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<tr>
<td>BMP</td>
<td>Best Management Practice</td>
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<tr>
<td>EC</td>
<td>Electrical Conductivity</td>
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<td>ECe</td>
<td>Extracted Soil Water Electrical Conductivity</td>
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<td>FLREC</td>
<td>Fort Lauderdale Research and Education Center</td>
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<td>GPS</td>
<td>Global Positioning System</td>
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<td>IDT</td>
<td>Irrigation Drainage Tile</td>
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<td>IFAS</td>
<td>Institute of Food and Agricultural Sciences</td>
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<td>IN</td>
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<td>MGD</td>
<td>Million Gallons per Day</td>
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<td>pH</td>
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<td>PVC</td>
<td>Polyvinyl Chloride</td>
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<td>ROS</td>
<td>Reactive Oxygen Species</td>
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SALTMOD      A Computer Program for the Prediction of the Salinity of Soil Moisture, Ground Water and Drainage Water, Depth of the Water Table, and the Drain Discharge in Irrigated Agricultural Lands

SI          Seepage Irrigation

SJRWMD   St. John’s River Water Management District

SOP          Standard of Operation

TCAA      Tri-County Agricultural Area

TDS          Total Dissolved Solids

TMDL      Total Maximum Daily Load

TSS          Total Soluble Solids

UF          University of Florida

USEPA    United States Environmental Protection Agency

USGS      United States Geological Services

WBL      Wetland and Biogeochemistry Laboratory

WUE          Water Use Efficiency

WWQL      Wetlands and Water Quality Laboratory
TEMPORAL AND SPATIAL VARIABILITY OF AGRICULTURAL IRRIGATION WATER SALINITY AND EFFECTS OF IRRIGATION AND DRAINAGE PRACTICES ON SOIL SALINITY IN NORTHEAST FLORIDA

By

Eunice Yacoba Yarney

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Chair: Mark Clark
Major: Soil and Water Science

Irrigation water salinity has been a concern for growers in the TCAA, northeast Florida for many years. This issue becomes most apparent during low rainfall years when salts can concentrate in the soil due to evaporation and reduced leaching, coupled with increased crop irrigation. This research was conducted to evaluate temporal and spatial trends in groundwater salinity using 1975/76 survey results as a baseline, and whether Irrigation Drainage Tile (IDT) systems could reduce the volume of irrigation water used as well as soil salinity, compared with conventional seepage irrigation (SI).

Groundwater from 134 wells in the TCAA were collected between September, 2013 and June, 2015 and analyzed for electrical conductivity (EC). Fourteen wells were same wells sampled in 1975/76 and the rest were unmatched wells located within the same extent as the 1975/76 survey. Three farms were also monitored for volume of irrigation water used by SI and IDT systems from August, 2014 to August, 2015. Finally, soil samples were collected (Fall, 2013; Fall, 2014; and Summer, 2015) from the same SI and IDT fields at six farms to evaluate soil salinity differences.
Groundwater salinity in the 14 matched wells increased in the 40-year period (1975-2015) by 0.2 ± 0.55 dS/m. However, in the short-term (2013-2015), groundwater salinity decreased by an average of 0.19 ± 0.31 dS/m per year in 134 wells sampled. Volume of irrigation water used was found to be lower in IDT systems at two farms (40% and 37% less), and higher (45%) in a third farm, compared with SI. Overall, IDT systems in all farms monitored used 15% less water, compared with SI. Finally, IDT field soils were found to be significantly lower in salinity than SI fields in five out of six farms, supporting the hypothesis that IDT systems can potentially reduce soil salinity. Among all sampled depths combined, IDT reduced soil salinity by 39.7% compared with seepage irrigation. These findings provide important information with regard to trends in irrigation water salinity in the area as well as alternative drainage and irrigation techniques that can be effective at mitigating soil salinity during low rainfall periods.
Salinity in Crop Production

Salinity issues in agricultural production are evident in vast parts of the world at different intensities (Qureshi et al., 2008). Several estimated costs to crop production have been reported for high salinity concentrations in irrigation water and or soil solution (Ritzema et al., 2007; Scherer et al., 2015), some of which are direct and can be alleviated, others being indirect and can hardly be controlled. Salinity is the amount of soluble salts in water (water salinity) or in soil (soil salinity). It can be measured as electrical conductivity (EC) in decisiemens per meter (dS/m) (Rhoades et al., 1999) or as total dissolved solids (TDS) in milligram per liter (mg/l) (Fipps, 2003). High EC implies greater amount of salts in solution, similar to high TDS. Sources of salts may be natural where certain regions have large salt deposits spanning over several geological time scales (Brady & Weil, 2002), or may be human influenced. In agricultural systems, management activities can contribute to increased groundwater use and soil salinity. Some of these activities include fertilization type and regime, irrigation water quantity and quality and groundwater withdrawal rates.

Irrigation water and soil salinity is an issue of concern in agricultural systems because it ultimately affects crop yield. Salinity tolerance thresholds for various crops have been established by researchers indicating potential losses in yield at varying percentages, based on exceeded various effect thresholds (Ayers & Westcot, 1985; Fipps, 2003). Crop fatalities occur at certain maximum salinity concentrations which have also been established for several crops.
Crop physiological changes under saline conditions are discussed in depth in chapter three of this dissertation. It is however worth noting that the impact of salinity on crop production is not solely dependent on the salinity concentration, but is an interplay of the latter, local climatic conditions, seasonal variabilities, as well as management activities during crop production.

**Water Conservation in Crop Production**

Another issue of concern in agricultural production is water availability. Alternative measures are constantly attempting to improve crop use efficiency and minimize the amount of water used for irrigation purposes in crop production. Research being conducted worldwide relates to identifying more efficient irrigation systems, improved crop varieties with less water demand, effective irrigation timing, among others. Irrigation system efficiency plays a major role in water conservation in the agricultural sector. Increasing demand for food and water resources, amidst threats of climate change now and in the future requires the innovation and adoption of highly efficient irrigation systems, which use minimal amounts of water for optimum crop production.

**Background to Study**

**Agricultural Production in the Tri-County Agricultural Area**

The Tri-County Agricultural Area (TCAA) lies within three counties in northeast Florida; Putnam, St. Johns, and Flagler (Figure 1-1 and 1-2). These counties are located within the lower St. Johns river watershed and generally have a flat topography. Climatic conditions are favorable for intensive agriculture; humid subtropical with mean annual rainfall of approximately 1320.8 mm (FCC, 2016). Potato (*Solanum tuberosum*) is the main crop grown in the TCAA. Sandy soils with low water holding capacity and
variable rainfall characteristics, as well as production during lower rainfall months require intensive irrigation for crop production. Preparation for potato production begins late in September and potatoes are harvested usually in May. The geology of the area consists of surficial sand and clay mixed with thin beds of limestone and phosphatic material to a depth of more than 61 meters at some localities (Munch et al., 1979). Underlying these materials is the Floridan aquifer, which is a high yielding porous limestone aquifer that occurs throughout much of the Southeastern Coastal plain (Figure 1-3).

**Water Demand and Consumption in the Tri-County Agricultural Area**

Regional water demand by the non-agricultural sector keeps increasing with increasing population (BEBr, 2014; SJRWMD, 2013) as shown in (Figure 1-4). The report suggests that without further reduction in consumption of groundwater per capita, total water demand in the SJRWMD is expected to increase by approximately 1,188,619.3 m³/day (26%) by 2035. However, based on historical trends, agricultural water demand is projected to decrease due to increased water use efficiency (WUE) of irrigation systems and conversion of agricultural lands into residential areas (SJRWD, 2013) (Figure 1-5).

Groundwater from the Floridan aquifer is the main source of water supply for urban as well as agricultural use in the TCAA and its environs. According to Munch et al. (1979), the earliest known estimates of groundwater withdrawals for each county within the TCAA were prepared in 1956. Highest withdrawal rates between 1956 and 1975 were recorded in the St. Johns county (Figure 1-6). This was due to the high density of irrigation wells in the Hastings area (Munch et al., 1979). In the year 2012, St.
Johns county still had the highest withdrawal rates among the three counties (Figure 1-7).

Florida’s water management districts develop water supply plans to ensure the sustainability of groundwater resources. These plans identify existing and projected use as well as cover a wide range of conservation-related issues in the region. The water supply assessment report for 2003 (SJRWMD, 2006) details total water use (surface and groundwater) by land use activity for the district in 1995, 2000 and projected for 2025 (Figure 1-8). What is apparent from projected demands for 1995 - 2025 is that, although water use for agricultural irrigation is expected to decrease by 11%, public water supply is expected to increase by 84% and 42% for domestic and other small public supplies respectively. The overall change (all categories) will be a net increase of 31% for the projected 30-year period. This projected net increase is even higher (42%) for a 1-in-10 years’ drought condition (Figure 1-8). These numbers indicate the increasing demand for water resources within this region of Florida. Out of the projected water use of 6,760,518.3 m$^3$ in 2025, only 1,319,745.96 m$^3$ is estimated from surface water use, the rest from groundwater sources (5,440,772.4 m$^3$).

**Salinity Issues in the Tri-County Agricultural Area**

Water salinity is the total concentration of all dissolved salts in water (USEPA, 2006). Various salts dissolve and contribute to the salinity of water, among them being sodium chloride. In seawater, major ions contributing to salinity include chloride, sodium, sulfate, calcium and magnesium. In freshwater these ions are also present but in smaller concentrations (USEPA, 2006). The Floridan aquifer is not potable at some locations and is also susceptible to salt water intrusion (SJRWMD, 2013). Fresh water
in the Floridan aquifer normally has chloride concentrations varying from place to place and can be as low as 4.6 mg/L and as high as 3,600 mg/L (Spechler, 1994).

In most areas underlain by the Floridan aquifer, there is a contiguous confining layer partitioning the upper and lower Floridan aquifers, and also at the bottom of the lower Floridan aquifer (USGS, 2016). Another water bearing zone called the Fernandina permeable zone is a high-permeability unit that underlies the lower Floridan aquifer in parts of southeastern Georgia and northeastern Florida (Spechler, 1994) (Figure 1-9). Water from the Fernandina permeable zone varies in quality from fresh to saline. Saline water intrusion into the lower and eventually into the upper Floridan aquifers is probably through semi-confining units that are thin, or are breached by joints, faults, or collapse features (Spechler, 1994). In addition to this, the layer separating the upper and lower Floridan aquifers has higher transmissivity rates. This allows movement of water and solutes between the otherwise partitioned aquifers (Leve, 1983; Spechler, 1994).

As a result of these discontinuities and increased transmissivity between confining layers, elevated salts in the Fernandina permeable zone and in the lower Floridan aquifer are able to migrate vertically into the upper Floridan aquifer where water is withdrawn for household and irrigation purposes. Chloride concentrations in the Fernandina permeable zone can be as high as 16,800 mg/L (Spechler, 1994). Increasing salt concentrations in the Floridan aquifer have been recorded at different locations, increasing the cost of treatment of portable water, rendering some wells non-useable, and reducing crop yield, among other problems (Figure 1-10).
Research indicates that the existence of faults in northeast Florida possibly allows water of higher salt concentration from the Fernandina permeable zone to seep into the Upper Floridan aquifer although most of these known faults appear to be to the north of the TCAA (Figure 1-11 to 1-13) (Leve, 1983; Spechler, 1994; Toth, 1990). This can result in regional saltwater intrusion under extensive groundwater withdrawals, as well as effects of individual well pumping resulting in a localized cone of depression and corresponding up-coning of saline water. Freshwater overlays saline water in the aquifer because saline water has a higher density compared with freshwater. High fresh water tables exert pressure on the underlying saline water. However, under extensive groundwater withdrawals, the fresh water table decreases, reducing the pressure that it exerts on the saline water, and saline water intrusion occurs. Similar conditions prevail in localized conditions when up-coning of saline water occurs around wells in the aquifer when water withdrawals form a cone of depression in the freshwater table. This results in saline water intrusion in the said well.

Potential salt water intrusion from the Fernandina permeable zone is of concern to agricultural and water supply stakeholders in the region. Increased salinity in irrigation water supply can affect yields of certain crops if conductivity measures above 1.7 dS m\(^{-1}\) (Fipps, 2003). It is worth noting that due to evaporative concentration of irrigation water salts, soil salinities can increase to significantly higher levels than irrigation water salinity (Fipps, 2003). During high rainfall periods, elevated salts in irrigation water are typically not a significant problem in the region due to dilution and leaching of soil salts. However, during lower rainfall periods or extended drought conditions as experienced in the TCAA during 2010 - 2012, soil salinity concentrations
can increase and negatively impact yields (personal communication with producers in TCAA).

In addition to reduced crop yields, irrigation water salinity can also affect soil structure and ultimately crop yields (Fernald & Purdum, 1998; Fipps, 2003). Maintenance or restoration costs for saline soils also negatively impact crop production.

