Accounting for Salinity Leaching in Application of Recycled Water for Landscape Irrigation

DRAFT REPORT

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December 15, 2017

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ABOUT NWRI

A joint powers authority and 501c3 nonprofit organization, the National Water Research Institute (NWRI) was founded in 1991 by a group of California water agencies in partnership with the Joan Irvine Smith and Athalie R. Clarke Foundation to promote the protection, maintenance, and restoration of water supplies and to protect public health and improve the environment. NWRI's member agencies include Inland Empire Utilities Agency, Irvine Ranch Water District, Los Angeles Department of Water and Power, Orange County Sanitation District, Orange County Water District, and West Basin Municipal Water District.

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NWRI Publication Number: NWRI-2017-13

Suggested Citation:

Haghverdi, A., and W. Laosheng (2017). *Accounting for Salinity Leaching in Application of Recycled Water for Landscape Irrigation*. Report prepared for the California WateReuse Association by the National Water Research Institute, Fountain Valley, CA.

ABOUT SCSC

The Southern California Salinity Coalition (SCSC) was formed in 2002 is a coalition of water and wastewater agencies in Southern California dedicated to managing salinity in our water supplies. The organization is administered by NWRI. Member agencies include Eastern Municipal Water District (EMWD), Inland Empire Utilities Agency (IEUA), Metropolitan Water District of Southern California (MWDSC), Orange County Sanitation District (OCSD), Orange County Water District (OCWD), San Diego County Water Authority (SDCWA), Sanitation Districts of Los Angeles County (LACSD), and Santa Ana Watershed Project Authority (SAWPA).

The purpose of SCSC is to coordinate salinity management strategies and programs, including research projects, with water and wastewater agencies throughout Southern California. Its objectives include: establishing programs to address the critical need to remove salts from water supplies; preserving, sustaining, and enhancing the quality of source water supplies; supporting economic development; and providing outreach and education to the public.

ABOUT WATEREUSE CALIFORNIA

The mission of WateReuse California (WRCA) is to promote responsible stewardship of California's water resources by maximizing the safe, practical and beneficial use of recycled water. WRCA has seven regional chapters representing geographically diverse regions in California: Central Coast, Central Valley/Sierra Foothills, Inland Empire, Los Angeles, Northern California, Orange County, and the San Diego Region.

WRCA also supports the efforts of the of WateReuse, a national organization with headquarters in Alexandria, Virginia that advocates for policies, laws, and funding at the state and federal level to increase the practice of recycling water.

ACKNOWLEDGMENTS

This report is the product of a Research Team engaged by the Southern California Salinity Coalition (SCSC), and the National Water Research Institute (NWRI), a 501c3 nonprofit organization based in Southern California that administers SCSC. The Research Team is pleased to acknowledge the organizations and individuals whose support, assistance, and resources made this report possible.

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National Water Research Institute and Southern California Salinity Coalition

The Research Team appreciates the services of staff at NWRI and SCSC, who administered the review process and helped develop, prepare, and edit this report and other documents. The Author's thank the following NWRI and SCSC staff members for their research, editorial and administrative support:

- Mr. Kevin M. Hardy for providing coordinating the research effort and report development.
- Ms. Suzanne Sharkey and Ms. Gina M. Vartanian for conducting follow-up research and providing editorial support and report development.
- Ms. Brandi Caskey, Ms. Dawna Hernandez, and Ms. Elizabeth Pardo for administrative support.

WateReuse California

The Research Team was engaged by NWRI on behalf of WateReuse California. The Research Team would like to thank project staff including Jennifer West and Charles LaSalle for the opportunity to evaluate this topic.

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ACRONYMS AND EQUATION TERMS

CIMIS	California Irrigation Management Information System
DWR	Department of Water Resources (California)
EC	Electrical conductivity
ECa	Crop tolerance to soil salinity
EC_e	Electrical conductivity of saturation paste extract
EC_{iW}	Electroconductivity of irrigation water in deciSiemens per meter (dS/m)
ET	Evapotranspiration
ETo	Reference evapotranspiration
ETAF	Evapotranspiration adjustment factor
ETAFr	Evapotranspiration adjustment factor for recycled water
ETWU	Estimated total water use
IE	Irrigating efficiency
LA	Landscape Area
LF	Leaching fraction
LR	Leaching requirement
MAWA	Maximum applied water allowance
MAWAr	Maximum applied water allowance for recycled water
MWELO	Model Water Efficient Landscape Ordinance
PF	Plant factor
SLA	Special landscape area
TDS	Total dissolved solids

ABBREVIATIONS FOR UNITS OF MEASURE

A	Acre; 43,560 ft^2 [(5,280 ft/mi)^2 / (640 acre/mi^2)]
AF	Acre-foot (of water) = 325,892 gallons (a unit of water volume used in agricultural irrigation practice)
CFU	Colony forming units
cm^2	Squared centimeters
d	Day
dS/m	deciSiemens per meter
g	Gram
kg	Kilogram
L	Liter
mg	Milligram
mg/L	Milligram per liter
Mgal	Million gallons
MGD	Million gallons per day
mi	Mile
min	Minute
mL	Milliliter
Mm^3 day^{-1}	Million cubic meters per day
NTU	Nephelometric turbidity unit
ppm	Parts per million, ~milligrams per liter (mg/L)
µ	Micron
µg/L	Microgram per liter = parts per billion (ppb)
µm	Micrometer

EXECUTIVE SUMMARY

Overview

The use of recycled water for irrigation in California is increasing. According to the most recent Municipal Wastewater Recycling Survey conducted by the Department of Water Resources (DWR), a total of 714,000 acre-feet per year (AFY) of recycled water was put to beneficial reuse in 2015 in California, and 26% of the water was used to irrigate landscape and golf courses. Given that the State Water Board's Recycled Water Policy aims to increase the use of recycled water above the 2002 level by at least one million AFY by 2020, and by two million AFY by 2030, the area of landscape irrigated with recycled water is likely to increase. However, recycled water typically contains more salts and nutrients than potable water. This variable water quality must be considered when planning for landscape irrigation because excessive concentrations of constituents, including sodium, chloride, boron, and heavy metals, in recycled water can stunt and damage plants and cause build-up of salts in soil.

Plants species, and even varieties of the same plant species, differ in their tolerance to salts and the amount of metabolic energy required to adjust to a saline environment; therefore, when using recycled water for irrigation, it is essential to maintain a desired salt balance in the active root zone to sustain satisfactory landscape performance. Applying water to leach excess salts from the root zone is the accepted best practice for maintaining this balance. The minimum amount of water required to flush out the excess salts in the root zone that are detrimental to plant growth is called the leaching requirement (LR). The LR represents additional irrigation water beyond the crop evapotranspiration requirement needed to regulate salt accumulation in the root zone. LR is used throughout the agricultural industry to determine how much water is needed to maintain a soil salinity that can be tolerated by a crop.

