Urban Landscape Irrigation with Recycled Wastewater

by
Yaling Qian

March 2006

Completion Report No. 204

Urban Landscape Irrigation with Recycled Wastewater

by
Yaling Qian
Department of Horticulture and Landscape Architecture
Colorado State University

March 2006

Colorado Water Resource Research Institute
Completion Report Number

Funding provided by:

United States Geological Survey
Grant Number 01HQGR0077
Project Number 2003CO71B

Colorado Agricultural Experiment Station
Project Number 658

The Rocky Mountain Turfgrass Research Foundation

And

Horticultural Research Institute

Abstract

As the population of Colorado's Front Range continues to grow, increased use of recycled wastewater (RWW) is viewed as one approach to maximize the existing water resource and stretch Colorado's urban water supplies. Understanding the responses of urban landscape plants and soils to recycled wastewater irrigation and identifying proper management practices are critical to the long-term success of this practice. From 2003-2005, research was conducted to assess variability of chemical properties of recycled wastewater in the Front Range of Colorado and to evaluate landscape soils and plants that are currently under recycled wastewater irrigation.

Survey data indicated that, rather than cost savings, the availability and reliability of the water were the main reason for using RWW for irrigation.

Recycled wastewater samples were collected from irrigation ponds and sprinkler outlets on landscape sites. Results indicated that there were variations in water quality between wastewater treatment facilities. In all cases, the water samples met or exceeded the regulations in regard to of E. coli count as defined in the state Regulation 84, therefore the water is suitable for landscape irrigation. Nevertheless, RWW does contain varying quantities of soluble ions, with an average electrical conductivity (EC) value of 0.84 dS m^1. The chemical constituents of recycled wastewater were dominated by sulfate, bicarbonate, chloride, and sodium. The average sodium and chloride concentrations of 37 water samples collected from all the sites were 99 mg/L and 95 mg/L, respectively. Adjusted sodium absorption ratio (SAR) of RWW samples ranged from 1.6 to 8.3.

To assess recycled wastewater irrigation on the long-term changes of soil, we compiled soil test data from landscape sites that were near metropolitan Denver, CO. Among these sites, six had been irrigated exclusively with domestic RWW for 4, 5, 13, 14, 19, and 33 years, respectively. The other six with similar turf species, age ranges, and soil textures had used surface water (average EC = 0.23 dS m^{-1}) for irrigation. Our results indicated that soils (sampled to 11.4 cm) from sites where RWW was used for at least four years exhibited 0.3 units of higher pH and 200 percent, 40 percent, and 30 percent higher concentrations of extractable Na, B, and P, respectively. Compared to sites irrigated with surface water, sites irrigated with RWW exhibited 187 percent higher EC and 481 percent higher sodium adsorption ratio (SAR) of saturated paste extract. However, extractable Mg was reduced by 15 percent ($P < 0.005$). Comparison of soil chemical properties before and 4 or 5 years after RWW irrigation on two golf courses also revealed the following findings: a) 89-95 percent increase in Na content; b) 28-50 percent increase in B content; and c) 89 - 117 percent increase in P content at the surface depth.

Generally, turfgrasses had a good appearance, showing salinity damage only on a few sites with poor drainage, heavy soil structure, or shallow water table. However, chronic decline of conifer trees were often observed under RWW irrigation. Ponderosa pines grown on sites irrigated with RWW for 5-33 years exhibited 10 times higher needle burn symptoms than those grown on sites irrigated with surface water (33 percent vs. 3

percent). Tissue analysis indicated that ponderosa pine needles collected from sites receiving RWW exhibited 11 times greater Na^{+} concentration, two times greater Cl^{-}, and 50 percent greater B concentrations than samples collected from the control sites. Stepwise regression analysis revealed that the level of needle burn was largely influenced by leaf tissue Na^{+} concentration. Tissue Ca level and K/Na ratio were negatively associated with needle burn symptoms, suggesting that calcium amendment and K addition may help mitigate the needle burn syndrome in ponderosa pine caused by high Na^{+} in the tissue.

The project indicated that both problems and opportunities exist in using RWW for landscape irrigation. The use of recycled wastewater for irrigation in urban landscapes is a powerful means of water conservation and nutrient recycling, thereby reducing the demands of freshwater and mitigating pollution of surface and ground water. However, potential problems associated with recycled wastewater irrigation exist. Salts (especially the relatively high Na^{+} and high EC) in the treated wastewater were associated with needle burn symptoms observed in ponderosa pines subjected to RWW irrigation. The significantly higher soil SAR in RWW-irrigated sites compared to surface water irrigated sites provided reason for concern about possible long-term reductions in soil hydraulic conductivity and infiltration rate in soil with high clay content, although these levels were not high enough to result in short-term soil deterioration. This information is useful to landscape planners and managers to determine what should be monitored and what proactive steps should be taken to minimize any negative effects during planning and managing landscapes receiving recycled wastewater. Understanding the responses of urban landscape plants and soils to recycled wastewater irrigation and identifying proper management practices are critical to the long-term success of the water reuse practice.

Acknowledgements

The author thanks Dr. Robert Ward and many water managers and wastewater treatment specialists from Colorado water entities for guidance and discussion. Mr. Brent Mecham, Northern Colorado Water Conservancy District, contributed to the initial development of the survey forms and the initial soil sample collection, for which the author greatly appreciates. Gratitude is due to Ms. Sarah Wilhelm, Mr. Steve Lohman (Denver Water), Dr. Reagan Waskom, Dr. Jim Klett and Dr. Steve Newman for reviewing manuscripts, to Mrs. Ronda Koski for assisting in sample collection and data entry, and to Dr. Jinmin Fu for conducting plant tissue analysis.

Much assistance was provided by Mr. John Hoofnagle, Mr. Lance Johnson, Mr. Michael Osley, Mr. Chuck Clark, Mr. Don De Schepper, Mr. Marshall Fearing, Mr. Joel Christensen, Mr. Barry L Dunbar, Mr. Bob Kinder, and Mr. Chad Clark, who allowed and helped us to collect soil, water, and plant tissue samples from the landscape facilities, and contributed to the success of the project through their insight and advice.

Table of Contents

List of Tables

List of Figures

INTRODUCTION

The rapid population growth in many municipalities in the arid and semi-arid western United States continues to place increasing demands on limited fresh water supplies. Many cities and districts are struggling to balance water use among municipal, industrial, agricultural, and recreational users. The population increase has not only increased the fresh water demand but also increased the volume of wastewater generated. Treated or recycled wastewater (RWW) appears to be the only water resource that is increasing as other sources are dwindling. Use of RWW for irrigating landscapes is often viewed as one of the approaches to maximize the existing water resources and stretch current urban water supplies (US EPA, 2004).

Recycled wastewater (i.e. effluent water or reclaimed wastewater) is treated wastewater from the community to meet standards issued through Federal or State Water Acts. During treatment, suspended solids are removed, pathogens are disinfected, and partial to substantial reduction in nutrients occurs, depending on treatment stage (Harivandi, 1994; Pettygrove and Asamo, 1985). However, recycled wastewater may still contain different levels of dissolved solids, ions, nutrients (NO_3 and P_2O_4), and other elements.

Colorado has 1000+ wastewater treatment facilities and 500+ industrial treatment facilities. Along the Front Range of Colorado, the bulk of treated wastewater is discharged into rivers and watersheds. Wastewater disposal in rivers has the benefit of maintaining adequate flow and boosting water volumes for downstream users. However, river disposal may accelerate the eutrophication process in natural waters and increase costs to downstream public water systems. The U.S. Geological Survey's National Water-Quality Assessment program indicated that one of the principal contamination sources in the South Platte River basin is the discharge of wastewater from wastewater treatment plants (although manure and fertilizer are the largest contamination sources) (Litke, 1995 and 1996). Wastewater treatment plants discharge about 200 million m^3 per year of effluent water directly into the streams in the South Platte River basin, which contains 7000 tons of nitrogen and 860 tons of phosphorous.

Turfgrass needs to be fertilized to maintain color, density, and vigor, although the amount of fertilizer applied annually to turf depends on a number of factors (species, weather, soil, age, and clipping management). Nitrogen, P, and K are three important elements in maintaining a healthy turf stand with N causing the greatest response. Due to the dense plant canopy and active root systems, turfgrass landscapes are increasingly being viewed as environmentally desirable disposal sites for wastewater (Pepper and Mancino, 1993; Anderson et al., 1981). Research done in southern U.S. has indicated that dense, well-managed turfgrass areas are among the best bio-filtration systems available for removal of excess nutrients and further reclamation of RWW (Hayes et al., 1990; Pepper and Mancino, 1993).

An early water reuse project in Aurora, Colorado indicated excellent public acceptance of landscape irrigation with recycled wastewater (Warren and Swanson, 1981). Although the complexity of water rights in Colorado complicates the legal rights to reuse water, in general, imported water and nontributary water (such as water from deep aquifers) are usually available for reuse (Warren and Swanson, 1981). Using recycled wastewater in urban landscape irrigation can free-up potable water supplies for public consumption, thereby enhancing the long-term infrastructure for drought protection on the Front Range of Colorado. It also simultaneously reduces problems related to wastewater discharge and disposal. Using recycled wastewater for landscape irrigation in Colorado started in the 1960's in Aurora and Colorado Spring to irrigate golf courses. The demand of recycled water for landscape irrigation has since increased. To meet the demands, several wastewater treatment facilities have been constructed to provide recycled wastewater for urban landscape irrigation.