**Research Rationale**

**Temporal Salinity Trends in the TCAA**

Due to increasing population in Florida, water demand is projected to increase by 492,103.5 m$^3$ (31%) by 2035, assuming no further decrease in per capita consumption, with an additional increase of 124,918.6 m$^3$ (6%) during a drought year (SJRWMD, 2013). This will possibly contribute to intrusion of saline groundwater from the Fernandina permeable zone into the lower Floridan aquifer and eventually, into the fresh Upper Floridan aquifer due to changes in potentiometric head. Typically, confining layers between aquifers limit the amount of vertical water movement between the layers, and saltwater intrusion is principally a result of horizontal saltwater intrusion. However, due to the presence of natural fractures in the Floridan aquifer system, as well as higher transmissivity rates between the lower and upper Floridan aquifers, there is vertical upwelling of saline water inland near the boundary between St. Johns and Flagler counties, and not just in surficial aquifers near the coast (Spechler, 1994). In agricultural systems, increased pumping of groundwater for irrigation purposes results in localized upconing of higher salinity water. Crop yields are reduced when thresholds for salt tolerance are exceeded. It would be interesting to know if long-term changes in groundwater salinity is consistent with water withdrawal projections, which would suggest salt water intrusion from the Fernandian aquifer into the upper Floridan aquifer.
Analysis of long-term data sets would also indicate potential time- or seasonal-controlled occurrences related to changes in groundwater salinity.

**Water Conservation in Crop Production**

Agricultural nutrient runoff and its impacts to the lower St. Johns River have resulted in the establishment of a Total Maximum Daily Load (TMDL) of nutrients, as well as increased implementation of Best Management Practices (BMPs) by growers under the Basin Management Action Plan (BMAP). One area of BMP implementation focuses on improved water management and water conservation to minimize runoff not associated with a rainfall event. By minimizing irrigation related runoff, nutrient loads are also expected to be reduced. Water conservation practices initially focused on nutrient management may also have implications for salinity by reducing the overall withdrawal of water from the upper Floridan aquifer and associated up-coning of more saline water from the lower Floridan aquifer. The Irrigation Drainage Tile (IDT) system lacks extensive research in the TCAA and so it would be interesting to evaluate how much water can be conserved compared with the conventional seepage irrigation system.

**Soil Salinity Comparison under IDT and Seepage Irrigation and Drainage Systems**

In the TCAA, potato is the major crop grown annually. Total acreage of farmland used for potato production in the TCAA is about 26,000, which is about 51.6% of the whole of the TCAA (Singleton, 1990). Potato production has been in existence for over 100 years. Crops like cabbage and Asian vegetables are also grown. Approximately 94% of all irrigated potatoes grown in Florida are grown in the TCAA.

Potatoes are moderately sensitive to salts and so the use of irrigation water salinity exceeding 3 dSm\(^{-1}\) is not recommended (Fernald, & Purdum, 1998). According
to Fipps (2003), there are potential yield reductions based on different irrigation and soil water ECs (EC\textsubscript{iw} and E\textsubscript{Ce}). At an EC\textsubscript{iw} of 1.1 dS/m, the potential yield reduction is 0%. Furthermore, there is a 10% yield reduction at EC\textsubscript{iw} of 1.7 dS/m, 25% at EC\textsubscript{iw} of 2.5 dS/m and 50% at an EC\textsubscript{iw} of 3.9 dS/m at 25\textdegree{}C. Compared with other crops, potatoes can tolerate a higher level of soil salinity (Fernald, & Purdum, 1998). However, in low rainfall and drought conditions, soil salt concentrations can build up rapidly and significantly reduce yield.

Low rainfall conditions in 2010-2012 within the TCAA raised concerns about irrigation water and soil water salinity concentrations when growers experienced different degrees of crop failures. They attributed it partially to increased soil salinities and so options were explored to help reduce or control soil salinity and improve crop yields. It would be interesting to evaluate how the alternative irrigation practice (IDT), compared to the traditional (SI), could possibly help alleviate this problem.

**Research Questions, Objectives, and Hypotheses**

In view of the above mentioned interests and or concerns, this research was initiated to potentially answer the following research questions (RQ) to help in the management of groundwater resources as well as soil salinity in the TCAA.

**RQ1:** What is the past and present extent of groundwater salinity in the TCAA? For this research question, the objective was to compare present (2013-2015) groundwater salinity in the TCAA with that of a groundwater quality survey conducted in the past (1975-1976) by the St. Johns River Water Management District (Munch et al., 1979). This RQ is referred to as the ‘long-term evaluation’ as it covers two sets of data about 40 years apart. It was hypothesized that groundwater salinity in the TCAA has not changed in the past 40 years.
**RQ2:** To what extent is irrigation water salinity a result of localized effects (up-coning during the pumping season) vs. short-term regional changes in groundwater salinity within the TCAA?

For RQ2, the objective was to evaluate temporal up-coning effects during the pumping season and short-term regional trends in groundwater salinity in the TCAA. This related to short-term observations over a three-year period (2013-2015). Two hypotheses were posited for RQ2.

**Hypothesis\textsubscript{2a}:** Localized up-coning effects during the pumping season significantly increase irrigation water salinity compared to non-pumping season concentrations.

**Hypothesis\textsubscript{2b}:** Short-term regional groundwater salinity did not change over the most recent three-year period.

**RQ3:** What effects will an alternative irrigation practice have on water use and soil salinity in the TCAA? The objective for RQ3 was to measure water use and soil salinity in fields with IDT and compare with that of conventional seepage irrigation. Similar to RQ2, two hypotheses were posited for RQ3.

**Hypothesis\textsubscript{3a}:** IDT practice will record lower water use than conventional seepage irrigation.

**Hypothesis\textsubscript{3b}:** Fields with IDT practice will have lower soil salinity compared with that of SI.
Figure 1-1. Map showing the extent of the Tri-County Agricultural Area, Northeast Florida (http://www.sjrwmd.com/agriculture/costsare.html)
Figure 1-2. Actual parcels of agricultural lands within the TCAA (SJRWMD, 2010)
Figure 1-3. Floridan aquifer system, thickness in feet (Fernald & Purdum, 1998)
Figure 1-4. Population projections for 2012 through 2035 (SJRWM, 2014)

Figure 1-5. Water demand projections by water use category (2010 and 2035) (SJRWM, 2014). * Note: English units used (1mgd = 0.0038 m$^3$/day)
<table>
<thead>
<tr>
<th></th>
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<th></th>
</tr>
</thead>
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<td>11,200</td>
<td>11,380</td>
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<tr>
<td>Flagler</td>
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<td>6,500</td>
<td>8,230</td>
<td>4,500</td>
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Figure 1-6. Historical ground water withdrawals for irrigated crops in Putnam, Flagler and St. Johns counties (Munch et al., 1979) * Note: English units used (1 mgd = 0.0038 m$^3$/day)
Figure 1-7. Total water use by county and category in SJRWMD in 2012 (SJRWMID, 2012). * Note: English units used (1mgd = 0.0038 m³/day)

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<tr>
<th>County</th>
<th>Freshwater Public Supply</th>
<th>Domestic Self-Supply</th>
<th>Commercial/Industrial Fresh Water</th>
<th>Agricultural Irrigation Self-Supply</th>
<th>Recreational Self-Supply</th>
<th>Thermoelectric Power Generation Self-Supply</th>
<th>Total Freshwater</th>
<th>Commercial/Industrial Saline Water</th>
<th>Reuse</th>
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<td>82.65</td>
<td>0.00</td>
<td>23.05</td>
<td>105.66</td>
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</table>
| Total          | 540.07                   | 64.72                | 84.91                            | 372.34                             | 60.33                   | 7.23                                        | 1,129.60        | 3.08                              | 151.47| 1,281.15      

Note: Water use is in million gallons per day (mgd). Estimated amounts are based on best available data as of Sept. 9, 2013. Source of domestic self-supply is assumed to be groundwater, and domestic self-supply is an estimate.
Table 1-8. Total water use for 1995, 2000 and 2025 by category of use in the St. Johns River Water Management District (SJRWMD, 2006). * Note: English units used (1mgd = 0.0038 m³/day)

<table>
<thead>
<tr>
<th></th>
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<th></th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Ground</td>
<td>Surface</td>
<td>Total</td>
<td>Ground</td>
<td>Surface</td>
<td>Total</td>
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<td>549.47</td>
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<td>Domestic and Other Public Supply</td>
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<td>71.09</td>
<td>64.50</td>
<td>0.00</td>
<td>64.50</td>
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<td>387.95</td>
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<td>601.69</td>
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<td>72.66</td>
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<td>133.68</td>
<td>90.56</td>
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<td>Thermolectric Power Generation</td>
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<td>10.86</td>
<td>18.91</td>
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<tr>
<td>Total</td>
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<td>318.28</td>
<td>1,363.85</td>
<td>1,175.80</td>
<td>310.47</td>
<td>1,486.27</td>
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</table>

All water use in million gallons per day

2025 public supply water use includes 1.7 mgd from an unspecified source and provider in Volusia County.
Figure 1-9. The Florida Aquifer system.
(http://pubs.usgs.gov/ha/ha730/ch_g/jpeg/G050.jpeg)
Figure 1-10. Trend analysis of Floridan aquifer chloride data (http://floridaswater.com/groundwaterreport/trendanalysis.html)
Figure 1-11. Salt water intrusion from the Fernandina permeable zone as a result of existent faults (Spechler, 1994)
Figure 1-12. Map showing the geologic structure and altitude of the top of the Floridan aquifer (Leve, 1983)
Figure 1-13. Major structural features in the TCAA region (Spechler, 1994)
CHAPTER 2
LONG AND SHORT-TERM GROUNDWATER SALINITY EVALUATION

Background

Previous Salinity Investigations in the TCAA

Groundwater investigation of the agricultural areas of St. Johns, Putnam, and Flagler counties (Figure 2-1 and 2-2) was conducted by SJRWMD after the board recognized the problem of saline water intrusion in the TCAA. Prior investigations in the area had indicated this problem, but no authorized institution was in place at the time to initiate measures to curtail the problem. The passage of the Water Resources Act of 1972 led to the establishment of the SJRWMD whose governing board considered the issue of saline water intrusion in the area worthy of intensive study (Munch et al., 1979). The investigation sought to understand the causes of groundwater saline contamination and to delineate those areas where it occurred.

The SJRWMD investigation was initiated in March 1975 and completed in September 1976 with the objectives of studying the interrelationships of water quality (chloride concentration), potentiometric levels, hydrogeology, well characteristics and groundwater withdrawals in those areas affected by the saline contamination. This data would also create the foundation for a hydrological data base which could be utilized in future computer modeling and permitting activities in the area (Munch et al., 1979). Groundwater samples were collected from wells, mostly irrigation wells, in March, July and September of 1975 and in May and September of 1976. The samples were analyzed for variables including EC and chloride content. The wells were located within three sub-study regions representing regions of high and low water use, and the periphery of the TCAA (Figure 2-3).
Current Salinity Investigations in the TCAA

Long-term groundwater salinity evaluation

Low rainfall conditions in the TCAA between 2010 and 2012 resulted in an expression of salinity issues on different farms in the area. Reduction in crop yields set growers and researchers alike thinking of potential impacts of increased irrigation water salinity on crop yields. A search for previous related investigations led to the 1975-76 (hereafter referred to as ‘past’) effort by the SJRWMD described in the background to the study. It was evident that a more recent assessment of groundwater salinity would be useful to compare present groundwater salinities with that of the past. This led to the current research being initiated in September, 2013 with the goal of comparing groundwater salinity trends in 2013 - 2015 (hereafter referred to as ‘present’) in the TCAA, with that of the past survey conducted in 1975-1976 (Munch et al., 1979). The objectives were to conduct a temporal and spatial comparison of groundwater salinity in the TCAA in the past with the present. It was hypothesized that groundwater salinity concentrations in the TCAA have not changed in the past 40 years.

Short-term groundwater salinity evaluation

In contrast to the evaluation of changes in groundwater salinity over the 40-year period, there was also an interest in evaluating changes in regional and localized groundwater salinity in the three-year sampling period (2013-2015). Irrigation of crops is seasonal and during low rainfall periods in the production cycle. This potentially creates localized changes in groundwater salinity. Results of this short-term study could suggest the regional effect(s) of rainfall on groundwater salinity, as well as localized effects of pumping groundwater for irrigation purposes.
It was hypothesized that groundwater salinity in the TCAA would change during the present sampling period (2013-2015) and localized up-coning effects during the pumping season would increase groundwater salinity compared with the non-pumping season.

**Methods**

**Long-Term Temporal Groundwater Salinity Evaluation**

**Selecting sampling wells**

In an effort to delineate salinity hot spots in SJRWMD, a survey was conducted by the water management district in 1975/76 (past), in which groundwater was sampled from 131 wells and tested for parameters like chloride concentrations and EC. A report of the findings was published in 1979 (Munch et al., 1979), and was the reference for the long-term groundwater salinity conducted in 2013-2015. Based on this report, measured EC of sampled groundwater in 1975/76 served as the baseline for comparison with the measured groundwater EC in 2013-2015.