California's Model Water Efficient Landscape Ordinance (MWELO) includes a maximum applied water allowance (MAWA) calculation that does not fully account for differences in LR which naturally arise from variations in plant varieties, soil conditions, and irrigation water TDS levels

Key Conclusions

Based upon a review of the best available scientific evidence, the Authors propose that the Department of Water Resources and other interested stakeholders consider the following key conclusions of this White Paper:

1. Excess root zone salts, other dissolved solids and nutrients are harmful to plant health.

2. Differences in LR provide a sound scientific rationale for permitting and granting variances to established evapotranspiration adjustment factor (ETAF) limits in existing MAWA calculations.

3. Accommodating a LR based variance to established ETAF limits would require the addition of a single mathematic operation to existing MAWA calculations.

4. Permitting and granting variances to established ETAF limits based on differences in LR is not inconsistent with other policy objectives and technical requirements of the MWELO.

Policy Guidance

Including the LR allows applicants, regulators and other stakeholders to determine the optimal irrigation volume that will minimize the negative effects of excess salts, other TDS and nutrients on plant and soil health while still adhering to water conservation principles. Because LR is designed to provide for an irrigation volume that is adequate to leach salts to a level below the landscape effective root zone so that plant roots are not continually exposed to the damaging effects of high-salinity soil and water – and no more – the Authors propose a simple model to calculate an evapotranspiration adjustment factor (ETAF) that is sufficient to maintain plant and soil health when recycled water is used. **The model provides a scientific rationale for permitting and granting variances, when appropriate, to allow for greater irrigation volumes to leach salts, sustain soil integrity, and support plant health when high-TDS recycled water is used for landscape irrigation.** More specifically, the authors propose:

1. Where the calculated ETAF for recycled water (ETAFr) is less than or equal to 1.0, which is the ETAF granted to areas irrigated with recycled water, then no additional water is required beyond what is calculated for the upper limit of water application, and the landscape should grow and function as designed.

2. Where the calculated ETAFr is greater than 1.0, the authors suggest adjusting the upper limit of water application as needed to allow for leaching of salts from the active root zone to protect landscape plants from the toxic effects of high-TDS water.

CHAPTER 1: INTRODUCTION

1.1 Purpose of this White Paper

An ever-growing population, combined with increasing water scarcity, has intensified the demand for high-quality water for urban consumption across the State of California. These water supply demands have created an urgent need to establish novel water conservation strategies and develop new water resources for metropolitan areas. Increasingly, recycled water is being recognized as an important source of water supply, and numerous communities have invested in recycled water projects to provide water for approved beneficial purposes including landscape irrigation for residential and non-residential areas and crop irrigation.

The use of recycled water for irrigation in California is increasing. According to the most recent Municipal Wastewater Recycling Survey conducted by the Department of Water Resources (DWR), a total of 714,000 acre-feet per year (AFY) of recycled water was put to beneficial reuse in 2015 in California, and 26% of the water was used to irrigate landscape and golf courses.[1] Given that the State Water Board's Recycled Water Policy aims to increase the use of recycled water above the 2002 level by at least one million AFY by 2020, and by two million AFY by 2030 by substituting as much recycled water for potable water as possible,[2] the area of landscape irrigated with recycled water is likely to increase.

Although recycled water typically contains higher total dissolved solids (TDS) than potable water does, it can be used to irrigate plants if irrigation practices are managed effectively to prevent the buildup of excess salts in the root zone and appropriate salt tolerant landscape species are selected. This White Paper provides a scientific basis for determining how much high-TDS recycled water should be used for landscape irrigation.

Because recycled water is of different quality than potable water, it requires special management practices when used to irrigate plants. Most recycled waters contain 140 to 400 mg/L more salt than potable sources (Tanji et al., 2005), and many plants used for landscaping, including turf grasses commonly planted on recreational fields, are sensitive to elevated salt concentrations. When recycled water is regularly used to irrigate a landscape area, excess salt tends to accumulate in the soil and in the water that plants take up from the root zone. When that happens, the landscape plants may be damaged or killed unless enough water is applied to wash or "leach" salt through the soil column. Researcher have created well-understood and widely used models that predict the amount of water needed to adequately leach salt from the active root zone and protect plant health; these models account for a number of variables including soil characteristics, plants' water needs, and the salt content of the irrigation water. These models have been used successfully by the agricultural sector for years to maximize crop yields and soil health.

Although the goals of landscape matainence differ from those of agricultural production, existing models are still relevant and can be used to support recommendations for irrigation. When recycled

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[1] California State Water Resources Control Board, 2015 Municipal Wastewater Recycling Survey. See: https://www.waterboards.ca.gov/water_issues/programs/grants_loans/water_recycling/munirec.shtml

[2] California State Water Resources Control Board, Policy for Water Quality Control for Recycled Water (Recycled Water Policy), Revised January 22, 2013, Effective April 25, 2013. See: https://www.waterboards.ca.gov/water_issues/programs/water_recycling_policy/docs/rwp_revtoc.pdf

water is being used to irrigate landscapes subject to California's water efficient landscape ordinance, there is a need to (a) establish a scientific basis for determining the minimum irrigation volume required to maintain plant health for landscape amenities irrigated with recycled water; and, (b) propose a framework for ensuring that recycled water irrigation practices consistent with these minimum requirements are as effective as MWELO in maintaining plant health and ensuring water conservation.

To that end, this paper is designed to provide science-based guidance to assist DWR in making policy determinations related to the efficient use of recycled water for landscape irrigation.

1.2 The California Model Water Efficient Landscape Ordinance

The Water Conservation in Landscaping Act (Assembly Bill 325, Clute) was signed into law on September 29, 1990. This statute directed DWR to adopt a statewide Model Water Efficient Landscape Ordinance (MWELO) by January 1, 1992.[3] The statewide MWELO was amended in 2010 and again in 2015, and DWR has initiated the process to further amend it in 2018. Local agencies can adopt their own version of the MWELO, or can collaborate with neighboring agencies to adopt a regional ordinance, provided that the local or regional ordinance is at least as effective as the statewide requirements.[4]

The MWELO relies on a quantitative approach based on evapotranspiration (ET) rates to calculate the maximum applied water allowance (MAWA), which is the upper limit of irrigation water that may be applied to a landscape area. The calculation accounts for climate, plant type, and irrigation system efficiency, but does not accommodate for variations in the total dissolved solids (TDS) concentration of the water used for irrigation. The lack of guidance to address high TDS is important because recycled water, which numerous communities have invested in to meet their landscape irrigation needs, contains a higher concentration of salt than potable water does, and the salt may damage plants and soil if not managed appropriately. Experts in irrigation management propose that when high-TDS water is used for landscape irrigation, additional water beyond what the MWELO prescribes may be needed to flush excess salt from the root zone to maintain plant health and soil quality

