



Southern California Salinity Coalition
2018 WHITE PAPER

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

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Funded by:





Southern California Salinity Coalition

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ABOUT THE SOUTHERN CALIFORNIA SALINITY COALITION

The Southern California Salinity Coalition (SCSC) was formed in 2002 to address the critical need to remove salts from water supplies and to preserve water resources in California. SCSC members include the following water and wastewater agencies in Southern California: Eastern Municipal Water District, Inland Empire Utilities Agency, Metropolitan Water District of Southern California, Orange County Sanitation District, Orange County Water District, San Diego County Water Authority, Sanitation Districts of Los Angeles County, and Santa Ana Watershed Project Authority. The mission of SCSC is to improve the management of salinity in our water supplies through activities such as: establishing proactive programs to remove salts in water supplies; preserving, sustaining, and enhancing the quality of source water supplies, and educating the general public on challenges associated with salinity. SCSC is administered by the National Water Research Institute (NWRI), a nonprofit organization located in Orange County, California. Visit www.socalsalinity.org for more information.

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The mission of WateReuse California is to promote the responsible stewardship of California's water resources by maximizing the safe, practical, and beneficial use of recycled water. WateReuse California 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. WateReuse California also supports the efforts 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. Visit www.watereuse.org for more information.

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ACRONYMS AND EQUATION TERMS

CIMIS	California Irrigation Management Information System
DWR	California Department of Water Resources
EC	Electrical conductivity
EC _e	Electrical conductivity of saturation paste extract
EC _{iw}	Electrical conductivity of irrigation water in deciSiemens per meter (dS/m)
ET	Evapotranspiration
ET _o	Reference evapotranspiration
ETAF	Evapotranspiration adjustment factor
ETAF _r	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
MAWA _r	Maximum applied water allowance for recycled water
MWELo	Model Water Efficient Landscape Ordinance
NRCS	Natural Resources Conservation Service
PF	Plant factor
SAR	Sodium adsorption ratio
SLA	Special landscape area
TDS	Total dissolved solids
USDA	U.S. Department of Agriculture

ABBREVIATIONS FOR UNITS OF MEASURE

A	Acre (area) = 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)
AFY	Acre-foot per year
CFU	Colony forming units
cm ²	Square centimeters
d	Day
dS	DeciSiemens
dS/m	DeciSiemens per meter
g	Gram
kg	Kilogram
L	Liter
m	Meter
mg	Milligram
mg/L	Milligram per liter
Mgal	Million gallons
MGD	Million gallons per day
mi	Mile
min	Minute
mL	Milliliter
Mm ³ /d	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

The Southern California Salinity Coalition (SCSC) partnered with WaterReuse California in 2017 to develop a White Paper on “Accounting for Salinity Leaching in the Application of Recycled Water for Landscape Irrigation.” Referred to as total dissolved solids (TDS), salinity is the concentration of dissolved mineral salts in water. The goal of this White Paper is to provide science-based guidance to the California Department of Water Resources (DWR) related to determining how much recycled water should be used for landscape irrigation to reduce the impact of salinity and maintain the health of plants.

For more than 100 years, California has been using recycled water in a variety of ways, including landscape irrigation; customers include golf courses, cemeteries, and nurseries, among others. At issue is how to best manage the use of recycled water for landscape irrigation. Recycled water usually contains more TDS than potable water, and these salts will accumulate in the soil unless additional water is applied to flush (or leach) them out. The salts associated with salinity can affect the health of plants, causing stunted growth, wilting, and other damage, including plant death.

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. Consequently, when irrigating landscape with recycled water, users must maintain a salt balance in the active root zone to sustain healthy plants. Applying water to leach excess salts from the root zone is the accepted best practice for maintaining this balance.

Recently, the DWR initiated a process to amend the 2015 Model Water Efficiency Landscape Ordinance (MWELo), which was originally adopted in 1992 (and updated in 2009 and 2015) to “promote the values and benefits of landscaping practices that integrate and go beyond the efficient use of water,” among other purposes. The MWELo was designed to set minimum standards to regulate the design and installation of landscaping in California, and includes a strategy to calculate how much irrigation water should be applied to a landscape to (a) meet the physiological needs of plants and (b) maximize the efficiency of water usage.

The 2015 MWELo includes a maximum applied water allowance (MAWA) calculation that allows recycled water users to apply additional irrigation water beyond what would be permitted if potable water was used for the same landscape. The challenge is that the calculation does not fully account for natural variations such as the salinity of the water used for irrigation. Consequently, the allowance may not be sufficient to protect salt-sensitive plants, such as turf grass, when high-TDS recycled water is used.

To effectively and efficiently use recycled water to irrigate landscapes subject to MWELo, there is a need to (a) establish a scientific basis for determining the minimum irrigation volume required to maintain plant health for landscape areas 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.

