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Effects of Reclaimed Water on Citrus Growth and Productivity

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1. Introduction

Sewage wastewater or effluent is often viewed as a disposal problem. However, it can be a source of water for irrigation, creating an alternative disposal method for wastewater treatment facilities, benefiting agriculture as an alternate source of irrigation water, and reducing the demand for use of surface or ground water for irrigation (Parsons et al., 2001a and b). Treated wastewater, also known as reclaimed water, is typically treated municipal sewage from which excess plant nutrients, organic compounds and pathogens have been removed. The terms wastewater, treated wastewater and reclaimed water will be used interchangeably in this chapter.

The characteristics and treatment of these treated waters will be described and discussed in this chapter along with use as an irrigation source for citrus production. Potential disadvantages of using reclaimed water for agricultural irrigation include real or perceived concerns about reductions in surface and ground water quality (i.e. nutrients and heavy metals), harmful effects on workers that come in contact with treated wastewater (i.e. organic compounds and pathogens), and the safety of crops for human consumption (i.e. carcinogens and pathogens) (Parsons & Wheaton, 1996; Parsons et al., 1995). In some arid regions where freshwater supplies are limited, irrigation with reclaimed water is already commonly practiced (Feigin et al., 1991). Israel was a pioneer in the development of wastewater re-use practices, but was quickly followed by many other countries (Angelakis et al., 1999). Israel and the Palestinian Autonomous Regions, for example, are projected to use 3500 million m³ of water in 2010, with 1400 million m³ (40% total water supply) used for irrigation. Treated sewage water used for irrigation would be approximately 1000 million m³ or 70% of agricultural water demand and will play a dominant role in sustaining agricultural development (Haruvy, 1994). Wastewater is a preferred marginal water source, since its supply is reliable and uniform, and is increasing in volume due to population growth and increased awareness of environmental quality (Haruvy & Sadan, 1994). Costs of this water source are low compared with those of other unconventional irrigation water sources (e.g. desalinization) since agricultural reuse of urban wastewater serves also to dispose of treated urban sewage water (Haruvy & Sadan, 1994). Total cost of supplying wastewater for agricultural reuse (i.e. treatment, storage and conveyance costs) minus total costs of alternative safe disposal (e.g. deep well injection and wetlands creation) must be

considered when developing wastewater reuse systems (Angelakis et al., 1999; Arora&Volutchkov, 1994; Haruvy, 1997)).

2. Wastewater reuse: the general case

The rapid development of irrigation has resulted in an increased water demand. Accessible water resources (e.g. rivers and shallow aquifers) in most agricultural areas are now almost entirely committed (Angelakis et al., 1999). Alternative water resources are therefore needed to satisfy further increases in demand. This is particularly a necessity in regions which are characterized by severe mismatches between water supply and demand. Low water resource availability and temporal symmetries in availability result in water provided for human consumption and other urban use with less water for agricultural use. The reduction in water availability for agriculture can lead to reduced sustainability of agricultural enterprises and/or environmental problems (Angelakis et al., 1999). One potential alternate source of irrigation water for agriculture situated near large urban centers is treated wastewater. Reclaimed water contains many nutrients essential for plant growth, and may have an effect similar to that of frequent fertigation with a dilute concentration of plant nutrients (Nielsen et al., 1989). In addition, recycling these nutrients may prevent pollution of surface or ground water (Sanderson, 1986).

In the Mediterranean basin, wastewater has been used as a source of irrigation water for centuries. In addition to providing a low cost water source, the use of treated wastewater for irrigation in agriculture combines three advantages 1) using the fertilizing properties of the water can partially eliminate synthetic fertilizers demand and contribute to decrease nutrient concentration of rivers, 2) the practice increases the available agricultural water resources, and 3) in some areas, it may eliminate the need for expensive tertiary treatment (Angelakis et al., 1999).

In a review by Haruvy (1997) wastewater quality or treatment levels are defined by various constituents such as 1) organic matter- biochemical oxygen demand, chemical oxygen demand and total suspended solids; 2) organic pollutants (i.e. stable organic matter that may affect health); 3) trace elements resulting from industrial water use; 4) pathogenic microorganisms; 5) potential plant nutrients (e.g. N and P); and 6) salinity. Treatment processes are generally divided into primary, secondary and advanced or tertiary processes. Primary treatment includes basic treatment such as screening to remove coarse solids and solid precipitates. Secondary treatment includes low-rate processes (e.g. stabilization or sediment ponds) with high land and low capital and energy inputs, and high rate processes (e.g. activated sludge) with low land and high capital and energy inputs (Pettygrove & Asano, 1985). Tertiary stages of treatment further improve water quality by nitrification and denitrification to reduce water N.