Wells which were sampled in the past were targeted for resampling in the present for long-term groundwater salinity evaluation. To locate these wells, coordinates provided in Munch et al. (1979) were entered into an excel spreadsheet and imported into ArcMap 10.3.1 software. The coordinates were also displayed with google earth for better visualization (Figure 2-4). A total of 131 wells were targeted for resampling and included both household and commercial irrigation wells located on farms.

**Identifying property owners**

The survey report (Munch et al., 1979) was missing property owner information for the wells. However, consent was needed from the present owners before the wells could be sampled. Efforts were made to identify the current owners of all properties on
which wells were located. Some wells were on properties leased to current owners and others under the same management as in the past. To identify the current well owners, the ‘Florida parcel data statewide - 2012’ dataset was downloaded from the Florida Geographic Data Library (FGDL) and imported into ArcMap 10.3.1. This dataset was published by Florida Department of Revenue (FDR) and included parcel owner information. The shapefile was then intersected with the shapefile of wells sampled in the past using the ‘intersect’ geoprocessing tool in ArcGIS 10.3.1. The attribute table for the intersecting shapefile was then explored for parcel owner information for the wells. Other information such as current land use was also derived from this dataset. It should be noted that results for 17 out of 131 wells were “unknown” for land parcel ownership.

**Contacting property owners**

Property ownership information provided by the FDR dataset included names and addresses of respective parcel owners. Property owners were initially contacted by mail. Letters soliciting for voluntary participation in the research were sent to all the addresses identified from the parcel dataset. Multiple wells were located on some parcels and in such instances, only one letter was sent out to owners of such parcels. In all, 101 letters were sent out to identified property owners, out of which only two responses were received, agreeing to participate in the research. The owners were to express their interest by contacting us via email or phone call. Due to the poor response for this mail-out, a second set of letters were sent out about two months later. This generated no response at all. Six out of 101 letters were returned as “undeliverable”. It was therefore decided that making phone calls to the owners to explain the research objectives would be the best and final resort.
Phone numbers of property owners were identified using "people smart" website. All owners whose phone numbers were retrieved were then contacted. Out of the contacts reached, 25 owners agreed to participate in the research. Some of these owners had multiple wells on their properties. Some phone numbers retrieved were not in service, while others were in service but no one ever picked the calls or returned missed calls. Some owners were also not interested or mentioned the wells were no longer existent or in use.

Well identification trips were made to the 25 properties, and using hand-held GPS, well coordinates were matched with that recorded in Munch et al. (1979). From the 25 properties visited, 16 wells were confidently matched with coordinates of wells sampled in the past (Figure 2-5). However, one out of the 16 wells could be sampled just one time in the current study and another was sampled just once in the past study. Therefore, 14 wells were used for long-term temporal groundwater salinity statistical evaluation.

In addition to the 16 wells matching those sampled in the past, growers were solicited to join a voluntary program which would form a network of monitoring wells to provide long-term data on irrigation water salinity. This network comprised of 118 new wells and the 16 matched wells from the 1975 survey (Figure 2-6).

**Collecting water samples**

Wells were sampled at least quarterly from September, 2013 until June, 2015. Based on logistics, some of the wells were also sampled more frequently. All the wells were however sampled to mimic the 1975/76 sampling efforts (sampling months) as much as possible. Some wells were free-flowing or being pumped at the time of
sampling while others were not free-flowing and power to the pumps were shut down. This made sampling impossible at those times. Again, some wells needed to be primed when the groundwater table was very low. In such situations, sampling was impossible as resources were not available to prime the wells, and consent from owners was needed before priming.

To sample wells, connecting valves and spigots were opened and water was allowed to run for a maximum of five minutes. Wide-mouth field sample bottles (125 ml) were then rinsed three times with well water and filled. The bottles were capped and stored in coolers without ice for EC analysis in the laboratory.

**Electrical conductivity analysis**

All water samples were analyzed in the Wetland Biogeochemistry Laboratory (WBL) on campus at the University of Florida, Soil and Water Sciences Department. EC was reported in decisiemens per meter (dS/m). The Accumet AR50 pH/conductivity meter with probes was used to analyze the water samples. The probe was calibrated with either potassium chloride (200 µS/m at 25°C) or sodium chloride (1,413 µS/m at 25°C) conductivity standards.

**Long-Term Spatial Groundwater Salinity Evaluation**

Methods used in the selection of sampling wells, identification of property owners, contacting property owners, and collection of water samples were the same for both spatial and temporal groundwater salinity evaluation. However, additional methods used in the spatial evaluation are outlined below.
Spatial interpolation of groundwater salinity

All well EC measurements from both past and present surveys were entered into excel spreadsheets, imported into, and mapped with ArcGIS 10.3.1. Using “geostatistical analyst” tool, ordinary kriging method of interpolation was used to generate EC values in other parts of the study area where no wells were existent for sampling, or if otherwise, were not sampled in either of the surveys (Figures 2-7 and 2-8). After interpolating the EC values, the kriging maps were exported as raster maps to conduct further spatial analysis.

Validation of interpolated groundwater salinity

In order to validate salinity trends predicted by ordinary kriging interpolation method, means of measured EC values were compared with means of predicted EC values using the two-sample t-test in JMP Pro 12 software (SAS Institute, 2015). Predicted EC values from the raster map were extracted using ArcGIS 10.3.1. spatial analyst tool ‘extract values to points’ was used in the extraction process. The ‘input point feature’ was the past wells’ shapefile and the ‘input raster ‘was the past wells’ raster map. All parameters were left at default values. The output point feature was past wells’ shapefile with the predicted EC from the raster map appended as a column in the attribute table. The values were copied into an excel spreadsheet, imported into JMP Pro 12 software, and statistically analyzed to test the difference between the means of the measured past and predicted past EC values. There was no significant difference (p = 0.08) between measured and predicted EC for the past wells (Figure 2-9) suggesting that measured EC in the past was well predicted by ordinary kriging interpolation method. Mean measured EC was 2.04 dS/m and predicted was 1.96 dS/m. In the case
of present wells, predicted EC was significantly lower (p = 0.01) than the observed (Figure 2-10), suggesting that ordinary kriging interpolation method underestimated the predicted EC, compared with the measure EC. Mean measured EC was 2.31 dS/m and predicted was 2.25 dS/m.

**Virtual sampling of wells in the past and present survey periods**

In an effort to obtain EC values of all wells in the past and present survey periods, all past wells were virtually sampled in the present and vice versa, using spatial analyst tool ‘extract values to points’ (Figure 2-11). The respective measured point feature shapefile (past/present) was used as ‘input point feature’ and the opposite raster map (from kriging interpolation) was the ‘input raster’. All parameters were left at default values. The output point feature was either the present or past wells’ shapefile with the predicted EC from the raster map appended as a column in the attribute table. The values were copied into excel spreadsheets, imported into JMP Pro 12 software, and statistically analyzed to test the difference between the means of the measured past and predicted present EC and vice versa.

**Short-Term Temporal Groundwater Salinity Evaluation**

**Selecting sampling wells**

A total of 134 wells were sampled in 2013-2015 and used for the short-term groundwater salinity evaluation. These included 16 wells which were also identified to have been sampled in 1975/76.

**Solicitation for participation**

Growers were contacted in person at their farms and during grower meetings in order to explain the goals and objectives of the study to them. The University of
Florida/Institute of Food and Agricultural Sciences (UF/IFAS) Horticultural and Agricultural extension agents for Putnam, Flagler, and St. Johns counties offered their support in contacting the growers. They had an idea of which growers would possibly agree to participate based on their frequent interactions with them. This made recruiting volunteers faster and easier. The growers were a bit skeptical about the intended use of results from the study; research only versus regulatory. The extension agents were trusted and motivated the growers to participate in the study. Advertisement was also made in the Tri-County commercial agriculture newsletter soliciting for participation from all growers in the area. In all, 17 growers agreed to participate in the study, resulting in 118 wells being sampled at different times during the study period. Farms in the network had multiple wells ranging from four to 21 wells.

**Collecting water samples**

Water samples were first collected in September, 2013 and growers subsequently agreed to send monthly samples to a designated site. These samples were analyzed in WBL at University of Florida (UF) Soil and Water Sciences Department for EC. Growers were provided with a protocol for sampling and well water sampling ended in June, 2015.

**Short-Term Spatial Groundwater Salinity Evaluation**

**Spatial interpolation of average annual change in groundwater EC (2013-2015)**

Ordinary kriging interpolation was used to generate a spatial map which predicted the average annual change in groundwater EC in the study area based on the observed changes in the 134 wells monitored between 2013 and 2015. The interpolation method used was as described in the long-term spatial evaluation section.

Groundwater samples collected from March to June and mid-October to mid-November in 2013-2015 were designated as pumping season samples, whiles those collected from mid-November to end of February, and July to mid-October were designated as non-pumping season samples. This designation was based on recorded active irrigation events due to low rainfall conditions and halted irrigation activities due to high rainfall conditions.

Statistical Analysis

JMP Pro 12 software was used for all the statistical analysis in this chapter. The paired t-test was used to determine whether groundwater salinity in the past differed from that in the present. The paired t-test was used to test the difference between groundwater salinity of measured and virtually sampled wells in the past and present survey periods. Bivariate analysis was used to determine the trends in groundwater salinity from 2013 until 2015. EC values of wells with at least seven samples were used in the analysis. Those wells with fewer than seven samples were excluded from the analysis. The two-sample t-test was used to test the differences in groundwater salinity during the pumping and non-pumping seasons of the study period.

Results

Long-Term Temporal Groundwater Salinity Evaluation

Sixteen out of 131 wells sampled in the past were located and re-sampled in the present (Figure 2-5). However, 14 wells had enough samples for individual well statistical comparison. Overall results showed that there was an average increase of 0.2 ± 0.55 dS/m in groundwater EC over the 40-year period in the 14 wells. The 14 wells were still not sufficient to statistically confirm this average increase, resulting in a non-
significant increase ($P = 0.99$) for matched pairs analysis using JMP software (Figure 2-12). With regards to individual wells, results indicated that groundwater salinity in 10 out of 14 wells increased, while 4 out of 14 wells decreased in the 40-year period (Table 2-1, Figure 2-13).

**Long-Term Spatial Groundwater Salinity Evaluation**

Spatial analysis involving virtually sampled wells indicated an overall increase in the present groundwater salinity compared with the past, consistent with the temporal evaluation results from the 14 wells. For present wells virtually sampled in the past, the present was significantly higher ($2.31 \pm 0.98$ dS/m) ($p<0.0001$) than the virtual past ($2.13 \pm 0.53$ dS/m) (Table 2-2 and Figure 2-14). Likewise, for the past wells virtually sampled in the present, the virtual present was significantly higher ($2.17 \pm 0.49$ dS/m), ($p = 0.048$) than the past ($2.05 \pm 1.13$ dS/m) (Table 2-3 and Figure 2-15).

**Short-Term Groundwater Salinity Evaluation**

Overall, a decreasing trend in groundwater salinity was observed in 90% percent of the wells sampled between 2013 and 2015 (Figure 2-16). The average annual change in EC measured was between -$1.34$ dS/m and $0.86$ dS/m. Spatial interpolation of the average annual change in groundwater EC also indicated a generally decreasing trend with pockets of increasing groundwater salinity (Figure 2-17).

**Seasonal Groundwater Salinity Evaluation**

Overall, this study did not find evidence of a statistically significant difference between groundwater salinity measured during the pumping ($2.43 \pm 0.93$ dS/m) and non-pumping ($2.48 \pm 0.89$ dS/m) seasons ($p = 0.66$) (Figure 2-18). The mean difference is however negative, indicating that the pumping season overall had lower groundwater
salinity compared with the non-pumping season. This is evidenced in individual irrigation wells where groundwater salinity generally decreased during the pumping seasons throughout the sampling period (Figure 2-19). There were however few exceptions to this. Wells on Farm 7 for instance (Figure 2-20) overall showed significant increase in groundwater salinity in the pumping season than in the non-pumping season ($p = 0.02$). Mean EC for wells on Farm 7 was $3.85 \pm 1.28$ dS/m during the pumping season and $2.31 \pm 0.36$ dS/m during the non-pumping season.