DWR plans to update the 2015 MWELo in 2018, and the new ordinance will go into effect on January 1, 2020, so that it will correspond with the release of the updated California Green Building Standards

Code. SCSC and WaterReuse California supported the development of this White Paper to provide a scientific rationale to account for the additional salt in recycled water and to include this rationale in the updated ordinance. As such, an alternate equation is proposed to calculate how much recycled water is required to adequately leach salt from the active root zone and, therefore, preserve the health and integrity of the landscape.

The alternative equation includes the leaching requirement (LR), defined as the minimum amount of water required to leach excess salts from the root zone. The LR represents additional irrigation water needed beyond that required by plants to replace water lost by evapotranspiration (ET), which is the sum of evaporation (the water lost from the earth's surface) plus transpiration from plants (the release of water from plant leaves). Because the LR is designed to provide for a volume of irrigation water that can adequately leach salts from the root zone, it can be used to calculate an evapotranspiration adjustment factor (ETAF) that is more precise and can sufficiently maintain plant and soil health when high-TDS recycled water is used as the source of irrigation water. Based on the calculation:

- Where the calculated ETAF for recycled water (ETAF_r) is less than or equal to 1.0, which is the factor granted to areas irrigated with recycled water in the 2015 MWELO, then no additional water is required beyond what is calculated for the upper limit of water application (MAWA), and landscape plants should grow and function as designed.
- Where the calculated ETAF_r is greater than 1.0, then the user should adjust the upper limit of water application (MAWA), as needed, to allow for the leaching of salts from the root zone to protect landscape plants from the effects of high-TDS water.

CHAPTER 1: INTRODUCTION

The Southern California Salinity Coalition (SCSC) partnered with WaterReuse California in 2017 to develop a White Paper on “Accounting for Salinity Leaching in the Application of Recycled Water for Landscape Irrigation.” The two organizations developed this White Paper in response to plans to update the 2015 Model Water Efficiency Landscape Ordinance (MWELO) in 2018. The goal of this White Paper is to provide science-based guidance to the California Department of Water Resources (DWR) for determining how much recycled water should be used for landscape irrigation to reduce the impact of salinity and maintain the health of plants.

1.1 Overview of Water Supply Needs and Water Recycling in California

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. 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 2060.¹

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 statewide, and the risk of drought may increase along with the magnitude and effects of extreme dry and wet years.

These water supply demands have created a 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. Numerous communities in California have invested in recycled water projects to provide water for approved beneficial purposes, including landscape irrigation for residential and non-residential areas. According to the most recent Municipal Wastewater Recycling Survey conducted by the DWR, a total of 714,000 acre-feet (AF) of recycled water was put to beneficial reuse in 2015 in California, with 26 percent used for landscape irrigation.² 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. Healthy vegetation is considered essential to (a) maintaining and improving environmental conditions and (b) increasing resiliency in an era of changing climate (Gago et al., 2013).

The use of recycled water to maintain urban landscape particularly is important in southern coastal California (the Los Angeles-to-San Diego corridor), and estimates indicate additional demand on regional water resources in the future due to a two-fold population increase above the Year 2000 population in both neighboring Nevada and Arizona by Year 2030 (Tanji et al., 2008; Wu et al., 2009). The application of recycled water for irrigation is especially attractive because municipal wastewater is produced close

¹ California Department of Finance. <http://www.dof.ca.gov/Forecasting/Demographics/projections/>

² 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

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 supplies (Wu et al., 2009; Tanji et al., 2008).

Estimates indicate that the water needs of 30 to 50 percent of the 17 million additional people who will live in California by 2030 could be satisfied by an additional 4 million cubic meters per day (Mm^3/d) (approximately 3,200 AF per day or 1.2 million acre-feet per year (AFY)) of recycled water (California Department of Water Resources, 2004). Given that the State Water Resource Control Board's Recycled Water Policy aims to increase the use of recycled water above the 2002 amount by at least 1 million AFY by 2020 and 2 million AFY by 2030 by substituting as much recycled water for potable water as possible,³ the area of landscape irrigated with recycled water likely will increase.

1.2 Overview of Issues Associated with Recycled Water Use for Landscape Irrigation

Irrigating landscapes with recycled water has become an essential strategy for offsetting the use of potable water supplies in California; however, using recycled water for irrigation can present its own challenges.

The criteria for recycled water, including the quality of recycled water meant for landscape applications, are provided in Title 22 of the California Code of Regulations (CCR). Per Title 22, pathogen removal is necessary to reduce the likelihood of adverse effects on public health and the environment in areas irrigated with recycled water. Unlike pathogens, TDS is not considered a risk to human health; therefore, limits for TDS in recycled water are not included in Title 22. Because wastewater treatment plants producing recycled water for irrigation are not designed to remove salts, the recycled water used for irrigation typically contains more salts and nutrients than potable water. Excessive concentrations of these constituents, including sodium, chloride, boron, and heavy metals, can stunt and damage plants and cause salts to accumulate in soil. Over time, salt build-up may eventually cause landscape vegetation to fail.