While the environmental and conservational benefits of wastewater reuse in landscape and turfgrass irrigation are obvious, the major concerns associated with wastewater reuse include: 1) additional costs in installing irrigation pipelines and irrigation equipment maintenance (such as, prevention of nozzle plugging); 2) health risk due to the possibility of the presence of pathogens; 3) salt damage to landscape plants and salt accumulation in soil surface and soil profile; and 4) leaching of excess nutrients to ground water.

To ensure human health and to protect environments, comprehensive regulations for water reclamation and reuse have been established in many states with water shortages (such as AZ, CA, FL, and TX) (State of Arizona, 1987; State of California, 1978; State of Florida, 1989; and State of Texas, 1990). Colorado represents a state that has begun to recognize water reuse as a viable alternative to surface water discharge and as a valuable water resource (Warren and Swanson, 1981). The first water reuse regulation in Colorado (Regulation No. 84) has been developed and became effective on November 30, 2000 (State of Colorado, 2000). Landscape irrigation (including golf courses, parks, greenbelts, open space, schools, cemeteries and business complexes) is the major permitted use under regulation 84.

There is limited information available in Colorado concerning the effects of irrigating with recycled wastewater on landscape plant performance and soil characteristics. Most research addressing these issues has been conducted in the Southwest U.S. where the soil type, turfgrass species, and climate conditions are quite different from Colorado. Research is needed on our unique soil and climate conditions and vegetation types. Information on the chemical and biological properties of recycled wastewater is useful in determining the long-term effects on landscape plants and soils. Water treatment facilities usually conduct water tests (including metals and pathogens) on a regular basis, and possess long-term records and treatment protocols. Such information is useful in assessing suitability and potential long-term effects of recycled wastewater irrigation on landscape plants and soil health if they are systemically collected and analyzed.

The growth in water reuse has created the need to investigate the effects of recycled wastewater irrigation on urban landscape soils, plants, and the ecosystem as a whole. This type of research will be useful to landscape planners and managers to determine what should be monitored and what proactive steps should be taken to minimize any negative effects during planning and managing landscapes receiving recycled wastewater. Understanding the responses of urban landscape plants and soils to recycled wastewater irrigation and identifying proper management practices are critical to the long-term success of this practice.

The objectives of this project were:

1) To assess variability of chemical properties of recycled wastewater applied to landscape in the Front Range of Colorado; and

2) To evaluate landscape plants and soils that are currently under recycled wastewater irrigation.

PROCEDURES

1. Survey of wastewater treatment facilities and landscape facilities:

For the first part of the project, we prepared and sent surveys to the wastewater treatment plants that were supplying water for irrigating landscapes in the greater Denver area (Appendix 1).

Our survey of the wastewater treatment facilities included questions that addressed issues regarding current wastewater disposal methods, volume, and reuse opportunities. The survey results provided information about the potential impacts of recycled wastewater on water infrastructure. Wastewater treatment plants were further contacted to request existing water quality analysis data, which include pH, biological oxygen demand (BOD), chemical oxygen demand (COD), E-coli, and other basic chemical characteristics.

Since most water treatment plants do not test agronomic parameters, such as salinity level and sodium concentration of recycled wastewater, water samples were collected from irrigation ponds, irrigation sprinkler outlets, and quick couplers at irrigation sites to test salinity level, sodium concentration, and bicarbonate content at the Soil and Water Testing Lab at Colorado State University.

We prepared and sent surveys to landscape facilities that are currently using recycled wastewater for irrigation (Appendix 2). Landscape managers were further interviewed to share their experience and provide insight about the best management practices to reduce problems associated with recycled wastewater irrigation.

To evaluate the landscape sites that are currently under recycled wastewater irrigation, five golf courses and one city park in the greater Denver area were selected for further investigation. These facilities had been irrigated with RWW for 4, 5, 13, 14, 19, and 33 years, respectively, as of 2003 (Table 1). On all recycled wastewater irrigation sites, RWW from wastewater treatment plants is stored in irrigation ponds and used exclusively as the irrigation source. For all golf courses, turfgrass grown on fairways were perennial ryegrass (*Lolium perenne* L.), Kentucky bluegrass (*Poa pratensis* L.), or a mixture of both. On average, fairways received approximately 65 cm of RWW and were fertilized at 75 kg ha^{-1} N annually. Gypsum was applied at 0.5-2.7 Mg ha^{-1} on fairways annually. At Golf Course II, an acid injection unit was used, and at Golf Course I and III, sulfur burner units were installed in the irrigation systems. The acid injection unit injects sulfuric acid into irrigation water as irrigation water enters the pump systems. Sulfur burner units heat elemental sulfur to create sulfurous acid that is injected into irrigation water. Both acid injection and sulfur burner units were installed to reduce the bicarbonate content and pH of irrigation water.

Concurrently, five golf courses and one city park with similar ranges in age, soil texture, landscape management regimes, and plant species, but irrigated with surface water were selected as controls (Table 1). Most of the surface water comes from melting snow of the Rocky Mountains and exhibits good quality (Table 3). Control sites were fertilized with about 150 kg ha^{-1} N annually. Turfgrass received approximately 55 cm of irrigation water annually. Gypsum was not applied. The average water quality values of surface water and recycled wastewater (RWW) used in all selected landscape sites are presented in Table 3.

2. Assessment of soil characteristics

Soil samples were collected from the selected landscape sites to evaluate the impacts of recycled wastewater irrigation on landscape soils. A total of 103 soil samples (54 samples were from sites with RWW irrigation and 49 were from sites with surface water irrigation) were collected to a depth of 11.4 cm in 2002-2003 to test soil chemical properties. Soil samples were tested by Brookside Laboratories, Inc, New Knoxville, OH. Parameters of each soil sample tested included pH, extractable salt content (Ca, Mg, K, Na, Fe, Mn, Cu, Zn, P, and B), base saturation percent of Ca, Mg, K and Na, soil organic matter (SOM) content, and cation exchange capacity (CEC).

Brookside soil-testing lab provided information on analytical methods. Soil pH was analyzed using a saturated paste extract. Sieved soil samples were extracted using the Mehlich III extractant (0.015 M NH_4F + 0.20 M CH_3COOH + 0.25 M NH_4NO_3 + 0.013 M HNO_3 + 0.0005 M EDTA chelating agent) to determine Ca, Mg, K, Na, Fe, Mn, Cu, Zn, B, and P by inductively-coupled plasma-emission spectrophotometry instrumentation. Mehlich III extracted Ca, Mg, K and Na plus soil buffer pH data are used to calculate CEC. Base saturation percent of Ca, Mg, K and Na was calculated by dividing the extracted Ca, Mg, K and Na by the calculated CEC, respectively. Base saturation percent of Na is considered the exchangeable sodium percentage (ESP). Soil organic matter was determined by reaction with $Cr_2O_7^{2-}$ and sulfuric acid. The remaining unreacted $Cr_2O_7^{2-}$ is titrated with $FeSO_4$ using ortho-phenanthroline as an indicator, and oxidizable organic matter was calculated by the difference in $Cr_2O_7^{2-}$ before and after reaction (Nelson and Summers, 1982).

In 2004, three additional soil samples from each site were collected to measure soil EC and SAR of saturation paste in the Soil, Plant, and Water Analytical Lab at Colorado State University. Electrical conductivity of soil saturation paste extract was determined with a conductivity meter. Cation (Ca, Mg, and Na) concentrations of saturated paste extracts were analyzed by inductively-coupled plasma-emission spectrophotometry instrumentation and SAR was calculated.

3. Assessment of ponderosa pine and turfgrass under RWW irrigation

Ponderosa pine trees were typically grown on the irrigated roughs along fairways of golf courses and along walkways and driveways in city parks in the greater Denver area. Turfgrass grown understory on all landscape sites were Kentucky bluegrass (*Poa pratensis* L.), perennial ryegrass (*Lolium perenne* L.), or a mixture of both. Turfgrasses were mowed at 5.1-7.6 cm during the growing season. Turfgrass on fairways were mowed at 1.5-2.0 cm.

Plant sampling from RWW-irrigated vs. surface water-irrigated sites. In 2004, ponderosa pine tree health on all sites was evaluated. On each golf course site, three fairways were randomly selected. On each fairway, we drove from tee to putting green, the first three ponderosa trees that we encountered were visually rated for plant health and two branchlets were collected for plant tissue analysis. On the park site, three ponderosa pine trees were randomly selected and visually rated for plant health and two branchlets were collected from each tree for plant tissue analysis. The sampling height was 1.5-2.5 m. The visual evaluation was done by rating the percentage needle area that showed leaf necrosis (needle burn). Turfgrass clippings were collected in the middle of each of the three selected fairways or three locations in the park. Turf quality was visually rated on a 1 to 9 scale, with 1 being dead, 9 being high quality, and 6 being acceptable turfgrass quality.