**Discussion**

**Long-Term Temporal Groundwater Salinity Evaluation**

Ten out of 14 wells evaluated for long-term groundwater salinity trends showed an increase in groundwater salinity in the present, compared with the past. It is however worth noting that there were not enough wells sampled to generate sufficient statistical power to detect the difference between the past and present, and also there was so much variability in salinity among the wells. The overall increasing trend could possibly be attributed to drought conditions in the TCAA prior to the sampling period. Low rainfall conditions from 2010 to 2012 preceded the sampling period (2013 - 2015). Loss of freshwater potentiometric head could have facilitated saline water intrusion, resulting in the observed increased groundwater salinity. It can also be attributed to groundwater salinity dynamics which might be influenced by rainfall and water withdrawal rates. Another possible reason that could be assigned to the observed increasing trend could be that this study coincided with a period in which groundwater salinity was naturally trending up and would eventually trend down as we found in the short-term evaluation (Figure 2-21).
Long-Term Spatial Groundwater Salinity Evaluation

Spatially interpolated groundwater salinity in the TCAA showed an overall increase in the present compared with the past. This can be attributed to reasons as assigned to the temporal groundwater salinity evaluation results in the previous section. There were pockets of very high and low salinity conditions represented by the blue and red colors in the kriging maps. Some of these pockets probably give an indication of geologic conditions which might be prevalent in the area, or intense agricultural activity leading to very high withdrawal rates and therefore localized saline water intrusion. The potato growing season in the TCAA coincides with low rainfall periods, necessitating frequent irrigation schedules. Although few growers grow different crops all year long, most growers grow potatoes whose growing season begins late in September until early May. This season overlaps with low rainfall conditions in northeast Florida.

Short-Term Temporal and Spatial Groundwater Salinity Evaluation

The decreasing trend in groundwater salinity observed between 2013 and 2015 could be attributed to typical rainfall conditions in the area. The years 2010-2012 received very low rainfall below the normal average of about 1320.8 mm per annum in the TCAA. However, rainfall in 2013-2015 was about the typical average. Drought conditions in 2010-2012 could potentially have reduced the potentiometric head of freshwater which pushes the saltwater back in the aquifer. When rainfall conditions normalized in 2013, the freshwater head could have increased, thereby displacing the saltwater and reducing groundwater salinity measured in the following years. This short-term evaluation gives an indication that rainfall conditions potentially influence groundwater salinity in the TCAA.
Seasonal Groundwater Salinity Evaluation

The study did not find evidence of an overall statistically significant difference between groundwater salinity measured during the pumping and non-pumping seasons. This could have been due to the general decreasing trend observed from the short-term regional groundwater evaluation. Individual wells however experienced variations in groundwater salinity changes during the two seasons. Farm 7 (Figure 2-20) wells showed significantly higher EC in the pumping season compared with non-pumping season. This could be due to localized geological conditions at the farm, or irrigation well depth. In this study, well depth information was not easily accessible. This plays a role in groundwater salinity as deeper wells could tap into saline groundwater in the lower Floridan Aquifer. Therefore, variations in well EC could be attributed to individual well depths.

Conclusions

Long-Term Groundwater Salinity Evaluation

Temporal and spatial groundwater salinity trends over a 40-year period (1975-2015) were evaluated for the TCAA. It was hypothesized that groundwater salinity in the TCAA has not changed in 40 years. Out of 131 wells sampled in 1975/76, 14 wells were confidently identified and sampled in 2013/15. Analysis of EC indicated that overall, average groundwater salinity generally increased by about 0.2 ± 0.55 dS/m. Ten out of the 14 wells recorded increasing groundwater salinity whiles the rest recorded decreasing groundwater salinity. It should be noted that groundwater samples were taken in two snap-shots of time and could be that groundwater is generally increasing in salinity or there are some dynamics in groundwater salinity which can better be interpreted with continuous long-term data. This notwithstanding, this finding can help
inform the impacts of regional and localized water withdrawals on groundwater salinity dynamics.

**Short-Term Groundwater Salinity Evaluation**

Similar to the long-term groundwater salinity evaluation, temporal groundwater salinity trends over three-year period (2013 - 2015) were evaluated for the TCAA. It was hypothesized that short-term regional groundwater salinity did not change in those years. In contrast to the long-term observed trend, short-term analysis of groundwater salinity from 134 wells revealed a decreasing trend of about 0.19 ± 0.31 dS/m per year over the three-year period (2013 - 2015).

It should be noted that rainfall conditions were about normal starting (1,320.8 mm) in 2013, and compared with the low rainfall conditions (1,016 mm) from 2010 - 2012. This could have increased the freshwater potentiometric head, displacing the saline water further in the aquifer. The long and short-term groundwater studies provided insight into groundwater salinity dynamics over long and short periods of time, and under different rainfall regimes. This sheds light on the potential contribution of rainfall to groundwater salinity dynamics but also confirms the need for continuous long-term data sets to better understand these dynamics.

**Seasonal Groundwater Salinity Evaluation**

A second objective for short-term (2013 - 2015) groundwater evaluation was to evaluate seasonal variations in groundwater salinity. It was hypothesized that localized up-coning effects during the pumping season significantly increases irrigation water salinity compared to the non-pumping season. The study however found no significant
difference between irrigation well water salinity during pumping and non-pumping seasons.

Table 2-1. Long-term groundwater salinity EC of 14 wells analyzed in the past (1975/76) versus in the present (2013/15)

<table>
<thead>
<tr>
<th>Well ID</th>
<th>Past EC (dS/m) ± 1SD</th>
<th>Present EC (dS/m) ± 1SD</th>
<th>P-value</th>
<th>Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>EL 388</td>
<td>1.44 ± 0.42</td>
<td>1.89 ± 0.34</td>
<td>0.13</td>
<td>Non-Significant</td>
</tr>
<tr>
<td>HA 169</td>
<td>1.49 ± 0.20</td>
<td>0.75 ± 0.05</td>
<td>0.004</td>
<td>Significant</td>
</tr>
<tr>
<td>HA 99</td>
<td>2.38 ± 0.11</td>
<td>2.78 ± 0.28</td>
<td>0.008</td>
<td>Significant</td>
</tr>
<tr>
<td>MI 111</td>
<td>1.94 ± 0.26</td>
<td>2.73 ± 0.22</td>
<td>0.001</td>
<td>Significant</td>
</tr>
<tr>
<td>MI 215</td>
<td>2.09 ± 0.10</td>
<td>1.97 ± 0.20</td>
<td>0.35</td>
<td>Non-Significant</td>
</tr>
<tr>
<td>OR 333</td>
<td>2.60 ± 0.62</td>
<td>3.25 ± 0.42</td>
<td>0.02</td>
<td>Significant</td>
</tr>
<tr>
<td>OR 58</td>
<td>1.96 ± 0.26</td>
<td>2.50 ± 0.19</td>
<td>0.02</td>
<td>Significant</td>
</tr>
<tr>
<td>OR 68</td>
<td>1.56 ± 0.23</td>
<td>1.85 ± 0.11</td>
<td>0.06</td>
<td>Significant</td>
</tr>
<tr>
<td>OR 69</td>
<td>1.77 ± 0.15</td>
<td>2.03 ± 0.27</td>
<td>0.15</td>
<td>Non-Significant</td>
</tr>
<tr>
<td>PE 168</td>
<td>2.05 ± 0.13</td>
<td>1.75 ± 0.14</td>
<td>0.02</td>
<td>Significant</td>
</tr>
<tr>
<td>PE 284</td>
<td>0.96 ± 0.12</td>
<td>1.02 ± 0.06</td>
<td>0.47</td>
<td>Non-Significant</td>
</tr>
<tr>
<td>PE 401</td>
<td>0.80 ± 0.004</td>
<td>0.82 ± 0.04</td>
<td>0.34</td>
<td>Non-Significant</td>
</tr>
<tr>
<td>PE 422</td>
<td>0.73 ± 0.21</td>
<td>0.83 ± 0.04</td>
<td>0.36</td>
<td>Non-Significant</td>
</tr>
<tr>
<td>PE 428</td>
<td>1.36 ± 0.20</td>
<td>0.88 ± 0.03</td>
<td>0.02</td>
<td>Significant</td>
</tr>
</tbody>
</table>

Table 2-2. Average groundwater salinity in the present (2013/15) compared to virtually sampled well salinity in past (1975/76)

<table>
<thead>
<tr>
<th>Present average EC (dS/m)</th>
<th>Virtual past average EC (dS/m)</th>
<th>P-value @ α = 0.05</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.31 ± 0.98</td>
<td>2.13 ± 0.53</td>
<td>&lt;.0001</td>
</tr>
</tbody>
</table>

Table 2-3. Average groundwater salinity in the past (1975/76) compared to virtually sampled salinity in the present (2013/15)

<table>
<thead>
<tr>
<th>Past average EC (dS/m)</th>
<th>Virtual present average EC (dS/m)</th>
<th>P-value @ α = 0.05</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.05 ± 1.13</td>
<td>2.17 ± 0.49</td>
<td>0.048</td>
</tr>
</tbody>
</table>
Figure 2-1. Research study area (Putnam, Flagler and St. Johns counties).
Figure 2-2. The extent of the Tri-County Agricultural Area within the three counties. (http://www.sjrwmd.com/agriculture/costshare.html)
Figure 2-3. Generalized locations of observation wells in the 1975-1976 study (Munch et al., 1979).
Figure 2-4. Wells sampled in 1975/76 by SJRWMD (Munch et al., 1979).
Figure 2-5. Wells sampled in 1975/76 and also identified and sampled in 2013/15
Figure 2-6. All wells sampled in 2013-2015 study.
Figure 2-7. Map of interpolated EC for the past (1975/76) sampling period.
Figure 2-8. Map of interpolated EC for the present (2013/15) sampling period.
Figure 2-9. Results of matched pairs analysis: validation of ordinary kriging interpolation of past wells’ EC. Red line indicates no difference between observed and predicted values.
Figure 2-10. Results of matched pairs analysis: validation of ordinary kriging interpolation of present wells’ EC. Red line indicates no difference between observed and predicted values.
Figure 2-11. Schematic diagram of virtual sampling of past (1975/76) wells in the present (2013/15) and vice versa. Oval shape represents present sampling period and triangle represents past sampling period. Blue colored dots represent wells sampled in the present and brown dots represents wells sampled in the present.
Figure 2-12. Matched Pairs (Difference plot): Average present EC (dS/m) - Average past EC (dS/m). Mean difference (solid red line) and 95% confidence interval above and below (dashed red lines). Means not significantly different at Alpha 0.05 level (P = 0.99).
Figure 2-13. Average measured EC in the past (1975/76) versus present (2013/15).
Figure 2-14. Results of matched pairs analysis: Difference between present wells’ EC and virtually sampled past EC. Red line indicates no difference between present and virtual past values.
Figure 2-15. Results of matched pairs analysis: Difference between virtual present wells’ EC and past sampled past EC. Red line indicates no difference between virtual present and past values.
Figure 2-16. Average annual change in irrigation well EC from 2013-2015.
Figure 2-17. Map of interpolated annual change in groundwater EC from 2013-2015.
*NP = Non-pumping, PP = Pumping

Figure 2-18. One way Analysis (t-test) of average well EC during the pumping and non-pumping seasons.
*NP = Non-pumping, PP = Pumping

Figure 2-19. Change in average well EC between pumping and non-pumping seasons from 2013-2015.
Figure 2-20. Irrigation water salinity during pumping and non-pumping season
Figure 2-21. Hypothetical groundwater dynamics and observed long- and short-term groundwater salinity trends.
CHAPTER 3
EVALUATING WATER CONSERVATION POTENTIAL AND SOIL SALINITY IN SEEPAGE IRRIGATION AND IRRIGATION DRAINAGE TILE FIELDS

Background

Water Conservation in Agricultural Irrigation Practices

In a world of increasing demand for food and water, their security remains a critical issue especially at a time when the world’s water resources are threatened by climate change. Only 3% of the world’s water is fresh, most of which is locked up in ice caps and glaciers. Intensive agricultural production, which aims to ensure food security requires intensive irrigation of crops in many parts of the world. In semi-arid and arid regions for instance, irrigation is often the only way to grow a crop. Alternative irrigation practices are constantly being investigated to minimize the amount of water used for irrigation purposes in crop production. Research being conducted worldwide attempts to identify more efficient irrigation systems, improved crop varieties with less water demand, effective irrigation timing, among others. Irrigation system efficiency plays a major role in water conservation in the agricultural sector.