Although recycled water typically contains higher levels of TDS than potable water, it can be used to irrigate plants if (a) appropriate salt-tolerant landscape species plants are selected and (b) irrigation practices are managed to prevent the buildup of excess salts in the root zone. 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. According to various sources, recycled waters contain 140 to 400-milligram per liter (mg/L) more salt than potable sources (Tanji et al., 2005). Recycled water from agencies surveyed by the U.S. Bureau of Reclamation and project partners averaged 825 mg/L in 2007 (WRF, 2007). Many plants used for landscaping, including turf grasses commonly planted on recreational fields, are sensitive to elevated salt concentrations. When recycled water is used regularly to irrigate a landscape area, excess salts tend to accumulate in the soil and 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. This problem is more pronounced in arid and semi-arid climates, where precipitation is not sufficient to leach soluble salts from the active root zone. Research has demonstrated that these excess salts limit productivity in turf grasses and cause decreased growth and shoot density and thinning of the turf as individual grass

³ 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_revto.pdf

plants die (Harivandi, 1984); therefore, turf grasses may require leaching water to survive under high-salinity conditions.

The effects of salinity of irrigation water and soil on crop health is not a new issue (Childs and Hanks, 1975; Maas and Hoffman, 1977; Jury et al., 1978; Rhodes et al, 1989; Shalhevet, 1994; Katerji et al., 2003), and researchers 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 variables such as soil characteristics, the water needs of plants, and the salt content of the irrigation water, and have been used successfully by the agricultural sector for years to maximize crop yields and maintain soil health. Although the goals of landscape maintenance differ from those of agricultural production, existing models are still relevant and can be used to support recommendations for irrigation.

1.3 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, directing DWR to adopt a statewide Model Water Efficient Landscape Ordinance (MWELO) by January 1, 1992.⁴ The overall goal of MWELO is to promote efficient landscapes in new developments and retrofitted landscapes. MWELO was developed by a taskforce of stakeholders in California, including landscape and construction industry professionals, environmental protection groups, water agencies, and state and local governments,⁵ and was amended in 2009 and 2015. DWR has initiated the process to further amend it in 2018 before implementing the new ordinance in 2020.

Specifically, previous versions of MWELO have included objectives designed 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 in irrigation practices; and (e) encourage water agencies to promote the efficient use of water. The ordinance contains comprehensive regulatory guidelines on topics such as soil management, design plans for landscaping, irrigation, grading, irrigation scheduling and auditing, stormwater management, and rainwater retention. 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 statewide requirements.⁶

The MWELO includes strategies for how to “use water efficiently without waste by setting a Maximum Applied Water Allowance (MAWA) as an upper limit for water use and reduce water use to the lowest practical amount.”⁷ To do so, MWELO relies on a quantitative approach based on evapotranspiration (ET) rates to calculate the MAWA, which is the upper limit of irrigation water that may be applied to a landscape area. For any specific landscaped area, the MAWA includes the following factors:

⁴ 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.

⁵ The MWELO regulation is available at <http://www.water.ca.gov/wateruseefficiency/landscapeordinance/>.

⁶ 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>.

⁷ California Code of Regulations, Title 23, Div 2, Chap 2.7 (23 CCR § 490).

- Reference Evapotranspiration (ET_o). The ET_o is a “standard measurement of environmental parameters which affect the water use of plants”⁸ and is derived from “an estimate of the evapotranspiration of a large field of four- to seven-inch tall, cool-season grass that is well-watered.”⁹ The ET_o is used to accommodate regional differences in California’s climate.¹⁰
- Evapotranspiration Adjustment Factor (ETAF). The ETAF is a coefficient used to adjust the reference evapotranspiration value to accommodate differences in (a) the water needs of plants and (b) efficiency of the irrigation system. 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 2015 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).

The ordinance has been implemented successfully in many regions throughout California. Because the MWELo applies to most new and rehabilitated landscapes associated with residential, commercial, industrial and institutional projects that require a permit, plan check, or design review, the ordinance affects water users in urban areas throughout the state.

1.4 Need to Account for Salinity in the Model Water Efficient Landscape Ordinance

In calculating an applicable MAWA for each landscape project, the 2015 MWELo accounts for regional differences in climate, mixture of plants (i.e., ornamental plants and flowers, trees, turf, etc.), and the efficiency of the irrigation system. The calculation, however, does not fully account for salinity of the water; therefore, MWELo makes no regulatory accommodation for variations in the TDS of the water used for irrigation. Although the 2015 MWELo does allow 20 percent more¹¹ irrigation volume to be applied when recycled water is used, this allowance may not be sufficient to protect plant health in cases where high-TDS water is applied to a salt-sensitive landscape. The lack of specific guidance for recycled water users is important because when high-TDS water is used for landscape irrigation, additional water beyond what MWELo prescribes may be needed to flush excess salt from the root zone to maintain plant health and soil quality. Because the 2015 MWELo is not designed to account for the actual amount of salt in recycled water, the current regulation may not meet DWR’s stated goals to preserve plant health while ensuring efficient irrigation practices. As a result, to use recycled water both effectively and efficiently for landscape irrigation, it will be important to (a) establish a scientific basis for determining the minimum irrigation volume required to maintain plant health for landscape areas irrigated with recycled water; and (b) propose a framework for ensuring that recycled water irrigation

⁸ 23 CCR §491 (mmm).

