Salt Management Guide for Landscape Irrigation with Recycled Water in Coastal Southern California

A Comprehensive Literature Review

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Extended Executive Summary

Salt Management Guide for Recycled Waters
Used for Irrigation of Landscapes in Coastal Southern California

A comprehensive review of the scientific literature has been conducted to consolidate in one document the factors that affect the use of recycled waters for irrigating landscapes in California's south coastal region, where potable water is becoming increasingly scarce. Although many opportunities exist for using recycled waters in urban areas and the California Recycled Water Task Force encourages such use, some landscape professionals are reluctant to use recycled water out of concerns that the water may be excessively saline and harmful to landscape plants.

This document presents a Salinity Management Guide for the irrigation of landscapes with recycled water, including guidelines on evaluating water quality, controlling salinity in the root zone, discovering the tolerance of plants to salinity and salinity-related effects, and diagnosing and solving problems that might be encountered in the irrigation of turfgrasses, trees, shrubs, and ground covers. It also includes related aspects of landscape irrigation, including California's Water Recycling Criteria, selecting plants, choosing and using irrigation systems, calculating the water needed by the plants, and mitigating problems with the soil.

Title 22 Regulations and Present Use of Recycled Waters for Landscape Irrigation

California's Water Code states that using a potable source of water when nonpotable water could be safely used instead is a wasteful or unreasonable use of water. The state's recycled water regulations are contained in Title 22, Code of Regulations on Water Recycling Criteria. These regulations require tertiary treatment and disinfection of recycled waters used to irrigate parks and playgrounds, school yards, residential landscapes, and golf courses with unrestricted access. This level of treatment, which is aimed at protecting public and ecological health, exceeds the level of treatment of most potable water supplies and meets the level of treatment required for most wastewaters discharged to waters of the state. The regulations require that recycled water used to irrigate cemeteries, freeway landscapes, golf courses with restricted access, ornamental nurseries, and sod farms receive somewhat less treatment, i.e., secondary treatment and disinfection levels of 2.2 to 23 median counts of total coliform bacteria per 100 mL of water.

Of the current 533,000 acre-ft of recycled waters used in California, about 21% is used to irrigate landscapes, mostly turfgrasses in golf courses and lawns. Opportunities to further use recycled waters exist; i.e., recycled waters could be used to irrigate golf courses, lawns, trees, shrubs, ground covers, vines, ornamental plants, and flowers of other landscapes now being irrigated with potable waters.

Significant Constituents in Water Used to Irrigate

Most recycled waters do not inherently contain excessively high levels of salinity, even though they typically contain about 140 to 400 more milligrams of salts per liter than do the potable waters from which they originated. The salinity of waters may affect plants due to osmotic effects; i.e., plants must expend more energy to extract water from the soil when that water is more saline, and plants may suffer slowed growth, damaged leaves, and death in the severest cases. Plants have a wide range of tolerance of salinity, and many could be irrigated with recycled waters.

If communities use sodium chloride-based water softeners, the recycled water originating from such communities may contain elevated numbers of sodium and chloride ions. Moreover, use of cleaning agents, such as detergents, may elevate concentrations of boron in recycled waters. Plants differ in their sensitivity to sodium and chloride ions and boron. Sensitive plants typically exhibit damaged leaves and, in severer cases, defoliation and death. Excessive levels of sodium may also cause an imbalance in the mineral nutrition of plants, such as a deficiency of calcium.

Another significant constituent in recycled waters is nitrogen in the form of dissolved ammonia or ammonium ions and nitrates. The concentration levels of these forms of nitrogen are dependent on the wastewater treatment processes used. Ammonia or ammonium ions in recycled waters are eventually oxidized into nitrate ions in the soil. Other forms of nitrogen, such as organic nitrogen and nitrite, occur in smaller concentrations. Nitrogen in recycled water used to irrigate can pose problems if the nitrates not taken up by plants leach below their roots and contribute to the contamination of underlying groundwater basins. Such leaching of nitrates may be minimized if the amount of nitrogen in recycled water is taken into account in fertilizer applications and if less nitrogen-containing fertilizer is consequently applied.

The combined effects of salinity and sodicity of irrigation water can affect the soil's permeability, reducing water infiltration rates and soil permeability. Sodicity is usually evaluated by its ratio of sodium to calcium plus magnesium, known as the sodium adsorption ratio (SAR), and salinity is typically assessed by electrical conductivity (EC). A moderate SAR and a low level of EC may result in reduced permeability in some types of soil. The detrimental effects of a moderate SAR on a soil's permeability may be partially overcome by a moderate level of EC. The treatment processes for recycled waters involve the use of additives that elevate the SAR, such as sodium hypochlorite, frequently used to disinfect, and bicarbonate and carbonate from the lime, used to neutralize the water's pH. Another parameter of sodicity is the residual sodium carbonate (RSC), which is the sum of bicarbonate and carbonate ions minus the sum of calcium and magnesium ions. It can be used to evaluate the detrimental effects of sodicity, which can cause the dispersal of organic matter and clays in the soil, resulting in dark unsightly matting on the turf of golf courses and slower water infiltration into turf soils.

Some communities blend several sources of water for potable purposes, such as imported water from the Colorado River Aqueduct and the California Aqueduct with local surface and well waters. These sources contain differing salinities. For example, the Colorado River water contains about 750 mg of total dissolved solids (TDS)/L, the California Aqueduct water contains about 450 mg of TDS/L, and well water contains as little as 200 mg of TDS/L from granitic watershed and alluvium. Blending practices tend to change, according to the demand for water and the availability of source waters. As a result, water salinity and sodicity may change seasonally with changes in blending. This situation causes the quality of recycled water to fluctuate. Landscape irrigators need to keep abreast of these changes in water quality, so as to manage irrigation appropriately. This caution is particularly important when plants in the landscape are sensitive to salinity and sodicity and when the concentrations of nitrogen are high.

Selecting Plants for Coastal Southern California

Plants vary in their requirement for sunlight, water, and nutrients, as well as in their susceptibility to adverse environmental conditions. Although many plants can tolerate a wide range of conditions, others have distinct preferences for particular climates and soils and do not thrive elsewhere. The natural distribution of plants is determined by the interaction of many environmental factors, including the intensity and duration of sunlight; the temperature; the properties of the soil; the availability of plant nutrients; the amount of rainfall; the amount and quality of irrigation water; any wind, floods, or fires; and biotic interactions, such as competing with other plants for space and sunlight, being consumed by plant-eating animals, and being exposed to disease-causing microbes.

Plant ecologists have combined environmental and climatological data to delineate plant environment zones or regions. One can determine from this information the type of plants that will thrive in these zones. We have reviewed several comprehensive guides for selecting shrubs, trees, and ground covers, including Perry's 1981 book, *Trees and Shrubs for Dry California Landscapes*, a comprehensive general-purpose guide that lists 360 species of plants, emphasizing species that survive with limited water. Part I of his book, titled "Regional Plant Environments," describes nine plant environments and includes a detailed guide for selecting plants. Part II, titled "Planting Guidelines," covers appropriate planting concepts within the constraints of function, aesthetics, costs, resources, and maintenance requirements. Perry also wrote a 1992 book, "Landscape Plants for Western Regions," which builds on his 1981 book and includes sections on "Issues and Goals," "Regional Characteristics," "Estimating Water Needs of Landscapes," and lastly, "Plant Palettes," for selecting plants that can be combined to achieve visual and aesthetic character, along with cultural compatibility.

The *Sunset Western Garden Book*, which is available in more than four editions, is perhaps the best-known and most widely available guide to selecting plants. As with Perry's 1992 book, this book includes a system of climatological zones depicted on maps. A major portion of the book is a plant encyclopedia that describes several thousand species of plants used for landscapes in the western United States. Labadie's 1978 book, *Native California Plants*, which evolved from his years of teaching at Merritt College in Oakland, CA, covers 101 species of plants that are native to California. A number of brief lists of plants for particular situations, such as plants that do well in partial shade and plants that tolerate wind, is appended to the book.

Lenz and Courley's 1981 book, *California Native Trees and Shrubs*, also presents a map-illustrated system of climatological zones. Based on the authors' 50 years of horticultural experience at the Rancho Santa Ana Botanic Garden, the book focuses on trees and shrubs for southern California. It contains a comprehensive glossary and a cross-index of the common and scientific names of plants. Lenz also published a book in 1956, *Native Plants in California*, as part of a series of papers published by the Rancho Santa Ana Botanic Garden. In that book, he names 102 species of native flora suitable for use by landscape professionals.

After Perry and others, we have listed 57 ground covers appropriate for coastal southern California, identifying them as native or not and the regions where they flourish, i.e., in the coastal margin, intermediate valleys, coastal foothills, inland valleys, or inland foothills. This document includes a map of these regions as well as tables identifying well over 300 shrubs and trees of various heights, including 56 shrubs up to 5 ft tall, 85 shrubs up to 10 ft tall, 96 shrubs from 10 to 18 ft tall, 60 trees up to 25 ft tall, 49 trees up to 40 ft tall, and 45 trees that are 40 ft or taller.

Ground covers listed include Little Sur manzanita (*Arctostaphylos edmundsii)*, bearberry (*Arctostaphylos uva ursi*), coast sagebrush (*Artemisia pynocephala*), maritime ceanothus

(*Ceanothus maritimus*), common buckwheat (*Eriogonum fasciculatum*), juniper (*Juniperus* spp.), annual lupine (*Lupinus nanus*), and creeping sage (*Salvia sonomensis*). Small shrubs listed include Monterey manzanita (*Arctostaphylos hookeri*), hollyleaf ceanothus (*Ceanothus purpureus*), golden yarrow (*Eriophyllum confertiflorum*), tree lupine (*Lupinus arboreus*), Mexican sage brush (*Salvia leucantha*), evergreen currant (*Ribes viburnifolium*), and purple sage (*Salvia leucophylla*). Medium-sized shrubs include star acacia (*Acacia verticillata*), quail bush (*Artiplex lentiformis*), coyote brush (*Baccaris pilularis consanguinea*), carmel ceanothus (*Ceanothus griseus*), bush lantana (*Lantana camara*), Oregon grape (*Mahonia aquifolium*), redberry (*Rhamnus croceus*), rosemary (*Rosmarinus officinalis*), and cape honeysuckle (*Tecomaria capensis*). Large shrubs include Catalina ironwood (*Lyonothanmus* spp.), California buckeye (*Aesculus californica*), western redbud (*Cercis occidentalis*), white escallonia (*Escallonia bifida*), Italian jasmine (*Jasminum humile*), cape pittosporum (*Pittosporum viridiflorum*), and elderberry (*Sambucus* spp.). Small trees include common manzanita (*Arctostaphylos manzanita*), palo verde (*Cercidium spp.*), crape myrtle (*Lagerstroemia indica*), tree mallow (*Lavatera assurgentiflora*), scrub oak (*Quercus dumosa*), and Italian buckthorn (*Rhamnus alaternus*). Medium-sized trees include peppermint tree (*Agonis flexuosa*), weeping bottlebrush (*Callistemon viminalis*), cypress (*Cupressus spp.*), walnut (*Juglans spp.*), Chinese pistache (*Pistacia chinensis*), live canyon oak (*Quercus chysolepis*), and holly oak (*Quercus ilex*). And large trees include madrone (*Arbutus menziesii*), coast live oak (*Quercus agrifolia*), aleppo pine (*Pinus halepensis*), Monterey pine (*Pinus radiata*), blue oak (*Quercus douglassii*), valley oak (*Quercus lobata*), and Leyland cypress (*Cupressocyparis leylandii*).

Other guides to plants are located on the website of the Rancho Santa Ana Botanic Garden in Claremont, CA, which includes a “California Classics Plant Palette,” and the website of the San Diego Chapter of the California Native Plant Society, which lists “Easy-to-Grow California Native Plants for San Diego County” and “12 Most Wanted Native Shrubs That Succeed in a Garden Without Your Really Trying.”

We have listed 12 cool-season turfgrasses and 6 warm-season turfgrasses suitable for California. Cool-season grasses include Kentucky bluegrass (*Poa pratensis*), tall fescue (*Festuca arundinacea*), weeping alkaligrass (*Puccinellia distans*), and red fescue (*Festuca rubra*). Warm-season grasses include seashore paspalum (*Paspalum vaginatum*), zoysiagrass (*Zoysia* spp.), kikuyugrass (*Pennisetum clandestinum*), and St. Augustine grass (*Stenotaphrum secundatum*). These turfgrasses provide a landscaping base for athletic fields, golf course, parks, playgrounds, home lawns, office parks, and cemeteries. Turfgrasses also play an important role in conserving soil and controlling pollution in places such as flood control basins, greenbelts, freeways, and street medians. Temperature, moisture, and sunlight are the most important climatic factors affecting the performance of turfgrass. Warm-season grasses usually lose their greenness and go dormant in the winter, if the average temperature drops below 50 to 60 ^{o}F. Cool-season grasses do not lose their greenness, unless the average temperature drops below 32 ^{o}F for an extended period. It should be noted that grasses vary in their greenness from bright green Kentucky bluegrass (*Poa pratensis*) to apple-green annual ryegrass (*Lolium multiflorum*) or grayish-green bermudagrass (*Cynodon dactylon*).