The sampled ponderosa pine branchlets were brought to the lab and needles were separated to different age groups. One and 3-year-old needles were selected for ion analysis. To measure ion concentrations, needles and turfgrass clippings were rinsed with deionized water to remove possible contamination from the surfaces and dried at 70 C for 24 hours. Dried plant tissues were ground in a Wiley mill to pass through a screen with 425-µm openings. Approximately 1 g of screened and dried sample was weighed and ashed for seven hours at 500 C. Ash was dissolved in 10 ml of 1N HCl and diluted with deionized water. Solution aliquots were analyzed for Na^{+} K^{+} Ca^{++}, Mg^{++}, B, and other metals by inductively-coupled plasma atomic emission spectrophotometry (ICP-AES) (Model 975 plasma Atomcomp, Thermo Jarrell Ash Corp., Franklin, Mass). Chloride was determined with a Cl-selective electrode (Model 96-17B, Thermo Electron Corp., San Jose, Calif.).

***4. Data analysis*.**

For water quality assessment, means and standard error were calculated for individual water quality variables from water samples collected from different sites and from different wastewater treatment facilities. Data were subjected to analysis of variance (SAS, 2005) to test the effect of irrigation water source on individual soil chemical characteristics, the degree of needle burn symptoms, turf quality, and ion concentrations of plant tissues. Stepwise regression and correlation analyses were performed to relate the degree of needle burn symptoms and turfgrass quality to plant tissue test variables. Means were separated using Fisher's protected LSD.

RESULTS AND DISCUSSION

1. Current status of water reuse in Colorado

Based on data from the Colorado Department of Public Health and Environment, Water Quality Control Commission there are about 10 permitted recycled wastewater facilities that treat wastewater for reuse purposes (Table 2). Currently, RWW reuse in the Front Range of Colorado is approximately 30-40 million gallons per day. There are several more water treatment facilities that will join the reuse program in the near future. Denver Water has completed a water recycling plant that can supply up to 30 million gallons per day. If we assume the landscape irrigation season is 6 months, then Denver Water's recycling plant can provide 5.5 billion gallons of recycled water each year, which will represent about 1/8 of the landscape irrigation water demand in the city of Denver (Denver water supplies ~82 billion gallons per year, of which 50 percent is used for landscape irrigation). However, there exists a seasonal imbalance between supply and demand.

Golf courses are by far the leading urban landscape users of recycled wastewater; mainly because golf courses have intensively managed turf (dense grasses utilize the nutrients in the wastewater) that requires a significant amount of water. A survey conducted in 1978 reported that 26 respondents across the country were using recycled wastewater. A more recent survey conducted by the National Golf Foundation (NGF) reported approximately13 percent of golf courses (approximately 2000 golf courses) nationwide now use RWW for irrigation, and this increased to 34 percent in the Southwest (GCSAA, 2003). In Colorado, the use of RWW has risen significantly in recent years. Based on a survey conducted by Colorado State University and Allied Golf Associations of Colorado, there are about 260 golf courses in Colorado and 61 percent of the irrigation water came from surface water while 10 percent was from recycled wastewater in 2000 (Davies et al., 2004) (Fig. 1). In 2001 the percentage of surface water declined to 59 percent and recycled wastewater use increased to 16 percent. By 2002, surface water use had declined to 52 percent and recycled wastewater had increased to 20 percent (Fig. 1).

Since most of the reuse takes place during the growing season, RWW generated during the winter season is generally discharged to the watershed. Lakes and ponds in golf courses can serve as storage sites. However, turf managers have to deal with problems associated with algae, weeds, and odor through aeration, air injection, and the use of fountains and water falls. Based on a study conducted at the University of Nevada, algae population (measured as algal chlorophyll) increased 436 percent in irrigation ponds as the irrigation water source changed from potable water to recycled wastewater (Devitt et al., 2005). The increasing algae problems will decrease the aesthetic value of the ponds.

Our survey on landscape facilities that use recycled wastewater indicated that cost was not the driving force for landscapes to use RWW. Rather the availability and reliability of the water were rated as the two main reasons for using RWW for irrigation. This is not surprising considering drought conditions during 2001-2004. The extreme drought in 2002 caused several golf courses to shut down due to the restrictions on the use of potable water for irrigation at golf courses.

There is generally no economic advantage for golf courses to use RWW for irrigation over ditch water or well water. Based on our survey, the average cost for ditch water and recycled wastewater for golf courses are $70 and $291 per acre foot, respectively, along the Front Range of Colorado. Golf Course I paid $245 per acre foot in 2003 with a 9 percent increase in price each year through 2011 for recycled wastewater while the previous water source (canal water) only cost $75 per acre foot. Golf Course V pays $488 per acre foot for RWW. Golf Course III pays $385 per acre foot. Golf course II pays nothing for their RWW, instead they built the infrastructure for bringing the water which cost over $100,000. However, compared to potable water use for landscape irrigation, there is generally an economic advantage for golf courses to use RWW, although the advantages vary from site to site.

2. Water Quality Assessment:

As the criteria set forth in Regulation 84 (State of Colorado, 2000), water treatment professionals typically use human health related parameters such as E-coli count, turbidity, total suspended solids, nitrogen and phosphorous content to evaluate water quality. Data from five advanced wastewater treatment plants in the Front Range of Colorado revealed that, although there were variations in water quality between wastewater treatment facilities, in all cases, the water quality of effluent exceeded the regulations in the terms of E-coli count, turbidity, and suspended solids as stated in Regulation 84, i.e. the values of e-coli count, turbidity, and suspended solids were lower than the allowed standards (Table 3).

While these water quality criteria do help to protect public health and the environment, they do not address the water chemistry considerations that affect the suitability of treated wastewater for landscape irrigation. Landscape managers are often concerned about salinity and sodicity related parameters, as well as other chemical constituents. Recycled wastewater chemistry tends to be dominated by sulfate, bicarbonate, chloride, and sodium. These 4 ions comprise of about 70 percent of total dissolved salts (Table 3). Sodium, bicarbonate, chloride, and boron are typically added to domestic wastewater as a result of food processing, water softening, the use of soap and detergent, etc. These inorganic ions are not reduced by conventional sewage treatment that is aimed to remove solids, decrease organic matter, disinfect pathogens, and reduce nutrient levels.

Water testing results of 37 RWW samples collected from 6 landscape sites (Table 3) were reviewed for suitability in landscape irrigation based on irrigation water quality guidelines established for irrigated agriculture (Table 4). The guidelines in Table 4 were initially adapted from the University of California Committee of Consultants to cover a wide range of conditions encountered in California's irrigated agriculture. These guidelines have been adapted for wastewater irrigated agricultural land (Westcot and Ayers, 1985) and for recycled wastewater irrigated urban landscapes and golf courses (Huck, 1994; Harivandi, 1994).

The average electrical conductivity (EC) of over 30 recycled wastewater samples from 6 reuse sites was 0.84 dS/m and the range was 0.47 to 1.32 dS/m. An electrical conductivity higher than 0.75 dS/m indicates the water may impose negative effects on salt sensitive plants. Periodic leaching of salts is required to mitigate the potential salinity problem.

Adjusted sodium absorption ratio (SAR) of recycled wastewater from reuse sites ranged from 1.6 to 8.3. Based on the interactive effect of salinity and sodicity on soil infiltration and percolation, most of the water samples collected showed slight to moderate effects on soil infiltration and permeability (Table 4 and Fig. 2). Additional management (such as Ca product topdressing or amendments and frequent aerification) is needed to mitigate these effects.

One of the other concerns of recycled wastewater irrigation is the presence of high levels of particular ions (sodium, chloride, and boron) that are toxic to some trees and shrubs. With sprinkler irrigation, sodium and chloride frequently accumulate by direct adsorption through the leaves that are moistened. Sodium and chloride toxicity could occur on sensitive plants when their concentrations exceed 70 and 100 mg/L, respectively. The average sodium concentration of over 30 water samples collected was 99 mg/L, ranging from 30 to 170 mg/L. The average chloride concentration was 95 ppm. Chloride leaches easily through the soil profile and chloride toxicity to turf and landscape plants should be minimal if soil is well drained and salts are regularly leached. However, if the sites have poor drainage, soil percolation is impaired or limited, or have a shallow water table present, chloride applied over time can accumulate to a toxic level.

The N concentration found in this study was lower than what has been reported for recycled wastewater by the wastewater treatment plants (Lazarova and Bahri, 2005). The discrepancy likely resulted from the difference in sampling sites. Samples collected in this study were from irrigation ponds and quick couplers after irrigation pond storage. Algae in irrigation ponds may have used up some of the N in RWW. As landscape managers start to use RWW for irrigation, they need to have the water source tested on regular basis, and calculate N and P input via RWW irrigation. These amounts of N and P should be deducted from their fertilization program. For example, if N content in RWW is 10 ppm, then 27 lb nitrogen per acre is added per acre-foot of irrigation water. This amount of N should be deducted from the fertilization program.

It needs to be noted that the wastewater treatment systems have and will continuously evolve in response to the growth and regulatory requirements. Regular monitoring will be helpful to assess the potential dynamics of RWW quality.