Environmental hazards may be caused by each constituents (e.g. nutrients, heavy metals) left in wastewater and may leach below the root zone increasing groundwater pollution (Feigin et.al, 1990). Salinity of reclaimed water is generally within acceptable ranges and often lower than other irrigation sources, however, salinity levels may be acceptable only for ground application and not direct plant contact in some treatments processes (Basiouny, 1982). Leaching of fertilizers, pesticides and salts from soils irrigated with treated wastewater or over application of poor quality wastewater has resulted in the progressive loss of subsurface water quality and decrease in groundwater resources in some areas (Lapena et al., 1995). However, when properly managed, the use of treated wastewater in

agriculture to conserve water resources and to safely and economically dispose of wastewater is a very feasible option.

Treated municipal wastewater has become an important potential source of irrigation and plant nutrients and has been used successfully in the production of high yield marketable quality crops for decades (Allen & McWhorter, 1970; Crites, 1975; Day, 1958; Henry et al., 1954; Stokes et al., 1930). The response of plants and soils to municipal treated effluent is dependent on the quality of the applied effluent and nature and efficiency of the wastewater treatment, with generally higher treated water resulting in the best growth and yields (Basiouny, 1984). Recently, wastewater has been used to increase yield and improve quality of grain crops (Al-Jaloud et al., 1993; Day & Tucker, 1977; Day et al., 1975; Karlen et al., 1976; Morvedt & Giovdane, 1975; Nguy, 1974), cotton (Bielorai et al., 1984; Feigin et al., 1984), forage (Bole & Bell, 1978) and vegetable crops (Basiouny, 1984; Kirkham, 1986; Neilsen et al., 1989 a, b, c, 1991; Ramos et al., 1989). Reclaimed water has been successfully used to irrigate many fruit crops; apples (Nielsen et al., 1989a), cherries (Neilsen et al., 1991), grapes (Neilsen et al., 1989a), peaches (Basiouny, 1984) and citrus (Esteller et al., 1994; Kale & Bal, 1987; Koo & Zekri, 1989; Morgan et al., 2008; Omran et al., 1988; Wheaton & Parsons, 1993; Zekri & Koo, 1990).

3. Guidelines for wastewater reuse in irrigation

The Ganga is the most important river system in India. It rises from the Gangotri glacier in the Himalaya mountains at an elevation of 7138 m above mean sea level as a pristine river. Half a billion people (almost one tenth of the world's population) live within the Ganga river basin at a average density of over 500 per km² (Singh et al., 2003). This population is projected to increase to over one billion people by 2030. Sewage treatment plants provide agricultural benefits by supplying irrigation and nonconventional fertilizers in the Ganga river basin as an alternate disposal of effluent into the river (Singh et al., 2003). Areas with extensive agriculture and rapidly escalating population must use water resources in a sustainable way and require guidelines to insure the health of the population and maintain water quality and the environment in sensitive areas such as the Gana river basin.

Wastewater reuse guidelines typically cover four areas for each application (i.e. type of crop irrigated): chemical standards, microbiological standards, wastewater treatment processes and irrigation techniques (Angelakis et al., 1999). The degree of treatment required and the extent of monitoring necessary depend on the specific use and crop. In general, irrigation systems are categorized according to the potential degree of human exposure.

The highest degree of treatment is always required for irrigation of crops that are consumed uncooked (Angelakis et al., 1999). However, wastewater is often associated with environmental and health risks. As a consequence, its acceptability to replace other water resources for irrigation is highly dependent on whether the health risks and environmental impact entailed are acceptable. Evaluation of reusing wastewater is the quality of the water in terms of the presence of potentially toxic substances or of the accumulation of pollutants in soil and crops. It is important to access the source of the wastewater for heavy metals from industries or synthetic chemicals normally present in urban wastewater (e.g. oils, disinfectants). There have also been debates about applicable microbiological practices and the type of crops that should be irrigated with treated effluent (Asano & Levine, 1996). One set of guidelines established in California, USA and now accepted nationwide and other

countries of the world, promote very high water quality standards (comparable to drinking water standards), confident that costly treatment practices provide safe enough water (i.e. free of enteric viruses and parasites) for who can afford it. The "California criteria" (State of California, 1978) stipulate conventional biological wastewater treatment followed by tertiary treatment, filtration and chlorine disinfection to produce effluent that is suitable for irrigation (Arora & Voutchkov, 1994). In support of this approach, Asano & Levine (1996) reported two major epidemiological studies conducted in California during the 1970s and 1980s. These studies scientifically demonstrated that food crops irrigated with municipal wastewater reclaimed according to the California approach could be consumed uncooked without adverse health effects. However, the nutrients removed by the tertiary treatment are not available for fertilizing of the crops.