We have listed 35 California-native plants cited by the Rancho Santa Ana Botanical Gardens for oak woodland landscapes, 34 California-native plants for riparian woodland landscapes, and 40 California-native plants for scrubland landscapes. Native plants associated with oak woodland landscapes include the trees California buckeye (*Aesculus californica*), coast live oak (*Quercus agrifolia*), and mesa oak (*Quercus engelmannii*); the shrubs California coffeeberry (*Rhamnus californica* and cultivars), redberry (*Rhamnus croceus*), toyon (*Heteromeles arbutifolia*), sunset manzanita (*Arctostaphylos "Sunset"*), and bush anemone (*Carpenteria californica*); the ground covers prostrate coyote bush (*Baccaris pilularis* var. *pilularis*), Carmel creeper (*Ceanothus griseus* var. *horizontalis*), creeping snowberry (*Symphoricarpus mollis*), and island alumroot (*Heuchera* maxima); and the perennials narrow-leaf milkweed (*Aschlepias fascicularis*), coyote mint (*Monardella villosa*), California buttercup (*Ranunculus californica*), and meadow rose (*Thalictrum fendleri* spp. *polycarpum*). Native plants associated with riparian woodland landscapes include the trees white alder (*Alnus rhombifolia*), western sycamore (*Platanus racemosa*), Fremont cottonwood (*Populus fremontii*), California bay (*Umbellularia californica*), and valley oak (*Quercus lobata*); the shrubs western redbud (*Cercis occidentalis*), creek dogwood (*Cornus sericea*), mock orange (*Philadelphus lewisii*), California rose (*Rosa californica*), and interior rose (*Rosa woodsii* var. *ultramontana*); the ground covers Edmunds manzanita (*Arctostaphylos edmundsii*), compact Oregon grape (*Mahonia aquifolium "compacta"*), creeping barberry (*Mahonia repens*), and evergreen currant (*Ribes viburnifolium*); the perennials showy milkweed (*Asclepias speciosa*), coral bells (*Heuchera* spp. and cultivars), deer grass (*Muhlenbergia rigens*), giant chain fern (*Woodwardia fimbriata*), and Pacific Coast iris (*Iris douglasina* and cultivars); and the vine Roger's Red California grape (*Vitis californica "Roger's Red"*). Native plants associated with scrubland landscapes include the tree elderberry (*Sambucus mexicana*); the shrubs black sage (*Salvia mellifera*), California buckwheat (*Eriogonum fasciculatum*), chaparral whitethorn ceanothus (*Ceanothus leucodermis*), and bigberry manzanita (*Arctostaphylos glauca*); the ground covers Edmunds manzanita (*Arctostaphylos edmundsii*), prostrate California buckwheat (*Eriogonum fasciculatum* cvs.), Matilija poppy (*Romneya coulteri*), and Haye's iva (*Iva hayesiana*); the perennials narrow-leaf milkweed (*Asclepias fascicularis*), California fuchsia (*Zauschneria* spp. and cultivars), Canyon Prince wild ryegrass (*Leymus condensatus "Canyon Prince"*), and Wayne Roderick's daisy (*Erigeron "Wayne Roderick"*), and the vine Anacapa Pink morning glory (*Calystegia macrostegia "Anacapa Pink"*).

From Labadie, we have excerpted 100 native plants recommended for California landscapes categorized according to the type of plant (ground cover, shrub, or tree) and the dimensions of the plant's height and spread, as well as notes relating to the environmental conditions under which they thrive, such as soils of various permeability and other properties; the amount of sun and shade; and tolerance of drought, extremes in temperature, and sprinkler irrigation with saline water. Recommended drought-tolerant native plants include the trees blue oak (*Quercus douglasii*), interior live oak (*Quercus wislinzeni*), and Catalina mountain mahogany (*Cercocarpus betuloides* var. *traskiae*); the shrubs chamise (*Adenostoma fasciculatum*), summer holly (*Comarostaphylis diversiloba*), California buckwheat (*Eriogonum fasciculatum*), and California holly grape (*Mahonia pinnata*); and the ground covers Carmel creeper (*Ceanothus griseus* var. *horizontalis*) and dwarf coyote bush (*Baccharis pilularis*). Native plants that require deep, well-drained soils include the trees California buckeye (*Aesculus californica*), coast redwood (*Sequoia sempervirens*), Monterey pine (*Pinus radiata*), and torrey pine (*Pinus torreyana*); the shrubs southern fremontia (*Fremontiadendron mexicanum*), redberry (*Rhamnus croceus*), purple sage (*Salvia leucophylla*), and rhododendron (*Rhododendron macrophyllum*), and the ground covers hollyleaf ceanothus (*Ceanothus purpureus*), island bush snapdragon (*Galvensia speciosa*), and Santa Barbara ceanothus (*Ceanothus impressus*). Native plants that thrive in full sun include the trees western hemlock (*Tsuga heterophylla*), fern-leaf Catalina ironwood (*Lyonothamnus floribundus*), torrey pine (*Pinus torreyana*), Catalina cherry (*Prunus lyonii*), and California black oak (*Quercus kelloggii*); and the shrubs California holly grape (*Mahonia pinnata*), Santa Cruz Island buckwheat (*Eriogonum arborescens*), laurel sumac (*Malosma laurina*), and Nevin's barberry (*Mahonia nevinii*). Native plants that require shade and moist soils include the trees California bay (*Umbellaria californica*) and Pacific dogwood (*Cornus nuttallii*); the shrubs evergreen currant (*Ribes viburnifolium*), western azalea (*Rhododendron occidentale*), bush anemone (*Carpenteria californica*), and ocean spray (*Holodiscus discolor*); and the ground covers snowberry (*Symphoricarpos albus*), giant chain fern (*Woodwardia fimbriata*), western sword fern (*Polystichum munitum*), and wild ginger (*Asarum caudatum*). Native plants that do best in coastal areas include the trees tanbark oak (*Lithocarpus densiflora*), Lawson cypress (*Chamaecyparis lawsoniana*), Catalina ironwood (*Lyonothamnus* *floribundus*), and Pacific wax myrtle (*Myrica californica*); and the shrubs laurel sumac (*Malosma laurina*) and salal (*Gaultheria shallon*). Native plants that tolerate sprinkler irrigation by saline water include the tree Bishop pine (*Pinus muricata*) and the ground covers Point Reyes creeper (*Ceanothus gloriosus*) and Monterey manzanita (*Arctostaphylos hookeri*).

We have also summarized notes about selecting plants for certain types of landscapes, including a general landscape design guide, turf and trees for golf courses, turf for playing fields and parks, and plants for medians and street sides.

Tolerance by Plants of Salinity and Boron

An extensive review of the scientific literature was conducted to prepare a list of landscape plants appropriate for the south coastal region of California, as well as lists of landscape plants according to their tolerances of salinity and boron. Many earlier studies on the salt tolerances of plants were conducted in solution cultures or soil pots that were surface irrigated, i.e., via the soil. However, much landscape irrigation is conducted via sprinklers, which wets and exposes leaves to salts in the irrigation water. Fortunately, recent studies regarding the salt tolerances of plants have involved evaluating the response of plants to salts in both sprinkler irrigation and irrigation via the soil.

A book by Perry (1981) of California State University–Pomona identifies 36 salt-tolerant trees and shrubs grown in south coastal California, including 25 rated for their tolerance of salts when sprinkler irrigated, 19 rated for their tolerance of salts when irrigated via the soil, and 8 rated for their tolerance of both sprinkler irrigation and irrigation via the soil. Salt-tolerant trees include the beefwood (*Casuarinas* spp.), desert gum (*Eucalyptus rudis*), and coral gum (*Eucalyptus torquata*) varieties of eucalyptus and the torrey (*Pinus torreyana*), and aleppo (*Pinus halepensis*) varieties of pine. Salt-tolerant shrubs include bird of paradise bush (*Caesalpina gilliesii*), Italian jasmine (*Jasminum humile*), sandhill sage (*Artemesia pycnocephala*), pittosporum (*Pittosporum crassifolium*), and Little Sur manzanita (*Arctostaphylos edmundsii*).

A study at the University of California–Davis by Wu et al. (2001) and Wu and Gao (2005) evaluated the salt tolerances of landscape plants irrigated by sprinklers versus the salt tolerances of landscape plants when irrigated via the soil. Three waters of varying qualities were used: a potable well water with an EC of 0.6 decisiemens (dS)/m, water with an EC of 0.9 dS/m to which 500 mg of sodium chloride/L was added to the well water, and water with an EC of 2.1 dS/m to which 1,500 mg of sodium chloride/L was added to the well water. The well waters to which sodium chloride was added resembled typical recycled water in the San Francisco Bay region. Sprinkler-irrigated plants were categorized as highly tolerant, tolerant, moderately tolerant, or sensitive, depending on the degree of symptoms of salt-related stress that developed in the leaves. Soil-irrigated plants were categorized as highly tolerant, tolerant, moderate, or sensitive, depending on the level of soil salinity tolerated. Those plants tolerant of saline spray were found to be equally tolerant of soil salinity, and those plants sensitive to saline spray were found to be also sensitive to soil salinity.

Wu and his team of researchers tested the salt tolerances of a total of 87 trees, 67 shrubs, and 59 ground covers and vines with both sprinkler and soil irrigation. Salt-sensitive trees included red maple (*Acer rubrum*), Chinese hackberry (*Celtis sinensis*), cornelian cherry (*Cornus mas*), ginkgo (*Ginkgo biloba*), jacaranda (*Jacaranda mimosifolia*), crape myrtle (*Lagerstoemia indica*), southern magnolia (*Magnolia grandifolia*), Chinese pistache (*Pistacia chinensis*), laurel oak (*Quercus laurifolia*), and coast redwood (*Sequoia sempervirens*). Salt-sensitive shrubs included abelia (*Abelia grandiflora*), shrimp plant (*Justicia brandegeana*), camellia (*Camelia japonica*), croton (*Codiaeum variegatum*), poinsettia (*Euphorbia pulcherrima*), coral plant (*Jatropha multifida*), California holly grape (*Mahonia pinnata*), heavenly bamboo (*Nandina domestica*), photonia (*Photinia fraseri*), and roses (*Rosa* sp.). Salt-sensitive ground covers and vines included carpet bugle (*Ajuga repens*), lady fern (*Athyrium filix-femina*), caladium (*Caladium* sp.), peperomia (*Peperomia obtusifolia*), verbena (*Verbena* sp.), coral vine (*Antigonon leptopus*), bleeding heart vine (*Clerodendrum thomsoniae*), and violet trumpet vine (*Clytostoma callistegioides*).

We have categorized 17 species of turfgrass as sensitive, moderately sensitive, moderately tolerant, or tolerant based upon their responses to soil salinity. Sensitive species include annual bluegrass (*Poa annua*), colonial bentgrass (*Agrostis tenuis*), hard fescue (*Festuca langifolia*), rough bluegrass (*Poa trivialis*), and Kentucky bluegrass (*Poa pratensis*), while moderately sensitive species include annual ryegrass (*Lolium multiflorum*), buffalograss (*Buchloe dactyloides*) and creeping bentgrass (*Agrostis palustris*). Moderately tolerant species include zoysiagrasses (*Zoysia* spp.), perennial ryegrass (*Lolium perenne*), and tall fescue (*Festuca arundinacea*), and tolerant species include bermudagrass (*Cynodon* spp.), St. Augustine grass (*Stenotaphrum secundatum*) and seashore paspalum (*Paspalum vaginatum*).

We have compiled in this document a list of the salt tolerances of 97 species of flowers from various sources in the scientific literature, much of it by researchers at the U.S. Salinity Laboratory, Riverside, CA. Very sensitive species include Peruvian lily (*Alsthoemeria* hybrids), anthurium (*Anthurium andreanum*), rex begonia (*Begonia Rex-cultorum*), cosmos (*Cosmos bipinnatus*), orchid (*Cymbidium* spp.), poinsettia Barbara Ecke (*Euphorbia pulcherrima "Barbara Ecke"*), fuchsia (*Fuchsia hybrida*), amaryllis (*Hippeastrum hybridum*), and bird of paradise (*Strelitzia reginae*). Sensitive species include begonia (*Begonia bunchii*), ornamental cabbage (*Brassica oleracea*), camellia (*Camellia japonica*), cyclamen (*Cyclamen persicum*), poinsettia Redsails (*Euphorbia pulcherrima "redsails"*), golden marguerite (*Euryops pectinatus*), gladiola (*Gladiolus* spp.), hibiscus (*Hibiscus rosa-sinensis*), impatiens (*Impatiens* × *hawkeri*), geranium (*Pelargonium* × *hortorum*), rose (*Rosa* × *hybrida*), and pansy (*Viola* × *wittrockiana*). Moderately sensitive species include ageratum (*Ageratum houstonianum*), snapdragon (*Antirrhinum majus*), dusty miller (*Artemesia stelleran*), China aster (*Callistephus chinensis*), coreopsis (*Coreopsis grandiflora*), jade plant (*Crassula ovata*), pinks (*Dianthus barbatus*), gerbera daisy (*Gerbera jamesonii*), globe amaranth (*Gompherena globosa*), giant turf lilly (*Ophiopogon jaburan*), azalea (*Rhododendron hybrids*), lisianthus (*Eustoma grandiforum*), and zinnia (*Zinnia elegans*).

We have also compiled a list of 42 ornamental plants according to their tolerances of boron, after Mass (1984). Extremely sensitive ornamental plants include Oregon grape (*Mahonia aquifolium*), photinia (*Photinia* × *fraseri*), xylosma (*Xylosma congestum*), wax-leaf privet (*Ligustrum japonicum*), Japanese pittosporum (*Pittosporum tobira*), Chinese holly (*Ilex cornuta*), juniper (*Juniperus chinensis*), and American elm (*Ulmus americana*). Sensitive ornamental plants include zinnia (*Zinnia elegans*), pansy (*Viola adorata*), violet (*Viola tricolor*), larkspur (*Delphinium* spp.), glossy abelia (*Abelia* × *grandiflora*), rosemary (*Rosmarius officinalis*), oriental arborvitae (*Platycladus orientalis*), and geranium (*Pelargonium* × *hortorum*). Moderately sensitive plants include gladiola (*Gladiolus* spp.), poinsettia (*Euphorbia pulcherrieues*), China aster (*Callistephus chinensis*), gardenia (*Gardenia* spp.), southern yew (*Podocarpus macrophyllus*), bush cherry (*Syzgium paniculatum*), and blue dracaena (*Cordyline indivisa*).

The book *Abiotic Disorders of Landscape Plants* by Costello et al. (2003) provides useful guidelines for assessing the salt tolerance of a plant and diagnosing plant-related problems. The authors list the salinity tolerances and boron tolerances of 610 landscape plants in several tables for shrubs, trees, palms, ground covers, vines, herbaceous plants, and turfgrasses. This list is useful for comparing species and for discovering the salt or boron tolerance of a particular species already chosen for or planted in a landscape.

Other useful tables in Costello et al. (2003) provide information on common fertilizers and their relative salinities, such as the salt content of commercially available organic soil amendments including animal manures, peat, and redwood compost. Yet another table in the book provides guidance for readers who need to interpret chemical data resulting from laboratory tests of soil, water, and plant tissue.

Clearly, some landscape plants are sensitive to salinity and boron. However, there exists a wide array of trees, shrubs, turfgrasses, ground covers, vines, flowers, and ornamental plants that could be irrigated with recycled waters containing moderate salinities and moderate concentrations of sodium, chloride, and boron. Many are listed in this document.

Water Quality Guidelines

The quality of recycled waters may have measurable or observable effects, some of which are adverse, on plants, soils, and irrigation systems.

The assessment and management of irrigation are much more established for agricultural irrigation than for landscape irrigation, except for the irrigation of turf. Thus, a significant portion of this literature review explored the applicability of the management of agricultural irrigation to the management of landscape irrigation in terms of evaluating water quality, diagnosing problems, and implementing management practices. The primary difference between the two is that the management of agricultural irrigation is aimed at maximizing yield, whereas the management of landscape irrigation is focused on maintaining the aesthetic quality and appearance of the landscape.