⁹ Ibid.

¹⁰ Map of ET_o zones according to California Irrigation Management Information System (CIMIS) is available at: http://www.cimis.water.ca.gov/App_Themes/images/etozonemap.jpg.

¹¹ The 2015 MWELo includes an ETAF of 1.0 for special landscape areas, which is 20 percent higher than the ETAF of 0.8 specified in the 2009 MWELo.

practices consistent with these minimum requirements are as effective as MWEL0 in maintaining plant health and ensuring water conservation.

Notably, 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, such as landscape irrigation; therefore, having a regulatory process to accommodate the difference in TDS between potable and non-potable recycled water would be valuable for several reasons, including:

1. The 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 landscapes that rely on recycled water for irrigation.
3. Recycled water purveyors have designed publicly owned recycled water treatment facilities and distribution systems based on 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.

1.5 Interest in Developing the White Paper

Beginning in June 2017, representatives from SCSC (which is administered by the National Water Research Institute [NWRI]), began collaborating with WateReuse California to document in a White Paper how to account for salinity leaching in the application of high-TDS recycled water for landscape irrigation. The groups' interest in this topic developed when they became aware that DWR would update MWEL0 in 2018. All three organizations approached the topic from different perspectives.

- SCSC is a coalition of eight agencies working to address the need to remove salts from water supplies and preserve water resources in California. It is interested in the economic impact of salinity on landscape maintenance.
- NWRI is a joint powers and nonprofit organization in Southern California that sponsors research and programs focused on ensuring safe, reliable sources of water. It administers SCSC. Among its interests, NWRI works to advance the science and application of water treatment technologies for both the potable and non-potable reuse of recycled water.
- The mission of WateReuse California, a trade organization, is to promote responsible stewardship of California's water resources by maximizing the safe, practical, and beneficial use of recycled water. WateReuse California's position is that the use of recycled water to replace potable sources provides a benefit equivalent to water conservation. Several of its stakeholders provided anecdotal evidence that water agencies are producing high-salinity recycled water that can damage high-value landscapes, including athletic playing fields and forests, unless it is applied in a volume great enough to flush salts to below the active root zone.

1.6 Research Team

SCSC contacted Lorence Oki, Ph.D., a recognized expert at University of California, Davis, Cooperative Extension, who specializes in irrigation management for urban horticulture and water quality effects on plant growth. Dr. Oki helped develop a salt-tolerant plant list to support DWR's irrigation efficiency efforts. His colleague, Karrie Reid, recommended contacting researchers at UC Riverside Cooperative Extension based on their experience with recycled water.

In August 2017, SCSC staff engaged two scientists at University of California, 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 is required to leach salts from the soil and protect plant health. The Research Team included: 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 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 White Paper, the Research Team reviewed publications identified by 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 electrical conductivity of the recycled water and the crop's tolerance to soil salinity. Their contributions were then incorporated into this White Paper. Biographical information on Drs. Haghverdi and Wu is provided in **Appendix A**.

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 treatment and efficient irrigation management, recycled water can be used effectively in urban and agricultural settings. However, it may be necessary to take special measures to minimize the potential negative effects on plant and soil health 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 intended use.

2.2 Characteristics of Recycled Water

Although 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 such as 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 the build-up of salts in soil.

Despite variations in the chemical characteristics of recycled water across treatment facilities, once treatment is complete, the most significant remaining constituents that could damage landscape plants are typically sodium and chloride. Other elements in the recycled water, including boron, selenium, magnesium, and cadmium, 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, that may be beneficial to both soil and crops; however, because excess nutrients may cause unwanted effects, the application of fertilizer 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 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. The 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 extract¹² (EC_e) is an indicator of the salt tolerance threshold of a plant, while TDS indicates the weight of residue remaining after evaporating a given volume of water or soil extract (mass per unit volume). The TDS typically is expressed in milligrams per liter (mg/L) 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, evapotranspiration, and spatiotemporal changes of soil salinity within the root zone, the salinity profile of each soil 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 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 the 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, the 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 deciSiemens per meter

¹² Electrical conductivity (EC) of the saturated soil-paste extract (EC_e) may be determined by measuring the EC of the saturated soil-paste (EC_p) 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).

(dS/m) will impair most crop 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.¹³ For soils 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 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 electrical conductivity 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).¹⁴ 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 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 typically is 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.

¹³ The database and maps illustrating soil salinity and sodicity throughout California are available online at <https://sjvp.databasin.org/datasets/58b3b7b6e8de4747bece8154f3bf2379>.

¹⁴ 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.