MWELO ordinances promote water efficiency in new and retrofitted landscapes throughout California.[5] Specifically, the statewide MWELO is intended to: (a) promote water use conservation and efficiency; (b) establish a structure for the design, maintenance, and management of water efficient landscapes; (c) reduce water use to the lowest practical amount; (d) promote regional consistency; and, (e) encourage water agencies to promote the efficient use of water. The statewide MWELO accomplishes these intentions through calculations that determine the maximum applied water allowance (MAWA) for each landscaped area. For any specific landscaped area, the MAWA includes the following factors:

- <u>Reference Evapotranspiration (ETo)</u>. The ETo is a "standard measurement of environmental parameters which affect the water use of plants"[6] and is derived from "an estimate of the

[3] California Department of Water Resources. Status of Adoption of Water Efficient Landscape Ordinances, Pursuant to AB 1881 Section 65597. See: http://www.water.ca.gov/wateruseefficiency/docs/LandscapOrdinanceReport_to_Leg-4-22-2011.pdf
[4] California DWR (2015). Updated Model Efficient Landscape Ordinance, Guidance for Local Agencies. http://www.water.ca.gov/wateruseefficiency/landscapeordinance/docs/2015%20MWELO%20Guidance%20for%20Local%20Agencies.pdf
[5] California DWR. See http://www.water.ca.gov/wateruseefficiency/landscapeordinance/
[6] 23 CCR §491 (mmm)

evapotranspiration of a large field of four- to seven-inch tall, cool-season grass that is well-watered."[7] The ETo is used to accommodate regional differences in California's climate.[8]

- Evapotranspiration Adjustment Factor (ETAF). The ETAF is a coefficient used to adjust the reference evapotranspiration value to accommodate differences in (a) plants' water needs and (b) irrigation system efficiency. For the purposes of MWELO, the ETAF is calculated from the plant factor (PF), which describes the amount of water a species requires for optimum health, and the irrigation efficiency (IE), which is the volume of irrigation water used that becomes available for plant uptake. For ease of use, the MWELO prescribes the following ETAFs: 0.45 for non-residential areas; 0.55 for residential areas; 0.80 for existing non-rehabilitated landscapes, and 1.0 for certain special landscapes, which includes areas irrigated with recycled water.

- Landscape area (LA). Includes all planting areas, turf areas, and water features and is expressed in square feet. Areas irrigated with recycled water are designated as "special landscape areas" (SLA).

1.3 The Need for this Effort

In calculating an applicable MAWA for each project, the statewide MWELO accounts for regional differences in climate, the project's mix of plantings (i.e., ornamental plants and flowers, trees, turf, etc.), and irrigation system efficiency. However, the calculation does not include a factor to fully account for salinity of the water, and therefore MWELO makes no regulatory accommodation for variations in the total dissolved solids (TDS)[9] concentration of the water used for irrigation. The lack of guidance for recycled water users is important because when high-TDS water is used for landscape irrigation, additional water beyond the MAWA may be required to leach salts to a level below the landscape effective root zone so that plant roots are not continually exposed to high-TDS soil and water., which may damage and kill plant species that are sensitive to salt. Because the MWELO currently does not incorporate a salinity leaching requirement into its calculation, the regulation does not account for the additional salt in recycled water and therefore cannot meet DWR's stated goals to preserve plant health while ensuring efficient irrigation practices. Therefore, in cases where recycled water is used, a different MAWA (designated MAWAr, for recycled water) beyond what the MWELO

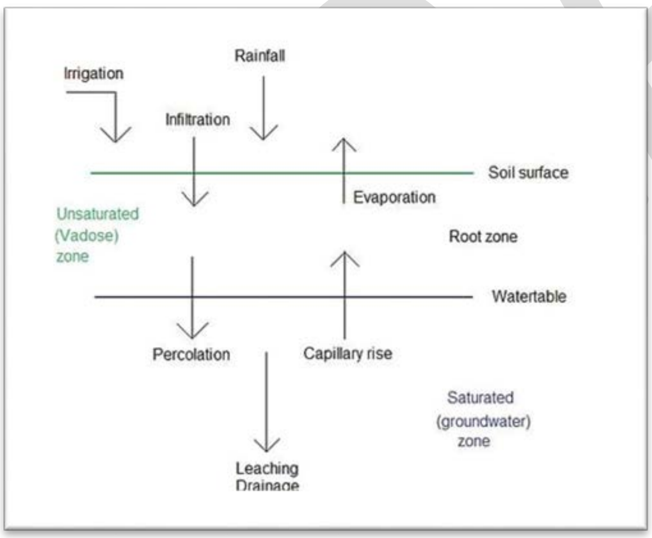

Figure 1: Leaching Cycle

[7] Ibid
[8] Map of ETo zones according to California Irrigation Management Information System (CIMIS) is available at: http://wwwcimis.water.ca.gov/App_Themes/images/etozonemap.jpg
[9] TDS is the term used to describe the inorganic salts and small amounts of organic matter present in solution in water solution. The principal constituents are usually calcium, magnesium, sodium, and potassium cations and carbonate, chloride, sulfate, and nitrate anions (World Health Organization, 2004). TDS may arise naturally from mineral springs, carbonate deposits, salt deposits, and sea water intrusion, or from water treatment chemicals, stormwater, agricultural runoff, wastewater discharges, and the piping or hardware used to convey the water to its point of treatment or end use.

prescribes may be needed to flush excess salt from a landscape's root zone to ensure that plants thrive and soil integrity is maintained.

Utilities that supply irrigation water for urban landscapes do not routinely deploy water treatment processes capable of selectively reducing salts in recycled water produced for non-potable end uses. Therefore, a regulatory process to accommodate the difference in TDS between potable and non-potable recycled water would be valuable several reasons, including:

1. TDS concentration in recycled water varies regionally. Regions that produce recycled water from a high-TDS source water are especially likely to experience problems with meeting irrigation water efficiency goals due to the high salt content of the water supply.

2. Communities across California have made substantial investments in planting and maintaining urban landscape plants that rely on recycled water for irrigation.

3. Recycled water purveyors have designed publicly owned recycled water treatment facilities and distribution systems on the basis of the water demand to maintain healthy urban landscapes.

4. Urban landscapes irrigated with recycled water provide areas for recreation, enhance the natural and built environment, prevent soil erosion, improve fire protection, and replace ecosystems lost to development.