We recommend the Water Quality Guidelines advanced by the United Nations' Food and Agriculture Organization (FAO) (Ayers and Westcot, 1985). These guidelines for using recycled water to irrigate croplands and landscapes are used worldwide. A Committee of Consultants from the Agricultural Experiment Station of University of California initially proposed these guidelines after extensive consultation with the U.S. Salinity Laboratory. The FAO then adopted and extended the guidelines.

The FAO guidelines consist of a matrix in which specific irrigation-related problems are aligned vertically and degrees of restriction on use are aligned horizontally. The problems include salinity, infiltration or soil permeability, specific ion toxicity, and miscellaneous effects. Each problem is then associated with particular constituents of water quality, such as salinity by the EC and the TDS; infiltration by the SAR and the EC; specific ion toxicity by the concentrations of soluble sodium, chloride, and boron; and miscellaneous effects by nitrogen in the form of ammonia and nitrate, bicarbonate, and the pH. The degrees of restriction on use are categorized into none, slight to moderate, and severe, with numeric values or ranges of numeric values for each parameter identified in cited problems. Though these three categories are somewhat arbitrary since there are no clear-cut specific boundaries to distinguish the categories and since changes occur gradually, the numeric guidelines were based on the collective opinions of soil, plant, and water scientists with extensive research and practical experience.

When one uses the FAO's water quality guidelines, there are a number of caveats and assumptions regarding yield potential, conditions at the site, methods and timing of irrigation, and the uptake of water by crops. The guidelines cover a wide range of conditions encountered in irrigated agriculture and should be used as an initial evaluation and modified with local expertise as needed. In particular, the guidelines are not plant specific and may be too restrictive for some salt-tolerant species of plants and perhaps not restrictive enough for some sensitive species.

These guidelines were applied to four representative compositions of recycled waters in California. These waters had levels of EC ranging from 1.0 to 1.6 dS/m, SAR ranging from 3.4 to 4.9, <0 to 1.7 meq of RSC/L, 157 to 185 mg of sodium/L, 188 to 226 mg of chloride/L, 0.4 to 0.6 mg of boron/L, 0.2 to 31.3 mg of ammonium/L expressed as nitrogen, and 0.8 to 13.9 mg of nitrate/L expressed as nitrogen. All of these waters tended to rank in the "slight to moderate restriction on use" categories, with some exceptions. These exceptions were that three waters fell in the "no restriction on use" category with regard to RSC and boron hazards and that one of them fell in the "severe restriction on use" category due to its elevated concentrations of nitrogen and an RSC value of moderate concern.

Certain management practices can help decrease the moderate to severe restrictions on use. One such practice is to take into account the nitrogen in recycled water and reduce the amount of nitrogen-containing fertilizer applied. Another is to inject an acid or add a calcium-containing amendment to water with a high RSC to prevent organic matter and clays in the soil from dispersing and water from poorly infiltrating. Yet another practice is to replace sensitive plants that may be detrimentally affected by salinity or concentrations of specific ions with more tolerant plants. It is our considered opinion that the FAO water quality guidelines tend to be on the conservative side. This view was confirmed by a case study of irrigation of turfgrasses with recycled waters.

Salinity Control in the Root Zone

The soil is the medium from which plants extract water and essential mineral nutrients. It also supports the roots of plants. Salts tend to accumulate in the root zone of actively transpiring plants, as water is lost to the atmosphere through transpiration from plants and evaporation from the soil, leaving behind the dissolved mineral salts in the soil water. These dissolved mineral salts have an osmotic effect: as salts increase in the soil, plants must expend greater energy to draw water from the soil. Also, some ions of these salts, such as sodium and chloride, as well as boron, may accumulate to concentrations in the soil that are high enough to harm plants. Maintaining a salt balance in the root zone is critical for satisfactory plant performance in a semiarid climate with insufficient rainfall for leaching salts from the root zone. In surface-irrigated soils with unimpeded drainage, salts leach from the upper root zone and accumulate in the lower root zone.

Fortunately, most landscape plants are more densely rooted at and near the surface of the soil, where the soil tends to be least saline. Plants extract soil water from the more saline deeper root zone only when the soil water that is available in the less saline portions at and near the surface becomes limited. The extent to which salts accumulate in the lower root zone is regulated by the leaching fraction (LF), the ratio of the depth of drainage water to the depth of irrigation water. The depth of drainage water is the irrigation water minus the water lost to the atmosphere from transpiration by plants and evaporation from the soil. In freely draining soils, a comparatively small depth of drainage may be sufficient to maintain a salt balance in the root zone. An LF of 0.15 to 0.2 is usually adequate to maintain a salt balance for most agricultural crops irrigated with typically saline water. This LF also should be applicable to landscape plants with a similar range of salt tolerances.

Using the FAO approach of computing the accumulation of salts in quartile root zones, i.e., four increments of depth, the principles and applications of steady-state LF were addressed by considering the pattern in which roots extract water, as well as the irrigation water's LF and EC. The EC of the drainage water past the root zone may be estimated from the ratio of the EC of the irrigation water to the LF. Computations can be facilitated with an Excel model that is based on the assumption that salts are a conservative parameter; i.e., salts are not chemically reactive, such as in mineral precipitation, mineral dissolution, and cation exchange. This model is in an appendix. Also considered were the impact of rainfall on the leaching of salts, any mixed qualities of supply waters, and reclamation leaching with use of a mixing cell Excel model that includes the initial salinity of the soil. This model is also in an appendix.

More complex aspects of root zone salinity were addressed, including a chemical equilibrium model (WATSUIT) and its use in assessing the accumulation of salts in quartile root zones. WATSUIT was also used to assess the precipitation of calcite and gypsum as a function of the LF for Colorado River water. Based on these data, a simplified reactive salt accumulation model was developed that incorporated prescribed increments of soil depth (typically more than four) and their initial concentrations of soil salinity into the mixing cell model. This Excel model is also in an appendix.

Shaw et al. (1995) conducted a case study on the composition of drainage from the root zone from plots of turfgrass irrigated with potable and recycled waters. These plots were located at the Whispering Palms site on the sandy soils of the San Dieguito River's flood plains in San Diego County. Turfgrasses involved in this experiment included cool-season grasses, namely, tall fescue (*Festuca arundinacea*) and a Kentucky bluegrass (*Poa pratensis*)-perennial ryegrass (*Lolium perenne*) mixture, and warm-season grasses, namely, bermudagrass (*Cynodon dactylon*) and kikuyugrass (*Pennisetum clandestinum*). Irrigation was scheduled according to the water budget method and with the use of real-time data about local weather. Water infiltrated into the soil from irrigation and rainfall is lost to the atmosphere via transpiration by plants and evaporation from the soil, which is collectively referred to as evapotranspiration (ET). In the study conducted by Shaw et al., the ET of the grasses in inches per day approximately equaled 0.6 × the reference ET (ET_o) for warm-season grasses and 0.8 × ET_o for cool-season grasses. Rainfall from January 1993 through November 1994 was 25.1 in. The cool-season grasses received 105 in. of irrigation, while the warm-season grasses received 84 in. of irrigation. The calculated ET for cool-season grasses was 74.5 in. and for warm-season grasses was 54.1 in. Irrigation water plus rainfall minus ET equaled the drainage out of the root zone, which averaged 56 in. for cool-season grasses and 54 in. for warm-season grasses. The LF for cool-season grasses was 0.42. The LF for warm-season grasses was 0.50.

The potable water in the case study had an EC of 1 dS/m, a SAR of 2.7, 0.15 mg/L of boron, 0.2 mg/L of nitrate expressed as nitrogen, and 0.07 mg/L of ammonium expressed as nitrogen. The recycled water in the case study had an EC of 1.4 dS/m, a SAR of 4.8, 0.5 mg of boron/L, 11.2 mg of nitrate/L expressed as nitrogen, and 0.2 mg of ammonium/L expressed as nitrogen. Shaw and his colleagues analyzed samples of soil from the root zone, i.e., 0–24 in. below the surface, and samples of soil from below the root zone, i.e., 24–36 in. below the surface. The EC of the extract from a saturated soil paste (EC_e) of root-zone samples ranged from 2.7 to 3.3 dS/m, and the EC_e of samples from below the root zone ranged from 1.7 to 2.5 dS/m. The EC_e was only two to three times greater than the EC of irrigation waters because of comparatively high LFs. The plots of turfgrass all received 544 lbs. per acre of nitrogen-containing fertilizer. The nitrogen in the recycled water used to irrigate was equivalent to 225 lbs. per acre. However, nitrate concentrations in the root zone for all treatments were low, ranging from 0.4 to 3.2 mg/L expressed as nitrogen, indicating that the grasses extracted much nitrogen. Turfgrasses are known to be heavy feeders of nitrogen and are often described as luxury consumers of nitrogen.

Based on the aforementioned data, the mass loading and emission of nitrogen and TDS were estimated. The plots irrigated with potable water had a mass loading of 548 lbs. of nitrogen per acre. The recycled-water treatments had a mass loading of 769 lbs. of nitrogen per acre. The mass emission of nitrogen from bermudagrass irrigated with potable water was 47 lbs. per acre and from kikuyugrass irrigated with potable water was 59 lbs. per acre. The mass emission rate of TDS from bermudagrass irrigated with recycled water was 84 lbs. per acre and from kikuyugrass irrigated with recycled water was 59 lbs. per acre. These rates of mass emission amounted to the leaching of 8 to 13% of the nitrogen from water and fertilizers. The plots irrigated with potable water had an average mass TDS loading of 5.7 tons per acre, while the plots irrigated with recycled water averaged 9.2 tons per acre. The mass emission rate of TDS from bermudagrass irrigated with potable water was 8.8 tons per acre (or 150% drained) and for kikuyugrass irrigated with potable water was 7.3 tons per acre (or 125% drained). The mass emission rate of TDS from bermudagrass irrigated with recycled water was 7.2 tons per acre (or 77% drained) and from kikuyugrass irrigated with recycled water was 8.8 tons per acre (or 94% drained). The percentage of salts that drained ranged from 77 to 125%. This range is acceptable, considering that several sinks and sources of salts within the root zone were not considered in this mass balance, with only mass inputs and mass outputs calculated. Though the 150% salt leaching appears to be unacceptable, it should be noted that the initial EC_e of the soil for bermudagrass irrigated with potable water was 1.7 dS/m, which is higher than the initial EC_e of all the others, which ranged from 1.1 to 1.2 dS/m.

This case study demonstrated that recycled water can be beneficially used to irrigate established turfgrasses, thus conserving potable waters. Relatively few problems were noted. Shaw et al. (1995) had initial concerns about the EC, the SAR, the nitrate, and the boron in the recycled water, but they caused no significant problems. However, Shaw et al. (1995) state that the reliability of the recycled water's quality is a key. Any significant changes in quality should be noted and appropriate management practices taken to avoid problems.

In contrast to the situation with established turfgrasses, there can be some concerns when using recycled water to establish new turf stands by vegetative parts or seed. Depending upon soil and water salinity levels, newly seeded turf may demonstrate reduced germination percentages, poor seedling vigor, and an overall lower establishment and maturation rate. Cool-season varieties overseeded into established warm-season turf show similar problems that are generally associated with higher total salinity and sodium concentrations of the recycled waters. Sod, springs, and stolons can also be affected, showing slower root development and stacking of roots into the soil. Higher seeding, springing, and stolonizing rates and planning for a longer establishment must be considered when using waters of moderate salinities for irrigation of turfgrasses. Another, more effective approach is to irrigate with nonsaline water until turfgrass stand is well established.

Irrigation Systems and Water Requirements of Landscape Plants

An irrigation system's major function is to provide water to plants in a manner suitable for fostering their growth and performance in the landscape. The system should be able to meet the landscape's peak demands for water, apply enough water to leach salts through the landscape's root zone, and perhaps be useful in meeting other needs, such as the control of frost. The system should be appropriately and effectively designed, installed, built, operated, and maintained. The major components for successful irrigation include design, installation and construction, operation, and maintenance. A well-designed system contains appropriate irrigation and drainage components for the plants, includes specific construction details and maintenance requirements, meets regulatory guidelines, and includes a water budget and an irrigation schedule to establish the landscape, as well as sustain it.

The components of an irrigation system typically include the following: a pump when needed; a main line and laterals; a flow meter; flow control and pressure-regulating valves; filters when needed; parts that apply the water, such as sprinkler heads, bubblers, drip emitters, or drip tapes; and a timer to regulate the time and duration of irrigation. The parts of a system that distribute and apply recycled water—the pipelines, pumps, valves, sprinkler heads, bubblers, etc.—are all colored purple to clearly distinguish them from parts of systems that distribute and apply potable water. If secondary effluent is used or recycled water that was held in storage ponds before application is used, then a filtration system is needed. If acids or other amendments are injected into the irrigation system, the system's components must be selected or modified to tolerate these amendments.

Sprinkler irrigation is the most common method of irrigating with recycled water. The sprinkler heads may consist of a spray head that delivers water in all directions simultaneously or may consist of a rotating or impact stream head that directs water over a wider radius than spray heads do. The sprinkler heads may be those that pop up when operating, or they may be attached to a riser. Drip irrigation may be placed on a surface, as with a surface drip system, or be placed below the surface, as with a buried or subsurface drip system.

When one is irrigating landscapes, the differing water needs of the mix of plants in the specific landscape must be kept in mind. For example, in a landscape consisting of both trees and turf, the trees may need to be irrigated separately with bubblers and drip irrigation because their water requirements differ from those of turfgrasses.

The installation and construction phase of an irrigation system includes not only installing the system but coordinating other activities, such as grading the land, preparing the soil, selecting plants, and installing lighting and signage. Operating the irrigation system consists of determining the landscape's water budget and scheduling its irrigation. Maintenance is essential for an efficiently operating system. Proper cultural treatment of plants and other components of the landscape not only improves the landscape's appearance and value but can also affect the use of water in the landscape.

The ET of crop plants has been widely investigated and known, but such is not the case with the ET of landscape plants, except for that of turfgrasses. In agriculture, the ET of crops (ET_c) is estimated by a number of methods. Weather-based estimates of ET are obtained by multiplying the reference ET (ET_o) by the crop coefficient (K_c). The monthly K_c for cool-season and warm-season turfgrasses in California is available in this document. The K_c for established trees and shrubs is also available in this document. The daily ET may be estimated and compiled as weekly, monthly, or seasonal ET by using data from the California Irrigation Management Information System (CIMIS), a network of over 120 stations strategically placed throughout the state providing hourly and daily ET_o that is electronically based on the amount of sunlight, the temperature, the relative humidity, wind speed, etc. A few water agencies have installed their own weather stations. Some irrigators may use historic ET_o values instead of real-time data.