CHAPTER 4: CURRENT MODEL WATER EFFICIENT LANDSCAPE ORDINANCE GUIDELINES FOR IRRIGATION WITH RECYCLED WATER

4.1 Calculating the Irrigation Allowance According to MWELO

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:

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

- MAWA is the maximum applied water allowance (per year, in gallons).
- ETo is the reference evapotranspiration (ET); the ETo values for cities and counties throughout California are provided in Appendix A of MWELO.¹⁵
- 0.62 is a conversion factor (converts acre-inches/acre/year to gallons/square foot/year).
- ETAF is the ET adjustment factor (0.55 for residential and 0.45 for non-residential areas). Note that areas irrigated with recycled water are characterized as a Special Landscape Area¹⁶ by MWELO and are allowed an ETAF of 1.0.
- LA is total landscape area in square feet.
- SLA is total special landscape area (irrigated with recycled water) in square feet.

MWELLO 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:

$$ETWU = ETo \times 0.62 \times ETAF \times LA \quad (2)$$

4.2 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 be factored in to the calculation to determine if a different adjustment is required for recycled water with a given TDS concentration.

$$ETAF = \frac{PF}{IE} \quad (3)$$

¹⁵ For areas not covered by Appendix A of MWELO, use a reference ET from a CIMIS station (<http://www.cimis.water.ca.gov/>).

¹⁶ 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.

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

The term “Leaching Requirement” (LR) refers to additional irrigation water in excess of what is 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

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

$$LR = \frac{EC_{iw}}{5 \times EC_e - EC_{iw}} \quad (4)$$

where EC_{iw} is the salinity of irrigation water in deciSiemens per meter (dS/m) and EC_e is crop tolerance¹⁷ 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:

$$ETWUr = 0.62 \times \frac{PF \times ET_o}{IE \times (1 - LR)} \times LA \quad (5)$$

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

Using Equations 2, 3, and 5, the ETAF for the areas irrigated with recycled water (ETAF_r) can be calculated with Equations 6 (spray irrigation) and Equation 7 (drip irrigation). The MWEL0 specifies irrigation efficiencies of 0.75 and 0.81 for spray and drip irrigation, respectively.

$$ETAF_r = \frac{PF}{0.75 \times (1 - LR)} \quad (6)$$

$$ETAF_r = \frac{PF}{0.81 \times (1 - LR)} \quad (7)$$

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 researchers at the U.S. Salinity Laboratory (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.

Four plant factor ranges¹⁹ are articulated in MWEL0:

- 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 calculated ETAF_r is less than or equal to the current ETAF granted to special landscape areas (i.e., 1.0), then no additional water beyond the volume calculated using an ETAF value of 1.0 needs to be applied to leach salts from the active root zone. However, if the ETAF_r is greater than 1.0, then adjust the upper limit of irrigation water application (MAWA_r) for the area of the landscape (designated a “special landscape area” or SLA) irrigated with recycled water, as shown in Equation 8:

$$MAWA_r = ET_o \times 0.62 \times [(ETAF \times LA) + ((ETAF_r - ETAF) \times SLA)] \quad (8)$$

In cases where the entire landscape area is irrigated with recycled water, a simplified equation should be used in which (a) the entire landscape area is a SLA (i.e., $LA = SLA$), and (b) ETAF_r is determined from the calculated leaching requirement, as shown in Equation 9.

$$MAWA_r = ET_o \times 0.62 \times ETAF_r \times SLA \quad (9)$$

Refer to **Appendix B** for sample ETAF_r calculations. The conversion equations in **Appendix C** can be used to estimate the TDS of recycled water corresponding to the equivalent EC values. Consult the graphs in **Appendix D** for a method to estimate the LR and ETAF.

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 create 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 salts 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, because salt is more difficult to remove from soils with these properties.

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.

5.3 Water Quality and Plant Selection

The MWELO does not include the leaching requirement when allocating potable water for irrigation. Because the salinity of recycled water typically is higher than the potable water available at the same location, the leaching requirement becomes even more important for landscapes irrigated with recycled water. The same analytical approach (i.e., Equations 4 and 5) can be used to calculate leaching requirements for both potable water and recycled water. More water should be allocated to leach the additional salinity due to use of recycled water. This additional water can be calculated from the difference in the leaching requirement between potable water and recycled water.

Researchers have investigated how plants typically used in California landscapes, including turf fields, can tolerate 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 1,500 mg/L. Most plants tolerated the 500 TDS water, and numerous species demonstrated moderate to severe stress when spray-irrigated with 1,500 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.” Conversely, a study sponsored by the U.S. Bureau of Reclamation, WaterReuse Foundation, and water and wastewater agency partners in California found that Title 22 recycled water 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 tolerate irrigation with high-TDS water.

A beneficial strategy for increasing the success of landscapes is 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 in Tanji et al. (2008).

Notably, this document only considers the leaching requirement for the control of salinity in the root zone for a healthy landscape, and does not consider other constituents in recycled water.