In contrast to the California approach, the guidelines produced by the World Health Organization (WHO) are less stringent and require a lower level of water treatment (WHO, 1989). The WHO guidelines are, however, more restrictive in assuring microbiological quality of treated water, requiring monitoring of fecal Coliform bacteria (also required in the California criteria) as well as human parasitic nematodes.

Outside of Europe, other countries (e.g. Israel, South Africa, Japan and Australia) have chosen criteria more or less similar to those adopted by California (and elsewhere in the US). Most countries in Europe accept the 1989 WHO guidelines but contain additional criteria such as treatment requirements and/or use limitations in order to ensure proper public health protection. The California approach has the most data in its own support and thus has been accepted by more countries because of its "safety first" philosophy but is the most expensive to implement.

4. Risk assessment

Shuval et al. (1997) developed a preliminary model for the assessment of risk of infection and disease associated with wastewater irrigation of vegetables eaten uncooked based on a modification of the Haas et al. (1993) risk assessment model for drinking water. The modifications included determining the amount of wastewater that would cling to irrigated vegetables and estimates of the concentration of pathogens that would be ingested by consuming vegetables irrigated with wastewater of different propagule densities. The model was validated with data from a cholera epidemic caused in part by consumption of wastewater irrigated vegetables and provided reasonable approximation of the levels of disease that really occurred. The risk assessment, using this model, of irrigation with treated wastewater effluent meeting the WHO guidelines (WHO, 1989, 1,000 fecal coliform bacteria 100 ml⁻¹) indicates the risk of contracting a virus disease is about 10⁻⁶ to 10⁻⁷. Regli et al. (1995) concluded that guidelines for drinking water standards should be designed to ensure that human populations are not subjected to the risk of infection by enteric disease at > 10⁻⁴ for a yearly exposure. Thus this preliminary study suggested that the WHO guidelines provided a factor of safety some 1 to 2 orders of magnitude greater than that called for by the United States Environmental Protection Agency (USEPA) (USEPA, 1992) for microbial standards for drinking water.

5. Wastewater irrigation of Florida citrus: a case study

Florida has experienced rapid growth in population during the last 50 years with a 5.5-fold population increase from 1950 to 2000 (U.S. Census Bureau, 1997; Perry & Mackum, 2001;

Smith, 2005). Groundwater withdrawal for domestic and irrigation use has increased by 15.5 and 20.7 times, respectively, during the same period (Marella & Berndt, 2005). Likewise, the amount of wastewater generated by cities in Florida has increased more than five-fold since 1950. Environmental concerns about degradation of surface waters by treated effluent water have caused many communities to consider advanced secondary treated wastewater (reclaimed water) reuse. Currently there are 440 reclaimed water reuse systems in Florida irrigating 92,345 ha with 2,385 million liters of reclaimed water per day (Florida Department of Environmental Protection, 2005). The majority of these systems irrigate golf courses, public right-of-ways, and home landscapes. However, 6,144 ha of production agriculture are currently irrigated with reclaimed water, with citrus (*Citrus* spp L.) orchards accounting for all but 364 ha (Morgan et al., 2008).

Florida citrus production benefits from irrigation because the average annual rainfall of more than 1200 mm is unevenly distributed throughout the year with approximately 75% of annual rainfall occurring from June to September (Koo, 1963). Furthermore, Florida citrus trees are grown on sandy soils with very low water holding capacity, particularly orchards in the central "ridge" portion of the state. Typical available water content values for central Florida ridge citrus soils range from 0.05 to 0.08 cm³ cm⁻³ (Obreza & Collins, 2003). Increased water use by the growing population and localized water shortages during low rainfall years have resulted in the development of water use restrictions, and decreases in permitted water use for agriculture. Increased use of reclaimed water for agricultural irrigation would not only reduce the wastewater disposal problem for urban areas, but could also reduce the amount of water withdrawn from surficial and Floridan aquifers for irrigation.

Water for irrigation is no longer abundant and restrictions on the use of available groundwater in agriculture are becoming more severe. Due to the increasing demand for water, water use for agricultural purposes has become strictly regulated in Florida (Koo & Zekri, 1989; Wheaton & Parsons, 1993; Zekri & Koo, 1990). Additionally, urban growth, especially in the coastal areas of Florida, has increased the need for efficient and environmentally safe disposal of reclaimed water. The Department of Environmental Regulation (FDER) has restricted the disposal of municipal reclaimed water into lakes, rivers and streams, so alternative disposal sites need to be found (Maurer & Davies, 1993).

Wastewater has been recognized as a possible important source of major plant nutrients (e.g. N, P and K), although the chemical composition of wastewater varies between locations (Berry et al., 1980). Long term studies using reclaimed water to irrigate citrus for up to 60 years in Egypt found no adverse effects on tree growth compared to ground water irrigated citrus (Omran et al., 1988). Similarly, irrigation with reclaimed water increased growth and yield of citrus on well drained sandy soils of the Florida Ridge with no adverse effects on health and yield of mature trees (Koo & Zekri, 1989; Zekri & Koo, 1990). Similar results were observed for young citrus trees grown of well drained soils (Wheaton & Parsons, 1993).