Estimating coefficients for other types of plants for landscapes, especially heterogeneous mix of plants, is more difficult than for turfgrasses. Research-based data regarding the water needed by plants in landscapes with a mix of plants are limited. Plant species with differing needs for water exist, and those needs are influenced by their location in the landscape and their interaction with the surrounding environment. This complexity severely limits the ability to accurately estimate water needs using the ET_o-K_c approach. Despite these limitations, several approaches for estimating water needed by a landscape have been proposed.

One popular method, the Water Use Classification of Landscape Species (WUCOLS) (University of California Cooperative Extension and California Department of Water Resources, 2000), introduces a landscape coefficient (K_L) adjusted to take into account for differences in landscape species (K_s), plant density (K_d), and microclimate (K_{ms}). Though this method takes into account factors that affect the K_L, quantitative data are not readily available, and thus $ET_o \times K_L$ produces a rough initial estimate of ET that will need to be adjusted after the initial estimates are obtained. Procedural guidelines to assign numerical values for Ks, K_d, and K_{ms} for high, moderate, low, and very low values for landscape coefficient factors are outlined in WUCOLS III. Since California's climate varies substantially, hundreds of plant species are evaluated for six regions (climatic zones). It is expected that, after extensive application and testing, the WUCOLS approach will become more reliable.

With many recycled waters, irrigating beyond what is needed for ET is typically required for leaching salts. The irrigation system's uniformity of application is another important factor for adding water beyond what is needed for ET. The irrigation system's uniformity of distribution should be considered in the total water applied, too. It should be noted, though, that runoff from areas irrigated with recycled water is prohibited.

Uniform distribution of applied water is extremely important for root zone salinity management in golf and sports turf. Achieving a uniform application will maintain a uniform wetting front when one is leaching salts through the soil profile and prevents the development of excessively wet or dry area associated with poor root distribution. In golf or sports turf situations, this precaution not only impacts aesthetics but also safety implications (e.g., firm footing) and customer satisfaction by providing a dry playing surface.

Scheduling irrigation involves calculating when and how much to irrigate. When to irrigate is determined by one of several methods, including the flexible or soil water depletion method, the fixed calendar method, or the soil moisture sensor method. How much to irrigate is determined by estimates of the plant's ET, the irrigation system's rate of application, and the system's uniformity of distribution. A number of water calculators are available to schedule irrigation, including some from local water districts and other local agencies. A properly designed and well-managed irrigation system will provide optimal amounts of water to landscape plants, except perhaps when a mixture of species needs to be irrigated.

Soil Problems and Management Options

As previously discussed, the quality of recycled water may affect plants and soils. Specifically, salinity of water and specific ions in water may affect plants and the soil's permeability. There are other aspects of particular note when irrigating a landscape with recycled water.

One such aspect is the salinity of the soil, denoted by the EC of an extract of saturated soil paste (EC_e) that may affect the growth of plants, and the sodicity of the soil, indicated by the exchangeable sodium percentage (ESP) or SAR. Soils are considered nonsaline if the EC_e is less than 4 dS/m, the ESP is less than 15%, and the pH_s (pH of the saturated soil paste) is less than 8.5. Saline soils have an EC_e of more than 4 dS/m, an ESP of less than 15%, and pH_s of less than 8.5. Sodic soils have an EC_e of less than 4 dS/m, an ESP of greater than 15%, and pH_s of more than 8.5. Saline-sodic soils have an EC_e of more than 4 dS/m, an ESP of more than 15%, and pH_s of less than 8.5.

Measuring the salinity of water in terms of the EC or TDS is quite straightforward, but measuring the salinity of soil is more challenging due to its dynamic nature. The salinity of soil changes over time, with irrigation and rainfall replenishing water in the soil and evaporation and transpiration depleting it. Moreover, dissolved mineral salts are highly mobile in the soil due to their transport by the flow of water. Thus, the roots of plants are exposed to temporal and spatial changes in soil salinity. Such changes pose a challenge in measuring soil salinity. Methods for measuring soil salinity include sampling the soil and analyzing the EC_e in a laboratory; measuring the salinity of soil water in terms of its electrical conductivity, i.e., the EC_{sw}, with the use of devices such as an EM-38 electromagnetic probe or a time domain reflectometry (TDR*)* probe; and using ceramic suction probes to collect soil water from moist soils and then measuring the EC as EC_{sw}.

As pointed out earlier, soil salinity may be controlled by the LF. When the plant's threshold salt tolerance is known, the average salinity of the root zone may be regulated with the leaching requirement (LR), which includes enough water to meet the plant's ET and to leach salts yet remain within the plant's threshold salt tolerance. As previously discussed with well-drained sprinkler-irrigated soils, the root zone at the surface is where salts are leached and the lower root zone is where salts accumulate. Fortunately, most plants have the densest roots in the upper root zone nearest the surface, where it is least saline, and the sparsest roots in the lower root zone, where it is most saline. Drip irrigation results in a different pattern of salt distribution. The wetted zone of drip-irrigated soils is somewhat ellipsoidal in shape, with salts tending to accumulate in the outer edges of the wetted perimeter. After prolonged drip irrigation, salts may accumulate between drip emitters to levels that are detrimental to plants and may need to be leached with the use of sprinkler irrigation. Heavy rainfall on salinized drip-irrigated soils will redistribute the salts vertically and horizontally, affecting salt-sensitive plants. To prevent such redistribution of salts by reducing the lateral flow of salts, operation of drip irrigation is recommended during rainfall.

A high ESP and SAR in the soil will adversely affect the structure of the soil, especially at the surface, causing aggregates of soil to break down and clays and organic matter in the soil to disperse. This process, in turn, reduces the rate at which water infiltrates the soil. Excess ESP is commonly ameliorated by adding calcium amendments, such as gypsum ($CaSO_4 \cdot 2H_2O$), to the soil or into the irrigation water. As acids react with soil calcite ($CaCO_3$) to produce soluble calcium, sometimes acids, such as sulfuric acid, and acid-forming amendments, such as elemental sulfur, are used to reduce ESP. Slow water infiltration may also be caused by surface crusting in some soils, which results from the beating action of raindrops and the spray of water from sprinklers, or from the compaction of soil from vehicular and foot traffic, especially in a clayey, moist soil.

Maintaining adequate plant nutrition is important to keep plants healthy and attractive. Plants need 17 essential mineral nutrients. Three of these—carbon, hydrogen, and oxygen—are readily available from the atmosphere and water. Another three—nitrogen, potassium, and phosphorus—are known as primary nutrients because plants need them in large amounts. Three more—calcium, magnesium, and sulfur—are secondary nutrients and required by plants in lesser amounts. The remaining eight elements are required in trace amounts and are known as micronutrients. They are zinc, iron, manganese, copper, boron, molybdenum, chlorine, and nickel.

When these nutrients become less available to plants, visible symptoms of deficiency are often noted. Symptoms include discolored leaves, spotted leaves, dead leaf margins, and injured buds. It should be noted that some symptoms of deficiency may look like symptoms of another deficiency. For example, symptoms of a deficiency of manganese closely resemble symptoms of a deficiency of iron or symptoms of damage from the pre-emergence application of herbicides. The location of symptoms on the plant can be very useful in diagnosing deficiencies. For example, symptoms of deficiencies of the three most commonly limited nutrients—nitrogen, phosphorus, and potassium—become noticeable on older leaves first, while symptoms of deficiencies of sulfur, iron, and zinc first become apparent on newly emerging leaves and symptoms of deficiencies of boron and calcium manifest early on as dead buds or the dieback of growing tips.

Landscapes contain a wide range of plant species, and therefore, it is not surprising that mineral nutrient requirements can vary widely as well. For instance, turfgrasses require a large amount of nitrogen, while many species of flowers require higher proportions of phosphorus and potassium. Inorganic and organic fertilizers can be added to nutrient-deficient soils.

The grading of land in landscapes may result in the loss of topsoils, if topsoils are removed with cut portions, leaving behind infertile soil, or if infertile soils are used as fill soils, e.g., if infertile fill soil from a construction site is used to convert a landfill to a golf course. These infertile-soil landscapes established on sandy and gravelly soils, as in river floodplains or stream channels, typically require more fertilization.

Diagnosing and Solving Problems

The last chapter of this document covers the diagnosis of problems and suggested management solutions. The chapter focuses on salinity-related problems encountered in landscapes, but since such problems should not be viewed in complete isolation, it also includes other landscape problems. A problem encountered in landscapes may have multiple abiotic and biotic causes; thus, accurately diagnosing and appropriately solving a problem may be challenging. Sources of abiotic stress that may cause or contribute to the injury or disease of a plant include salinity, deficiencies and excesses of minerals, extremes of moisture and temperature, wind, air pollutants, and drift of herbicide. Sources of biotic stress that may cause or contribute to the injury or disease of a plant include insects, mammals and birds, bacteria, fungi, nematodes, and viruses. These problems need to be addressed in a timely and comprehensive manner to avoid high maintenance costs and sustain the quality of landscapes. This last chapter, drawing upon information from previous chapters, summarizes irrigation and drainage problems and the abiotic factors that cause problems for plants.

We consider such problems related to irrigation and drainage as plants suffering from water stress, which could be caused by insufficient irrigation and may be solved by increasing the duration and/or rate of irrigation enough to satisfy the plant's ET; the presence of dry or wet areas, which could be caused by poor uniformity of irrigation and may be solved by changing the spacing of lateral lines and sprinkler heads or nozzles to improve the uniformity of irrigation; excessive ponding, which could be caused by water with a high SAR and a low EC and may be solved by adding gypsum to the soil; waterlogging, which could be caused by compacted soil and may be solved by reducing foot and machinery traffic; and runoff, which could be caused by the slow infiltration of water through the soil and may be solved by decreasing the rate and/or duration of irrigation.

We also consider such problems involving turfgrasses and lawns as localized dry and wet spots, which could be caused by compacted soil at the surface and may be solved by core-aerating the soil; spotty bare spots with salt crust, which could be caused by an excessively saline soil and may be solved by conducting localized leaching to remove salts; bare spots with dispersed organic matter, which could be caused by an excess of RSC in the water and may be solved by injecting acids into the source water; uniform abnormal yellowing of leaves, which could be caused by a deficiency of nitrogen and may be solved by applying nitrogen-containing fertilizers and improving drainage; unusual yellowing of younger leaves, which could be caused by a deficiency of iron and may be solved by applying iron chelate or other iron-containing fertilizers; the dark green discoloration of older leaves, which could be caused by a deficiency of phosphorus and may be solved by applying appropriately broadcasted phosphorus-containing fertilizers; and leaf rolling, which could be caused by a deficiency of potassium and may be solved by broadcasting potassium-containing fertilizer and incorporating it into the ground as much as possible.

We furthermore consider such problems involving trees and shrubs as atypically yellowed and prematurely dropping leaves, which could be caused by excessive irrigation and/or poor drainage and may be solved by decreasing irrigation and improving drainage and aeration; abnormally light green and short needles on conifers, which could be caused by a deficiency of nitrogen and may be solved by applying a nitrogen-containing fertilizer or improving the restricted growth of roots; the bronzing of lower leaves with purple or brown spots, which could be caused by a deficiency of phosphorus and may be solved by applying a phosphorus-containing fertilizer and checking for damages from the use of herbicide; deadened tips of needles in conifers, which could be caused by a deficiency of potassium and may be solved by applying a potassium-containing fertilizer; uncharacteristically yellowish and undersized new leaves with green veins, which could be caused by a deficiency of iron and may be solved by adding acidic amendments or iron chelates to lower the soil's pH; discolored leaves, which could be caused by sunburn or scalding and may be solved by selecting more sun-tolerant plants; trees appearing stressed by lack of water, with dropping leaves and injured bark and trunk, which could be the result of wind damage and may be solved by selecting wind-tolerant plants and providing wind breaks; and unusually yellowish to brown leaves or needles, which could be caused by air pollution and may be solved by selecting more ozone-tolerant plants.

The appendices, in addition to the Excel models, contain a glossary, acronyms and abbreviations used in this report, and conversion factors for SI (Système International) and non-SI units, chemical units and other useful conversions, a table for field capacity and available soil moisture as a function of soil texture, and a subject index.

This Salt Management Guide will be heavily cited and attached in the forthcoming interactive CD, the Salt Management Guide for Landscape Professionals.

Chapter I. Introduction

K. Tanji and B. Sheikh

California will need to improve its efficiency of water use, both in the agricultural and urban sectors, to meet its water needs by 2030. This exigency is indicated by the most recent water plan of the state (California Department of Water Resources, 2004). The plan further suggests that California water providers will find it advantageous to recycle more water than they currently do. Recycled water produced from wastewater already treated to a fairly high level, typically tertiary (secondary treatment, filtration, and disinfection), can be used in many nonpotable applications and, therefore, can help reduce the overall demand for fresh water.

Currently, California's agricultural, industrial, and urban sectors use a total of about 530,000 acre-ft of recycled municipal wastewater per year. About 46% is used to irrigate agricultural crops. About 21% is used for landscape irrigation and about 14% for groundwater recharge. The rest—19%—goes to various uses, such as cooling water for oil refineries and power plants and flushing toilets and urinals, as well as to environmental enhancements, such as supplying water for wetlands and ponds, including reflecting ponds. In urban areas, recycled water often is used to irrigate golf courses, commercial and residential landscapes, plant nurseries, parks and greenbelts, school yards and playing fields, and highway medians and margins. According to a recent survey, 409 parks or playgrounds and 295 schools' grounds in California are irrigated with recycled water (Crook, 2005).

By the year 2030, it is estimated that an additional 1.2 million acre-ft of recycled water will be available annually. That water, if used, could free up enough fresh water to meet the household water needs of 30 to 50% of the 17 million additional people who will live in California in 2030 (California Department of Water Resources, 2004). The expanded use of recycled water for landscape irrigation is of especially high priority in south coastal California (the Los Angeles-to-San Diego corridor) in order to help alleviate current and future shortfalls of potable water.

Recycled water is used for many nonpotable uses in California at the present time. Though many additional opportunities for using recycled water in California's urban areas exist and though such use is encouraged by the state (California Recycled Water Task Force, 2003), some landscape irrigators are reluctant to use recycled water. Some do not fully understand that recycled water can be safe and suitable for irrigating landscapes. Some believe that recycled water may be excessively saline and therefore harmful to landscape plants.