6. CONCLUSIONS AND RECOMMENDATIONS

6.1 Key Conclusions

Based upon a review of the best available scientific evidence, DWR and other interested stakeholders should consider the following key conclusions of this White Paper:

1. Excessive salts, other dissolved solids, and nutrients in the active root zone are harmful to plant health.
2. The LR calculation provides a sound scientific rationale for permitting and granting variances to the ETAF limits in existing MAWA calculations.
3. An LR-based variance to established ETAF limits can be accommodated by enhancing the existing MAWA calculations with one additional calculation.

6.2 Recommendations for Policy Guidance

Including the LR in the MAWA calculation will allow applicants, regulators, and other stakeholders to determine the optimal irrigation volume that will minimize the negative effects of excess salts, other dissolved solids, and nutrients on plant and soil health while still adhering to water conservation principles. Because the LR is designed to provide for an irrigation volume that is adequate (and not excessive) to leach salts to a level below the effective root zone so that plant roots are not continually exposed to the damaging effects of high-salinity soil and water, a simple model can be used to calculate an ETAF that is sufficient to maintain plant and soil health when recycled water is the source of irrigation water. **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:

1. Where the calculated ETAF for recycled water (ETAF_r) is less than or equal to 1.0, which is the factor granted to areas irrigated with recycled water, then no additional water is required beyond what is calculated for the upper limit of water application (MAWA), and landscape plants should grow and function as designed.
2. Where the calculated ETAF_r is greater than 1.0, then the user should adjust the upper limit of water application, as needed, to allow for the leaching of salts from the active root zone to protect landscape plants from the toxic effects of high-TDS water.

7. REFERENCES

- AghaKouchak, A., Feldman, D., Hoerling, M., Huxman, T., and J. Lund (2015). Water and climate: Recognize anthropogenic drought. *Nature*, 524, 409-411.
- Ayers, R.S. and D.W. Westcot (1985). *Water Quality for Agriculture*. FAO Irrigation and Drainage Paper 29. Food and Agriculture Organization of the United Nations, Rome, 174 pp.
- Burt, C.M., and S.W. Styles (2011). *Drip and micro irrigation design and management*. 4th Edition. Irrigation Training and Research Center (ITRC). Cal Poly, San Luis Obispo, CA.
- California Department of Water Resources. *Drought Tips* (1993). Number 92-16. Published by California Department of Water Resources, Water Conservation Office; University of California (UC); UC Department of Land, Air and Water Resources; USDA Drought Response Office; USDA Soil Conservation Service; and USDI Bureau of Reclamation, Mid-Pacific Region. http://www.water.ca.gov/pubs/drought/leaching_drought_tip_92-16_/92-16.pdf. Accessed online 12/08/2017.
- Childs, S., and R.J. Hanks (1975). Model of soil salinity effects on crop growth. *Soil Science Society of America Journal*, 39(4), 617-622.
- Corwin, D.L., Rhoades, J.D., and J. Šimůnek (2007). Leaching requirement for soil salinity control: Steady-state versus transient models. *Agricultural Water Management*, 90, 165-180.
- Gago, E.J., Roldan, R. Pacheco-Torres, and J. Ordóñez (2013). The city and urban heat islands: A review of strategies to mitigate adverse effects. *Renewable and Sustainable Energy Reviews*, 25, pp. 749-758.
- Harivandi, M.A. (1984). *Managing Saline, Sodic, or Saline-Sodic Soils for Turfgrasses*. California Turfgrass Culture. Cooperative Extension University of California. 34(2-3). https://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcs143_010754.pdf. Accessed online 12/20/2017)
- Jury, W., Frenkel, H., Fluhler, H., Devitt, D., and L. Stolzy (1978). Use of saline irrigation waters and minimal leaching for crop production. *California Agriculture*, 46(5), 169-192.
- Katerji, N., van Hoorn, J.W., Hamdy, A., and M. Mastrorilli (2003). Salinity effect on crop development and yield, analysis of salt tolerance according to several classification methods. *Agricultural Water Management*. 62(1), 37-66.
- Maas, E. V., and G. J. Hoffman (1977). Crop salt tolerance—current assessment. *Journal of the irrigation and drainage division*, 103(2), 115-134.
- Maas, E. V. 1990. Crop salt tolerance, In *Agricultural Salinity Assessment and Management*. K. K. Tanji (ed.). ASCE Manuals and Reports on Engineering Practice No. 71, 262 pp., New York