Soil types and drainage patterns of the poorly drained flatwoods soils near the Florida coastline vary considerably due to the presence of a high water table (Maurer & Davies, 1993). The potential waterlogging of the flatwoods hold problems not associated with citrus grown on the Ridge. In a three year study, trees grown of poorly drained sandy soils were irrigated with a simulated reclaimed water, simulated reclaimed water with fertilizer added or ground water with fertilizer added for a period of three years after planting (Maurer & Davies, 1993). Trees irrigated with simulated reclaimed water and ground water with fertilizer added had significantly larger canopies and trunk diameters than trees irrigated

with simulated reclaimed water only indicating that use of reclaimed water alone was insufficient to support adequate growth of young citrus trees.

Prior to 1987, the City of Orlando and Orange County wastewater treatment plants discharged their effluent into Shingle Creek, a tributary of Lake Tohopekaliga (Zekri & Koo, 1989). Faced with the need to expand wastewater treatment volume and a state requirement to eliminate discharge of treated effluent to surface waters, the city and county entered a negotiated settlement with the Florida Department of Environmental Regulation and the United States Environmental Protection Agency to cease effluent discharge into Shingle Creek and develop an innovative reclamation program (Zekri & Koo, 1989). Initial funding of \$180,000,000 established the project which is called Water Conserv II (Parsons et al., 2001a). The Water Conserv II/Southwest Orange County Water Reclamation Project (Conserv II) involves the use of highly treated wastewater for citrus irrigation and groundwater recharge. It is one of the largest water reuse projects in the United States and the first reuse program permitted in Florida that involves irrigation of crops intended for human consumption. The program, which became fully operational in January, 1987, currently delivers approximately 133,000 cubic meters of reclaimed water per day (cmd) (275,000 cmd maximum flow) to approximately 1750 ha of citrus. Other users of reclaimed water from the Water Conserv II project are eight foliage greenhouse operations, four tree farms, two ferneries, and three golf courses. The reclaimed water is distributed through 80 km of pipelines maintained by the project. Excess reclaimed water is disposed of in 71 ha of rapid infiltration basins that recharge surficial and Floridan aquifers. Water Conserv II is the largest reclaimed water agricultural irrigation project of its type in the world and was the first project in Florida to be permitted to irrigate crops for human consumption with reclaimed water (McMahon et al., 1989).

Citrus groves in western Orange and eastern Lake Counties, Florida (lat. 28° 28' 20" N, long. 81° 38' 50" W, elevation 64 m) were selected for the Conserv II project because of their high demand for irrigation water and soil series which have high permeability. The predominant soil order in this area is Entisol, with Candler fine sand (hyperthermic, uncoated, Typic Quartzipsamment) being the dominant soil series (Obreza & Collins, 2003). The Candler series consists of excessively drained, very rapidly permeable soils formed from marine deposits. These soils are located in upland areas and typically have slopes of 0-12%. The A and E horizons consist of single-grained fine sand, have a loose texture, and are strongly acidic (pH = 4.0 - 5.5). A Bt horizon is located at a soil depth of 2 m and includes loamy lamellae of 0.1 to 3.5 cm thick and 5 to 15 cm long. This area is a primary aquifer recharge area for the lower Florida peninsula (Zekri & Koo, 1989). Use of reclaimed water for irrigation, in lieu of previous surface water discharges, benefited the urban sector by 1) reducing competition from the agricultural demand for potable water and 2) increasing available groundwater supplies through supplementing natural recharge of the aquifer. The agricultural sector benefited from the project by 1) providing citrus growers with a long-term source of water that will increase and not decrease with urban growth and 2) reduced irrigation pumping costs associated with deep wells previously used for irrigation.

To receive reclaimed water for irrigation at no cost, citrus growers were required to sign a contract with the City of Orlando and Orange County to accept 1270 mm of water per year for a period of at least 20 years. Initially, there was grower resistance because of concerns that use of the reclaimed water might damage citrus trees, or make the fruit unmarketable. As part of the contract, the growers requested long-term studies on the effects of reclaimed water on citrus tree health and fruit quality. Orchards were not now required to accept the

full 1270 mm of water per year under the contract because rapid infiltration basins (RIBs) were installed in the early 1990s. Due to the highly porous nature of the soils, the RIBs function as alternate disposal sites (particularly during the normally wet summer rainy season) where the reclaimed water is applied at high rates and allowed to percolate to the ground water. Still questions persisted regarding the effect of long-term use of wastewater on tree productivity.