To help foster a broader acceptance of recycled water, the Central Basin Municipal Water District, the WateReuse Foundation, the California Department of Water Resources, and several other institutions recently teamed up to begin informing the public and members of the landscape industry about the utility of recycled water. Part of that program involves developing an interactive, CD-based salt management guide for landscape professionals. Another part of the program involves outreach—developing and publishing an educational brochure. A third part involves researching the state of knowledge and publishing a literature review summarizing what is known at present regarding the factors that control the need for salt management when one is irrigating a landscape with recycled water. This document comprises the literature review component of the program. It should be noted that, although there are several indirect potable reuse projects involving groundwater recharge, this review does not address potable reuse or potential health-related groundwater contamination resulting from irrigation with recycled water. It also does not cover the public health aspects of using recycled water, as the authors do not have expertise on this topic. And, except in passing, this review does not address the effect of irrigating landscape plants with recycled water on the regional salinity of underlying groundwater basins, since regional salt balance in southern California is a complex topic that will require additional research, including three-dimensional modeling coupling unsaturated and saturated zones for transport of water and salts in site-specific hydrogeologic formations.

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Chapter II. Present Status: Potential Benefits of Irrigating Landscapes with Recycled Water, Current Use of Recycled Water, and Regulations

K. Tanji and B. Sheikh

II.A. Potential Benefits of Using Recycled Water
II.B. Current Uses of Recycled Water
II.C. California's Relevant Regulations
II.D. References

This chapter summarizes the potential benefits of using recycled water, given the increasing scarcity of potable water, as well as the current uses of recycled water for irrigating landscapes in California. The chapter also summarizes the state's regulations governing use of recycled water.

II.A. Potential Benefits of Using Recycled Water

Substituting recycled water for valuable and scarce potable water often serves to augment supplies of fresh water. Communities and water purveyors also may benefit in other ways, too. As mentioned in several publications (California Department of Water Resources, 2004; California Recycled Water Task Force, 2003; Sheikh et al., 1998; WateReuse Foundation, 2003), the benefits of using recycled water include the following:

- When uncertainties exist with a supply of traditional (potable) water, the use of recycled water for such nonpotable applications as landscape irrigation can help reduce the demand on a water system, thereby increasing the supply of available water and improving the reliability of its supply.
- Augmenting a water system with recycled water can, in some situations, decrease the diversion of fresh waters from sensitive ecosystems.
- Recycling treated wastewater reduces the discharge of effluent to sensitive environments and protects the quality of surface water and groundwater. Furthermore, recycled water may be used to enhance and create wetlands and riparian habitats.

- Using recycled water may reduce the costs of wastewater treatment and disposal. It may also provide other economic benefits to dischargers and, indirectly, to businesses and the public.
- In communities that recycle water, water purveyors may be able to "bank" a portion of their imported water during average and above-average water years or to reserve some of the imported water for use during dry years.
- The use of recycled water, obtained from a local source, often partially offsets the need to import water. That strategy, in turn, reduces the need for pumping and other energy-consumptive activities associated with importing water.

II.B. Current Uses of Recycled Water

Recycled water has been used in California since the late 1800s (California Department of Water Resources, 2004). Guidelines and regulations directed at public health protection with regard to water reuse have been in effect since the early 1900s. Use of recycled water has increased during the past several decades, as water agencies strove to meet shortfalls in supplies of potable water caused by drought or population growth and concurrent increases in the demand for water. Currently, with California's population continuing to increase by approximately 500,000 people per year and with additional new supplies of water virtually nonexistent or increasingly expensive to develop, recycled water could be considered the fastest-growing supply of water available (California Department of Water Resources, 2003).

The Office of Water Recycling at the California State Water Resources Control Board recently surveyed water users to determine the amount of municipal wastewater being recycled and the types of recycled water use (California State Water Resources Control Board Office of Water Recycling, 2002). The survey determined that, as of 2002, approximately 525,000 acre-ft of wastewater was being reclaimed and recycled in California each year. At that time the survey was conducted, 48.5% of the total amount of recycled water used in the state was used for agricultural irrigation, 21.1% for landscape irrigation, 9.3% for groundwater recharge, 7.8% for recreational impoundments, 4.9% for seawater barriers, and 11.1% for other uses. Note that these figures refer to direct and intentional use and exclude indirect or incidental reuse such as the disposal of treated wastewater effluent into rivers and streams and subsequent diversion of the river water by downstream water users.

According to data compiled by the Office of Water Recycling in 2003 (Table II.B.1), the proportion of total recycled water used for landscape irrigation in southern California ranges

Table II.B.1. Use of Recycled Water in Selected Service Areas in California ***(from California State Water Resources Control Board Office of Water Recycling, 2002)*****.**

Purpose	Amt. of water used in:			
	Los Angeles region	Santa Ana region	San Diego region	San Francisco Bay region
Agricultural irrigation	3,752 acre-ft/year or 2%	30,795 acre-ft/year or 37%	5,033 acre-ft/year or 16%	8,318 acre-ft/year or 28%
Landscape irrigation	26,229 acre-ft/year or 17%	28,135 acre-ft/year or 34%	24,191 acre-ft/year or 78%	10,114 acre-ft/year or 34%
Groundwater recharge	46,247acre-ft/year or 30%	0 acre-ft/year[a]	286 acre-ft/year or 1%	0 acre-ft/year
Seawater barrier	10,651acre-ft/year or 7%	15,000 acre-ft/year or 18%	0 acre-ft/year	0 acre-ft/year
Other uses	65,437 acre-ft/year or 43%	97,20 acre-ft/year or 12%	1,445 acre-ft/year or 5%	11,087 acre-ft/year or 38%
Total recycled water	152,316 acre-ft/year	83,650 acre-ft/year	30,955 acre-ft/year	29,519 acre-ft/year

[a] Currently, greater than 0%.

from 17% for the Los Angeles region to 78% for the San Diego region. From these figures, it is evident that opportunities exist to further use recycled waters to irrigate landscapes.

II.C. California’s Relevant Regulations

California’s regulations governing the use of recycled water are known as Water Recycling Criteria and are found in Title 22, Division 4, Chapter 3, of the California Administrative Code and are often simply referred to as Title 22, Code of Regulations on Water Recycling Criteria (California Department of Health Services, 2001). According to Section 13550 of the California Code, using a potable source of water—for example, to irrigate cemeteries, golf courses, landscaped areas along highways, greenbelts, and parks and playgrounds—is a wasteful or unreasonable use of water if reclaimed water is available that meets certain conditions (State Water Resources Control Board, 2000). These conditions include the following (Crook and Surampalli, 1996):

- The source of recycled water is of adequate quality for the proposed uses and available for such uses.
- The recycled water may be furnished for these uses at a reasonable cost comparable to, or less than, the cost of potable water.
- After concurrence with the California Department of Health Services, the use of recycled water from the proposed sources will not be detrimental to public health.

Secondary treatment of wastewater includes removal of biodegradable organic matter in solution or suspension and suspended solids (Tchobanoglous et al., 2003). Typically, conventional secondary treatment also includes disinfection.

Tertiary treatment of wastewaters includes removal of residual suspended solids after secondary treatment by usually membranes, granular medium filtration or micro-screen. Disinfection is also a part of tertiary treatment (Tchobanoglous et al., 2003).

- The proposed uses of recycled water will not adversely affect downstream water rights, will not degrade water quality, and is determined to be not injurious to plants, fish, and other wildlife.

Before recycled water can be used to irrigate a landscape, the water must be treated to certain secondary and tertiary levels (Table II.C.1). All recycled water used for landscape irrigation must be disinfected. Water that has not been disinfected is deemed unacceptable for any type of landscape irrigation. For irrigation of cemeteries, freeway margins, sod farms, and other such places where public contact with irrigation water is unlikely, the requirements for treating recycled water are less stringent than those for irrigation with recycled water of public use lands that have unrestricted access, such as golf courses, parks, and playgrounds. Undisinfected, secondarily treated recycled water is acceptable for ornamental nursery stock and sod farms, provided no irrigation with recycled water occurs for a period of 14 days prior to harvesting, retail sale, or access by the general public.

As pointed out by Levine and Asano (2004), new or advanced types of treatment processes eventually may be necessary to respond to chemicals that newly emerge and become introduced into municipal wastewater—for example, residues from pharmaceuticals and personal care products. However, these newly emerging chemicals appear not to have an adverse effect on landscape plants. Levine and Asano further assert that recycling treated wastewater is increasingly becoming a necessity. Especially in arid and densely populated areas, such as the Los Angeles basin, where freshwater resources are becoming scarce, recycling wastewater and prioritizing its reuse are essential activities if water supplies are to be truly sustainable in the future.

Table II.C.1. Allowed Uses of Recycled Water for Irrigating Landscapes in California ***(from WateReuse Foundation, 2003).***

Landscape for irrigation	**Status of:**			
	Disinfected tertiary recycled water	**Disinfected secondary-2.2[a] recycled water**	**Disinfected secondary-23[a] recycled water**	**Undisinfected secondary recycled water**
Cemeteries	Allowed	Allowed	Allowed	***Not allowed***
Freeway landscaping	Allowed	Allowed	Allowed	***Not allowed***
Golf courses with restricted access	Allowed	Allowed	Allowed	***Not allowed***
Golf courses with unrestricted access	Allowed	***Not allowed***	***Not allowed***	***Not allowed***
Ornamental nurseries and sod farms	Allowed	Allowed	Allowed	***Not allowed***
Parks and playgrounds	Allowed	***Not allowed***	***Not allowed***	***Not allowed***
Residential landscaping	Allowed	***Not allowed***	***Not allowed***	***not allowed***
School yards	Allowed	***Not allowed***	***Not allowed***	***Not allowed***

[a] Refers to 7-day median counts of total coliform bacteria per 100 mL of water.

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Chapter III. Water Quality Guidelines for Recycled Water Use for Landscape Irrigation

K. Tanji, S. Grattan, D. Shaw, and B. Sheikh

III.A. Water Quality Constituents of Concern in Irrigation Water
  III.A.1. Salinity or Osmotic Effects
  III.A.2. Specific Ion Toxicity
  III.A.3. Sodicity and Soil Permeability
  III.A.4. Other Constituents of Concern
III.B. Water Quality Guidelines
  III.B.1. Early Water Quality Guidelines
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  III.B.3. Caveats and Assumptions for Using Current Guidelines
III.C. Quality of Recycled Waters
  III.C.1. Representative Composition of Recycled Waters
  III.C.2. Evaluation of Representative Recycled Waters Using FAO Guidelines
III.D. A Case Study: Use of Potable and Recycled Waters on Turfgrasses at Whispering Palms Site
III.E. References

Most recycled waters do not inherently contain excessively high levels of salinity, though they typically carry about 150 to 400 mg of salts/L more than does the potable water from which they originated. Given a supply of potable water of low to moderate salinity, the recycled water resulting from it would still be quite suitable as irrigation water for all practical purposes, under most conditions.

Evaluating the suitability of waters for irrigation requires a broad understanding of water quality characteristics and interactions with plant, soil, and irrigation management systems. This chapter identifies key water quality parameters and describes how they are interpreted for suitability or to serve as water quality guidelines.

Since water quality assessment and management in irrigated agriculture are much more established than in landscape irrigation except for turf irrigation, a significant portion of this chapter involves what is applicable to irrigated crop production that is also applicable to irrigated landscape management in terms of evaluating water quality, diagnosing problems, and choosing management strategies. It should be noted, however, that a major difference in evaluating the suitability of waters for irrigating agricultural crops and waters for irrigating landscape plants is that the former is based on harvested crop yield, while the latter is based on aesthetic quality or appearance.

Discussions of the quality of irrigation water in the agronomic literature, which refer to water that is not recycled, are equally applicable to recycled water, as discussed in the following section. The principal book references on this topic include Ayers and Westcot (1985), Pettygrove and Asano (1986), and Tanji (1990).

III.A. Water Quality Constituents of Concern in Irrigation Water

Recycled water contains dissolved mineral salts, nutrients, and residues of chemicals used in the treatment and disinfection of the recycled water. Though all water supplies contain dissolved mineral salts, the dissolved-mineral content of recycled waters primarily depends on the quality of the source water supply and the incidental addition of a small amount of salts—typically from about 100 to 400 mg/L—stemming from the water's use for municipal and industrial purposes. A larger amount of salts will accrue if water softeners containing sodium chloride (NaCl) are used extensively in the community that contributes wastewater flowing to the wastewater treatment plant. Nutrients contained in recycled water include ammonia, ammonium ions, nitrates, and phosphorus. The concentrations of these nutrients will vary depending on the extent of wastewater treatment provided.

The principal constituents of concern with regard to the quality of recycled water for irrigation are the following: salinity, which contributes to osmotic effects that affect the availability of soil water to plants; specific ions toxic to sensitive plants—for example, sodium, chloride, and boron; and the combined effects of sodicity and salinity, which affect the rate at which water infiltrates the soil surface and the permeability of the soil profile. Other constituents of concern include nitrogen, bicarbonates, residual chlorine, and constituents that may cumulatively clog the small orifices of sprinkler irrigation systems. It should be noted that those parameters of water quality that affect human health, such as pathogenic bacteria, protozoa, and viruses, and those that affect the environment, such as dissolved oxygen and oxygen-demanding organics, are not addressed in this document.

III.A.1. Salinity or Osmotic Effects

The salinity of water affects plants due to osmotic effects: plants must expend more energy to extract soil water from saline soil solutions than from nonsaline soil solutions. A widely used indicator of the salinity hazard posed by waters to plants is electrical conductivity (EC, specific conductance), a lumped salinity parameter. Water salinity can be readily measured as EC having units of decisiemens per meter (dS/m), equivalent to millimhos per centimeter (mmhos/cm), and millisiemens per centimeter (mS/cm) in more saline waters and microsiemens per centimeter (µS/cm), equivalent to micromhos per centimeter (µmhos/cm) in less saline waters. EC is a readily obtained measure of how easily electric current is conducted by charged ions present in the water. Waters contain positively charged ions—major cations such as Na^+, Ca^{2+}, Mg^{2+}, K^+, NH_4^+, and H^+—and negatively charged ions—major anions such as Cl^-, HCO_3^{2-}, CO_3^{2-}, SO_4^{2-}, and NO_3^-. The higher the salt content, the greater is the EC. Since water is an electrolyte and since electrical neutrality prevails in nature, the milliequivalent-per-liter (meq/L, based on equivalent combining weight) concentration of cations is balanced by the meq/L concentration of anions. EC is the lumped salinity parameter that is preferred for use with water used to irrigate plants because EC can be readily related to osmotic pressure (OP in atmospheres = EC in dS/m × 0.36), affecting the availability of soil water to plants.