5. The benefits of irrigating urban landscapes with recycled water at volumes that maintain overall plant health are consistent with the intent of the statewide MWELO.

1.4 Drought and Water Efficiency

During the recent record-breaking drought, California experienced rapid drawdown of groundwater resources and surface reservoirs, fallowed agricultural fields, and negative ecological impacts on wildlife and forests (AghaKouchak et al., 2015; Williams et al., 2015). It is expected that competition for water and land resources among urban, environmental, and agricultural uses will intensify due to increased population and changes in land use and climate throughout California. Furthermore, climate change is altering precipitation and temperature patterns, and the risk of drought may increase along with the magnitude and effects of extreme dry and wet years statewide.

1.5 Increasing Need for Water Resources in California

California's population rose to nearly 40 million in 2016, and statistical projections by the California Department of Finance indicate it will increase to more than 50 million by 2060.[10] Because California contains some of the largest cities in the nation, and the largest increase in population has continued in big cities where urban water demands are expected to rise by 47 percent (Wu et al., 2009), it is critical to maintain sustainable urban water management practices. The DWR estimates that somewhere between 33 to 50 percent of all urban water use in California is for landscape irrigation. Consequently, it is vital to establish novel water conservation strategies and explore alternative water resources,

[10] California Department of Finance. http://www.dof.ca.gov/Forecasting/Demographics/projections/

including recycled water and harvested stormwater, to guarantee the long-term sustainability of urban landscapes, including plant and soil health.

The application of recycled water for irrigation is especially attractive because municipal wastewater is produced close to the urban landscapes that it will be applied to, and therefore, can offset the need to import water, alleviate pressure on traditional potable water resources, and improve the reliability of water supply (Wu et al., 2009; Tanji et al., 2008). California and Florida have the highest rate of recycled water reuse in the nation, with 2.5 and 2.2 Mm^3 day^{-1}, respectively (Cardenas and Dukes, 2016). This recycled water is approved by state agencies for a number of beneficial uses.

1.6 Use of Recycled Water for Irrigation in California

Most of the water recycled in California is currently used for irrigation: about two-thirds is applied to agricultural crops and landscape (California State Water Resources Control Board Office of Water Recycling, 2002). In urban areas, recycled water often is used to irrigate residential and commercial landscapes, golf courses, plant nurseries, and publicly maintained green areas, including parks and greenbelts, school yards, sport fields, and highway green spaces. Estimates indicate that the water needs of 30 to 50 percent of the 17-million additional people who will live in California in 2030 could be satisfied by an additional 4 Mm^3 day^{-1} of recycled water (California Department of Water Resources, 2004). The use of recycled water to maintain urban landscape particularly is important in southern coastal California (the Los Angeles-to-San Diego corridor), where municipalities already deal with shortfalls of potable water, and estimates indicate additional demand increases on regional water resources in the future due to a two-fold population increase above the Year 2000 population in both Nevada and Arizona by Year 2030 (Tanji et al., 2008; Wu et al., 2009).

1.7 Stakeholder Process for Developing the White Paper

Beginning in June 2017, representatives from the Southern California Salinity Coalition (SCSC) and the National Water Research Institute (NWRI) discussed a potential collaboration with WateReuse California (WRCA) to document the benefits of using recycled water for irrigation to reduce soil salinity. All three organizations approached the topic from different perspectives. The SCSC, which is a coalition of eight agencies that work to address the critical need to remove salt from water supplies and to preserve water resources in California, is interested in the economic impact of salinity on landscape maintenance. The NWRI, a joint powers and nonprofit organization in southern California that sponsors research and programs that focus on ensuring safe, reliable sources of water, also works to advance the science and application of water treatment technologies for potable reuse of recycled water. And the mission of WRCA, a trade organization, is to promote responsible stewardship of California's water resources by maximizing the safe, practical and beneficial use of recycled water. WRCA's position is that the use of recycled water to replace potable sources provides a benefit equivalent to water conservation.

1.8 Motivation for Conducting Research

The groups' interest in this topic developed when they became aware that DWR would update the MWELO in 2018. The ordinance provides a method to calculate how much irrigation water may be applied annually to the landscape to meet conservation goals. The calculation is based on the evapotranspiration adjustment factor (ETAF), which is a function of the plants' water needs and efficiency of the irrigation system, and assumes that potable water will be used for irrigation. The ordinance has been implemented successfully in many regionals throughout the state of California. Because the MWELO applies to any new or renovated landscape covering more than 500 square feet and requires that the landscape design and irrigation plan be managed to conserve water, the ordinance affects water users in urban areas throughout the state.

Although the ordinance recognizes that recycled water contains more salts than potable water and allows for a greater volume to be applied to leach excess salt from the soil, the amount currently allowed is not sufficient to protect all landscapes currently using recycled water for irrigation. Several of WRCA's member agencies WateReuse stakeholders had provided anecdotal evidence that water agencies in California using recycled water for outdoor landscaping have high-salinity water that will damage high-value landscapes such as athletic playing fields and forests unless it is applied in a volume great enough to flush salts to below the active root zone. WRA approached DWR to find out they could participate in the MWELO review so that this issue could be addressed in the revised ordinance.

1.9 Identifying the Expert Authors

NWRI contacted Lorence Oki, Ph.D., a recognized expert on in irrigation management for urban horticulture and water quality effects on plant growth at University of California, Davis, Cooperative Extension. Dr. Oki helped develop a salt-tolerant plant list to support irrigation efficiency efforts, and NWRI believed he could help develop a scientific rationale for requesting a variance for a "special landscape area," which includes landscapes irrigated with recycled water. Dr. Oki agreed that high-TDS recycled water would have a negative impact on the soil and plants unless proper landscape management practices were put in place. His colleague Karrie Reid recommended contacting researchers at UC Riverside Cooperative Extension since they had more experience with recycled water than the Extension staff at UC Davis.

In August 2017, NWRI and SCSC staff engaged two scientists at UC Riverside to become the Research Team that would review the literature on irrigation with recycled water and identify a quantitative process for determining if additional water would be required to leach salts from the soil and protect plant health. The Research Team is comprised of two scientists at University of California, Riverside: Amir Haghverdi, Ph.D., an expert in irrigation design and soil/water dynamics, and Laosheng Wu, Ph.D., a professor of soil physics. Both Research Team members have extensive experience with irrigation efficiency and soil salinity issues. Dr. Haghverdi's research emphasizes on agricultural and urban irrigation water management, while Dr. Wu's specializations include soil salinity, reclaimed wastewater for irrigation, and interaction between the soil's physical, hydrological, and chemical properties.