3. Impacts of recycled wastewater irrigation on landscape soils: Comparison of reuse sites vs. surface water irrigated sites

Sites irrigated with RWW exhibited an average soil salinity of 4.3 dS m^{-1} that was 187 percent higher than sites irrigated with surface water (EC=1.3 dS m^{-1}) (Qian and Mecham, 2005) (Table 5). Variations in the increase in EC under RWW irrigation appeared to relate to soil texture and drainage effectiveness (data not shown). Previously, Qian et al. (2001) reported that the salinity levels that caused 25 percent shoot growth reduction were 3.2 dS m^{-1} for a salt-sensitive Kentucky bluegrass cultivar and 4.7 dS m^{-1} for a salt-tolerant Kentucky bluegrass cultivar. It is apparent that the salinity build-up in sites irrigated with RWW would result in growth reduction of salt sensitive Kentucky bluegrass cultivars that may slow the recovery of turf from traffic injury and /or other biotic and abiotic stresses.

Soils from sites with RWW for irrigation exhibited 200 percent (278 mg kg^{-1}) higher concentration of extractable Na and 24 percent higher concentration of extractable Ca than sites irrigated with surface water (Table 5). The high Na content reflected the greater than 6 fold increase in Na via RWW. The higher Ca in RWW-irrigated sites than the control sites likely resulted from the combination of a 3.8 fold higher concentration of Ca in RWW and the regular application of gypsum. Higher Ca and Mg in the RWW combined with gypsum application helped prevent a greater degree of Na build up in the soil.

Extractable P at the surface 11.5 cm depth was 30 percent higher from sites with RWW irrigation than sites with surface water irrigation (Table 5). Runoff of P was likely to be minimal from turf sites due to the dense vegetation cover that could effectively prevent phosphorus runoff.

Soil pH was higher (approximately 0.3 units) in RWW-irrigated sites than in the control sites. Increases in soil pH under land application of wastewater have been previously reported (Schipper et al., 1996; Mancino and Pepper, 1992). In New Zealand, Schipper et al. (1996) found an increase in soil pH by 0.8 units after applying tertiary-treated domestic wastewater to a forest site for three years at 4.9 cm wk^{-1}. The author suggested that the rise in soil pH was likely related to a high rate of denitrification that produced hydroxyl ions. Mancino and Pepper (1992) found that recycled wastewater irrigation increased soil pH by 0.1-0.2 units when compared to potable water irrigation. The soil pH increase in our study likely resulted from the 0.2 unit higher pH and higher bicarbonate concentration in RWW than surface water. The average bicarbonate concentration in the RWW was 112 ppm. The small magnitude of increase in soil pH in this study suggests the effectiveness of management (such as using acid injection and utilization of a sulfur burner) in controlling soil pH. Golf Courses IV and V that did not receive acidification treatments exhibited 0.3-0.4 units higher soil pH than other RWW-irrigated sites (data not shown).

Soil B content was about 40 percent higher in the RWW-irrigated sites than in surface water irrigated sites. Although the average B concentration in the RWW was only 0.23 ppm, lower than the permissible limits for the allowable concentration of boron in irrigation water presented by Van der Leeden et al. (1990), we consistently observed an increase in B content in the soil. Likely the accumulation of B was associated with the borate adsorption by soil. With increasing soil pH, boron adsorption by soil would increase, reaching the maximum B adsorption by soil at a pH of 9 (Ayers and Westcot, 1985).

Despite the fact that Mg content was 2-fold higher in RWW than surface water (Table 2), soil Mg content was 15 percent lower in RWW-irrigated sites than the control sites (Table 3). The cation exchange site occupied by Mg was reduced, reflecting the replacement of this element with Na. In addition, application of gypsum might also reduce soil exchangeable Mg^{2+} since Ca^{2+} has much higher adsorption affinity than Mg^{2+}.

The ESP and SAR for RWW irrigated sites was 230 percent and 481 percent higher than the surface water irrigated soil, respectively (Table 5). Soil ESP and SAR would have continued to increase without the regular amendment of Ca products. In soil collected from the rough at Golf Course II that was not amended with Ca products, the ESP rose to as high as 15.0. Although the ESP and SAR values on most reuse sites are not high enough to be classified as a sodic soil, Halliwell et al. (2001) stated that the dispersion and deflocculation effects of sodicity might be evident in soils that are well below reported threshold values. Long-term uses of RWW with marginal high SAR_{adj} may result in reductions of soil infiltration and permeability in clayey soils and for sites with high traffic and compaction pressure. Further research is needed to monitor the soil hydraulic properties for sites irrigated with RWW.

Our results indicated predominant differences in soil SAR, EC, ESP, extractable soil Na, Ca, P, B, and Mg concentration and soil pH between RWW-irrigated and surface water-irrigated sites ($P < 0.001$). Differences in CEC, SOM, and K content between the two types of irrigation sites were not significant.

4. Effects of Long-Term Recycled Wastewater Irrigation on Visual Quality and Ion Concentrations of Ponderosa Pine and Turfgrass

Turfgrass

Generally turfgrasses exhibited good appearance, with both surface water and recycled wastewater irrigation (Table 6). We observed salinity stress on some localized sites with fine soil texture and poor drainage that were irrigated with RWW. Several fairways on Golf Course IV, which had been irrigated with RWW for 33 years, were replaced by more salt tolerant grass, such as alkaligrass [*Puccinellia distans* (L.) Parl].

The slight, but not significant, decline of turfgrass quality irrigated with RWW likely resulted from increased soil salinity level. Sites irrigated with RWW exhibited an average soil salinity of 4.3 dS m^{-1} , 187 percent higher than sites irrigated with surface water (EC=1.3 dS m^{-1}) (Table 6). Regression analysis indicated that there was a linear negative relationship between soil EC and turfgrass quality. Turfgrass clipping analysis indicated that clippings collected from sites irrigated with RWW exhibited higher concentrations of Na (6.4 times), Al (1.7 times), B (1.3 times), Mn (92 percent), S (65 percent), Si (37 percent), Ca (33 percent), Sr (44 percent) than samples collected from the control sites (Table 6).

Ponderosa Pine

Greater variations (CV = 37.4) in the incidence of needle burn or dieback existed among plants of ponderosa pine under RWW irrigation (Qian et al., 2005). On average, ponderosa pines grown on sites irrigated with RWW exhibited 10 times greater needle burn symptoms than those grown on sites irrigated with surface water (33 percent vs. 3 percent) (Table 7). The needle burn symptoms included needle tip necrosis, resin-infiltrated bands, and necrosis of distal regions of the needles. Severely affected trees exhibited needle dropping and/or thinning. We observed a few of the trees had died and those trees were excluded from the quality evaluation and sample collections. The ion concentrations in the needles were not different between year 1 and 3 needles; therefore, data were pooled for analysis. Tissue analysis indicated that ponderosa pine needles collected from sites irrigated with RWW exhibited 11 times greater Na^+, two times greater Cl^-, and 50 percent greater B concentrations than samples collected from the control sites (Table 7). The needle K/Na ratio of ponderosa pines receiving surface water for irrigation was 12.4, compared to 1.0 in RWW irrigated pines. In addition, ponderosa pine receiving RWW for irrigation had 39, 20 percent, 148 percent, 84 percent, 31 percent, and 53 percent higher Mn, P, S, Si, Ba, and Li concentrations in needles when compared to surface water irrigated ponderosa pines. Despite the fact that Mg concentration was 2-fold higher in RWW than surface water (Table 4), needle Mg concentration was 19 percent lower in RWW-irrigated pine than those receiving surface water (Table 7). This may reflect the replacement of Mg^{++} with Na^+ in soil cation exchange sites. Therefore, the chemical concentration in foliar tissue perhaps was not only influenced by the chemical constituents of RWW, but also by the individual salts readiness to leach, uptake and transport by plants, ability to compete with other ions, and compartmentation characteristics.

The needle burn symptom (including needle tip necrosis, a reddish brown color and a distinct boundary between the healthy and damaged parts of the needle) and high tissue Na and Cl accumulations have been described as typical symptoms of salt injury (Sucoff et al., 1975). Previously, Staley et al. (1968) described foliar chlorosis and tipburn syndrome of ponderosa pine in Denver area. After more than 10 years of examination and cultural treatment that implicated no fungal or insect causal agents, they found that the affected needles contained abnormally high levels of Na^+. The levels were 13 times higher than needles of healthy trees. The authors did not specify the source of Na^+. In a greenhouse study, Spotts et al. (1972) found that ponderosa pine tipburn syndrome was first observed on chloride salt-treated plants. They also found that pine injury that resulted from NaCl exceeded the injury degree induced by Ca and Mg chlorides.

Relationship of visual quality decline and degree of ion accumulations.

Regression analysis revealed that needle burn was largely influenced by needle Na^+ concentration with a linear regression coefficient of 0.77 (Fig. 3), indicating increasing needle burn was at least partially associated with the Na^+ accumulation in the needles. When needle Na^+ concentration increased beyond 1500 mg/kg, leaf tip burn became visually apparent. In a study evaluating the impact of NaCl applied to highways for deicing on pines and cedars, Hofstra and Hall (1971) also found that the percentage of necrotic foliage and the percentage of Na^+ and Cl^- in the leaf tissue were closely related.