Seepage irrigation is used extensively in Florida (Figure 3-1). In this system, water furrows are created between rows where crops are planted, and water is pumped into the furrows, which seep laterally and vertically into the soil to wet the field and irrigate crops in the field. This type of irrigation is relatively inexpensive but can uses significantly more water than the irrigated crops demand, thereby promoting high evaporative and runoff losses. Water conservation under such systems is poor, given the amount of excess water used.
One type of irrigation system whose water use efficiency (WUE) has not been researched as extensively as other practices is Irrigation Drainage Tile (IDT) (Figure 3-2). IDT systems are installed subsurface and are not visible in the fields, apart from control structures at the edge of the fields. Corrugated, perforated polyvinyl chloride (PVC) pipes are laid in dug-out trenches (about 90-100 cm) below the ground to create an irrigation and drainage network of pipes in the field. The pipes drain into drainage trenches at the outflow ends of the fields. To use the IDT for irrigation purposes, pumps are turned on and water is let into fields through the perforated pipes. Alternatively, in order to drain the fields of excess water due to rainfall for instance, water drains through the same pipes. Control structures are installed at the edges of the fields to allow regulation of discharge. Tile drainage use dates back to the Roman era, evolving into the use of modern corrugated PVC pipes used to drain fields of excess rain or irrigation water. Research indicates that drained fields provide the advantage of improved yields (Ng et al., 2002; Ritzema et al., 2008) as crops tend to be exposed to optimum root zone water content and good aerobic conditions. In addition to this, diseases associated with water stagnation are avoided and farm mechanization is improved in drier fields. Improved crop yields are attained under these optimal conditions. Modern tile drainage pipes can be perforated for the added benefit of sub-surface irrigation. Control structures designed and installed with tile drainage systems regulate the drainage of excess water from fields. In the United States, several agricultural farms have employed tile drainage as well as IDT systems at different scales. In Florida, Minnesota, and North Dakota, there is documented efforts to educate the public about how these systems work, as well as their benefits. According to Scherer et al. (2015) tile drainage
installation in the Red River Valley basin as well as other parts of North Dakota accelerated in the past 19 years due to increased rainfall, seasonally high water tables, as well as soil salinity in the region, which is related to water table behavior and soil moisture.

Similar to other alternative irrigation systems, IDT systems tend to be more efficient in terms of water use, compared with seepage irrigation. This is because IDT systems are installed subsurface and irrigate the plant root zone by raising the water table from below. Excess water use is reduced in such systems, compared with seepage irrigation systems. This is supported by Smastrala et al. (2001) where their study showed that the IDT system raised field water table quickly and more uniformly than the seepage irrigation system.

**Salinity in Crop Production**

Salinity is the amount of soluble salts present in the soil (soil salinity) or water (water salinity), usually measured as EC in decisiemens per meter (dS/m) (Rhoades et al., 1999). It can also be measured as total dissolved solids (TDS) in milligram of salts per liter of water (mg/L) (Fipps, 2003). High EC values correspond to high salinity when relatively large amounts of soluble salts present in a solution transmit greater electrical currents.

Salinity in crop production is an issue of concern because crop yield is highly dependent on the amount of salts a plant is exposed to at different growth stages. Vast areas of the world have and are still encountering problems with soil salinity at different intensities (Qureshi et al., 2008). In the Red River Valley alone, soil salinity accounts for about $50 million to $90 million of lost revenue to the agricultural sector (Scherer et al.,
They mention that the problem encompasses about 1.5 million acres in the region. In the arid and semi-arid regions of India, it is estimated that nearly 8.4 million ha of land is affected by soil salinity and alkalinity (Ritzema et al., 2007). Again in the Indus basin of Pakistan, it is reported that about 6.3 million ha are affected by different types and levels of salinity (Qureshi et al., 2008). These and several unmentioned examples indicate the extent of salinity problems worldwide. The situation might worsen in most parts of the world with climate change which is imminent.

**Sources of Soil Salinity**

Salt affected soils are common in Australia, Africa, Latin America, as well as the Mid-East (Abrol et al., 1988; Rengasamy, 2006). They are also predominant in certain parts of the USA (Bassil & Kaffka, 2001; Cihacek et al., 2012; Eliass & Stephen, 2001; He et al., 2015; Scherer et al., 2015). Soluble salts in soils originate from the weathering of primary minerals in rocks and parent materials in most cases (Brady & Weil, 2002). However, regions with precipitation-to-evaporation ratios of 0.75 or less are also typical of salt-affected soils (Brady & Weil, 2002). In most cases, salts are transported as ions dissolved in water from higher to lower elevation or flat areas, and from wetter to drier zones (Miller et al., 1981). Saline seeps for instance are low lying areas where saline groundwater emerges (Brady & Weil, 2002).

Human activity also contributes soluble salts to soils through crop management practices. This includes crop fertilization and the use of poor quality irrigation water. Soil types and local climatic conditions may intensify or reduce the effects of these factors. A lot of irrigation is needed to support intensive crop production. Nonetheless, irrigation water quality directly contributes to soil salinity by either increasing or decreasing the
amount of soluble salts in the soil. Good water quality, having a lower salinity than the soil, will ultimately reduce soil salinity if enough water is applied and salts are leached down the soil profile. Conversely, poor water quality with higher salinity than the soil will potentially increase soil salinity by depositing more salts despite any leaching effects. Soil salinity will peak in relation to irrigation water quality.

In some situations, salts are not leached down the soil profile due to insufficient irrigation, high water tables, low rainfall conditions, droughts, and impermeable subsoil layers. This significantly contributes to soil salinity (Gill & Terry, 2016; He et al., 2015). Also, consistent high water tables promote high evaporation rates which leave salts concentrated in the field. Fertilizer type and amount used directly contributes to soil salinity, especially in poorly drained soils.

Types of salts commonly found in irrigation water include sodium chloride (NaCl), sodium sulfate (NaSO₄), calcium chloride (CaCl), calcium sulfate (CaSO₄), magnesium sulfate (MgSO₄), and sodium bicarbonate (NaHCO₃) (Fipps, 2003; Grattan, 2002). These salts dissociate into cations and anions when in solution. Potassium ion (K⁺), carbonate (CO₃²⁻), and nitrate (NO₃⁻) also exist as constituents of irrigation water but in relatively lower quantities (Grattan, 2002).

**Effects of Salts on Plants**

Plants can roughly be categorized into halophytes (salinity tolerant) and glycophytes (salinity intolerant), with the majority of major crop species falling into the latter category (Gupta & Huang, 2014). It is worth noting that salt tolerant thresholds in halophytic plants also vary.
Soil salinity affects crops directly or indirectly resulting in the disturbance of the crop’s physiological and metabolic processes. Effects are at the cellular, tissue, and whole plant levels (Gupta & Huang, 2014). The intensity of the effects depends on stress duration and severity, growth stage of plant, its rooting habits, physiological constitution, as well as other environmental conditions like light, temperature, humidity and air pollution (Ayers & Westcot, 1985; Brady & Weil, 2002; Gupta & Huang, 2014; Shannon & Grieve, 1999). For example, generally crops grown in cooler climates or during the cooler times of the year will be more salt tolerant than during warmer climates (Ayers & Westcot, 1985). An old Alfafa crop is known to be more tolerant to salt-affected soils than young ones, and legumes which are deep-rooted show a greater resistance to such salt-affected soils than shallow-rooted legumes (Brady & Weil, 2002).

According to Gupta and Huang (2014), plant growth is suppressed with an increase in soil salinity in the form of osmotic stress, followed by ionic toxicity. Other effects of salinity stress on plants include nutrient deficiencies associated with high soil pH (Brady & Weil, 2002), delayed or advanced maturity depending on species, decreased root length and mass, and reduced germination rates and percentages (Shannon & Grieve, 1999). With an increase in the proportion of exchangeable Na⁺ in the soil solution, sodium carbonate forms, increasing the pH of the soil (Levy & Veilleux, 2007). This alkaline condition reduces the availability of nutrients such as iron, phosphate, zinc and manganese to the plants.

**Osmotic stress effect**

Plant roots absorb water and nutrients from the soil and transport them to the shoot and leaves for photosynthesis. There exists a gradient (potential) between the soil
solution and the plant cell solution which allows this transport (Brady & Weil, 2002). Soil water moves from an area with a higher potential (less negative) to an area with a lower potential (more negative). Under normal conditions, the plant root cells have a lower osmotic potential than the soil solution, allowing water (and nutrients) from the soil to move towards and into the plant roots. As soils become more concentrated with soluble salts, the soil solution potential becomes more negative as water molecules are attracted to more soluble salts. More water in the soil is retained at the permanent wilting coefficient than in a normal soil, making it more difficult for plant roots to remove the water (Brady & Weil, 2002). In addition to this, plants also expend more energy making osmotic adjustments within their cells, such as accumulating organic and inorganic solutes to lower the osmotic potential to counteract that of the soil solution outside the cells (Brady & Weil, 2002). The osmotic potential in soils with high salinity can be very low to the extent that young plant cells are plasmolyzed as water moves from the cells into the soil with a lower osmotic potential. Gupta and Huang (2014) assert that osmotic stress in the initial stage of salinity stress causes various physiological changes such as interruption of membranes, nutrient imbalance, and the impairment in the plant’s ability to detoxify reactive oxygen species (ROS), among others.

**Specific ion effect**

Plant response to salinity depends on salt type and plant sensitivity to the ions. According to Brady and Weil (2002), certain ions including sodium (Na\(^+\)), chloride (Cl\(^-\)), and bicarbonate (HCO\(_3\)\(^-\)) are quite toxic to many plants. However, different plant species tolerate these ions at different thresholds. Saline-sodic or sodic soils have high
levels of sodium ions (Na\(^+\)). Sodium ions compete with potassium ions (K\(^+\)) which is an essential nutrient for plant growth (Brady & Weil, 2002; Gupta & Huang, 2014). Both sodium and potassium ions (Na\(^+\) and K\(^+\)) share the same transport mechanism and so under salinity stress, Na\(^+\) out-competes K\(^+\) for the transporter, inhibiting the uptake of K\(^+\) by the plant and causing ion imbalance in the plant cells (Gupta & Huang, 2014). This results in plant physiological disorders.

**Other physiological effects**

Salinity-induced Reactive Oxygen Species (ROS) formation can lead to oxidative damages in various cellular components such as proteins, lipids, and DNA, interrupting vital cellular plant functions (Gupta & Huang, 2014). Amino acids such as cysteine, arginine, and methionine, which constitute about 55% of total free amino acids also decrease when exposed to salinity stress, reducing plant growth (Gupta & Huang, 2014).

**Soil structure and salinity effects**

Under sodic conditions, physical properties of the soil deteriorate through dispersion or breakdown of soil structure. This results in oxygen deficit in soils (Brady & Weil, 2002). Crops grown in such soils are therefore deprived of enough oxygen for growth due to limited air movement in such soils. Infiltration and percolation rates of water in such soils are also very low, resulting in poor plant and soil water relations (Brady & Weil, 2002).

**Effects of salinity on potato**

Ayers and Westcot (1985) suggest potential crop yield reductions of either 0%, 10%, 25% or 50% due to effects of increasing soil or irrigation water salinity (ECe or
EC\text{iw}). They propose that potato and corn have a yield potential of 100% at 1.7dS/m, 90% at 2.5dS/m, 75% at 3.8dS/m, and 50% at 5.9dS/m, with a maximum tolerable EC\text{e} of 10dS/m. In the case of EC\text{iw}, potato has a yield potential of 100% at 1.1dS/m, 90% at 1.7dS/m, 75% at 2.5dS/m, and 50% at 3.9 dS/m. Cabbage on the other hand can tolerate slightly higher concentrations for the same yield potentials. For EC\text{e}, a yield potential of 100% at 1.8dS/m, 90% at 2.8dS/m, 75% at 4.4dS/m, and 50% at 7.0dS/m, with a maximum tolerable EC\text{e} of 12dS/m is proposed. Similarly for EC\text{iw}, a yield potential of 100% at 1.2dS/m, 90% at 1.9dS/m, 75% at 2.9dS/m, and 50% at 4.6 dS/m is proposed.

In an experiment to determine the effect of water salinity on potatoes, Levy et al. (1988) reported that salinity lowered the water and osmotic potentials of leaves and tubers whiles increasing total soluble solids (TSS) and proline. Dry matter content was also increased in tubers. However, overall tuber yields were reduced. Leaf yellowing, senescence, and desiccation also occurred in all the cultivars they grew, in proportion to salinity concentrations. In addition to these effects, dry and fresh tuber weights were also reduced in all cultivars due to salinity stress.

In another experiment to evaluate the influence of soil and water salinity on emergence and early development of potatoes, Levy et al. (1993) found that emergence of all cultivars was delayed, in addition to growth retardation. They reported that tubers which were planted in salinized soils and irrigated with saline water did not achieve 80% emergence. This result was observed under the highest treatment of irrigation water with EC of 7.0dS/m. Fresh weights of plants also decreased with increasing salinity.
Van Hoorn et al. (1993) evaluated the effects of saline water on soil salinity and potato yield and observed that yield decreased with increase in soil salinity. This observation was consistent in both soil types (loam and clay) used in the study.

**Problem Statement**

The Tri-County Agricultural Area (TCAA) received relatively low annual rainfall of about 1016 mm from 2010 to 2012, compared with the annual average of about 1320.8 mm (2000-2015) (FAWN, 2015). Growers in the region experienced reduced crop yield during this time which was partially attributed to increased soil salinity (Personal communication: Dr. Mark Clark). Concerns therefore increased about the impacts of soil salinity especially during low rainfall conditions. Low rainfall conditions imply lowered leaching of salts down the soil profile as well as high ET rates which leave more salts concentrated in the field. In addition, irrigation rates are increased to compensate for the lowered rainfall conditions, thereby adding more salts to the irrigated fields. Groundwater in the TCAA has variable salinity with respect to location and time, as well characteristics such as well depth and penetration into the aquifer differ among wells (Munch et al., 1979). Increased irrigation from a poor water quality source, minimal leaching of salts, plus high ET rates can individually or cumulatively contribute to soil salinity build-up in the irrigated fields.