- Rhoades, J.D. (1974). Drainage for salinity control. In: J. van Schilfgaarde (Ed.), *Drainage for Agriculture*. Am. Soc. Agron. Monograph No. 17, pp. 433-462.
- Rhoades, J.D., Manteghi, N.A., Shouse, P.J., and W. J. Alves (1988). Estimating Soil Salinity from Saturated Soil-Paste Electrical Conductivity. *Soil Science Society of America Journal*. 53(2), pp. 428-433.
- Shalhevet, J. (1994). Using water of marginal quality for crop production: major issues. *Agricultural Water Management*, 25(3), 233-269.
- Tanji, K., S. Grattan, C. Grieve, A. Harivandi, L. Rollins, D. Shaw, B. Sheikh, and L. Wu (2008). Salt management guide for landscape irrigation with recycled water in coastal Southern California: A comprehensive literature review. http://salinitymanagement.com/Literature_Review.pdf. Accessed 10/18/2017.
- U.S. Salinity Laboratory Staff (1954). *Diagnosis and improvement of saline and alkali soils*. USDA Handbook 60, U.S. Government Printing Office, Washington, D. C.
- WaterReuse Foundation (2007) *Salinity Management Guide: The Links Between Soil, Salt and Recycled Water*. WRF Project: 03-12. <https://watereuse.org/salinity-management/index.html> Accessed 12/13/2017.
- Williams, A.P., Seager, R., Abatzoglou, J.T., Cook, B.I., Smerdon, J.E., and E.R. Cook (2015). Contribution of anthropogenic warming to California drought during 2012–2014. *Geophysical Research Letters*, 42(16), 6819-6828.
- Wu, L., Chen, W., French, C., and A. Chang (2009). *Safe Application of Reclaimed Water Reuse in the Southwest*. Technical Bulletin. UC ANR.
- Wu, L., X. Guo, K. Hunter, E. Zagory, R. Waters, and J. Brown (2001). *Studies of Salt Tolerance of Landscape Plant Species and California Native Grasses for Recycled Water Irrigation*. Slosson Report 2000-2001. <https://pdfs.semanticscholar.org/8c08/e9051bd0cc67c6c8c6a9fff12fa346db5f4a.pdf>. Accessed 12/13/2017.

APPENDIX A: RESEARCH TEAM BIOGRAPHIES

Amir Haghverdi, Ph.D.

*Assistant CE Specialist, Department of Environmental Sciences
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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 of identifying opportunities for synergy between research and extension activities. His current research themes include irrigation water management, soil hydrology, and precision farming. Dr. Haghverdi also is 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 Mashhad (Iran) and a Ph.D. in Biosystems Engineering from the University of Tennessee-Knoxville.



Laosheng Wu, Ph.D.

*Professor of Soil and Water Science and Chair, Department of Environmental Sciences
University of California, Riverside*

Dr. Wu also serves as a Cooperative Extension Specialist of Agricultural Water Management. His long-term goal is to promote the safe application of lower quality water, including recycled wastewater in agriculture and the 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 a B.S. in Soil Science and 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.



APPENDIX B: EXAMPLE EVAPOTRANSPIRATION ADJUSTMENT FACTOR AND LEACHING REQUIREMENT CALCULATIONS

Example 1: Kentucky Bluegrass in South Coast Marine and Transition Areas (ETo = 55) irrigated with high-TDS recycled water (~960 mg/L) for a special landscape area (ETAF = 1.0).

ECe (threshold salinity): 3.0 dS/m

ECiw (recycled water salinity of ~960): 1.5 dS/m

Irrigation System: Sprinkler

Plant Factor: 0.8

Special Landscape Area: 1,000 (square feet)

$$LR = \frac{EC_{iW}}{5 \times EC_e - EC_{iW}} = \frac{1.5}{(5 \times 3.0) - 1.5} = 0.11 \quad \text{(Equation 4, introduced on page 13)}$$

$$ETAFr = \frac{PF}{0.75 \times (1 - LR)} = \frac{0.80}{0.75 \times (1 - 0.11)} = 1.20 \quad \text{(Equation 6, introduced on page 13)}$$

MAWA (annual gallons allowed) calculated using the original 1.0 factor is:

$$MAWA = ETo \times 0.62 \times ETAFr \times SLA = 55 \times 0.62 \times 1 \times 1000 = 34,100$$

Because 1.20 is greater than the ETAF for recycled water (which is 1.0), it is recommended that additional water be allowed on top of the original 1.0 ETAF to ensure adequate leaching of salt from the root zone. The calculation is shown below:

$$MAWA_r = ETo \times 0.62 \times ETAFr \times SLA = 55 \times 0.62 \times 1.2 \times 1000 = 40,920$$

(Equation 9, introduced on page 14)

Altogether, the difference between MAWA_r and MAWA (i.e., 40,920-34,100 = **6,820**) is the extra water (annual gallons allowed) suggested for adequate leaching.

Example 2: Bermudagrasses in South Coast Marine and Transition Areas ($ET_o = 55$) irrigated with high-TDS recycled water (~960 mg/L) for a special landscape area ($ETAF = 1.0$).