In conducting research for this report, the researchers reviewed publications identified by NWRI and SCSC and summarized relevant research on the relationship between salinity and soil and plant health. In addition, the Research Team proposed a method for calculating how much water in excess of the 1.0 ETAF would be needed for irrigation based on the electric conductivity of the recycled water and crop tolerance to soil salinity. NWRI and SCSC then incorporated the Research Team's contributions into this report. Biographical information on Drs. Haghverdi and Wu is provided in Appendix C.

CHAPTER 2: CONSIDERATIONS WHEN USING RECYCLED WATER FOR LANDSCAPE IRRIGATION

Past experiences with the successful long-term implementation of recycled water for landscape and agricultural irrigation have demonstrated that, with proper water treatment and efficient irrigation management, recycled water can be used safely in urban and agricultural settings; however, it may be necessary to take special measures to minimize potential negative effects on plant and soil health that may be caused by irrigating with high-salinity recycled water.

2.1 Characteristics of Wastewater

Municipal wastewater often contains several types of impurities, including biodegradable organic matter, pathogens and indicator organisms, nutrients [nitrogen (N) and phosphorus (P)], potentially toxic substances, and dissolved minerals (Wu et al., 2009). The composition of impurities in municipal wastewater differs at each service location and likely varies with time within a single community due to variations in wastewater volume and the substances discharged into the wastewater treatment system. These impurities are removed in the wastewater treatment plant through a stepwise process in which some or all of four general treatments steps (i.e., preliminary, primary, secondary, and tertiary treatment) are applied. These wastewater treatment processes produce recycled water of a quality that is fit for the purpose of its approved intended use.

2.2 Characteristics of Recycled Water

Although the recycled water treatment processes effectively remove pathogens that could pose a health risk to humans and animals, these methods are not intended to treat water used for non-potable purposes (like landscape irrigation) to reach drinking water standards. As a result, recycled water typically contains more salts and nutrients than potable water. This variable water quality must be considered when planning for landscape irrigation because excessive concentrations of constituents, including sodium, chloride, boron, and heavy metals, in recycled water can stunt and damage plants and cause build-up of salts in soil.

Despite variations in the chemical characteristics of recycled water across treatment facilities, once treatment is complete, sodium and chloride typically are the most significant remaining constituents that could damage landscape plants. Other elements, including boron, selenium, magnesium, and cadmium, in the recycled water generally are below the safety levels for human health (Wu et al., 2009).

Although recycled water is likely to contain excess salts that can harm the landscape, it also may contain nutrients, including nitrogen, calcium, and magnesium, beneficial to both soil and crops. In order to minimize the unwanted effects of excess nutrients in irrigation water, fertilizer application should be designed to account for the nutrients added to soil irrigated with recycled water.

For a detailed discussion on the physical, chemical, and biological characteristics of recycled water, see Wu et al. (2009).

CHAPTER 3: IMPACTS OF IRRIGATION WATER SALINITY ON SOIL AND PLANT HEALTH

3.1 Measuring Salinity in Soil and Water

Because the salinity of irrigation water affects the health of the soil and plants that it contacts, it is important to quantify the salt load accurately before designing an irrigation plan. Salinity is frequently expressed in terms of TDS, and the electrical conductivity of the water (EC) is an indirect measurement of TDS. EC serves as a surrogate for the total amount of salt in a water sample, and higher EC is associated with higher salinity. The root zone EC of saturated soil-paste extract[11] (EC_e) is an indicator of a plant's salt tolerance threshold, while TDS indicates the weight of residue remaining after evaporating a given volume of water or soil extract (mass per unit volume) and is typically expressed in milligrams per liter ($mg\ L^{-1}$) or parts per million (ppm) for freshwater and recycled water. Soil salinity can be measured in the lab using soil samples or estimated *in situ* using soil sensors and other devices to help characterize the soil properties; however, because dissolved mineral salts are mobile in the soil and readily affected by variables such as irrigation water application, rainfall distribution, shallow groundwater, and evapotranspiration, as well as are influenced by spatiotemporal changes of soil salinity within the root zone, each soil's salinity profile tends to be dynamic.

3.2 Potential Negative Effects of Recycled Water on Plants and Soil

The main concerns regarding recycled water quality for irrigation are (a) osmotic stress that negatively affects the amount of water in the soil that is readily available water to plants, (b) specific ion toxicity to sensitive plants, and (c) infiltration reduction due to soil aggregate dispersion, which leads to soil surface sealing and reduction of soil permeability (Burt and Styles, 2011; Tanji et al., 2008). Dissolved mineral salts tend to accumulate in the active root zone as plants take up water to meet transpiration demand and as water evaporates from the soil surface. A higher concentration of salts increases the osmotic pressure of the water, making it more difficult (energy-consuming) for the plant to access the water (which, as a result, imposes physiological drought to plants). The effects of physiological drought include stunted growth, chlorosis, damaged leaves, wilting, and death in the most severe cases. As the concentration of some ions (e.g., sodium, chloride, and boron) increases within the soil profile, toxic effects that may damage crop tissue or cause an imbalance in plant nutrients are more likely to occur. Furthermore, the soil structure and, in turn, soil infiltration rate may be negatively affected by the combined effects of salinity and sodicity (i.e., the amount of sodium held in soil), thereby causing the breakdown of soil aggregates and dispersion of clays and soil organic matter (Tanji et al., 2008). All these negative effects may contribute to the failure of a landscape planting.

The Natural Resources Conservation Service (NRCS) and U.S. Department of Agriculture (USDA) publish soil maps depicting soil salinity and sodicity throughout California. The soils are characterized according to salinity class (based on EC values) and sodium adsorption ratio (SAR) class [a measure of the amount of sodium (Na) relative to calcium (Ca) and magnesium (Mg) in the water extracted from saturated soil paste]. According to the California State Soil Scientists, soils with an EC of 4 will impair most crop

[11] Electrical conductivity (EC) of the saturated soil-paste extract (ECe) may be determined by measuring the EC of the saturated soil-paste (ECp) and estimated saturated soil-paste water content (SP), for purposes of soil salinity appraisal. The method is suitable for both field and laboratory applications. (Rhoades et al, 1988).

growth, and soils with a SAR of 13 or more may experience increased dispersion of organic matter and clay particles, reduced hydraulic conductivity, and general degradation of soil structure.[12] For soil with a high EC/SAR, it is important to understand how irrigation with recycled water may contribute to changes in soil health.

3.3 Determining the Leaching Fraction to Optimize the Salt Balance

Plants species differ in their tolerance to salts and the amount of metabolic energy required to adjust to a saline environment; therefore, when using recycled water for irrigation, it is essential to maintain a desired salt balance in the active root zone to sustain satisfactory landscape performance. Applying water to leach excess salts from the root zone is the accepted strategy for maintaining this balance.