Soil salinity varies seasonally and can be influenced (exacerbated) by management practices. In regards to potato production, soil salinity concentrations in some fields are high enough to cause reduction in potato crop yields based on the 'no yield effect' salinity threshold of 1.7 dS/m proposed by Fipps (2003). In prolonged drought conditions, saline soils can potentially develop in the TCAA. This is especially true if salt water intrusion occurs in irrigation wells due to increased withdrawals. Parts
of northeast Florida are underlain by the Fernandina permeable zone which is very saline. Salt water intrusion from this zone is very probable if groundwater were over exploited for agricultural, domestic, and industrial use. Most of the irrigation wells currently have salinity concentrations exceeding the proposed threshold suitable for potato production which is 1.1 dS/m (Fipps, 2003) and are at a higher risk of increased salinity during drought conditions.

An irrigation practice commonly used in the TCAA is seepage irrigation (described previously). Due to large volumes of water used in seepage irrigation, poor water quality means large amounts of salt deposits in the irrigated fields. Soils in the TCAA are underlain by a spodic or argillic horizon which prevents fast and easy drainage of water down the profile. This condition prevents effective leaching of salts from the soil profile, increasing salt concentrations in the fields.

Another irrigation type used in the TCAA, Irrigation Drainage Tile (IDT) employs the use of perforated corrugated PVC pipes installed subsurface to irrigate crops. Primarily, this irrigation type also offers drainage capabilities for the field. This helps to drain excess water from rainfall, as well as leach salts from the fields. Currently, there exists a cost-share program between some growers in the TCAA and the SJRWMD where IDTs have been installed on farms. This program seeks to investigate alternative irrigation practices with regards to water conservation and reduced nutrient loading into the lower St. Johns river. This offered an opportunity to evaluate two irrigation and drainage practices for salinity management.

This research therefore sought to compare the effects of the two irrigation and drainage practices (seepage and IDT) on water use and soil salinity at selected farms in
the TCAA. It asked the question, “what effects do alternative irrigation and drainage practices have on water use and soil salinity in the TCAA?” The objectives were to account for the differences in water use and soil salinity in fields with IDT and seepage irrigation and drainage practices. It was hypothesized that fields with IDT will have lower water use as well as lower soil salinity compared with the conventional seepage irrigation fields.

**Methods**

**Study Site**

Three commercial farms (Farms 3-5) in the TCAA were monitored for irrigation water consumption. Soil samples were also collected from five commercial farms including the three farms monitored for irrigation water use (Farms 1 and 3-6) and one research farm (Farm 2) (Figure 3-3). Each farm installed and used IDT as well as conventional seepage irrigation during the growing and fallow seasons of 2013, 2014, and 2015. Salinity of groundwater used to irrigate both IDT and seepage fields were tested and found not to be statistically different for each farm (p> 0.05).

Sampling periods were designated as Fall or Summer. Fall sampling period was between October and January, which is the beginning of the growing season. At this time, it was anticipated that salts would be lowest in the fields due to summer rains which leached salts and there would also be no or minimal irrigation of crops. Summer sampling period was between May and July (end of the growing season but before the main rainy season) when it was anticipated that due to intensive irrigation and evaporative losses, salts would have concentrated and so field soil salinity would be highest at this time.
Water consumption by Seepage Irrigation and IDT Systems

Irrigation wells on three farms were equipped with flow meters (manufactured by Neptune and McCrometer) which automatically recorded the cumulative amount of water pumped. It was assumed that all water pumped was used for irrigation purposes and the same crops were grown on the seepage and IDT fields at each farm during the monitoring period. Meter readings were recorded weekly to calculate the amount of water used by the two irrigation systems. Water consumption was monitored for a year between August 2014 and August 2015.

Soil Sampling: Seepage Irrigation and IDT Fields

In order to compare soil salinity under the two irrigation and drainage practices, soil samples were collected from six farms and extracted soil water analyzed for EC. Each farm implemented both types of irrigation practices in different fields during the sampling period. A total of six seepage irrigated fields were sampled in the three sampling events, one on each farm, whereas eight IDT fields were sampled. Farm 1 had three IDT systems which were installed about a year apart, making them approximately three-year-old, two-year-old, and a year old by the final sampling period in Summer, 2015. This offered a temporal comparison of soil salinity reduction after IDT installation. Similarly, at Farm 6, the only IDT field was sampled during all three sampling seasons, offering a similar temporal comparison of soil salinity reduction after IDT installation (Table 3-1). Soil samples were collected at three distances (3 m, 5 m and 7 m) from reference water furrows or IDT laterals in each field. At each soil sampling location, four samples were collected from four soil depths: 0-30 cm, 30-60 cm, 60-90 cm, and 90-120 cm. This was replicated at three different zones in the field
representing regions of water inflow, which was 30 m downstream of the inlet; and outflow, which was 30 m upstream of the outlet, as well as the center of the fields (Figure 3-4). This totaled 3 distances * 3 zones * 4 depths = 36 soil samples per field, for most fields. Samples could not be collected at all four depths at some locations due to either high water table conditions or compaction of soil below a certain depth, preventing penetration of the sampling equipment.

The Amity Technology-4804 soil sampler was used for most of the soil sampling. A hand auger was used when the Amity sampler could not penetrate below 60 cm. The sampler was mounted on a tractor and its 150 cm probe was mechanically lowered into the soil to collect a sample from each of the sampling locations. The plastic sleeve in the probe which held the soil was then taken out of the probe, capped, labeled and stored in a container for transportation to the laboratory (Figure 3-5).

**Soil Salinity Analysis**

Soil samples were prepped and analyzed for soil EC in the wetlands and water quality laboratory (WWQL) and Wetlands and Biogeochemistry Laboratory (WBL) at the University of Florida, Soil and Water Sciences Department. Soil samples collected by hand auguring were composited and bagged in the field. The plastic sleeves used with the Amity soil sampler were cut-up in one-foot increment, soil was composited for each foot, and placed in plastic bags.

The next stage of processing involved preparing soil pastes from the samples (Rhoades, 1982). Any form of debris was removed from the composites and 30 ml disposable plastic cups were filled to about two-thirds of the volume with soil samples. Double deionized water was then added to the soil and mixed with a spatula until a
slurry paste was obtained. The mixtures were covered to minimize evaporation and allowed to sit for 24 hours to ensure equilibrium of dissolved ions. Soil pastes were always prepared by the same person to ensure consistency of the mixtures.

In extracting soil water from the samples, small quantities of soil pastes were placed in funnels with Whatman filter papers (medium fast or fast) and a vacuum pump was used to extract the soil water into 20 ml scintillation vials.

**Soil Water Electrical Conductivity Measurement**

EC of soil water extracts from the soil samples were measured using an Accumet AR50 pH/conductivity meter with probes. The probe was calibrated with either potassium chloride (200 µS/m at 25ºC) or sodium chloride (1,413 µS/m at 25ºC) conductivity standard.

**Statistical Analysis**

Water use for each irrigation practice was determined by add the total water use over the sampling period and dividing by the number of years sampled. The farms monitored had different hectare of land under different irrigation and drainage practices. Water consumed was therefore normalized with the size of land under each irrigation and drainage system and reported as cubic meters used per hectare per year.

To test whether there was a significant difference in soil salinity under the seepage and IDT systems, two-sample t-test analysis was employed, using the JMP Pro 12 software.

**Results**

**Water consumption by Seepage Irrigation and IDT Systems**

Irrigation water consumption was lower in IDT systems compared with seepage systems in two out of three farms (Farm 3 and 4), and higher in IDT than seepage in
one out of the three farms (Farm 5). At Farm 3, IDT irrigation used 4034.3 m³/ha/yr less (40%) water than seepage between August 2014 and August, 2015. Likewise, Farm 4’s IDT system used 1,228.7 m³/ha/yr less (37%) water than seepage between August 2014 and August 2015. Farm 5 was an exception where IDT used 2,395.5 m³/ha/yr more (45%) irrigation water, compared with seepage (Figure 3-6). Overall IDT systems used 2,867.5 m³/ha/yr (15%) less water than seepage irrigation.

**Soil Salinity Comparison: Seepage versus IDT Fields**

**Overall differences between irrigation systems**

Mean soil salinity in IDT fields for all six farms and all three seasons sampled was significantly lower (0.98 ± 0.71 dS/m) than in SI fields (1.71 ± 1.13 dS/m, p<0.0001) (Figure 3-7). The same trend was observed in the individual sampling seasons of Fall 2013, 2014 and Summer 2015. In all three sampling seasons, mean IDT field soil EC was significantly lower than that of SI fields (Table 3-2, Figures 3-8 to 3-10).

**Overall differences with soil depth**

At all four depths sampled, mean soil EC in IDT fields for all six farms were significantly lower (p<0.0001) than SI fields. At soil depth 0-30 cm, mean soil EC was 0.78 ± 0.67 dS/m for IDT and 1.30 ± 1.12 dS/m for SI fields. Similarly, at soil depth 30-60 cm, mean soil EC was 0.85 ± 0.62 dS/m and 1.65 ± 1.13 dS/m for IDT and SI fields respectively. The lower two depths recorded similar soil salinities with IDT soils still significantly lower than SI field soils. At soil depth 60-90 cm, mean soil EC was 1.13 ± 0.71 dS/m for IDT and 2.03 ± 1.10 dS/m for SI, whereas at depth 90-120 cm, mean soil EC was 1.13 ± 0.75 dS/m and 1.97 ± 1.01 dS/m for IDT and SI fields respectively.
Figures 3-12 to 3-14 show soil salinity differences with depth in IDT and SI fields for the three sampling periods (Fall 2013; 2014; and Summer 2015).

**Overall differences with field zone**

For all field zones sampled, IDT field soil EC was significantly lower (p<0.0001) than SI fields in a pairwise comparison. At the centers of the fields, mean IDT field soil EC was 1.08 ± 0.85 dS/m and 1.81 ± 1.27 dS/m for SI fields. Inflow zones recorded mean soil EC of 0.9 ± 0.66 dS/m for IDT fields and 1.81 ± 1.19 dS/m for SI fields. Finally, outflow zones recorded mean soil EC of 0.97 ± 0.59 dS/m and 1.50 ± 0.89 dS/m for IDT and SI fields respectively (Figure 3-15). Figures 3-16 to 3-18 show soil salinity differences in zones for the three different sampling seasons.

**Overall differences with distances from reference water furrows or IDT laterals**

Similar to previous trends recorded, IDT field soils were significantly lower in soil salinity, compared with SI soils at all distances from reference furrows or IDT laterals (p<0.0001). At a distance of 3 m, mean soil EC was 1.01 ± 0.73 dS/m for IDT fields and 1.59 ± 1.05 dS/m for SI fields. At 5 m, mean soil EC was 0.96 ± 0.73 dS/m for IDT and 1.71 ± 1.06 dS/m for SI fields. Finally, at 7 m, mean soil EC was 0.98 ± 0.67 dS/m and 1.83 ± 1.27 dS/m for IDT and SI fields respectively (Figure 3-19).

**Post-installation performance of IDT systems**

Two farms monitored for soil salinity reduction several months after IDT installation showed that soil salinity was reduced significantly by the second sampling period following IDT system installation. However, there were no significant differences in soil salinity between the second and third sampling periods (variable months post-installation).
At Farm 6, mean soil EC of the IDT field just before installation was 1.90 ± 0.76 dS/m. However, at the second sampling event which was 11 months post-installation, mean soil EC had been significantly reduced to 0.86 ± 0.61 dS/m. At the final sampling event (19 months post-installation), mean soil EC had been reduced to 0.67 ± 0.36 dS/m, but was not significantly different from the previous sampling event (Figure 3-20).

Farm 1 had three different aged IDT fields (IDT1; IDT2; and IDT3). IDT1 field was sampled at one and seven months post-installation. At one month post-installation, mean soil EC for the field was 2.79 ± 0.72 dS/m. However, at the second sampling event (seven months post-installation), soil EC had been significantly reduced to 1.3 ± 1.02 dS/m (Figure 3-21). IDT2 field was sampled at 12 and 17 months post-installation. At 12 months, mean soil EC was 0.85 ± 0.72 dS/m and was significantly lower at 17 months’ sampling (0.48 ± 0.3 dS/m) (Figure 3-22).

Finally, IDT3 field soils were sampled three times at 12, 24 and 29 months post-installation. At 12 months, mean soil EC was 1.51 ± 1.14 dS/m, significantly reduced to 0.46 ± 0.22 dS/m at 24 months, and increased (but not significantly) to 0.63 ± 0.47 dS/m at 29 months (Figure 3-23).