In addition to Na concentration, stepwise regression analysis revealed that increasing Cu and Ni also exhibited positive relations with increasing levels of needle burn, although needle Cu and Ni concentrations did not differ significantly between surface water- and RWW-irrigated ponderosa pines (Table 7). Tissue Ca^{++} level and K/Na ratio were negatively associated with needle burn, suggesting Ca^{++} amendment and K^+ addition may help mitigate the needle burn syndrome in ponderosa pine associated with high Na^+ in the tissue. In a greenhouse study, Warren et al. (2004) found that $CaCl_2$ amendment improved shoot growth and visual appearance of loblolly pine (*Pinus taeda* L.) irrigated with untreated laundry wastewater. Supplemental additions of Ca^{++} have been found to improve soil structure, water infiltration, and leaching. The actions of Ca^{++} in salt stressed plants also include the reduction of sodium binding to cell walls and plasma membrane, alleviating membrane leakiness, and preventing salt-induced decline in cell production and elongation (Bressan et al., 1998; Rengel 1992), and improving uptake of important nutrients such as K^+ (Cramer et al., 1987). Metabolic toxicity of Na^+ is also a result of its ability to compete with K^+ for binding sites essential for cellular function. More than 50 enzymes are activated by K^+, but Na^+ cannot substitute in this role (Tester and Davenport, 2003). Thus high levels of Na^+ or low K/Na ratio can disrupt various enzyme processes in the cytoplasm. The decline in ponderosa pine health in this study might be associated with failure of maintenance of adequate K/Na ratio.

Different conifers and pine species differ in their salt tolerance. In a greenhouse study to assess salinity tolerance of 20 landscape trees and shrubs, Monk and Peterson (1962) ranked ponderosa pine as intermediate in its salinity tolerance. During the 2-year experiment, ponderosa pine survived irrigation water at 6,000 mg/L total dissolved salts, whereas nine other species [including blue spruce (*Picea pungens* Engelm.), Douglas fir (*Pseudotsuga menziesii* Franco), black walnut (*Juglans nigra* L.), linden (*Tilia cordata* P.

Mill.)] did not survive the lowest salt treatment (4,000 mg/L total dissolved salts). In comparison, five species [including black locust (*Robinia pseudoacacia* L.), honeylocust (*Gleditsia triacanthos* L.)] survived 10,000 mg/L salt treatment. In evaluating various pine species in Southern Ontario that were grown along the roadside and subjected to winter NaCl de-icing, Hofstra and Hall (1971) reported that white pine (*Pinus strobus* L.) and red pine (*Pinus resinosa* L.) were highly damaged, Scots pine (*Pinus sylvestris* L.) was moderately damaged, and Austrian pine (*Pinus nigra* Arnold.) and mugo pine (*Pinus mugo* Turra) suffered little damage. The authors further demonstrated that although Austrian and mugo pine generally were far less damaged than other pines, individual plants showed varying amounts of injury. However, all pines contained similar levels of Na^+ and Cl^- at similar levels of damage. Townsend and Kwolek (1987) found that ponderosa pine have a higher salt tolerance than white pine and cembra pine (*Pinus cembra* L.), and Scots pines. From studies conducted in northern California and Nevada using synthetic wastewater, Jordan et al. (2001) and Wu et al. (2001) found that some pines, including stone pine (*Pinus pinea* L.), mondell pine [*Pinus eldarica* (Medw.) Silba.], and aleppo pine (*Pinus halepensis* L.), were salt tolerant and were recommended for use in sites with RWW sprinkler irrigation.

SUMMARY AND RECOMMENDATIONS

The issues surrounding recycled wastewater irrigation are complex and further research is needed to provide more information.

Both problems and opportunities exist in using recycled wastewater for landscape irrigation. Water reuse in urban landscapes is a powerful means of water conservation and nutrient recycling, thereby reducing the demands of freshwater and mitigating pollution of surface and ground water. Wastewater treatment facilities may realize cost savings due to disposal costs and the sale of the recycled water. Communities can benefit from reuse by eliminating or delaying the cost associated with obtaining additional sources and facilities for freshwater. Due to these reasons, currently there are hundreds of successful water reclamation and reuse operations in the United States.

The challenge of water reuse is to maintain long-term sustainability. Two main concerns over the use of recycled wastewater for irrigation are 1) potential problems caused by excessive sodium and salinity, and 2) excessive nutrients or nutrient imbalance. Soil salinity is a function of soil type, management, salinity of water used for irrigation, and the depth of water table. Clay soil is more prone to salt accumulation and sodium deterioration. A shallow water table can reduce leaching and introduce salts to the root zone. Therefore, the most salinity susceptible sites are sites with shallow water table, high clay content, poor drainage, and great soil compaction. Management practices that reduce water table, cap the topsoil with sand (especially for sports fields), improve drainage, and reduce compaction would reduce the potential sodium problems.

Based on our previous experiments and literature review (Lazarova and Bahri, 2005). The following are the best management practices that we can recommend for managing turf irrigated with reclaimed wastewater:

- ✓ Regularly monitor water and soil quality with water quality enforcement guidelines.
- ✓ Adequate leaching and provide sufficient drainage to remove excess Na and salts from the root zone;
- ✓ Additional chemical amendments to displace Na and reduce exchangeable sodium percentage;
- ✓ Addition of gypsum to irrigation water to adjust the SAR of irrigation water;
- ✓ Careful irrigation based on evapotranspiration and leaching requirements;
- ✓ Conversion to low angle nozzles to reduce leaf damage on trees and shrubs;
- ✓ Use conventional water with treated RWW in rotation;

- ✓ Dual plumbing to irrigate golf course greens with conventional water in cases of excessively high SAR or high salinity, as a last resort.
- ✓ More intensive cultivation programs (deep aeration and water injection) to maintain oxygen diffusion and water movement;
- ✓ More vigorous traffic control programs.
- ✓ Reduced nitrogen and phosphorous fertilization, accounting for the fertilizer value present in recycled wastewater;
- ✓ Fertilize to alleviate nutrient imbalance.
- ✓ Replace susceptible plants with better climate and soil adapted, salt tolerant species and cultivars;
- ✓ Maintain healthy plants – healthy plants withstand salinity better.

Table 1. Age of landscape facilities, years of recycled wastewater irrigation (RWI), principal soil series, and surface texture of principal soil series of landscape facilities selected for the project to evaluate long-term recycled wastewater irrigation (RWI) on soil properties and landscape plant health.

Experimental Site	Age	Years of RWI	Water Source	Principal soil series	Surface texture classification
Golf Course I	6	4	RWW	Renohill Ulm Platner	Clay loam Clay loam Loam
Golf Course II	47	19	RWW	Renohill Nunn Bresser	Clay loam Clay loam Sandy loam
Golf Course III	29	14	RWW	Renohill Fondis	Clay loam Silt loam
Golf Course IV	33	33	RWW	Fondis Nunn	Silt loam Clay loam
Golf Course V	13	13	RWW	Nunn Arvada	Clay loam Loam
City Park I	6	5	RWW	Platner Ulm	Clay loam Silt clay
Golf Course A	11		Ditch	Nunn Ulm	Clay loam Clay loam
Golf Course B	38		Ditch	Nunn Fort Collins	Clay loam Loam
Golf Course C	34		Ditch	Loveland	Clay loam
Golf Course D	38		Ditch	Nunn	Clay loam
Golf Course E	13		Ditch	Table Mountain Paoli Caruso	Loam Loam Loam
City Park A	8		Ditch	Nunn Fort Collins	Clay loam Loam

Table 2. Permitted recycling wastewater treatment facilities providing recycled wastewater for landscape irrigation in Colorado.

Facility	Treatment Capacity (million gallons per day)	Anticipated Reuse Volume (million gallons per day)
City of Aurora Sand Creek Reuse Plant	5	5
Centennial Water and Sanitation	3	1
City of Westminster	6	6
Plum Creek Wastewater Authority	3.55	1.2
City of Louisville	0.145	0.145
Upper Monument Creek	0.5	0.5
Colorado Springs-LVSWWTF	6	6
Fairways Metro District	0.107	0.103
Town of superior	2.2	1.2
Denver Water Recycling Plant	30	15
Total	**56.5**	**36.1**

Table 3. Average water quality values of ditch water and recycled wastewater (RWW) from advanced wastewater treatment plants in Colorado.

	Average†	
Parameter	Recycled wastewater	Ditch water
Total suspended solid (mg/L)	11.7 (0.9)	N/A
Turbidity (NTU)	1.64 (0.05)	N/A
E-coliform (E.coli/100ml)	9.7 (3.1)	N/A
pH	8.1 (0.6)	7.9 (0.3)
NH_4-N (ppm)	0.76 (0.20)	N/A
NO_3-N (ppm)	3.62 (0.33)	0.42 (0.16)
Total P (ppm)	0.47 (0.06)	0.10 (0.04)
Total dissolved solids (TDS) (ppm)	614 (44)	126 (35)
Conductivity (dS m^{-1})	0.84 (0.07)	0.23 (0.08)
SAR	3.1 (0.2)	0.9 (0.2)
Adjusted SAR	5.0 (0.3)	1.2 (0.2)
Sodium (ppm)	99 (5)	15 (5)
Chloride (ppm)	95 (6)	8 (4)
Bicarbonate (ppm)	112 (7)	57 (21)
Calcium (ppm)	61 (3)	16 (6)
Magnesium (ppm)	15 (1)	5 (2)
Sulfate (ppm)	160 (10)	25 (19)
Boron (ppm)	0.23 (0.02)	0.04 (0.01)
Iron (ppm)	0.35 (0.07)	0.53 (0.30)
Potassium (ppm)	12.7 (2.2)	0.90 (0.05)

† Average values of 37 RWW samples and five ditch water samples, respectively. N/A = data not available. Numbers in parenthesis indicate standard error.