Conserv II water is good quality water having low mineral concentrations and very low TDS (Zekri & Koo, 1990). Characteristics and chemical composition of reclaimed water provided by the Water Conserv II project are summarized in Table 1. This treated wastewater is highly treated having relatively low biological oxygen demand and mineral contents. In general, growers in the project have followed sound irrigation practices (Koo & Zekri, 1989; Zekri & Koo, 1990). An initial survey of orchards receiving reclaimed water from Conserv II was conducted from 1986 to 1989. No adverse affects of reclaimed water use on tree health and productivity were noted in the initial phase of the orchard survey, however, continued monitoring was suggested to determine long term effects (i.e. metal accumulation in soil, leaves or fruit).

Leaf samples indicated that both trees irrigated with reclaimed wastewater and ground water were adequately fertilized. No consistent trends were observed for leaf K, Ca, Mg and Cu contents. Although leaf Na content from trees irrigated with reclaimed wastewater was twice as high as trees on well water, Na content of both groups was well within the optimum standard values for citrus (Obreza & Morgan, 2008). While the surface six inches of soil did not show any consistent trends due to irrigation with reclaimed water, accumulation of nutrient elements became more apparent when the soil profile to one meter was examined. Higher N and P were found in the soil profile of reclaimed water irrigated groves in 1988 when compared to the well water groves. No differences were observed in the extractable soil K, Ca, Mg and Na of reclaimed water and control groves. Fruit from trees irrigated with reclaimed water had lower soluble solids and acid content in 1987 than fruit from control trees. Such effects of irrigation on juice quality are well documented (Koo & McCornack, 1965; Koo & Smajstral, 1984). In 1987, soil water content was considerably higher in the reclaimed water groves than the control groves resulting in lower soluble solids. In 1988, soil water content in the reclaimed groves was only slightly higher than the control groves and differences in soluble solids were not detected.

A long-term replicated small plot study was conducted from 1989 to 2000 to determine the affect of irrigation with reclaimed water on citrus trees on sandy soils and irrigated with water supplied by the Water Conserv II project (Parsons et al., 2001b). Reclaimed water was applied to citrus trees from planting to 10 years of age at 400, 1500 and 2500 mm per year at equal monthly amounts. Ground water applied at recommended rates based on daily evapotranspiration was provided as a control. The highest two treated wastewater irrigation rates promoted greater trunk and canopy growth. In the first three years, trunk diameters were similar for the ground water control and 400 mm rate of reclaimed water. From years four to 10, trees that received the 1250 and 2500 mm per year application rates were significantly larger than those receiving the 400 mm treatment. The 2500 mm per year reclaimed water rate produced well, even though the high irrigation rate caused a significant reduction in juice soluble solids, 19.3% more fruit per hectare than the 400 mm per year treatment resulting in 15.5% total soluble solids per hectare compared with the 400 mm rate because of the greater fruit production at the higher irrigation rate. These results show that irrigation with excessively high rate of reclaimed water was not detrimental to

canopy growth and fruit production. This was due to the good drainage of this sandy soil and the lack of root diseases. The slight reduction in juice soluble solids at the high irrigation rate was more than compensated for by the higher total soluble solids yield.

In the same study, leaf N contents were slightly lower in plants irrigated with groundwater than wastewater (Parsons et al., 2001b). It was concluded that this was due to elevated levels of organic matter found in wastewater which provided additional N. Higher leaf N was also found in treated wastewater irrigated sweet-cherry (Nielsen et al., 1991), apples (Nielsen et al., 1989c), cotton (Feigin et al., 1984) and peach trees (Basiouny, 1984). No significant differences in leaf P contents were found between plants irrigated with either groundwater or wastewater, in spite of wastewater supplying a higher soil P load. This is explainable considering that the amount of P supplied by both kinds of irrigation water was a small percentage of total P from soil and fertilizer sources. Leaf K, concentration in leaves of plants irrigated with groundwater was significantly higher than in plants irrigated with wastewater probably because the elevated Na levels in the wastewater inhibited K uptake by citrus plants (Banuls et al., 1990). Soil solution Na has been found to antagonize K uptake in other plants (Epstein, 1961; LaHaye & Epstein, 1969; Cramer et al., 1987). Plants irrigated with wastewater showed higher leaf content of Cl and Na than those irrigated with groundwater. Citrus is considered to be a salt sensitive crop (Mass & Hoffman, 1977) and salinity causes reduction in growth, ionic imbalance, and adverse water relations in citrus (Walker et al., 1982). Embleton et al. (1973) established 0.7% and 0.25% as the limit for Cl and Na concentrations, respectively. Above these tissue concentration limits, toxic effects are manifested in citrus. No salinity effects were observed over the 10 year study because the nearly 950 mm rainfall during Florida's rainy season (June to September) does not allow for accumulation of salts.