**Discussion**

**Water Consumption by Seepage Irrigation and IDT Systems**

The results support IDT’s hypothesized use of less irrigation water. At Farm 3, IDT used 40% less water per hectare of irrigated land than seepage, whereas Farm 4 IDT used 37% less water per hectare of irrigated land than seepage irrigation. This could be attributed to the operation mechanism of the IDT system. The water distribution system is laid sub-surface, compared with seepage which is completely above-ground. This significantly reduces direct exposure of water to the atmosphere.
and thus reduces evaporation rates. The distance that water needs to travel horizontally in a bed to completely wet the whole bed and irrigate crops is also reduced in IDT systems. This is because irrigation and drainage pipes are laid closer to each other for more efficient irrigation. In seepage systems, this travel distance is 9 m, whereas in most IDT systems it is 4.5 m. This implies that growers save water by not having to leave irrigation water running continuously to get the middle of the bed wet, while excess water drains out of the other end of the field through the water furrow as it happens in seepage irrigation practices.

Farm 5 was an exception where more water (45%) was used by the IDT compared with seepage. It could be a problem with the IDT network installation or poor management of the system during the period monitored. Unfortunately, our research didn’t have sufficient details related to the management of the IDT system to explain this exception to the findings. However, despite this deviation, accounting for all the three farms’ water savings, IDT used 15% less water per hectare of irrigated land than seepage irrigation. This indicates that IDT systems can potentially conserve water when managed efficiently.

Amount of irrigation water used relates to amount of salts deposited in fields, potentially promoting or reducing salt concentrations in fields. It can be directly inferred from amounts of water savings by IDT systems that at Farm 3, 40% less salts per hectare of irrigated land per year (approximately 2,840.12 kg/ha/yr) was deposited in IDT fields than seepage, whereas at Farm 4, 37% less salts per hectare of irrigated land per year (1,619.95 kg/ha/yr) was deposited in IDT fields than seepage irrigation. Again, Farm 5 was an exception where it was anticipated that 45% more salts per hectare of
irrigated land per year (3,121.24 kg/ha/yr) was deposited in IDT fields than seepage. This notwithstanding, accounting for all three monitored farms, 15% less salts per hectare of irrigated land was deposited in IDT than seepage fields per year. This is approximately 3,174.88 kg/ha/yr of salts, considering the irrigation water salinity of these fields.

**Soil Salinity Comparison: Seepage versus IDT Fields**

**Overall differences between irrigation systems**

Results from this study support the hypothesis that IDT field soils will have significantly lower soil salinity than seepage field soils. For all six farms, and in all three sampling seasons, mean IDT field soil EC was significantly lowered by about 37.2% than that of SI fields. Our results agree with observations made by researchers in India, USA and Canada where high water tables and soil salinity are issues of great concern (Ritzema et al., 2004; Ritzema et al., 2008; Schaik & Milne, 1962). In their study, Ritzema et al. (2008) reported a decrease in root zone soil water salinity by 50%, from an initial value of 11.5 dSm\(^{-1}\) to 6.0 dSm\(^{-1}\), two years after the installation of a sub-surface drainage system. Using a model, they predicted a further decrease to about 2.3 dSm\(^{-1}\). In another study conducted by AGVISE laboratories in the US, it was concluded that tile drainage reduced salinity significantly in the topsoil. Soil salinity of a tile-drained field for a local grower had been monitored for 10 years at the time of reporting their findings. They attributed this reduction to lowered water table by the drainage system and excessive rainfall which leached the salts. (AGVISE laboratories, 2016).

Compared with seepage irrigation, IDT systems offer a better potential for salts to leach down the profile and away from the crop root zone. This is made possible by the
perforated PVC pipes IDT systems employ for drainage purposes. Drainage is facilitated in seepage irrigation systems by gravity and slope of the land. It is therefore slow, allowing water to pound on the fields for longer periods, and evaporation rates to be higher. Leaching of salts is therefore limited in seepage systems and salts potentially concentrate in the soil especially during low rainfall conditions.

**Overall differences with soil depth**

At all four depths sampled, results for soil EC again supported the hypothesis that IDT fields would have significantly lower soil salinity compared with SI fields. Soil EC was lower at all depths in IDT fields compared with SI fields. This could be a result of the improved drainage of irrigation water and excess rainfall from the field, leaching salts which would have otherwise concentrated in the field due to increased evaporative losses. IDT pipes are also installed sub-surface and so less water is deposited on the surface soil, reducing the amount of salts deposited. Less water is also used overall to irrigate and therefore less salts are deposited.

**Overall differences with field zone**

Results for the different zones sampled (inflow, center, and outflow) revealed no exceptions to previous discussed findings. IDT’s potential to reduce soil salinity compared with seepage was still evident as IDT fields recorded significantly lower soil salinity than seepage fields in all three zones and for all three sampling seasons. In IDT fields, the center of the field was higher in soil salinity compared with the inflow and outflow zones. This was true for the overall zone analysis for all six farms, as well as in the individual seasons, except in Fall 2014 sampling season when the inflow and outflow zones were 0.1 dS/m higher than the center. This was the same in seepage...
fields too where the center of the field recorded higher soil salinity compared with the inflow and outflow zones. The exception was in Fall 2013 when the inflow zone recorded a higher salinity of about 0.6 dS/m than the center of the field. This observation could be attributed to soil characteristics in the center of the field, as well as flow dynamics of water in the fields.

**Overall differences with distances from reference water furrow and IDT lateral**

Similar to the previous findings related to irrigation system, soil depth, and field zone, IDT fields recorded significantly lower soil salinity at all three distances from a reference IDT lateral compared with the seepage field. This could be a result of the same reasons elaborated upon in the previous sections. Seepage fields need more water to effectively wet a bed in order to irrigate crops. Water furrows also expose much more surface area of the water to the atmosphere, and therefore increased evaporation. Addition of more water implies addition of more salts and also increased evaporation implies increased concentration of salts in the soil. In IDT fields, general results from all six farms indicated that soil closest to the IDT lateral (3 m) had on the average, the highest salts, which reduced at a distance of 5 m from the IDT lateral and was not significantly different further away (7 m) from the IDT lateral. However, it was the opposite in seepage systems where soil EC was lowest closer to the reference water furrow (3 m) and increased as one moved further (5 and 7 m) from the reference water furrow.

**Post-installation performance of IDT systems**

Four IDT fields were monitored for several months for soil salinity reduction after IDT installation. In all four fields, soil salinity was reduced in the months following installation. Two fields were sampled twice and the other two sampled three times. All
fields sampled twice had significantly lower soil salinity in the second sampling season (with time), compared with the first. However, there were no significant differences in soil salinity between the second and third sampling efforts for those fields which were sampled three times. It could be that the time was too short to observe any further reduction in soil salinity and or that the IDT systems were reaching peak performance given the conditions at the time. Rainfall had normalized by 2013 from the 2010-2012 drought and could be leaching the seepage fields of salts well enough, compared with the IDT fields. This also draws attention to the possibility of IDT systems being most efficient during low rainfall and post-concentration periods.

Conclusions

Results from this study supported the hypothesis that IDT systems will help conserve water by using less irrigation water, compared with SI. For all three farms monitored, IDT systems used 15% less water than seepage systems. This directly translates to 15% less salts (approximately 3,174.9 kg/ha/yr) deposited on IDT fields. The hypothesis that IDT fields will have less soil salinity (estimated by EC) was also supported by this study. For all 6 farms sampled in this study, IDT fields had less soil EC than SI fields. Soil EC was 37.2% less in IDT fields than in SI fields. This indicates that with proper management of the system, IDT has the potential to reduce soil salinity in crop production fields. This is more important during low rainfall periods or post-salt concentration in fields.
Table 3-1. Soil sampling information for IDT and SI fields at all six farms monitored between September 2013 and June 2015

<table>
<thead>
<tr>
<th>Field ID</th>
<th>IDT installation date</th>
<th>Fall 2013</th>
<th>Fall 2014</th>
<th>Summer 2015</th>
</tr>
</thead>
<tbody>
<tr>
<td>Farm 1 IDT-1</td>
<td>12/1/2014</td>
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<td>1/12/2015</td>
<td>7/09/2015</td>
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<tr>
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<td>Not Sampled</td>
<td>1/12/2015</td>
<td>7/09/2015</td>
</tr>
<tr>
<td>Farm 1 IDT-3</td>
<td>1/1/2013</td>
<td>10/11/2013</td>
<td>1/12/2015</td>
<td>7/09/2015</td>
</tr>
<tr>
<td>Farm 1 Seepage</td>
<td>N/A</td>
<td>10/11/2013</td>
<td>1/12/2015</td>
<td>7/09/2015</td>
</tr>
<tr>
<td>Farm 2 IDT</td>
<td>11/19/2013</td>
<td>Not Sampled</td>
<td>10/30/2014</td>
<td>6/25/2015</td>
</tr>
<tr>
<td>Farm 2 Seepage</td>
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<td>Not Sampled</td>
<td>10/30/2014</td>
<td>6/25/2015</td>
</tr>
<tr>
<td>Farm 3 IDT</td>
<td>11/2013</td>
<td>Not Sampled</td>
<td>12/09/2014</td>
<td>7/14/2015</td>
</tr>
<tr>
<td>Farm 3 Seepage</td>
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<td>Not Sampled</td>
<td>12/09/2014</td>
<td>7/14/2015</td>
</tr>
<tr>
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<td>7/22/2015</td>
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<td>Farm 6 Seepage</td>
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<td>11/20/2014</td>
<td>7/17/2015</td>
</tr>
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</table>

Table 3-2. Average soil EC in seepage and IDT fields for all six farms monitored and in all sampling periods

<table>
<thead>
<tr>
<th>Farm</th>
<th>SI field average soil EC (dS/m)</th>
<th>IDT field average soil EC (dS/m)</th>
<th>Difference (SI-IDT)</th>
<th>Soil EC reduction (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Farm 1</td>
<td>1.83 ± 1.71</td>
<td>0.92 ± 0.9</td>
<td>0.91</td>
<td>49.72</td>
</tr>
<tr>
<td>Farm 2</td>
<td>1.99 ± 0.57</td>
<td>0.82 ± 0.51</td>
<td>1.18</td>
<td>59.06</td>
</tr>
<tr>
<td>Farm 3</td>
<td>0.91 ± 0.45</td>
<td>1.03 ± 0.60</td>
<td>-0.12</td>
<td>-12.75</td>
</tr>
<tr>
<td>Farm 4</td>
<td>2.11 ± 0.94</td>
<td>0.67 ± 0.43</td>
<td>1.44</td>
<td>68.34</td>
</tr>
<tr>
<td>Farm 5</td>
<td>1.52 ± 0.93</td>
<td>1.25 ± 0.54</td>
<td>0.28</td>
<td>18.20</td>
</tr>
<tr>
<td>Farm 6</td>
<td>1.93 ± 0.98</td>
<td>1.15 ± 0.80</td>
<td>0.78</td>
<td>40.41</td>
</tr>
<tr>
<td>Average</td>
<td>1.71 ± 0.40</td>
<td>0.97 ± 0.20</td>
<td>0.74 ± 0.53</td>
<td>37.16</td>
</tr>
</tbody>
</table>
Figure 3-1. Seepage irrigation field with water furrow between two beds (16 rows of planted potato per bed). Water seeps laterally and vertically by gravity to irrigate crops.

Figure 3-2. Irrigation Drainage Tile (IDT) system: pipes being installed. Photos adapted from http://www.ads-pipe.com/pdf/en/AD430613AgIrrDrainBrochure.pdf
Figure 3-3. Google earth photo showing IDT and seepage fields from six farms where soil samples were collected. Red pins show seepage and yellow pins show IDT fields.
Figure 3-4. Location sampling scheme for soil sampling showing distance from water furrow or IDT lateral and sampling depth.
Figure 3-5. Soil samples collected with the AMITY Technology 4804 soil sampler.
Figure 3-6. Irrigation water consumption at Farms 3-5 from August 2014 - August 2015.
Figure 3-7. Mean soil EC for all six farms and all three sampling seasons ($p < 0.0001$).

Figure 3-8. Mean soil EC for all six farms and Fall 2013 sampling season ($p < 0.0001$).
Figure 3-9. Mean soil EC for all six farms and Fall 2014 sampling season (p < 0.0001).

Figure 3-10. Mean soil EC for all six farms and Summer 2015 sampling season (p < 0.0001).
Figure 3-11. Mean soil EC for all six farms and all sampling seasons by depth. Single asterisk indicates significant difference in soil salinity between SI field and IDT field at $\alpha = 0.05$. 
Figure 3-12. Mean soil EC for all six farms and Fall 2013 sampling season by depth. Single asterisk indicates significant difference in soil salinity between SI field and IDT field at $\alpha = 0.05$. 