EC_e (threshold salinity): 10 dS/m

EC_{iw} (recycled water salinity): 1.5 dS/m

Irrigation System: Sprinkler

Plant Factor: 0.6

Special Landscape Area: 1,000 (square feet)

Note that the conditions in Example 2 are identical to Example 1 except for the threshold salinity of the plant and the plant factor.

$$LR = \frac{EC_{iw}}{5 \times EC_e - EC_{iw}} = \frac{1.5}{(5 \times 10) - 1.5} = 0.03 \quad \text{(Equation 4, introduced on page 13)}$$

$$ETAF_r = \frac{PF}{0.75 \times (1 - LR)} = \frac{0.60}{0.75 \times (1 - 0.03)} = 0.82 \quad \text{(Equation 6, introduced on page 13)}$$

MAWA (annual gallons allowed) calculated using the original 1.0 factor is:

$$MAWA = ET_o \times 0.62 \times ETAF_r \times SLA = 55 \times 0.62 \times 1 \times 1000 = 34,100$$

(Equation 9, introduced on page 14)

Because 0.82 is less than the 1.0 ETAF for recycled water, no additional water beyond the water currently allowed by MWELo for special landscape areas is needed to leach salts to below the root zone.

Altogether, the MAWA of 34,100 (annual gallons allowed) is sufficient for adequate leaching.

APPENDIX C: CONVERSION OF TOTAL DISSOLVED SOLIDS TO ELECTRICAL CONDUCTIVITY

Tanji et al. (2008) provided the following equations to convert total dissolved solids (TDS) in milligrams per liter (mg/L) to electrical conductivity (EC) in deciSiemens per meter (dS/m):

$$TDS = EC \times 640$$

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

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

APPENDIX D: GRAPHS FOR USE IN ESTIMATING THE LEACHING REQUIREMENT AND EVAPOTRANSPIRATION ADJUSTMENT FACTOR

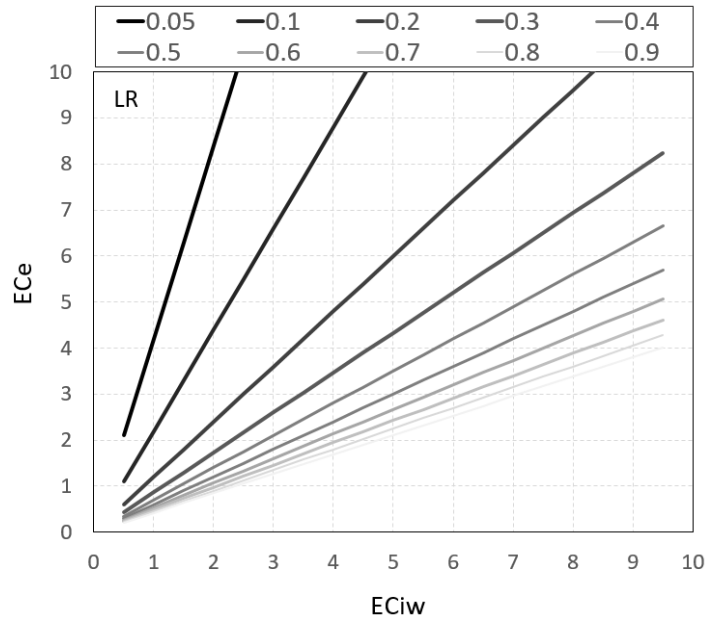


Figure D-1: Estimation of the leaching requirement (LR) based on irrigation water salinity (x axis) and crop tolerance to soil salinity (y axis). The calculation was completed using Equation 4. The legend shows LR values.

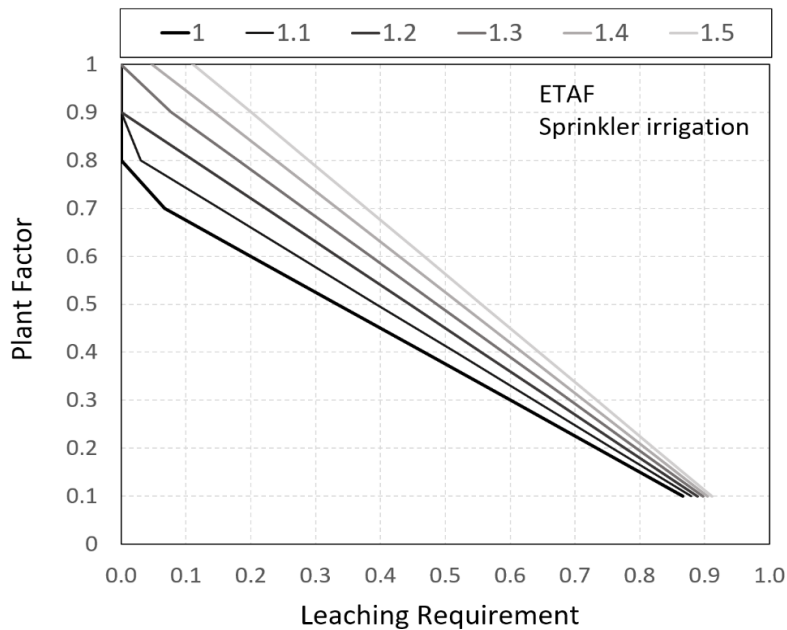


Figure D-2: Estimation of the evapotranspiration adjustment factor (ETAF) based on the leaching requirement and plant factor for sprinkler irrigation systems with an irrigation efficiency equal to 0.75. The calculation was completed using Equation 7. The legend shows ETAF values.