Another lumped salinity parameter for waters is total dissolved solids (TDS, sometimes referred to as dissolved residues). Obtained labor intensively in a laboratory, TDS is a parameter of capacity expressed in mass per unit volume: milligrams per liter (mg/L) or parts per million (ppm) on a volume basis for fresh waters and recycled waters and gallons per liter (g/L) or parts per thousand (ppt) on a volume basis for saline waters, such as seawater. The conversion of EC to TDS varies, depending on the composition of cations and anions and the overall concentration of dissolved salts. For example, a salt solution dominated by Na^+ and Cl^- ions has a higher EC than do Na^+ and SO_4^{2-} ions (or Na^+ and HCO_3^- ions) of equal meq/L concentration, because a Cl^- ion conducts more electricity than do SO_4^{2-} and HCO_3^- ions. Nevertheless, TDS in mg/L may be estimated from EC in dS/m by multiplying EC by a rule-of-thumb factor of 640 (a factor of 735 appears to fit better for waters of mixed composition such as Colorado River water). For ECs greater than about 5 dS/m, a conversion factor of 800 is suggested to convert EC into TDS.

A third salt concentration unit is tons of salt per acre-foot (ac-ft) of water, which can be estimated from TDS (tons salt/ac-ft = TDS in mg/L × 0.00136) or from EC (tons salt/ac-ft = EC in dS/m × 0.87; sometimes, a factor of 1.00 is used instead of 0.87).

A fourth salt concentration unit less frequently used in irrigation practice is total soluble cations or total soluble anions in meq/L. Analytical chemists check their water analyses in meq/L by balancing the sum of cations and anions. If there is a substantial imbalance, they reanalyze the water. Total soluble cations (or total soluble anions) in meq/L may be obtained by multiplying EC in dS/m by 10.

The accumulation patterns of salt in irrigated soils depends on the irrigation systems used and the amount of water applied that exceeds crop water demands (Figure III.A). When water is uniformly applied across the irrigated land, as in sprinkler and border irrigation, the surface soil depths become the zone of salt leaching and the bottom soil depths become the zone of salt accumulation. The extent of salt accumulated in the bottom of the root zone depends on the leaching fraction (LF, namely, the ratio of drainage out of the root zone to infiltrated water). The higher the LF, the less salt is accumulated in the soil. When water is applied by furrow irrigation, salts increase with soil depth in the bottom of the furrow while the beds of the furrow tend to accumulate salts. When water is applied by drip irrigation, salts tend to accumulate concentrically around the wetted perimeter of the zone irrigated.

Soils may contain soluble minerals that, when chemically weathered, contribute to the overall salinity in the soil solution. Soil minerals such as calcite ($CaCO_3$) and feldspars (sodic-, calcic-, and potassium silicates) have low solubilities and contribute relatively little to soil salinity, while minerals such as gypsum ($CaSO_4 \cdot 2H_2O$) have higher solubilities and may contribute significant concentrations of Ca and SO_4 ions. The solubility of gypsum in pure water is about 2,600 mg/L and much higher in the presence of Na^+ and Mg^{2+} ions (Tanji, 2002). Other more highly soluble evaporite minerals, such as sodium chloride, sodium sulfate, and magnesium sulfate, are sometimes present in strongly salt-affected soils. These highly soluble salts are readily leached by rainfall and irrigation into deeper zones, sometimes beyond the root zones.

The salinity parameter of interest on plant performance is EC to assess osmotic effects. Osmotic effects on plants are reflected by stunted growth, chlorosis, and wilting in some cases and death in the most severe cases. Plants vary in their tolerance to salts (osmotic effects) as indicated in Chapter V of this document. Salt tolerant plants expend less metabolic energy to adjust to a saline environment than do more salt-sensitive plants (Lauchli and Epstein, 1990).

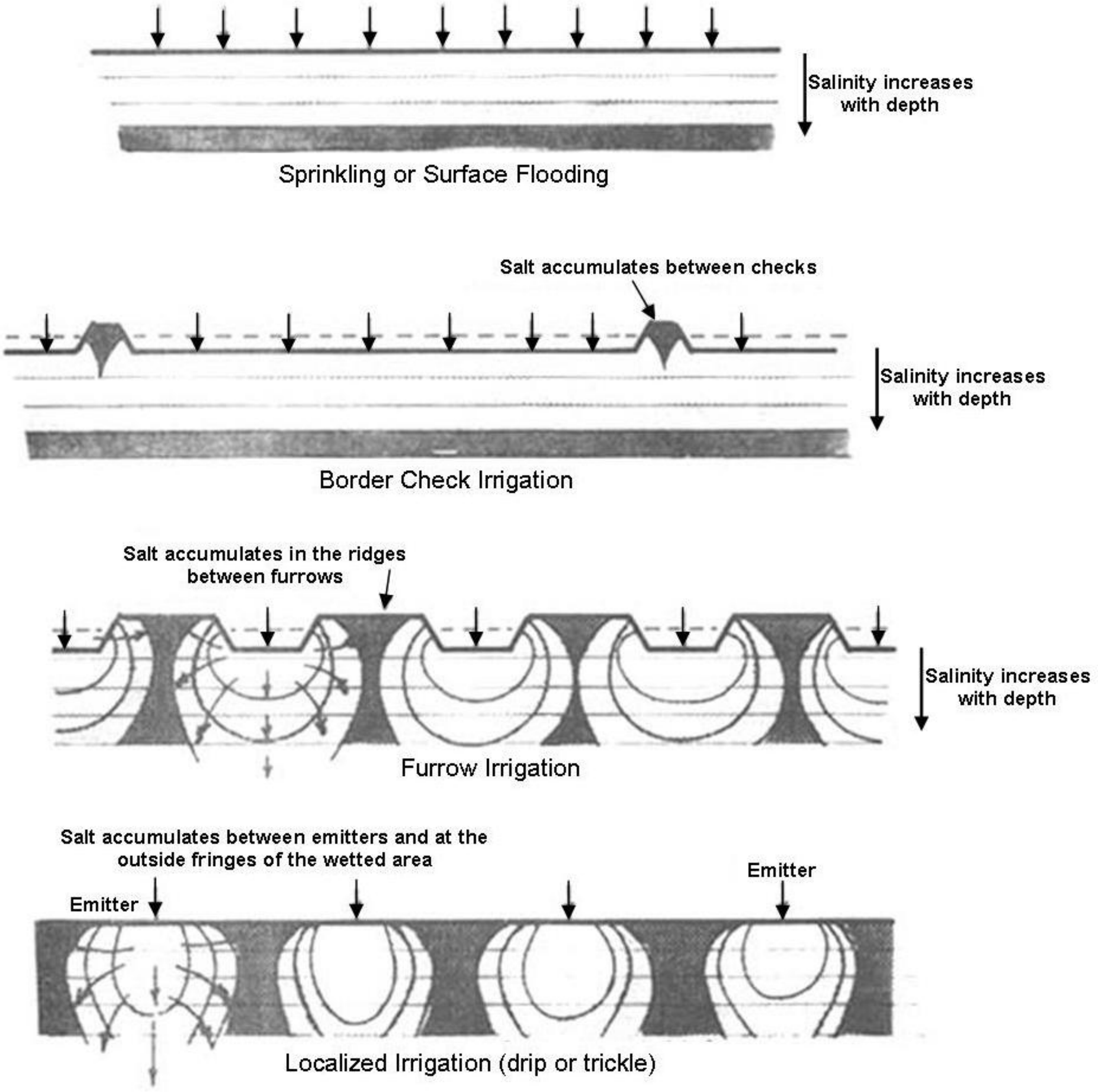

Figure III.A.1. Typical salt accumulation patterns in soils irrigated by sprinklers or surface flooding, border check irrigation, furrow irrigation, and drip irrigation *(Ayers and Westcot, 1985).*

III.A.2. Specific Ion Toxicity

Some plants may be sensitive to specific ions such as Na^+, Cl^-, and B, the last usually in the form of undissociated boric acid or H_3BO_3 at pH in the neutral range. These negative impacts are collectively known as specific ion toxicity (Chapter V). As pointed out above, the use of water softeners increases the concentration of Na^+ and Cl^- ions in recycled waters. Also, a few communities use potassium chloride (KCl) instead of sodium chloride (NaCl) in their water softeners, increasing the concentration of Cl^- ions in the recycled water. Use of boron-containing household cleansers may elevate concentrations of boron in recycled waters. The symptoms of specific ion toxicity include chlorosis and necrosis on marginal edges of leaves, necrotic spots on leaves, interveinal chlorosis on leaves, damage to growing tips, and death in the severer cases. Though some specific ions, particularly boron and chloride, are essential to plant growth in low concentrations, the range in concentration between essential and toxic is narrow in sensitive plants. Plants also vary in their tolerance to specific ions (Chapter V). Woody plants (e.g., trees and shrubs) tend to be more severely affected by specific ions than do annual plants, since specific ions may be translocated and accumulated over time in roots, trunks, leaves, and growing tips. Annual plants may suffer from specific ion toxicity if the water contains elevated concentrations of such ions and accumulates to a sufficient degree during the shorter growing period of the plants. Toxicity to specific ions, especially Cl^- and Na^+, can also occur in annuals and perennials from direct absorption through the leaves when wetted by sprinkler systems.

Visual diagnosis of foliar damage due to specific ions may be compounded by osmotic effects (salinity). As waters increase in salinity, specific ions also tend to increase in concentration, especially Na^+ and Cl^- ions. Thus, osmotic effects and specific ion toxicity frequently cannot always be clearly differentiated. In such cases, chemical analyses of leaf tissues for specific ions and salinity may more accurately reveal the cause(s) of plant damage or poor performance.

III.A.3. Sodicity and Soil Permeability

Excess Na^+ in waters may impact mineral nutrition in plants, causing Na-induced calcium deficiency and specific ion toxicity and affecting soil permeability and rates of water infiltration. Accumulation of excess adsorbed Na (exchangeable Na) on the soil exchange complex (negatively charged sites on soil colloids and organic matter) causes soil colloids and organic matter to disperse, resulting in the destruction of soil structure, particularly the larger pores, and reduced permeability of soil to water and gases. Dispersion of soil organic matter produces a black mucky mat on moist soil surfaces; such soils are referred to as black alkali soil.

Exchangeable Na on the soil exchange complex is most frequently appraised with the sodium adsorption ratio (SAR) of the soil solution, since the analytical method for determining exchangeable sodium is time-consuming. SAR is defined as the ratio $(Na^+)/(Ca^{2+}+Mg^{2+})^{0.5}$ when units are in millimoles per liter or as $(Na^+)/[(Ca^{2+}+Mg^{2+})/2]^{0.5}$ when units are in meq/L. Thus, SAR has units of $(\text{millimoles/liter})^{0.5}$ or $(\text{meq/L})^{0.5}$.

SAR_{adj} (or adjusted SAR) is sometimes used to account for the tendency of calcium to decrease in the soil solution due to the precipitation of calcite. The theoretical computation of SAR_{adj} is based on the Langelier saturation index (Langelier, 1936), which is used widely in the water industry. A much simpler method of calculating SAR_{adj} is based on tabular values of expected Ca^{2+} concentration from a matrix of ratio of HCO_3^- to Ca^{2+} and EC of the water (technically referred to as adj R_{Na} by Ayers and Westcot, 1985). This expected Ca^{2+} concentration replaces Ca^{2+} in the denominator of the SAR expression. Ayers and Westcot (1985) calculated SAR and SAR_{adj} for 250 water samples from throughout the world and noted that SAR was within ±10% of SAR_{adj} for most waters. In waters with more of a tendency to form carbonate minerals, SAR_{adj} may be markedly higher than SAR. This may be the case for some but not for all recycled waters with elevated HCO_3^- concentrations as a result of chemicals used in wastewater treatment processes. Ayers and Westcot (1985) now recommend taking SARadj × 0.5 as a more correct representation of SAR adjusted for the effects of calcite precipitation in irrigated soils.

The rate of water infiltration into soils and soil hydraulic conductivity are affected by the interaction between the SAR and the EC of the water. Moderate to high SAR (sodicity) may cause soil colloids to disperse and result in reduced infiltration rates. A relatively high EC (salinity or electrolyte concentration) may cause soil colloids to coagulate, resulting in increased infiltration rates. An illustrative interaction of SAR and EC is shown in Figure III.A.2 (after Henderson, 1955). The impact of electrolyte concentration (EC) on hydraulic conductivity of Columbia silt loam is shown by the curve labeled SAR-0. Note that reduced hydraulic conductivity of this soil may be partially overcome by increasing water salinity for waters of lower SARs.

Another view of the SAR-EC relationship (Figure III.A.3) is widely used to evaluate the effects of sodicity and salinity on rates of water infiltration in medium- to fine-textured soils (Ayers and Westcot, 1985). Note that the SAR poses the most hazard to soil permeability at low ECs and that this hazard may be partially overcome by increasing EC. Experience in California water recycling practice indicates that nearly all such recycled waters fall within the safe zone of this graph—that is, no reduction in infiltration rate occurs (B. Sheikh, personal communication).

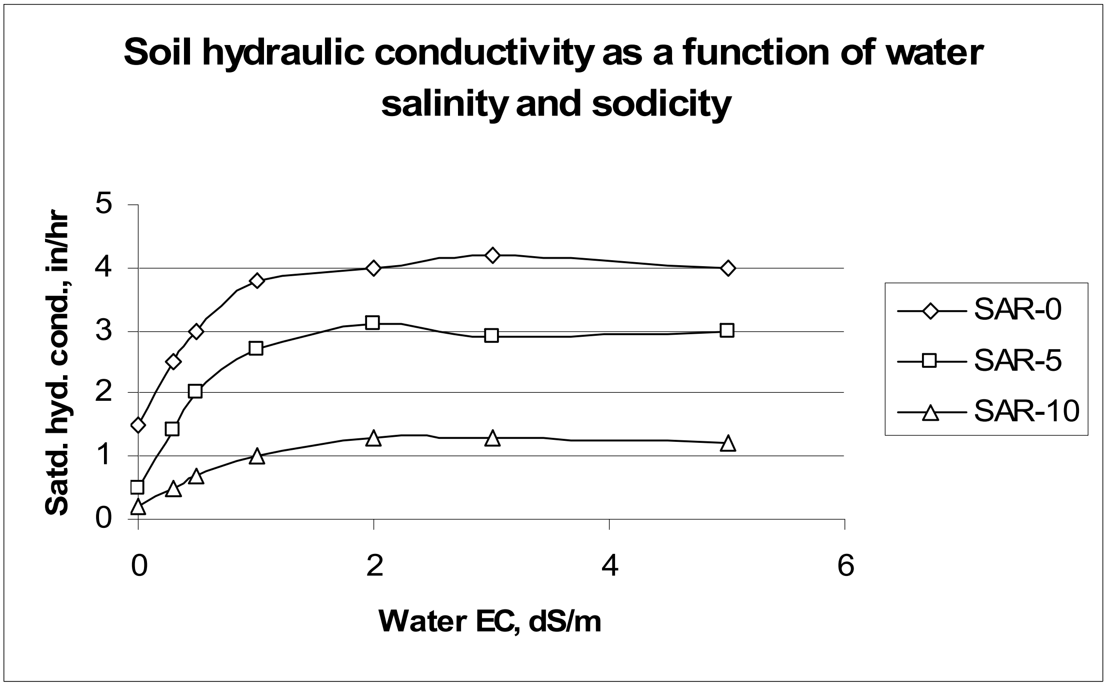

Figure III.A.2. The interaction of salinity and sodicity on the saturated hydraulic conductivity of Columbia silt loam *(after Henderson, 1955)*.