The ratio of the drainage water to irrigation water is called the leaching fraction (LF). The LF is the percentage of applied irrigation water that drains below the active root zone and can be estimated by determining the electroconductivity of the irrigation water (ECi) and threshold salinity value for the crop

The minimum amount of water required to flush out the excess salts in the root zone that are detrimental to plant growth is called the leaching requirement (LR). The LR represents additional irrigation water beyond the crop ET requirement needed to regulate salt accumulation in the effective root zone, which is the band of soil where most of the roots that take up water are located. The LR is used throughout the agricultural industry to determine how much water is needed to maintain a soil salinity that can be tolerated by a crop and will not cause a reduced yield. A relatively small LF or LR in the range of 0.15 to 0.2 is typically sufficient to maintain a salt balance in freely draining soils for most agricultural crops and landscape plants with a similar range of salt tolerances (Tanji et al., 2008).

Notably, different plant species and even varieties of the same plant species can differ in tolerance to salinity and should be observed for damage due to salt accumulation in soil.

For a detailed explanation on how to calculate the leaching fraction and leaching requirement, see Drought Tips, No. 92-16, at http://www.water.ca.gov/pubs/drought/leaching__drought_tip_92-16_/92-16.pdf

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[12] The database and maps illustrating soil salinity and sodicity throughout California are available online at https://sjvp.databasin.org/datasets/58b3b7b6e8de4747bece8154f3bf2379.

CHAPTER 4: CURRENT MWELO GUIDELINES FOR IRRIGATION WITH RECYCLED WATER

4.1 Origin of the Model Water Efficient Landscape Ordinance (MWELO)

A taskforce of stakeholders in California, including landscape and construction industry professionals, environmental protection groups, water agencies, and state and local governments, created the Model Water Efficient Landscape Ordinance (MWELO),[13] which initially went into effect in 1993 under the Water Conservation in Landscaping Act of 1990 (Barta et al., 2007). Managed by the California Department of Water Resources (DWR), the ordinance emphasizes California's limited water supply and ever-increasing demands, recognizes the importance of landscape as essential to the quality of life in California, and promotes water conservation and water use efficiency (California Department of Water Resources, 2015). The purpose of MWELO is "to promote the values and benefits of landscaping practices that integrate and go beyond the conservation and efficient use of water" and "use water efficiently without waste by setting a Maximum Applied Water Allowance as an upper limit for water use and reduce water use to the lowest practical amount."[14]

The MWELO emphasizes both the need to use limited water resources wisely and the benefits that landscape plants provide in urban areas. Healthy vegetation is essential to (a) maintaining and improving environmental conditions and (b) increasing resiliency in an era of changing climate (Gago et al., 2013). The ordinance contains comprehensive regulatory guidelines on topics including soil management, design plans for landscaping, irrigation, grading, irrigation scheduling and auditing, stormwater management, and rainwater retention.

4.2 Calculating Irrigation Allowance According to MWELO Regulations

The MWELO requires irrigation scheduling to be regulated by ET-based or soil moisture-based smart (automatic) irrigation controllers, and provides a quantitative ET-based equation to calculate the maximum applied water allowance (MAWA), which is the upper limit of irrigation water that the ordinance allows to be applied to the landscape. The MAWA may be calculated according to Equation 1:

$$MAWA = ETo \times 0.62 \times \left[(ETAF \times LA) + \left((1 - ETAF) \times SLA \right) \right] \quad (1)$$

- MAWA is the maximum applied water allowance (per year, in gallons).
- ETo is the reference evapotranspiration (ET).
- 0.62 is a conversion factor (converts acre-inches/acre/year to gallons/square foot/year).
- LA is total landscape area in square feet.
- SLA is total special landscape area (irrigated with recycled water) in square feet.
- ETAF is the ET adjustment factor (0.55 for residential and 0.45 for non-residential areas).

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[13] The MWELO regulation is available at http://www.water.ca.gov/wateruseefficiency/landscapeordinance/.

[14] California Code of Regulations, Title 23, Div 2, Chap 2.7. (23 CCR § 490).

Areas irrigated with recycled water are characterized as a Special Landscape Area[15] by MWELO and are allowed an ETAF of 1.0. Reference ET values (ETo) for cities and counties throughout California are provided in Appendix A of MWELO.[16]

MWELO encourages managers to use a long-term approach when designing landscape plantings and irrigation processes. To support a reasonable planning cycle, the guidance provides a calculation to determine the annual volume of irrigation water required to sustain the landscape.

The estimated total water use (ETWU) to meet annual irrigation needs is calculated as shown in Equation 2:

$$ETWU = ETo \times 0.62 \times ETAF \times Area \tag{2}$$

4.3 Calculating the Evapotranspiration Adjustment Factor

The equation for calculating the adjustment factor (ETAF) is made more robust and precise with the inclusion of additional variables, including the plant factor (PF), which categorizes plants according to water needs (i.e., very low, low, moderate, and high) and irrigation efficiency (IE), which varies according to the mechanical irrigation process (e.g., drip irrigation versus spray).

Equation 3 may be used to calculate a baseline ETAF for potable water use. This value will then be factored in to the calculation to determine if a different adjustment is required for recycled water with given TDS concentration.

$$ETAF = \frac{PF}{IE} \tag{3}$$

[15] The Special Landscape Area (SLA) designation is reserved for areas of the landscape dedicated solely to edible plants, areas irrigated with recycled water, water features using recycled water, and areas dedicated to active play such as parks, sports fields, golf courses, and turf playing surfaces.

[16] For areas not covered by Appendix A, use a reference ET from a CIMIS station (http://wwwcimis.water.ca.gov/).

CHAPTER 5: INCORPORATING THE LEACHING REQUIREMENT INTO THE MAXIMUM APPLIED WATER ALLOWANCE (MAWA)

The term "Leaching Requirement" (LR) refers to additional irrigation water in excess of that required to meet the evapotranspiration needs of plants. The purpose of the additional water is to leach excessive soluble salts from the root zone to prevent the accumulation of excess soluble salts in irrigated soils (Corwin et al., 2007).

5.1 Calculations that Include the Leaching Requirement

This chapter explains how the LR for recycled water can be calculated based on the following equations (Rhoades, 1974; Ayers and Westcot, 1985):

$$LR = \frac{EC_{iw}}{5 \times EC_e - EC_{iw}} \tag{4}$$

where EC_{iW} is the salinity of irrigation water in deciSiemens per meter (dS/m) and EC_e is crop tolerance[17] to soil salinity (dS/m), based on the measured EC of the saturated paste extract.[18] The substitution of LR into ETWU (Equation 2) yields:

$$ETWUr = 0.62 \times \frac{PF \times ETo}{IE \times (1 - LR)} \times Area \tag{5}$$

where *ETWUr* is the estimated total water use (in gallons) required per year for the areas irrigated with recycled water.