A second orchard monitoring project to determine any adverse effects on citrus tree health and production associated with long-term irrigation using reclaimed water started in 1995 and was terminated in 2004 (Morgan et al., 2008). The objective of this project was to determine whether long-term irrigation with treated municipal wastewater 1) reduced tree health (i.e. canopy appearance and leaf nutrient content), 2) decreased visual fruit loads, 3) impacted internal fruit quality (i.e. Brix, titratable acid, Brix:acid ratio, and/or 4) increased in soil contaminant concentrations. In 1994, 10 orchards irrigated with one of the two water sources were selected for a total of 20 orchards. These 20 orchards were paired so that trees of the same scion and relative age were irrigated with either water sources. The scions used were 'Hamlin' and 'Valencia' oranges (*C. sinensis* L.), 'Sunburst' tangerine (*C. reticulata* Blanco), and 'Orlando' tangelo (*C. reticulata* Blanco x *C. paradisi* Macfadyn) however, the root stocks were not always consistent among the two water sources. Random trees over a four hectare plot in each orchard were evaluated quarterly for canopy appearance, leaf color, fruit crop, and weed cover. Each orchard received a separate visual rating for each category on a 1-5 scale. A rating of 1 indicates a less dense canopy compared with visual inspection of orchards in the area at the same time period, leaf color would be chlorotic and/or have visual deficiency symptoms, the fruit crop would be low enough to be unharvestable, and the weed population would be very low indicating insufficient nutrition, soil water content or excess herbicide application. Ratings of 5 would indicate a thick dense canopy with excessive vegetative growth, dark green leaves with N concentrations above that considered optimum, a fruit crop considered to be well above the average for trees of comparable age and size in the area, and a dense weed population in the herbicide zone well in excess of standard grower practices.. Fruit samples (20 fruit) were taken from five trees in each

orchard just prior to harvest and analyzed for percent juice content, Brix, acid, and weight. Degrees Brix and total titratable acidity were determined according to methods approved for Florida citrus quality tests (Wardowski et al., 1995).

Samples of spring growth leaves (20 leaves from five trees) and soil (two cores from each of five trees) were taken from each orchard in Aug. or Sept. of each year from 1994 to 2004. Leaf samples were analyzed for N, P, K, Ca, Mg, Na, Zn, Mn, Fe, and B. Soil samples were taken at the same time to a depth of 60 cm and were analyzed for P, K, Ca, Mg, Zn, Mn, Al, Cu, Fe, Na, and Cl.

Citrus orchards in this project were irrigated with either groundwater or reclaimed water. Orchards irrigated with groundwater were managed using recommended practices receiving 30 to 40 cm of irrigation per year. However, orchards irrigated with reclaimed water had higher soil water content (Zekri & Koo, 1993), presumably because of more frequent irrigation. Orchards irrigated with reclaimed water had soil moisture content of $0.06 \text{ cm}^3 \text{ cm}^{-3}$ compared with $0.05 \text{ cm}^3 \text{ cm}^{-3}$ for orchards irrigated with ground water. Field capacity was estimated to be $0.65 \text{ cm}^3 \text{ cm}^{-3}$ for these soils, indicating that orchards irrigated with reclaimed water were near or above field capacity a higher proportion of the time compared with orchards irrigated with ground water. The quality of the reclaimed water used for irrigation was monitored monthly, and a report of average water constituent concentrations was provided to the growers (Table 1). The level of constituent concentrations in the reclaimed water are not considered to be toxic (Burton & Hook, 1979; Feigin et al., 1984). However, if soil or tissue accumulation were to occur, concentrations of heavy metals (i.e. cadmium, lead, and zinc) may approach toxic levels (Campbell et al., 1983; Feigin et al., 1984; Neilsen et al., 1991).

Prior to 1994, Zekri & Koo (1993) reported that soil to a depth of 0.5 m beneath trees irrigated with reclaimed water was usually 14.7 mm higher in water content and the trees had 6% higher canopy, leaf color, and fruit crop ratings than trees irrigated with groundwater. The higher ratings were attributed to consistently higher soil water content in the orchards irrigated with reclaimed water. For the period 1994 to 2004, mean quarterly canopy appearance, leaf color, and fruit crop, were significantly higher in orchards irrigated with reclaimed water compared with orchards irrigated with groundwater. Weed growth in orchards irrigated with reclaimed water was consistently higher, but not significantly different, than orchards irrigated with well water. The difference in mean rating for the four categories was 12.3% possibly indicating greater water use in reclaimed water blocks compared with orchards irrigated with well water.