‡ Adjusted SAR is calculated using the adjustment procedure documented by Westcot and Ayers (1985).

Table 4. Guidelines for interpretation of water quality for irrigation (From Ayers and Westcot, 1985).

Potential irrigation problem	Units	Degree of restriction on use		
		None	Slight to moderate	Severe
Salinity				
EC_w †	dS/m or mmho/cm	<0.7	0.7-3.0	>3.0
Total dissolved solids	mg/L	<450	450-2000	>2000
Permeability (Evaluate using EC_w and SAR together) ‡				
SAR=0-3	and EC_w	>0.7	0.7-0.2	<0.2
=3-6		>1.2	1.2-0.3	<0.3
=6-12		>1.9	1.9-0.5	<0.5
=12-20		>2.9	2.9-1.3	<1.3
=20-40		>5.0	5.0-2.9	<2.9
Specific ion toxicity (affects sensitive crops)				
Sodium				
Surface irrigation	SAR	<3	3-9	>9
Sprinkler irrigation	mg/L	<70	>70	-
Chloride				
Surface irrigation	mg/L	<140	140-350	>350
Sprinkler irrigation	mg/L	<100	>100	
Boron	mg/L	<0.7	0.7-3.0	>3.0
Bicarbonate (Overhead sprinkling only)	mg/L	<90	90-500	>500
pH	Normal range	6.5-8.4		
Residual chlorine (Overhead sprinkling only)	mg/L	<1.0	1.0-5.0	>5.0

† EC_w means electrical conductivity of the irrigation water.
‡ SAR means sodium adsorption ratio. For recycled wastewater, it is recommended that SAR be adjusted considering bicarbonate and sodium content in the water (Westcot and Ayers, 1985).

Table 5. Mean soil chemical properties from golf courses with long-term recycled wastewater irrigation vs. soils receiving surface water irrigation.

Soil Parameter	Recycled Water Irrigation	Surface Water Irrigation
Cation Exchange Capacity (meg/100g)	31.3	27.8
pH	7.7***	7.4
Ca (mg kg^{-1})	4524**	3605
Mg (mg kg^{-1})	518**	611
Na (mg kg^{-1})	419***	141
Fe (mg kg^{-1})	139*	172
Mn (mg kg^{-1})	58*	41
Cu (mg kg^{-1})	3.3*	5.7
Zn (mg kg^{-1})	12.0	11.1
OM (%)	3.1	3.1
Extractable P (mg kg^{-1})	75.0***	58.0
Boron (mg kg^{-1})	1.54**	1.10
Al (mg kg^{-1})	219*	304
K (mg kg^{-1})	395	375
Ca(%)	71.8	70.4
Mg%	14.4*	18.8
K%	3.6	4.2
Na%	6.6*	2.0
Electrical conductivity (dS m^{-1})	4.3*	1.5
Sodium adsorption ratio (SAR)	9.3***	1.6

*, **, *** Significantly different from surface water-irrigated sites at $P \leq 0.05$, ≤ 0.005, and < 0.001, respectively.

Table 6. Mean grass clipping ion concentrations of Kentucky bluegrass and perennial ryegrass grown on sites under long-term recycled wastewater (RWW) irrigation vs. surface water irrigation†

Parameters	Surface water	Recycled waste water
Soil EC (dS/m)	1.05*	2.6
Turf quality (1-9)	8.93	6.9
Al	164.47**	447.7
B	9.03**	20.5
Ca	3754.30**	5002.5
Fe	295.71	377.1
K	19047.80	17874.5
Mg	1610.33	1624.1
Mn	52.86**	101.6
Na	449.60**	3315.3
P	4915.00	4605.4
S	2547.90**	4214.8
Si	462.63*	632.0
Zn	45.05**	34.7
Ba	8.66	7.7
Cd	0.06	0.1
Cu	5.12	4.8
Li	9.04	10.8
Mo	2.55	2.8
Ni	0.74	0.9
Sb	0.14*	0.1
Sr	22.70**	32.6

† unless indicated, unit is mg kg^{-1}

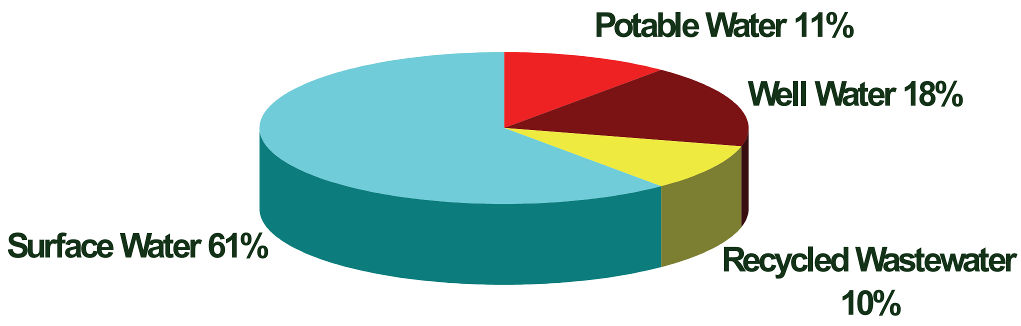
*, ** Significantly different between RWW-irrigated vs. surface water-irrigated sites at $P \leq 0.05$, ≤ 0.005, and < 0.001, respectively.

Table 7. Mean needle ion concentrations of ponderosa pine grown on sites under long-term recycled wastewater (RWW) irrigation vs. surface water irrigation. †

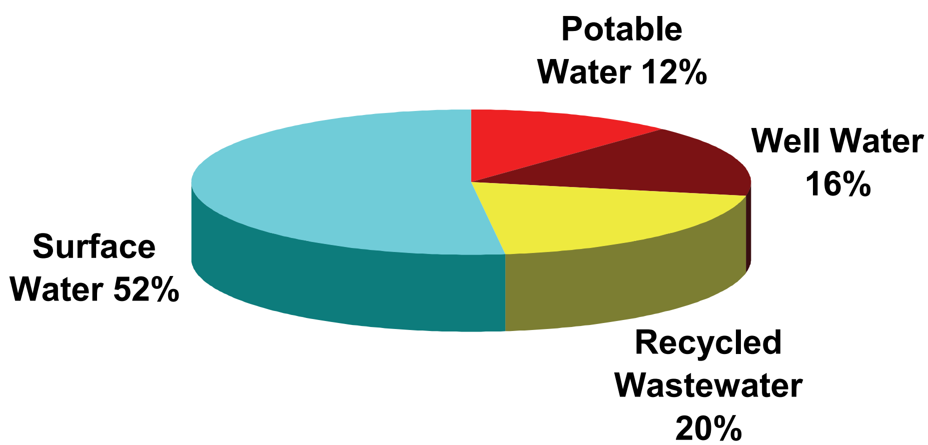
Parameters	Surface water	Recycled waste water
Soil EC (dS m^{-1})	0.89	1.9** [y]
Needle burn (0-100%)	3.17	33.6**
Al [z]	131.11	125.8
B	32.69	50.3**
Ca	3827.10	3321.0
Fe	167.79	149.5
K	2421.80	2497.8
Mg	1273.80	1030.9*
Mn	26.77	37.1**
Na	195.60	2475.2**
Cl	1383	3248.0**
P	869.41	1042.8*
S	391.20	971.5**
Si	393.01	722.4**
Zn	21.59	24.93
Ba	2.12	2.77**
Cd	0.06	0.06
Cu	2.56	2.74
Li	6.39	9.80**
Mo	0.32	0.33
Ni	0.17	0.15
Sb	0.09	0.05
Sr	16.47	14.88

† unless indicated, unit is mg kg^{-1}

*, ** Significantly different from surface water-irrigated sites at $P \leq 0.05$, ≤ 0.005, and < 0.001, respectively.



2000



2002

Fig. 1. Percentages of golf courses in Colorado to use particular irrigation water sources. (From Davies et al., 2003.)