- IDT field:
  - 0-30 cm: 1.01 ± 0.84 vs. 2.38 ± 1.90 *
  - 30-60 cm: 1.62 ± 1.01 vs. 3.03 ± 1.63 *
  - 60-90 cm: 2.09 ± 0.97 vs. 3.49 ± 1.01 *
  - 90-120 cm: 2.09 ± 0.74 vs. 3.22 ± 0.83 *

- SI field:
Figure 3-13. Mean soil EC for all six farms Fall 2014 sampling by depth. Single asterisk indicates significant difference in soil salinity between SI field and IDT field at $\alpha = 0.05$. 
Figure 3-14. Mean soil EC for all six farms summer 2015 sampling by depth. Single asterisk indicates significant difference in soil salinity between SI field and IDT field at $\alpha = 0.05$. 
Figure 3-15. Mean soil EC for all six farms and all sampling seasons by field zone. Single asterisk indicates significant difference in soil salinity between SI field and IDT field at $\alpha = 0.05$. 
Figure 3-16. Mean soil EC for all six farms and Fall 2013 sampling season by field zone. Single asterisk indicates significant difference in soil salinity between SI field and IDT field at $\alpha = 0.05$. 

- Center Zone: 2.14 ± 1.02 vs. 3.11 ± 1.58 *
- Inflow Zone: 1.47 ± 1.01 vs. 3.74 ± 1.29 *
- Outflow Zone: 1.5 ± 0.82 vs. 2.24 ± 1.04 *
Figure 3-17. Mean soil EC for all six farms and Fall 2014 sampling season by field zone. Single asterisk indicates significant difference in soil salinity between SI field and IDT field at $\alpha = 0.05$. 

- 0.70 ± 0.53 vs. 1.51 ± 0.94 *
- 0.8 ± 0.57 vs. 1.37 ± 0.8 *
- 0.82 ± 0.51 vs. 1.47 ± 0.88 *
Figure 3-18. Mean soil EC for all six farms and summer 2015 sampling season by field zone. Single asterisk indicates significant difference in soil salinity between SI field and IDT field at $\alpha = 0.05$. 

1. $1.02 \pm 0.68$ vs. $1.61 \pm 1.12$ *
2. $0.79 \pm 0.47$ vs. $1.54 \pm 0.67$ *
3. $0.93 \pm 0.45$ vs. $1.25 \pm 0.67$ *
Figure 3-19. Mean soil EC for all six farms and all sampling seasons by distance from reference water furrow or IDT lateral. Single asterisk indicates significant difference in soil salinity between SI field and IDT field at $\alpha = 0.05$. Row 2 = 3 m, Row 4 = 5 m and Row 6 = 7 m from reference water furrow or IDT lateral.
Figure 3-20. Temporal soil EC observed at Farm 6 for the IDT system post-installation. Different letters indicate significant difference in soil salinity between ages of IDT system at $\alpha = 0.05$.

Figure 3-21. Temporal soil EC observed at Farm 1 for IDT1 system post-installation. Different letters indicate significant difference in soil salinity between ages of IDT system at $\alpha = 0.05$. 
Figure 3-22. Temporal soil EC observed at Farm 1 for IDT2 system post-installation. Different letters indicate significant difference in soil salinity between ages of IDT system at $\alpha = 0.05$. 
Figure 3-23. Temporal soil EC observed at Farm 1 for IDT3 system post-installation. Different letters indicate significant difference in soil salinity between ages of IDT system at $\alpha = 0.05$. 
CHAPTER 4
RESEARCH CONCLUSIONS AND IMPLICATIONS

Long and Short-Term Groundwater Salinity Evaluation

Irrigation water salinity is of importance to crop production as it can directly affect soil salinity. The amount of irrigation water used affects the amount of salts deposited in the field and is dependent on variables such as soil characteristics (drainage capabilities, texture), irrigation water quality, rainfall, and evapotranspiration, among others. In addition to this, crops have different irrigation water and soil salinity thresholds they can tolerate at which yields are not negatively impacted. This study sought to evaluate temporal and spatial groundwater salinity trends in the TCAA after the area experienced low rainfall conditions from 2010-2012. The research questions posed were “what is the past and present groundwater salinity in the TCAA?” and “to what extent is irrigation water salinity a result of localized effects (up-coning during the pumping season) vs. short-term regional changes in groundwater salinity within the TCAA?”.

Two objectives were set to answer these questions, one focusing on long-term (40-year) trends and the other on short-term (3-year) trends. It was hypothesized for the long-term evaluation that groundwater salinity in the TCAA has not changed in the past 40 years. For the short-term evaluation objective, it was hypothesized that localized up-coning effects during the pumping season significantly increases irrigation water salinity compared to non-pumping season concentrations and short-term regional groundwater salinity did not change over the most recent three-year period.

Results from 14 wells sampled for the temporal long-term evaluation showed that there was an average increase of 0.2 ± 0.55 dS/m in groundwater EC in each well over
the 40-year period. This was not statistically significant; however, looking at individual wells, there was some variability as to whether there was an increase or decrease, and the extent. Groundwater salinity in 10 out of 14 wells increased (five of which were statistically significant), while 4 out of 14 wells decreased (three of which were statistically significant) in the 40-year period. The spatial variability in groundwater salinity trends over the past 40 years highlights the heterogeneous nature of groundwater salinity in the area and the site specific conditions that are likely influencing irrigation water salinity over time.

Spatial analysis using 134 wells confirmed increasing trend results observed in the 14 wells. Present wells were significantly higher than their virtual samples in the last 40 years by about 0.12 dS/m. Likewise, the past wells sampled 40 years ago, were lower in salinity than their virtual samples in the present by about 0.18 dS/m. Implications of these findings for the area are varied. Published research suggest that different crops have different thresholds for irrigation water salinity for which crop yields should not be negatively impacted (e.g. Fipps, 2003). For potato, this threshold is 1.1 dS/m. However, the average groundwater salinity measured in 134 wells in the TCAA was 2.31 dS/m. This indicates that yield may already be impacting yields where elevated irrigation water salinities occur. Variations exist on individual farms where local conditions exceeded the average groundwater EC. Again, as the long-term finding suggests, an increasing trend in groundwater salinity is not desirable, since TCAA groundwater salinity is already above the threshold that could be impacting potato production. Short-term findings showing a decreasing trend is encouraging but needs to be investigated through long-term monitoring to conclude what is happening with
regards to groundwater dynamics over longer periods. Regional water demand and withdrawals should also be monitored and regulated to avoid unnecessary pressure on groundwater resources which will allow salt-water intrusion into wells.

This study did not find any significant difference in groundwater salinity during the pumping and non-pumping seasons. However, some individual farms recorded increasing salinity during the pumping season. This could be a result of well depth and localized geological differences. This shows that groundwater salinity dynamics can be very localized in the TCAA and therefore growers need to monitor their irrigation well water so that they can manage irrigation practices in the best way.

Finally, this study was conducted at a time when rainfall had normalized (2013-2015) compared with a previous drought period (2010-2012). This could explain the increasing trend in EC observed in the long-term groundwater salinity evaluation. Drought conditions could have allowed more saline groundwater to rise prior to our sampling efforts due to reduced freshwater potentiometric head. Alternatively, the decreasing trend in EC observed in the short-term evaluation could be explained by increased freshwater potentiometric head from normalized rainfall pushing down the saline groundwater.

**Water Conservation Potential of Irrigation Drainage Tile and Seepage Systems**

In a world of limited fresh water resources, it is important that irrigation practices are as efficient as possible. This study set an objective to measure irrigation water use in IDT fields and compare that with conventional seepage irrigation. It was hypothesized that IDT practice will record lower water use than conventional seepage irrigation. Results showed that IDT systems in two out of three farms monitored, indeed used less amount of water for irrigation compared with their seepage counterparts. For all three
farms monitored, IDT systems reduced irrigation water use by 2,867.5 m$^3$/ha (15%) compared with seepage fields. This indicates that with proper management, IDT systems can potentially conserve water, a situation very important in low rainfall conditions, areas with naturally low rainfall events, and in a generally climate change-threatened world, where the fate of fresh water resources is uncertain. Assuming the TCAA region has about 13,354 ha of agricultural lands, and IDT practices are adopted on all agricultural lands, an estimated 38,292,595 cubic meters of water will be conserved each year based on this study’s findings. This can be improved with improved management of IDT systems.

In addition to water savings, total salt loading to agricultural fields (13,354 ha) from irrigation would potentially be reduced given a reduction in irrigation water use. For an estimated water savings of 38,292,595 m$^3$/yr, and given an average EC of 2.36 dS/m for all wells sampled between 2013 and 2015, it can be estimated that salt loading will be reduced to the tune of about 57,837,135.49 kg in a year.

When irrigation water is conserved, this also frees up water which can be allocated to different purposes based local needs. Salt water intrusion is also prevented when there is enough fresh groundwater head to push down the salty groundwater aquifer. Ultimately, irrigation water quality improves or remains in a good condition for irrigation purposes.

**Soil Salinity in Irrigation Drainage Tile and Seepage Fields**

In addition to evaluating the water conservation potential of IDT and seepage systems, this study also evaluated soil salinity in IDT and seepage fields. It was hypothesized that IDT fields would have lower soil salinity compared with SI fields. Based on results from this study, IDT fields on six farms significantly reduced soil
salinity by 37.16% on average, compared with SI fields. This was an average reduction of 0.74 ± 0.53 dS/m in soil EC. Research recommends that for potato yields not to be impacted, soil EC should not be greater than 1.7 dS/m. From our studies, the average soil EC for IDT fields in all six farms was 0.97 ± 0.2 dS/m and that for SI fields was 1.71 ± 0.4 dS/m. Variations however existed among farms and SI field EC can be seen to be slightly above the threshold for no-yield impact. IDT field EC was however lower than the threshold. Our study was conducted in a normal rainfall period when it was expected that rainfall will aid in the leaching of salts and there will be minimal salt concentration in the fields. In low rainfall and drought conditions, it is possible that soil EC will be very high in SI fields to severely impact crop yields.

Soil salinity evaluation by depth (0-120 cm), by field zone (inflow, center, and outflow), and distance from reference water furrows or IDT laterals (3 m, 5 m, and 7 m) all supported the hypothesis, proving that IDT fields consistently had lower soil salinity compared with SI fields.

The implications of these findings are significant and very practical in the TCAA. Soil salinity trends observed suggest a need to adopt practices that will help reduce the impacts of salinity in the future and especially during low rainfall or drought conditions when irrigation of crops will peak and less leaching of salts would occur. This includes irrigation water used and type of irrigation practice(s).

Finally, although the St. Johns River Water Management District has monitoring wells covering the spatial extent of their jurisdiction, research shows that monitoring wells on agricultural lands are somewhat limited especially in the TCAA and that many of the wells monitored are passive and not actively pumped as would be the case with
irrigation wells. Our data set will add to what already existents to improve historical trend analysis, as well as provide a network of wells with baseline salinity evaluated for future comparison.

**Future Research Opportunities**

**Groundwater salinity evaluation**

Continuous monitoring of groundwater salinity is important to help explain the spatial and temporal dynamics. Our research was conducted in two snap-shots of time for the 40-year evaluation and only three years for the short-term evaluation. Continuous monitoring of wells will offer better time series data for groundwater salinity evaluation.

**Soil salinity evaluation**

In addition to irrigation water salinity data collected, the soil salinity dataset from this research can be used to develop a decision support tool for growers. This tool can potentially estimate field soil salinity at any given time when variables like initial soil salinity, irrigation water salinity and volume, evapotranspiration rate, rainfall, among others are input by growers. The tool can help growers implement alternative management practices in order to optimize yields. Seasonal climatic changes can also be better predicted and managed to minimize crop loss in such situations. These estimates can be specific for the two irrigation practices (IDT and seepage irrigation) as coefficients can be obtained from the soil (and groundwater) salinity evaluations.
LIST OF REFERENCES


BIOGRAPHICAL SKETCH

Eunice Yacoba Yarney hails from Winneba, a coastal town in Central Region, Ghana. She pursued a bachelor’s degree in Natural Resources Management with a specialty in Freshwater Fisheries and Watershed Management. Her passion to learn about best approaches to include human stakeholders in environmental conservation pursuits led her to pursue and graduate with a Master of Philosophy in Environment, Society and Development at the University of Cambridge, UK in 2008. Right after this, she accepted an offer to pursue a Master of Science degree in Hydro Science and Engineering at the Dresden Technology University (TU Dresden) in Germany, with an objective to specialize in water resources management. She graduated in 2011, after she received another offer as a graduate research assistant to pursue a doctoral program in the Soil and Water Sciences department. Eunice firmly believes that for environmental conservation pursuits to be successful, human stakeholders who significantly alter the environment and are the ultimate consumers of natural resources should understand the science behind such pursuits. They therefore need very technical and complex research findings to be communicated in the simplest, understandable forms to them. Eunice aspires to be a scientist who will effectively communicate such research findings to stakeholders and the ordinary person on the street, to ensure the success of environmental conservation efforts, especially water resources.