Using Equations 2, 3 and 5, the ETAF for the areas irrigated with recycled water (ETAFr) can be calculated with Equations 6 (sprinkler irrigation) and Equation 7 (drip irrigation),

$$ETAFr = \frac{PF}{0.75 \times (1 - LR)} \tag{6}$$

$$ETAFr = \frac{PF}{0.81 \times (1 - LR)} \tag{7}$$

[17] To access a list of crop tolerance values to salinity, see Tanji et al. (2008).

[18] The standard paste-saturation method was developed by the US Salinity Laboratory researchers (1954) to estimate soil salinity in the lab using a reference water content. The method includes saturation of the soil sample with demineralized water, filtration under suction to separate water from soil, and evaluation of EC of the saturated paste extract. The saturated paste extract method is recommended for standardized representation of the soil-solution composition.

The MWELO specifies irrigation efficiencies of 0.75 and 0.81 for spray and drip irrigation, respectively. Four plant factor[19] ranges are articulated in MWELO:

- 0 to 0.1 (for very low water use plants).
- 0.1 to 0.3 (for low water use plants).
- 0.4 to 0.6 (for moderate water use plants).
- 0.7 to 1.0 (for high water use plants).

If the ETAFr is less than or equal to the current ETAF granted to special landscape areas (i.e., 1.0), then no additional water needs to be applied to leach salts from the active root zone; however, if the ETAFr is greater than 1.0, then the authors propose adjusting the upper limit of irrigation water application (MAWAr) for special landscape areas irrigated with recycled water:

$$MAWAr = ETo \times 0.62 \times \left[(ETAF \times LA) + \left((ETAFr - ETAF) \times SLA\right)\right] \quad (8)$$

Several ETAFr calculation examples are presented in Appendix A. The conversion equations in Appendix B can be used to estimate the TDS of recycled water to equivalent EC values.

Figure 1 may be used to estimate the leaching requirement based on the salinity of the irrigation water (ECiw) and the crop's tolerance to soil salinity (ECa). In **Figure 2**, estimated values are illustrated for the ETAF based on the leaching requirement (LR) and plant factor (PF) for sprinkler irrigation systems with irrigation efficiency equal to 0.75.

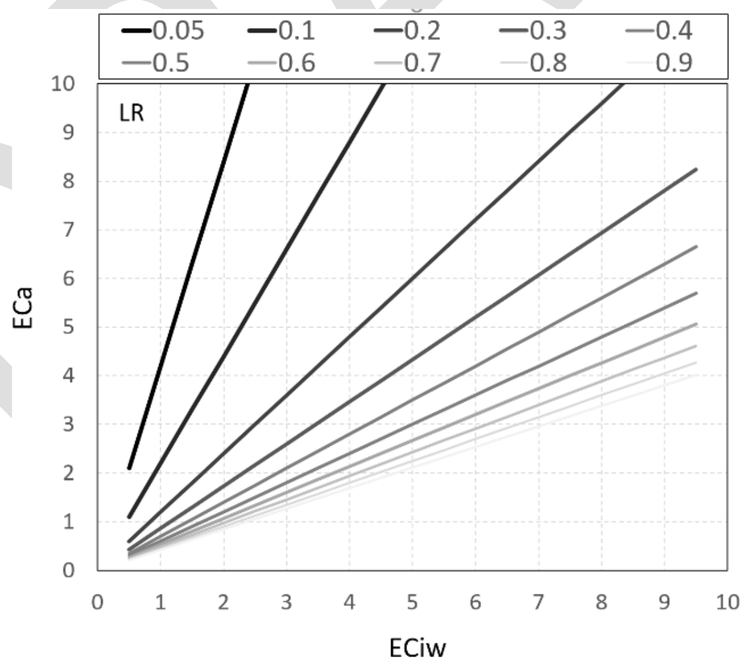

Figure 1: Calculation of the leaching requirement based on irrigation water salinity (ECiw) and crop tolerance to soil salinity (ECa).

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[19] Plant factors can be obtained from WUCOLS database at http://ucanr.edu/sites/WUCOLS/ and from horticultural researchers at academic institutions and/or professional associations, as approved by DWR.

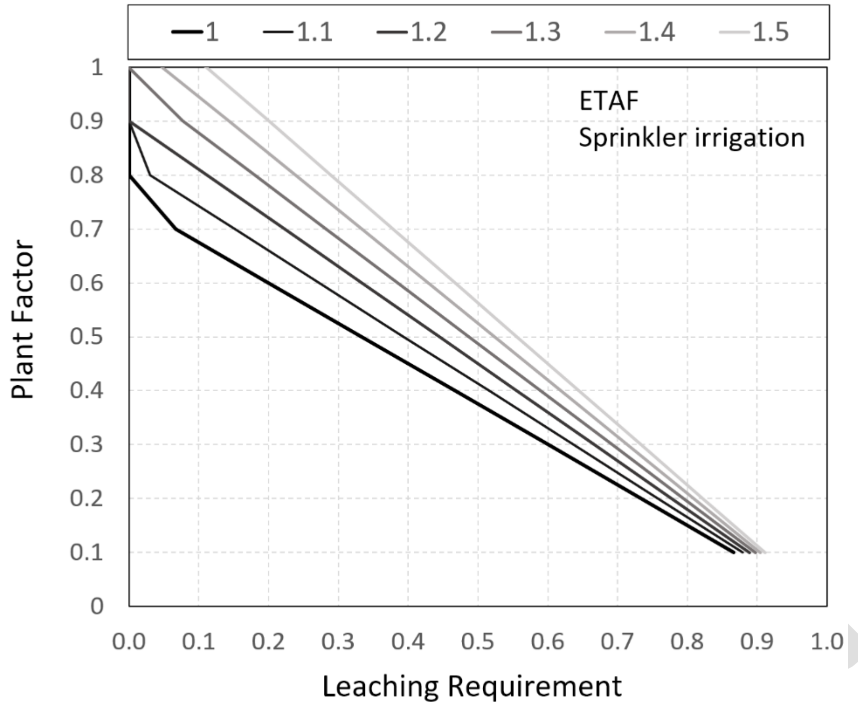

Figure 2: Estimation of the ETAF based on the leaching requirement and plant factor for sprinkler irrigation systems with an irrigation efficiency equal to 0.75.

5.2 Variables to Consider in Determining Leaching Requirements for Recycled Water

A number of variables will affect the accuracy of the LR calculation. For example, achieving a uniform irrigation application is essential to maintain a uniform wetting front throughout the leaching process. The irrigation method (e.g., sprinkler irrigation versus drip) will affect the distribution of water and salt throughout the root zone, and each method may be best suited to differing conditions and produce different challenges. For example, overhead irrigation with recycled water may expose plant leaves to salt, which may cause injury in some cases. Although drip irrigation eliminates this issue, this method does not provide uniform infiltration and leaching; therefore, the calculation presented in the previous section may not produce an accurate LR result for drip irrigation (Burt and Styles, 2011).