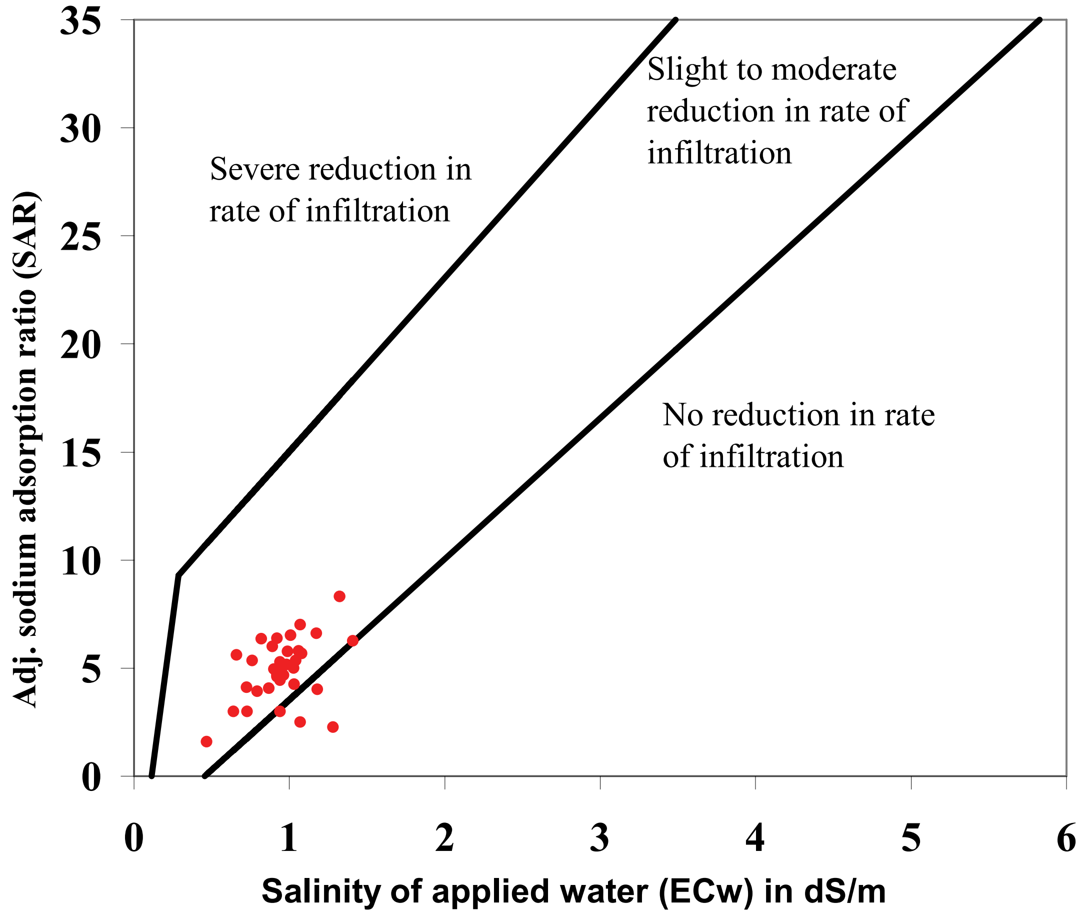


Fig 2. Relative rate of water infiltration as affected by salinity and adjusted sodium adsorption ratio of irrigation water (Adapted from Ayers and Westcot, 1985). The dots are the data points of water samples collected from Colorado water reuse sites.

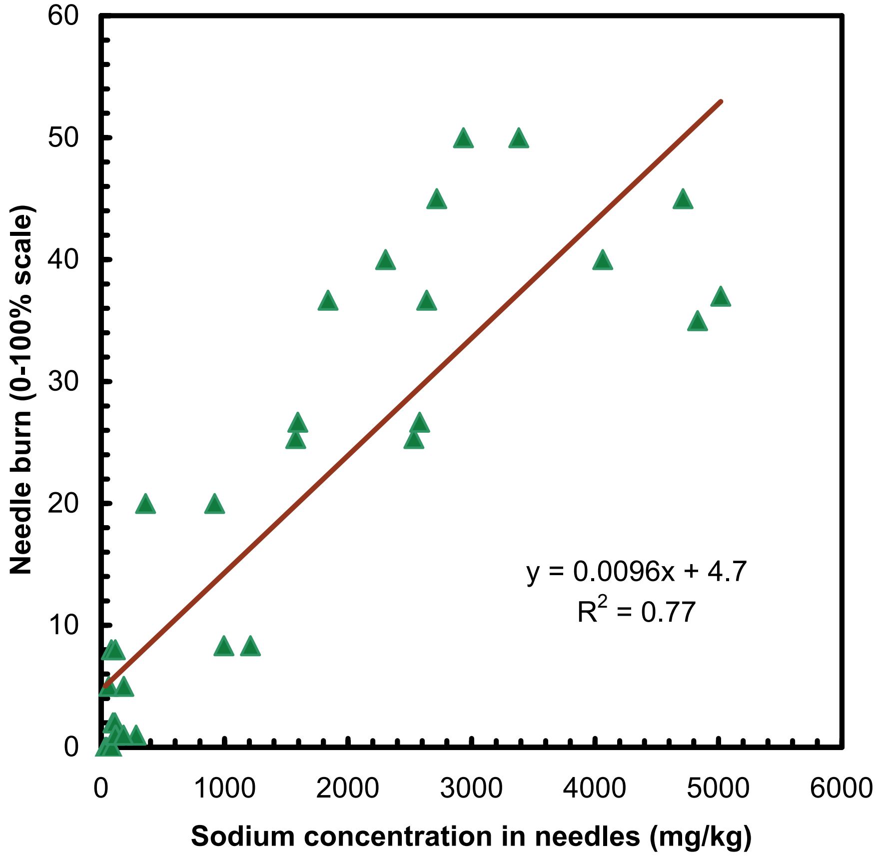


Fig. 3. Linear regression of the degree of needle burn and sodium concentration in needles of ponderosa pine subjected to recycled wastewater for irrigation.

LITERATURE CITED

Anderson, E.L., I.L. Pepper, and W.R. Kneebone. 1981. Reclamation of wastewater with a soil turf filter: I. Removal of nitrogen. J. Water Poll. Control Fed. 53:1402-1407.

Ayers, R.S. and D.W. Westcot. 1985. Water quality for agriculture. FAO irrigation and drainage paper No. 29. Rome: Food and Agriculture organization of the United Nation (FAO).

Bressan, R.A., P.M. Hasegawa, J.M. Pardo. 1998. Plants use calcium to resolve salt stress. Trends in Plant Sci. 3: 411-412.

Cramer, G.R., J. Lynch, A. Lauchli, and E. Epstein. 1987. Influx of Na^+, K^+, and Ca^{++} into roots of salt stressed cotton seedlings. Plant Physiol. 83:510-516.

Davies, S., P. Watson, D. Thilmany, A. Cramer, J. Wilson. P. Elzi and N. Prosser. 2004. Golf in Colorado: An Independent Study of the 2002 Economic Impact and Environmental Aspects of Golf in Colorado. Report to the Colorado Golf Association. http://www.golfhousecolorado.org/cga/index.html

Devitt, D.A., R.L. Morris, M. Baghzouz, M. Lockett, and L.K. Fenstermaker. 2005. Water quality changes in golf course irrigation ponds transitioning to reuse. HortScience 40:2151-2156.

Golf Course Superintendents Association of America. 2003. Water woes: a new solution for golf courses. At http://www.gcsaa.org/news/releases/2003/june/effluent.asp

Halliwell, D. J., K.M. Barlow, and D.M. Nash. 2001. A review of the effects of wastewater sodium on soil physical properties and their implications for irrigation systems. Aust. J. Soil Res. 39: 1259-1267.

Harivandi, A. 1994. Wastewater reuse for golf course irrigation. Lewis Pub. , Ann Arbor.

Hayes A.R., C.F. Mancino, W.Y. Forden, D.M. Kopec, and I.L. Pepper. 1990. Irrigation of turfgrass with secondary sewage effluents. II. Turf quality. Agron. J. 82:943-946.

Hofstra, G. and R. Hall. 1971. Injury on roadside trees: leaf injury on pine and white cedar in relation to foliar levels of sodium and chloride. Can. J. Bot. 49:613-622.

Huck, Mike. 1994. The use of effluent irrigation water: a case study in the west. United States Golf Association. Lewis Publishers, Ann Arbor.

Jordan, L.A., D.A. Devitt, R.L. Morris, and D.S. Neuman, 2001. Foliar damage to ornamental trees sprinkler-irrigated with reuse water. Irri. Sci. 21:17-25.

Lazarova, V. and A. Bahri. 2005. Water reuse for irrigation: Agriculture, landscapes and turfgrass. CRC Press.

Litke, D.W., 1996, Sources and loads of nutrients in the South Platte River, Colorado and Nebraska, 1994-95: U.S. Geological Survey Water-Resources Investigations Report 96-4029, 57 p. Abstract http://webserver.cr.usgs.gov/nawqa/splt/reports/LITKE1.html

Litke, D.W., 1995, Nutrients in the South Platte River, 1993-95: U.S. Geological Survey Fact Sheet FS-105-95, 2 p. http://webserver.cr.usgs.gov/nawqa/splt/factsheets/FSLITKE.html

Mancino, C.F. and I.L. Pepper. 1992. Irrigation of turfgrass with secondary sewage effluent: soil quality. Agron. J. 84:650-654.

Monk, R. and H.B. Peterson. 1962. Tolerance of some trees and shrubs to saline conditions. Amer. Soc. Hort. Sci. 81:556-561.

Nelson, D.W. and Sommers, L.E. 1982. Total carbon, organic carbon, and organic matter. *In* Methods of Soil Analysis Part 2. Chemical and Microbiological Properties, Page, A.L. Ed. American Society of Agronomy, Madison, WI.

Pepper, I. L. and C.F. Mancino. 1993. Irrigation of turf with effluent water. p. 623-641. *In*: M. Pessarakli (ed). Handbook of plant and crop stress. Marcel Dekker Inc. New York.