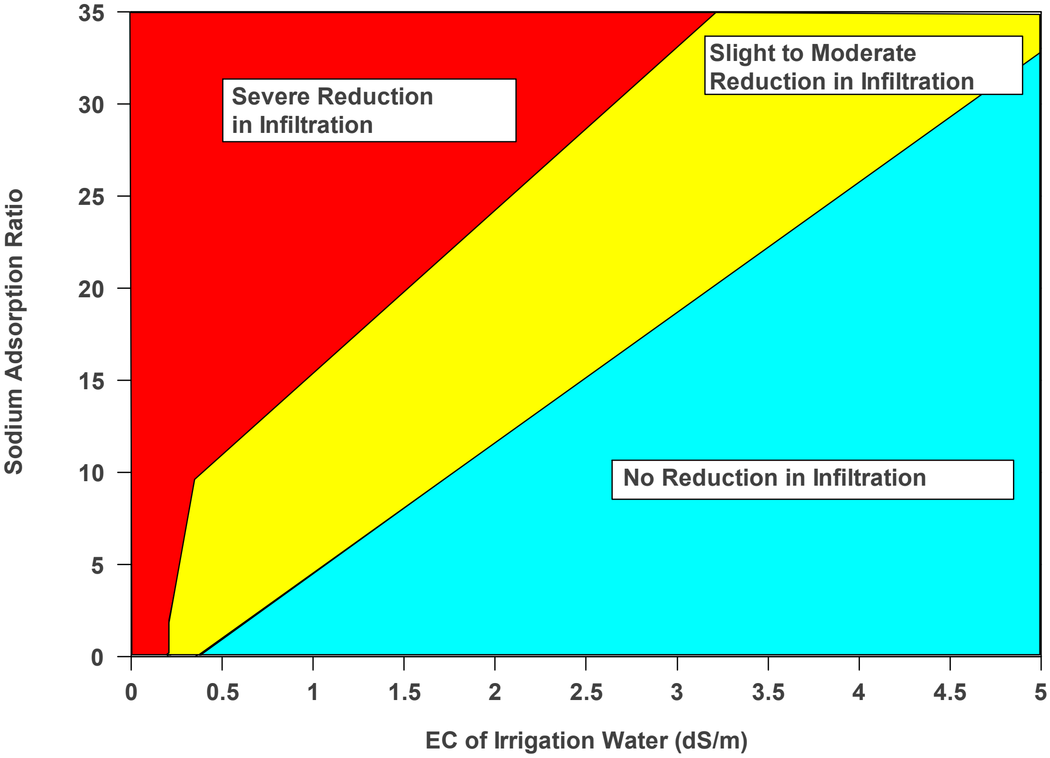

Figure III.A.3. A diagram to evaluate the effects of SAR and EC of waters on water infiltration rates in medium- to fine-textured soils *(after Ayers and Westcot, 1985).*

A second parameter of sodicity widely used before the advent of SAR is residual sodium carbonate (RSC), which is equal to (HCO_3^{2-} + CO_3^{2-}) – (Ca^{2+} + Mg^{2+}) in meq/L (Eaton, 1950). A positive difference between carbonate alkalinity and hardness would result in residual carbonates. When combined with Na^+, these carbonates disperse soil organic matter, forming a black residue known as black alkali on the surface of soils. RSC exceeding 1.25 meq/L may cause increasing problems with sodicity.

III.A.4. Other Constituents of Concern

Irrigation waters, especially recycled waters, may contain a number of other constituents of concern. They include nitrogen (nitrates and ammonium), bicarbonates, residual chlorine, and constituents that might plug the small orifices of irrigation systems, such as drip irrigation emitters.

Nitrogen

Some natural waters, especially groundwaters, may contain appreciable concentrations of nitrates from geochemical origins. Other ground- and surface waters may have an accumulation of nitrates leached from excessive land applications of chemical fertilizers, animal manures and dairy wastewaters, biosolids, and other products of wastewater origin. Untreated municipal wastewaters contain organic nitrogen and some NH_3. The organic nitrogen is oxidized in wastewater treatment into NH_3 (and NH_4^+) and is further oxidized into NO_2^- and NO_3^-. The oxidation of NH_4^+ by microbes results in the production of protons (H^+), and hence the acidified water is typically neutralized by chemicals such as lime. Thus, Title 22 recycled waters typically contain from 15 to about 50 mg of N of NO_3^- and NH_4^+ ions/L, which is equivalent to 41 to 136 lbs. of N per ac-ft of water applied (lbs./ac-ft = mg/L × 2.72). These sources of nitrogen, if not taken into account when fertilizing the plants with nitrogen, may cause excessive vegetative growth, lodging, delayed or reduced flower bloom, and the leaching of excess N beyond the root zone, possibly contaminating groundwater.

Phosphorus

Unlike the discharge of phosphorus-containing effluents into surface water, the land application of phosphorus from recycled waters is of little concern, given its low solubility, use by plants, and lack of mobility in the soil column. On the other hand, phosphorus is sometimes the limiting nutrient for algal productivity in surface water. Therefore, the discharge of phosphorus-containing effluents into surface waters may result in proliferic algal growth. Ponds, lakes, and reservoirs holding recycled water may present algal management problems.

Carbonates

Carbonate ions (HCO_3^- and CO_3^{2-}) are not found at elevated concentrations in waters and soil solutions since carbonate minerals have very low solubility product constants. In fact, the precipitation of carbonate minerals during evapoconcentration of soil water reduces the accumulation of soluble salts in soils. However, the deposition of carbonates from overhead sprinklers on fruits, such as table grapes, apples, and pears, and on flowering plants lowers the market quality of the fruits and flowers. The deposition of carbonates may also lead to plugging of irrigation systems.

The precipitation of carbonates of calcium and magnesium is of concern in constructed root zones used on golf greens and sports fields in arid climates when they are irrigated with water unusually high in alkalinity (carbonates) and hardness (calcium and magnesium). Such carbonate precipitation may lead to plugging of pores in sands because sands have less surface area than do clays. Consequently, it would be advisable to ensure that carbonate ions are not excessive in the recycled water.

Residual Chlorine

Molecular chlorine (Cl_2) and its related chlorine compounds—sodium hypochlorite (NaOCl), calcium hypochlorite ($Ca[OCl]_2$), and chlorine dioxide (ClO_2) —are used, usually as a final step in the treatment process. Hydrolysis of chlorine compounds forms hypochlorous acid (HOCl), which ionizes into hypochlorite ion (OCl^-) (Metcalf and Eddy, 2003). The combined concentration of molecular chlorine, hypochlorous acid, and hypochlorite ion is known as free available chlorine, which is a very good disinfection agent. However, free available chlorine reacts rapidly with ammonia and other organic nitrogen usually present in wastewaters, forming combined available chlorine, which is not as effective as free chlorine in disinfecting water. Unless the ammonia and organic nitrogen in wastewaters have not been oxidized to nitrate by the treatment processes, the primary disinfection agent in chlorinated recycled water will be combined chlorine.

Excessive levels of free residual chlorine in recycled waters that have been oxidized to the nitrate form—more than 5 mg/L—may result in root and foliar damage to sprinkler-irrigated plants, since free chlorine is a strong oxidizing agent. However, as pointed out above, most

Table III.A.1. Plugging potential of irrigation water used in drip irrigation systems *(Nakayama, 1982).*

Type of problem	Degree of potential restrictions on use		
	Little	Slight to moderate	Severe
Physical: suspended solids, mg/L	< 50	50–100	>100
Chemical: pH	<7	7–8	>8
TDS, mg/L	<500	500–2,000	>2,000
Manganese, mg/L	<0.1	0.1–1.5	>1.5
Iron, mg/L	<0.1	0.1–1.5	>1.5
Hydrogen sulfide, mg/L	<0.5	0.5–2.0	>2.0
Biological: bacterial population (maximum number/mL)	<10,000	10,000–50,000	>50,000

recycled waters contain little if any free residual chlorine, most of which if present will dissipate fairly quickly upon exposure to the atmosphere.

Because of stricter trihalomethane (THM) standards, there has been some changeover in the use of chlorine to chloramine for disinfection of potable waters. However, chloramine compounds have been identified as corrosive to certain metals and degrade rubber and some plastic elastomers in earlier irrigation equipment (AWWA Research Foundation, 1993). Most irrigation equipment is now manufactured with components resistant to chloramine degradation, but occasionally an older irrigation system that has been retrofitted to recycled water may demonstrate problems. Fortunately, PVC (polyvinyl chloride) and CPVC (chlorinated polyvinyl chloride) compounds typically used to manufacture irrigation pipe, fittings, and lake liners appear to be resistant to chloramine degradation.

Clogging Constituents

Recycled waters contain physical, chemical, and biological constituents that might cumulatively clog small orifices in sprinkler irrigation systems, such as drip emitters (Nakayama, 1982). Physical constituents include suspended solids, mainly sand fractions. Chemical constituents include those that form precipitates, such as calcium carbonate, iron and manganese hydroxides, and hydrogen sulfides. Biological constituents may result from microbial activities, such as the production of hydroxides and sulfides from microbially mediated redox reactions.

Table III.B.1. Water quality classification proposed by Wilcox and Magistad, U.S. Salinity Laboratory in 1943 *(Wilcox, 1948).*

Quality characteristic	Class I Excellent to good	Class II Good to injurious	Class III Injurious to unsatisfactory
EC, dS/m	<1	1—3	>3
Boron, mg/L	<0.5	0.5–2.0	>2.0
Chloride, mg/L	<178	178–355	>355
Sodium, % of cations	<60	60–75	>75

Table III.A.1 summarizes the plugging potentials of certain levels of these three types of constituents in water applied in drip irrigation systems (Nakayama, 1982). Constituents in most recycled waters, especially waters receiving Title 22 tertiary treatment, pose little potential restriction on use for virtually all of these parameters. A possible exception is TDS, which may pose slight to moderate potential restriction on use.

III.B. Water Quality Guidelines

For nearly a century, chemical constituents in water used to irrigate have been known to have some potential effect on soils and crops. A concerted effort to classify waters according to their suitability for irrigating crops and landscape plants has been made in the past 60 years or so. This section summarizes some earlier guidelines regarding water quality and then focuses on current guidelines.

III.B.1. Early Water Quality Guidelines

The U.S. Salinity Laboratory in 1943 suggested one of the earliest water quality classification schemes for irrigated agriculture (Wilcox, 1948). It involved four quality characteristics and three classes (Table III.B.1), including salinity (EC), specific ion toxicity (boron or chloride), and sodicity (Na%). Since then, H. Chapman of University of California–Riverside, L. D. Doneen of University of California–Davis, F. Eaton of the U.S. Department of Agriculture, H. Dregne and H. J. Maker of New Mexico State University, and J. P. Thorne and W. P. Thorne of Utah State University have advanced several more classification systems (Lunt, 1963).

In 1954, the U.S. Salinity Laboratory published Agricultural Handbook No. 60 (Richards, 1954), which became regarded worldwide as the definitive book on diagnosing and improving saline and alkali soils. Included in the handbook was a diagram for classifying irrigation water (Figure III.B.1) with regard to salinity hazard (EC) and sodium hazard (SAR), each with four levels of hazard for a total of 16 classes.

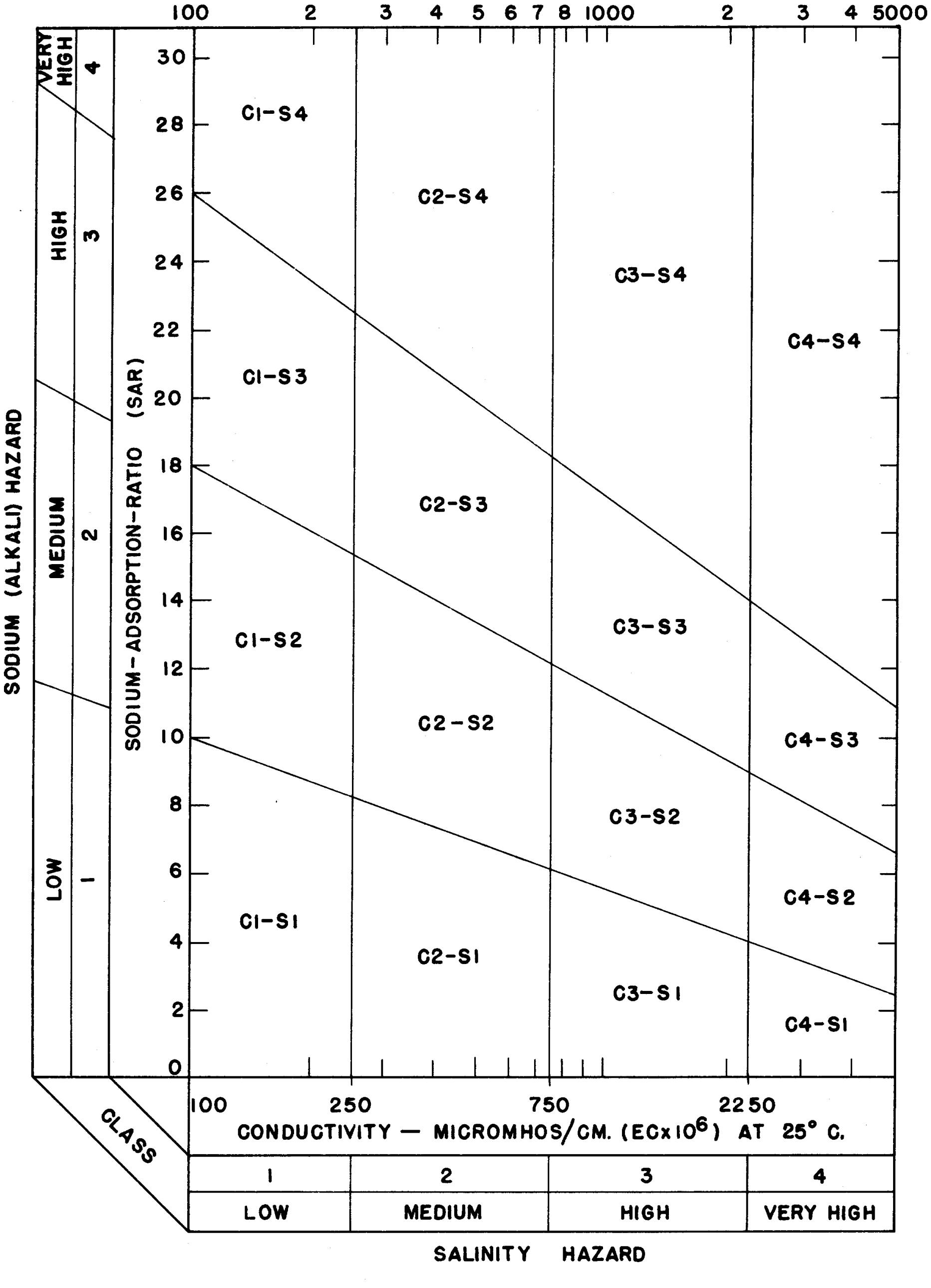

Figure III.B.1. Diagram for the classification of irrigation waters ***(Richards, 1954).***