Mean canopy, leaf color, and fruit crop ratings for trees irrigated with ground water were significantly greater than ratings from 2000 to 2004 compared with trees irrigated with the same water source from 1996 to 1999. Whereas, canopy, leaf color, and fruit crop ratings for the orchards irrigated with reclaimed water did not have a similar pattern. Reduced canopy appearance, leaf color, and fruit set in orchards irrigated with groundwater can be attributed to reduced rainfall from 1994-1999 (390 mm, 1998) compared with average rainfall from 2000 to 2004 (1191 mm). Significantly lower tree appearance in a drought year agrees with conclusions of Zekri & Koo (1993) that commercial citrus orchards irrigated with reclaimed water were commonly irrigated more frequently and/or with a greater volume than those irrigated with groundwater.

Weed growth as measured by weed cover ratings was higher in reclaimed water irrigated orchards for most years compared with those irrigated with groundwater. Higher weed growth ratings have been correlated with high irrigation rates of reclaimed water (Parsons

	Drinking water MACL	Well water typical concentrations ¹	Conserv II reclaimed water MACL	Typical Conserv II reclaimed water concentrations ¹
----- mg L ⁻¹ -----				
Arsenic	0.05	--	0.10	<0.005
Barium	2	--	1	<0.01
Beryllium	0.004	--	0.10	<0.003
Bicarbonate	--	--	200	105
Boron	--	0.02	1.0	<0.25
Cadmium	0.005	--	0.01	<0.002
Calcium	--	39	200	42
Chloride	250	15	100	75-81
Chromium	0.1	--	0.01	<0.005
Copper	1	0.03	0.20	<0.05
EC (µmhos)	781	360	1100	720
Iron	0.3	0.02	5	<0.4
Lead	0.015	--	0.1	<0.003
Magnesium	--	16	25	8.5
Manganese	0.05	0.01	0.20	<0.04
Mercury	0.002	--	0.01	<0.0002
Nickel	0.1	--	0.20	0.01
Nitrate-N	10	3	10	6.1-7.0
pH	6.5-8.5	7.8	6.5-8.4	7.1-7.2
Phosphorus	--	0.01	10	1.1
Potassium	--	6	30	11.5
Selenium	0.05	--	0.02	<0.002
Silver	0.1	--	0.05	<0.003
Sodium	160	18	70	50-70
Sulfate	250	23	100	29-55
Zinc	5	0.02	1	<0.06

¹ As reported in Parsons et al., 2001b.

Table 1. Maximum allowable contaminate limit (MACL) for Florida drinking water and Conserv II reclaimed water, and typical Water Conserv II reclaimed water concentrations. All values are in mg L⁻¹ except for pH and EC.

& Wheaton, 1992; Zekri & Koo, 1993). As with tree appearance and fruit crop, weed cover ratings only were significantly lower for orchards irrigated with groundwater in 1998 compared with other years, presumably due to lower rainfall. Growers have adjusted their herbicide practices to reduce the negative impact of increased weed growth due to higher irrigation use with reclaimed water by reducing reclaimed water use or increasing herbicide applications.

In five out of 11 years (1994, 1995, 1998, 2000, and 2001), mean fruit juice content or the percent of fruit weight in juice were significantly higher among trees in orchards irrigated with reclaimed water rather than ground water. These years with significant juice content differences among irrigation water sources lead to a significant year by water source

interaction for Juice content. Juice soluble solids or Brix was not significantly different among water sources. However, Brix were significantly different among water sources in 1994, 1997 and 1998 contributing to a significant year by water source interaction. Two of these years were considered dry years with below normal rainfall. Fruit weight were significantly higher for orchards irrigated with reclaimed water compared with fruit from orchards irrigated with ground water, however, no year * water source interaction was noted. Therefore, higher fruit crop ratings, fruit weights, and similar solids per fruit (during normal rainfall years) in orchards irrigated with reclaimed water would suggest similar or greater yields in terms of soluble solids per ha compared with orchards irrigated with groundwater. The previous study by Koo & Zekri (1989) found that reduced soluble solids and acid concentration in the juice was correlated with higher soil water content in the orchards receiving reclaimed water. Likewise, significant differences in fruit Brix and acid were seen in this study from 1994 to 1998, but not after 1998. This change in fruit Brix and acid may indicated a change in irrigation practices with orchards being irrigated with similar amounts some time after 1998. This shift in irrigation practice would correspond with construction of RIBs and reduced requirement for the use of reclaimed water. Because fruit yield was greater from orchards irrigated with reclaimed water, total soluble solids produced per ha were higher in the reclaimed water orchards than the groundwater irrigated orchards.