Pettygrove, G.S. and Asamo. 1985. Irrigation with reclaimed municipal wastewater - a guidance manual. Lewis Publishers, Inc., Chelsea MI.

Qian Y.L., J.M. Fu, J. Klett, and S.E. Newman. 2005. Effects of long-term recycled wastewater irrigation on visual quality and ion content of ponderosa pine. J. Environ. Hort. 23:185-189.

Qian Y.L. and B. Mecham. 2005. Long-term effects of recycled wastewater irrigation on soil chemical properties on golf course fairways. Agron. J. 97:717-721.

Qian,Y.L., S.J. Wilhelm, and K.B. Marcum. 2001. Comparative responses of two Kentucky bluegrass cultivars to salinity stress. Crop Science 41:1895-1900.

Rengel, Z. 1992. The role of calcium in salt toxicity. Plant, Cell and Environ. 15:625-632.

SAS institute. 2005. SAS/STAT user's guide. SAS Inst. Inc., Cary, NC.

Schipper, L.A., J.C. Williamson, H.A. Kettles, and T.W. Speir. 1996. Impact of land-applied tertiary-treated effluent on soil biochemical properties. J. Environ. Qual. 25: 1073-1077.

Spotts, R.A. , J. Altman, and J.M. Staley. 1972. Soil salinity related to ponderosa pine tipburn. Phytopathology 62:705-708.

State of Arizona. 1987. Regulations for the reuse of wastewater. Arizona Administrative Code, Chapter 9, article 7, Arizona dept. of Environmental Quality, Phoenix, AZ.

State of California. 1978. Wastewater reclamation criteria. California Administrative Code, Title 22, Division 4, Calif. Dept. of Health Services. Sanitary Engineering Section, Berkeley, CA.

State of Colorado. 2000. Reclaimed domestic wastewater control regulation. Colorado Dept. of Public Health and Environment Water Quality Control Commission, Regulation No. 84. Denver, CO.

State of Florida. 1989. Reuse of reclaimed water and land application. Florida Administrative Code, Chapter 17 - 610. Florida Dept. of Environmental Regulation, Tallahassee, FL.

State of Texas. 1990. Use of reclaimed water. Texas Administrative Code, Chapter 310, subchapter A, Texas Water Commission, Austin, TX.

Staley J.M., J. Altman, and R.A. Spotts. 1968. A sodium-linked disease of Ponderosa pine in Denver, Colorado. Plant Disease Reptr. 52:908-910.

Sucoff, E, R. Feller, and D. Kanton. 1975. Deicing salt (sodium chloride) damage to *Pinus ponderosa* Ait. Can. J. Bot. 58:546-556.

Tester, M. and R. Davenport. 2003. Na^+ tolerance and Na^+ transport in higher plants. Ann. Bot. 91:503-527.

Townsend, A.M. and W.F. Kwolek. 1987. Relative susceptibility of thirteen pine species to sodium chloride spray. J. Arboriculture 13:225-228.

US EPA. 2004. Manual: Guidelines for water reuse. EPA/625/R-04/108.

Van der Leeden, F., F.L. Troise, and D.K. Todd. 1990. The water encyclopedia, 2nd ed., Lewis Publishers, Boca Raton, FL 466. 1990.

Warren, M.E. and G.J. Swanson. 1981. Use of reclaimed wastewater for landscape irrigation. In Proceedings of Water Reuse in the Future 1:213-227.

Warren, S.L., A. Amoozegar, W.P. Robarge, C.P. Niewoehner, and W.M. Reece. 2004. Effect of graywater on growth and appearance of ornamental landscape plants. p. 647-654. *In* K.R. Mankin (ed.) Proc. of the 10th National Symp. on Individual and Small Community Sewage Systems. Am. Soc. Agric. Engr., St. Joseph, MI.

Westcot, D.W. and R.S. Ayers. 1985. Irrigation water quality criteria. p. 3:1-36. *In* Pettygrove and Asano (ed.) Irrigation with Reclaimed Municipal Wastewater - A Guidance Manual. Lewis Publishers, Inc., Chelsea, MI.

Wu, L., X. Guo, and A. Harivandi, 2001. Salt tolerance and salt accumulation of landscape plants irrigated by sprinkler and drip irrigation systems. J. Plant Nutri. 24: 1473-1490.

Appendix 1

Survey for the Recycled Wastewater Reuse Project
Colorado State University

1. The name of your wastewater treatment plant:
   ____.

2. What percentage of the wastewater are from:
   ______Domestic source ________ Industrial source _______ Storm water
   ______Others

3. The average daily discharge from the treatment plant is approximately ______ million gallons per week.

4. Based on the extent of treatments, the reclaimed wastewater from your treatment plant is considered to be:
   Secondary Tertiary

5. The current discharge method during growing season (May-October)
   Landscape Irrigation Discharge to streams Industrial reuse
   Agricultural irrigation Other:________________

   A. If it is used for landscape irrigation, who are the end users?____________________________________

   B. What percentage of your total treated wastewater is delivered for landscape irrigation:______________.

   C. The major treatment processes include:

   ____

   ____

   ____

   ____

   E. What is the price the landscape facilities pay for the reclaimed wastewater?

   ____

6. What is the current discharge method during off-season (winter months) when landscape irrigation requirements are minimal?
   Pond storage   discharge to the stream   other ___________________

7. Who owns the water rights to reclaimed wastewater?
   unsettled   downstream user   wastewater treatment entity   No one
   Other________________

8. If it is discharged to streams, this is because:
   The requirements to meet stream flow rate   have not received request for reuse
   Other _______________

9. Based on your observation, what are the major concerns relating to landscape reclaimed wastewater reuse?

____

____

____

10. Will you share your water test results with us?
   Yes   No

   If yes, who should we contact? ____________________

Please list your NAME, ADDRESS, and PHONE NUMBER. THANK YOU SO MUCH FOR PATICIPATING THIS RESEARCH PROJECT!!

Name______________________________________

Title_______________________________________

Address____

Tel____

Fax____

E-mail____

Appendix 2

Survey for the Reclaimed Wastewater Reuse Project
Colorado State University

1. The name of your facility: ____.

2. The landscape facility was built in ______ (year). The site started to use effluent water for irrigation in ____________(year).

3. Based on the extent of treatments, the reclaimed wastewater from your treatment plant for landscape irrigation is considered to be:
   Secondary Tertiary

4. What is the cost of the effluent water in your site? ______________________

5. In your opinion, what is the biggest advantage of using effluent water for irrigation? Please number the selections based on the level of advantage in your opinion (1= the greatest advantage)

_____ Cost saving
_____ Reliability
_____Availability
______ Environmental Benefit
____ Other_________________

6. What are your major concerns related to effluent water irrigation? Please number the selections based on the level of your concerns (1= the greatest concern).

_____ Public safety
_____ Salt damage to the trees
_____ Salt built up in the soil
_____ Excessive N
_____ Inflexibility in irrigation scheduling
_____ Reduce soil permeability
_____ Soggy turf
_____ Other_________________

7. What is the most effective management practice to reduce problems indicated in question 6?
____

____

8. How frequently do you sample and test the water quality and soil properties?

Once a year Once a month Other_____________

9. The turfgrass site sampled for the soil test is: _________________
   Putting green Fairway Rough Tee
   Park Home Lawns Open space
   Others: ________________

10. Fairways were:
    Irrigated daily Irrigated three times a week Irrigated twice a week
    Other:________________

11. The approximate irrigation amount for fairways was:
    30-40 inches per year
    20-30 inches per year
    10 –20 inches per year
    Less than 10 inches per year
    Approximately _______% ET
    Don't know

12. Do you have access to ET information? ________

13. The turfgrass on fairways is
    Kentucky bluegrass Tall fescue Perennial ryegrass
    Creeping bentgrass Buffalograss/Blue grama
    Mixture others____________

14. Turf clippings on fairways were: returned removed

15. The fairways were fertilized at a rate of _____ LB N /1000 ft^2/Year.

16. The fairways were aerated approximately:
    More than three times a year Three times a year Twice a year
    Once a year Less than once a year Never

17. The soil texture of the fairways is
    Clay Sand Loam Sandy clay loam Clay Loam
    Other___________ Don't know

18. Was any soil amendment or chemicals added through topdressing to reduce problems associated with effluent water irrigation?
    Yes No

    If yes, what is the chemical? _______________________________.

19. What trees, if any, have you observed to have had severe damage by wastewater irrigation?

_____________, ______________, ______________, _____________,

20. What trees have you never seen damage by wastewater irrigation?

____________, __________, _____________, ____________,

21. What woody ornamentals, if any, have you observed to have had severe damage by wastewater irrigation?

_____________, ______________, ______________, _____________,

22. What woody ornamentals have you never seen damage by wastewater irrigation?

____________, __________, _____________, ____________,

23. How frequently you and the water treatment facilities communicate regarding water quality issues?

____

Please list your NAME, ADDRESS, and PHONE NUMBER. THANK YOU SO MUCH FOR PATICIPATING THIS RESEARCH PROJECT!!

Name___________________________________

Title_____________________________________

Address____

Tel____

Fax____

E-mail____