Other variables can contribute to the success of leaching. Modifying the physical conditions of soil can improve drainage, which in turn can reduce the accumulation of salt in the root zone. Areas where natural drainage occurs through effective rainfall may require a lower leaching fraction for salinity control. Attention should be given to irrigation and salinity management of soils with restricted drainage capacity, including fine texture soils, soils with compacted layers, soils with layers of low hydraulic conductivity, and soils with shallow groundwater, as salt is more difficult to remove from these soils.

5.3 Water Quality and Plant Selection

Although the original potable water from which the recycled water is generated also will contain dissolved salts, the MWELO does not consider a leaching requirement in potable water allocation. The salinity of the recycled water typically is higher than the original potable water, which is why leaching becomes more important in landscape irrigated with recycled water. Researchers have investigated how plants typically used in California landscapes, including turf fields, can tolerate the elevated salt levels in recycled water. A study by Wu et al. (2001) evaluated the response of native California landscape plant and grass species to irrigation water with salt concentrations of 500 and 1500 mg/L. Most of the plants tolerated the 500 TDS water well, and numerous species demonstrated moderate to severe stress when spray-irrigated with 1500 TDS water. However, salt tolerance of any plant species will depend on local conditions including climate, irrigation practices, genetic mutations, and soil characteristics (Maas, 1990).

It is worth noting that Wu et al. contend that "most recycled waters contain less salt than the lower concentration (500 mg/L) used in this study." However, a study sponsored by US Bureau of Reclamation, WateReuse Foundation, and California water and wastewater agency partners found that Title 22 recycled water in the area typically has an electrical conductivity of 1.1 dS/m and about 825 mg/L TDS (WRF, 2007). These values were used to develop a salinity management guide to assist landscape professionals in designing landscapes that can survive when irrigated with high-TDS water.

A beneficial strategy for increasing the success of landscapes and recommended to include salt-tolerant plants in the design of landscape areas irrigated with recycled water as these plants are inherently more capable of withstanding the effects of high salts in the root zone or on leaves. Useful plants selection guidelines for sites irrigated with recycled water for Coastal Southern California Landscapes are provided by Tanji et al. (2008).

Notably, this document only considers leaching requirement for the control of salinity in the root zone for a healthy landscape without considering other potentially harmful constituents in recycled water.

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APPENDIX A: EXAMPLE ETAF CALCULATIONS

Example 1a: Kentucky Bluegrass in South Coast Marine and Transition Areas (ETo = 55) irrigated with high-TDS recycled water (~1000 mg/L) in a residential area (ETAF = 0.55)

ECe (threshold salinity): 3.0 dS m^{-1}

ECiw (recycled water salinity of ~1000): 1.5 dS m^{-1}

Irrigation System: Sprinkler

Plant Factor: 0.8

Special Landscape Area: 1000 (square feet)

$$LR = \frac{EC_{iW}}{5 \times EC_e - EC_{iW}} = \frac{1.5}{(5 \times 3.0) - 1.5} = 0.11$$

$$ETAFr = \frac{PF}{0.75 \times (1 - LR)} = \frac{0.80}{0.75 \times (1 - 0.11)} = 1.19$$

$$MAWA = ETo \times 0.62 \times \left[(ETAF \times LA) + \left((1 - ETAF) \times SLA \right) \right]$$

Since 1.19 is greater than current 1.0 ETAF, then the below adjustment is needed to MAWA:

$$MAWAr = ETo \times 0.62 \times \left[(ETAF \times LA) + \left((ETAFr - ETAF) \times SLA \right) \right]$$

$$MAWAr = ETo \times 0.62 \times \left[(ETAF \times LA) + \left((1.19 - ETAF) \times SLA \right) \right]$$

MAWAr = 55 X 0.62 X [(1.19-1.0) X 1000)] = 6,479

Example 2: Bermudagrasses

ECe (threshold salinity): 10 dS m^{-1}

ECiw (recycled water salinity): 1.5 dS m^{-1}

Irrigation System: Sprinkler

Plant Factor: 0.6

$$LR = \frac{EC_{iW}}{5 \times EC_e - EC_{iw}} = \frac{1.5}{(5 \times 10) - 1.5} = 0.03$$

$$ETAFr = \frac{PF}{0.75 \times (1 - LR)} = \frac{0.60}{0.75 \times (1 - 0.03)} = 0.82$$

Since 0.82 is less than current 1.0 ETAF no adjustment is needed to MAWA, therefore:

$$MAWAr = ETo \times 0.62 \times \left[(ETAF \times LA) + \left((1.0 - ETAF) \times SLA \right) \right]$$

APPENDIX B: CONVERSAION OF TDS TO EC

Tanji et al. (2008) provided the following equations to convert TDS (mg L^{-1}) to EC (dS m^{-1}):

$TDS = EC \times 640$

$TDS = EC \times 735$ (preferred for Colorado River water)

$TDS = EC \times 800$ (for saline waters)

APPENDIX C: RESEARCH TEAM BIOGRAPHIES

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University of California, Riverside

Dr. Amir Haghverdi's research focuses on developing and disseminating scientific knowledge, practical recommendations, and tools for sustainable urban and agricultural water resources management. His approaches include field research trials, laboratory analyses, and computer modeling, with a goal to identify opportunities for synergy between research and extension activities. Current technology transfer themes include irrigation water management, soil hydrology, and precision farming. Dr. Haghverdi is also interested in applications of advanced data acquisition and mining techniques including remote sensing, geographic information systems (GIS) and global positioning system (GPS) technologies, machine learning, and wireless sensors. He received a Ph.D. in Irrigation Engineering from Ferdowsi University of Mashahd (Iran) and a Ph.D. in Biosystems Engineering from University of Tennessee-Knoxville.

Laosheng Wu, Ph.D.
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Dr. Wu is also a Cooperative Extension Specialist of Agricultural Water Management. His long-term goal is to promote safe application of lower quality water including recycled wastewater in agriculture and urban environment. His current research investigates the fate and transport of trace organic compounds in soil and water receiving recycled wastewater application, evaluates the effect of salinity and other toxic elements from low quality irrigation water on crop growth, assesses soil quality response to recycled wastewater application, and develops optimal salinity leaching management practices for irrigated cropland. He received his B.S. in Soil Science & Agrichemistry from Zhejiang University, China; M.S. in Soil Physics from Oregon State University; and Ph.D. in Soil Physics from the University of Minnesota.