Irrigation with reclaimed water has increased soil concentrations of P, K, Mg, B, Na, and Cl when reclaimed water was used as an irrigation water source (Burton & Hook, 1979; Campbell et al., 1983; Feigin et al., 1984; Neilson et al., 1991). Elemental concentrations in soil samples taken in Aug. or Sept. of each year from orchards irrigated with either reclaimed or ground water varied from year to year but were not significant by years. Calcium was the only element significantly different by soil sample depth with higher concentrations found near the surface. This result was expected since calcium applied as lime applied for pH adjustments in orchards irrigated with either groundwater or reclaimed water, and Ca in the reclaimed water would be incorporated into this layer with little leaching over time. With the exception of increased P, Ca and Al no elements were found to be significantly different when comparing water sources. Soil in orchards irrigated with reclaimed water was significantly higher for P, Ca and Al compared with soils in orchards irrigated with ground water. However, no elements were found to be excessive (Maurer & Davies, 1993; Tucker et al., 1995). Lower extractable soil K was found in orchards receiving higher rates of reclaimed water despite the higher K concentration of reclaimed water. These data are consistent with findings of Zekri & Koo (1993) who reported P, Ca, and Mg were significantly higher and K significantly lower in soil samples from orchards irrigated with reclaimed water compared with orchards irrigated with groundwater.

Calcium was the only element with years * water source and depth * water source interactions. Soil calcium concentrations were significantly lower ($1034.7 \text{ kg ha}^{-1}$) in years with normal rainfall (2000-2004) compared with dryer years (1338.5 , 1996-1999). Differences in soil Ca concentration among the two irrigation water sources followed the same pattern during these years with soil from orchards irrigated with reclaimed water have higher concentrations than did soil from orchards with ground water (data not shown). Likewise, soil Ca concentrations followed the same pattern with depth regardless of irrigation water source resulting in higher concentrations in soil irrigated with reclaimed water at the selected depths compared with soil from orchards irrigated with ground water.

Leaf sample elemental concentrations were generally higher from orchards irrigated with reclaimed water compared with orchards irrigated with groundwater. While higher, significantly higher P and Ca concentrations in soils irrigated with reclaimed water did not lead to significantly higher leaf concentrations. These results can be explained by dilution of

leaf concentration by increased biomass production of trees irrigated with reclaimed water, reduced nutrient uptake efficiency, or a combination of the two. Unfortunately, differences in biomass accumulation were not determined in this study. However, only Mg and B were significantly higher in leaf samples from orchards irrigated with reclaimed water compared with samples from orchards irrigated with groundwater. Zekri & Koo (1993) found significantly higher Fe and B concentrations in more than half the years between 1987 and 1993. Based on this information, it is now recommended that orchards irrigated with reclaimed water not add B to micronutrients sprays. Zekri & Koo (1993) found significantly higher Na and Cl concentrations in leaf samples from orchards irrigated with reclaimed water, presumably from higher irrigation applications. However, Na and Cl were not significantly different from 1994 to 2004, further indicating a change in irrigation practice among orchards irrigated with reclaimed water.

6. Conclusion

Few detrimental effects on citrus orchards have been associated with irrigation using the reclaimed water. However, the impact of using reclaimed water on groundwater contamination have not been determined. Appearance of trees irrigated with reclaimed water was usually better, with higher canopy, leaf color, and fruit crop ratings, than orchards irrigated with groundwater. Higher weed growth in reclaimed water irrigated orchards was associated with higher soil water content. However, growers apparently have made adequate adjustments to their herbicide practices. Higher soil water content in the orchards receiving reclaimed water resulted in reduced fruit soluble solids. However, because fruit crop ratings and larger fruit size indicated greater fruit yield, total soluble solids produced per ha were similar to or higher in the reclaimed water irrigated orchards than in the groundwater irrigated orchards. Irrigation with reclaimed water generally increases soil P and Ca, and reduces soil K. Reduction of P and Ca and increases in K applied to citrus orchards irrigated with reclaimed water may be required adjustments in fertilizer applications to citrus orchards irrigated with reclaimed water. Likewise, leaf B concentration increased in most citrus trees irrigated with treated wastewater, requiring an adjustment in foliar nutrient application practices.

7. References

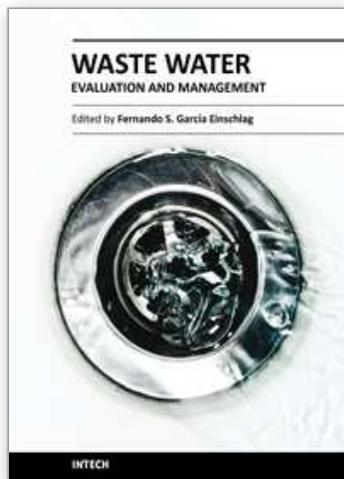
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Fresh water resources are under serious stress throughout the globe. Water supply and water quality degradation are global concerns. Many natural water bodies receive a varied range of waste water from point and/or non point sources. Hence, there is an increasing need for better tools to assess the effects of pollution sources and prevent the contamination of aquatic ecosystems. The book covers a wide spectrum of issues related to waste water monitoring, the evaluation of waste water effect on different natural environments and the management of water resources.

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