Low-salinity C1 waters—those with an EC of less than 0.25 dS/m—can be used to irrigate most crops on most soils with little likelihood that soil salinity will pose a problem. Moderate-salinity C2 waters—those with an EC of 0.25 to 0.75 dS/m—can be used for irrigation without special salinity control practices, if a moderate amount of leaching occurs or moderately salt-tolerant plants are grown. High-salinity C3 waters—those with an EC of 0.75 to 2.25 dS/m—can be used to irrigate only plants with good salt tolerance on soils without restricted internal drainage and possibly with special salt management measures required. Very-high-salinity C4 waters—those with an EC of more than 2.25 dS/m—are ordinarily unsuitable for irrigation but may be used to irrigate highly salt-tolerant crops and under such special circumstances as extensive leaching. Handbook 60 contained tables on fruit, vegetable, forage, and field crops with low, moderate, and high salt tolerances.

The sodium hazard was evaluated primarily on physical properties of soils as affected by accumulation of exchangeable sodium on the cation exchange sites and secondarily on specific ion toxicity of Na^+. The accumulation of exchangeable sodium is related to the SAR, a soil water parameter discussed above. Unlike salinity hazard, the classification of sodium hazards has a negative slope on the SAR-versus-EC matrix. Low-sodium-hazard S1 waters can be used to irrigate almost all soils with little danger of accumulating harmful levels of exchangeable Na but not when such Na^+-sensitive crops as stone fruits and avocados are involved, since such crops may accumulate injurious concentrations of Na^+. Medium-sodium-hazard S2 waters may be used for irrigation of coarse-textured or organic soils with good permeability. Irrigating with these waters will present an appreciable hazard in fine-textured soils with high cation exchange capacity, especially under low LFs. If gypsum is present in the soil, the sodium hazard will be reduced, since Ca^{2+} dissolved from gypsum will reduce levels of exchangeable Na. Use of high-sodium-hazard S3 waters for irrigation may result in harmful levels of exchangeable Na in most soils and will require special soil management, such as good drainage, high leaching, and additions of organic matter. Gypsiferous soils may not develop harmful levels of exchangeable Na with this type of water. Chemical amendments may need to be used to lower exchangeable Na. Very-high-sodium-hazard S4 waters are generally unsuitable for irrigation.

Though the U.S. Salinity Laboratory system for classifying irrigation water with regard to EC and SAR (Figure III.B.1) was broadly accepted and applied, some noted that the diagonal lines appeared to have the wrong slope for the permeability of fine- to medium-textured soils. A water with low sodium hazard and low salinity hazard infiltrates slowly over the long term, while a water with low sodium hazard and medium to high salinity infiltrates at an acceptable rate (see, e.g., Figure III.A.2). SAR can cause soil colloids, especially clay minerals such as smectites, to disperse, resulting in a poor rate of water intake, while EC coagulates soil colloids, promoting a good rate of water intake, so that the adverse effects of SAR are partially overcome by higher salinity (Figure III.A.3). Currently, Figure III.A.3 is used to appraise the combined EC-SAR effects on the permeability of soil, while Figure III.B.1 is used to assess the hazards of exchangeable sodium on plants and soils.

Agricultural Handbook No. 60 also included a system for classifying permissible limits of boron in waters (Table III.B.2) suggested by Scofield (1936). Boron, an essential element for plants at very low concentrations, is injurious to plants at slightly above essential concentrations. Citrus, stone fruits, and beans are particularly sensitive to boron. (Refer to Chapter V for a listing of boron-sensitive plants.)

Handbook 60 additionally contained a system for classifying RSC (Table III.B.3) advanced by Eaton (1950). This parameter is used by many water-testing soil and horticultural laboratories. Waters having an RSC of 1.25 to 2.5 may be used to irrigate if Ca-producing amendments, as well as good soil and water management practices, are also used.

In the early 1960s, a number of disagreements arose over the use of various classification systems. In 1963, the University of California Water Resources Center convened a workshop to evaluate various systems for classifying agricultural water (Lunt, 1963), where a consensus was reached on recommendations for a new classification system (Table III.B.4). It excluded consideration of the aforementioned SAR-EC relationship for soil permeability (Figure III.A.2).

Table III.B.2. Permissible limits of boron for several classes of irrigation waters *(after Scofield, 1936).*

Boron class	Concn of boron in irrigation water (mg of boron/L) for:		
	Sensitive crops	Semitolerant crops	Tolerant crops
1	<0.33	<0.67	<1.00
2	0.33–0.67	0.67–1.33	1.00–2.00
3	0.67–1.00	1.33–2.00	2.00–3.00
4	1.00–1.25	2.00–2.50	3.00–3.75
5	>1.25	>2.50	>3.75

Table III.B.3. Suitability of waters for irrigation based on RSC *(after Eaton, 1950).*

RSC in meq/L	Suitability
<1.25	Probably safe
1.25–2.5	Marginal quality for irrigation
>2.5	Not suitable for irrigation

In the mid- to late 1960s, nitrate contamination of groundwaters was increasingly detected. This phenomenon was of concern to public health, as some of those waters served as sources of drinking water. One investigation conducted in the Upper Santa Ana River Basin (Ayers and Branson, 1973) identified excess fertilizers, animal manure, dairy wastewaters, and municipal and industrial wastewaters as the major sources of nitrate in groundwaters. The safe disposal and wise use of nitrogen-containing wastes and their salt content became a concern. The California Regional Water Quality Control Boards requested reevaluations of land treatment and recycling of animal wastes and dairy wastewaters. In 1973, a University of California Committee of Consultants convened to reevaluate and revise water quality guidelines for producing crops (Ayers and Branson, 1975). The revised guidelines (Table III.B.5) were streamlined to categorize certain levels of constituents in irrigation water as presenting either “no problems,” “increasing problems,” or “severe problems.” The electrolyte effect on the permeability of soil, specific ion toxicity differentiated by root absorption versus foliar absorption, the significance of NH_4^+ and NO_3^- in waters, and the deposit of carbonates on plants were all considered in these guidelines.

Table III.B.4. Recommended water classification system, UC Water Resources Center *(Lunt, 1963).*

Salinity hazard	**Low**	**Medium**	**High**	**Very high**	
EC, dS/m	<0.75	0.75–1.50	1.50–3.00	3	
Sodium hazard	**Low**	**Medium**	**High**	**Very high**	
SAR, $(mM/L)^{0.5}$	<3	3-5	5-8	>8	
Boron hazard	**Safe for sensitive crops**	**Sensitive crops will show injury**	**Semitolerant crops will show injury**	**Tolerant crops will show injury**	**Hazardous for nearly all crops**
Boron, mg/L	<0.5	0.5–1.0	1.0–2.0	2.0–4.0	>4.0
Chloride hazard	**Safe for sensitive crops**	**Sensitive crops will show injury**	**Medium tolerant crops will show injury**	**Moderately tolerant crops will show injury**	
Chloride, mg/L	<71	71–142	142–284	>284	
RSC hazard	**Probably low**	**Intermediate**	**Probably high**		
RSC, meq/L	<0	0–1.25	>1.25		

Table III.B.5. Guidelines for the interpretation of quality of water for irrigation ***(Ayers and Branson, 1975).***

Problem and related constituent in irrigation water	Water quality guidelines		
	No problem	Increasing problems	Severe problems
Salinity, EC_w in dS/m	<0.75	0.75–3.0	>3.0
Permeability, EC_w in dS/m	>0.5	<0.5	<0.2
Adjusted SAR	<6	6–9	>9
Specific ion toxicity			
From root absorption:			
Sodium, adjusted SAR	<3	>3	
Chloride, mg/L	<142	142–355	>355
Boron, mg/L	<0.5	0.5–2.0	2.0–10.0
From foliar absorption (sprinklers):			
Sodium, mg/L	<69	>69	
Chloride, mg/L	<106	>106	
Miscellaneous			
NH_4-N + NO_3-N, mg/L	<5	5–30	>30
HCO_3, mg/L (only with overhead sprinklers)	<90	90–520	>520
pH	normal range: 6.5–8.4		

III.B.2. Current Guidelines

Ayers and Westcot (1976)[1] developed the most widely used water quality guidelines for irrigation (Table III.B.6). Given in detail in *Irrigation and Drainage Paper 29* of the Food and Agriculture Organization (FAO), these guidelines were based on the 1975 University of California Committee of Consultants Guidelines with some revisions.[1] The FAO guidelines included recommended maximum concentrations of trace elements in irrigation waters (Table 111.B.7), much of which was based on accumulation of trace elements in soils under long-term normal irrigation and potential uptake of trace elements by plants (Pratt, 1972).

Later, Ayers and Tanji (1981) recommended that the FAO guidelines could also be used for irrigating crops with wastewater. A few years later, Ayers and Westcot (1985) revised the FAO guidelines. These guidelines were further adapted in a guidance manual on irrigation with reclaimed municipal wastewater (Pettygrove and Asano, 1986). Currently, the FAO guidelines are applied internationally in irrigated agriculture and nationally in the use of recycled water to irrigate crops and landscapes.

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[1] *Robert Ayers, a UC Extension Water Specialist and coauthor of the 1975 UC Committee of Consultants' Water Quality Guidelines (Ayers and Branson, 1975), took a sabbatical leave at the FAO in Rome. There he worked with soil scientist Dennis Westcot of FAO, who currently is a private consultant after service with the California Central Valley Regional Water Quality Control Board, to adapt and expand on the UC Committee of Consultants Water Quality Guidelines.*

Table III.B.6. Guidelines for interpretation of water quality for irrigation *(Ayers and Westcot, 1985).*

Potential irrigated problem	Units	Degree of restriction on use		
		None	Slight to moderate	Severe
Salinity (affects crop water availability)				
EC_w	dS/m	<0.7	0.7–3.0	>3.0
TDS	mg/L	<450	450–2,000	>2,000
Infiltration (affects infiltration rate of water into the soil)				
SAR[a] = 0-3, and EC_w =	$(meq/L)^{0.5}$[a]	>0.7	0.7–0.2	<0.2
SAR = 3-6, and EC_w =		>1.2	1.2–0.3	<0.3
SAR = 6-12, and EC_w =		>1.9	1.9–0.5	<0.5
SAR = 12-20, and EC_w =		>2.9	2.9–1.3	<1.3
SAR = 20-40, and EC_w =		>5.0	5.0–2.9	<2.9
Specific ion toxicity (affects sensitive crops)				
Sodium (Na)				
Surface irrigation, SAR	$(meq/L)^{0.5}$	<3	3-9	>9
Sprinkler irrigation, Na^+	mg/L	69	>69	
Chloride (Cl)				
Surface irrigation, Cl^-	mg/L	<142	142–355	>355
Sprinkler irrigation, Cl^-	mg/L	<106	>106	
Boron (B)	mg/L	<0.7	0.7–3.0	>3.0
Trace elements (see Table IV.C.5)				
Miscellaneous effects (affects susceptible crops)				
Nitrogen, NO_3-N	mg/L	<5	5–30	>30
Bicarbonate (HCO_3)	mg/L	92	92–518	>518
pH	No problems expected with normal pH range of 6.5–8.4			
Residual chlorine[a] (overhead sprinkling only)	mg/L	<1	1–5	>5

[a] *Added by Pettygrove and Asano (1986). For clogging, see Table III.A.1.*

III.B.3 Caveats and Assumptions for Using Current Guidelines

The FAO Water Quality Guidelines were developed based on the collective opinions of several soil, plant, and water scientists with extensive research and practical experience. With these guidelines, a wide range of conditions encountered in irrigated agriculture is covered, and water quality is evaluated in terms of the “degree of restriction on use”; i.e., as water quality is degraded, it requires higher management skills to safely use that water. These guidelines should be used as a first approximation for considering the suitability of water for irrigation and then modified for local conditions as needed. Not plant specific, they may be too restrictive for some more tolerant plants and perhaps not restrictive enough for some more sensitive plants.

The guidelines are based on the following assumptions:

Yield Potential

No restrictions on use indicate full production capability without the use of special management practices. Restrictions on use indicate that the choice of crop may be limited or that special management practices are required to attain full production capability. This situation may not be as predominant a concern in the case of landscape plants, as their visual appearance is more important than is harvested yield or biomass.

Table III.B.7. Recommended maximum concentrations of trace elements in irrigation waters that might limit crop production due to toxicity and/or limit the utilization of the produce (adapted from *National Academy of Sciences and National Academy of Engineering [1972]* and *Pratt [1972]).*

Element	Recommended maximum concn (mg/L)
Al (aluminum)	5.0
As (arsenic)	0.10
Be (beryllium)	0.10
Cd (cadmium)	0.01
Co (cobalt)	0.05
Cr (chromium)	0.10
Cu (copper)	0.20
F (fluoride)	1.0
Fe (iron)	5.0
Li (lithium)	2.5
Mn (manganese)	0.20
Mo (molybdenum)	0.01
Ni (nickel)	0.20
Pb (lead)	5.0
Se (selenium)	0.02
Sn (tin)	N/A
Ti (titanium)	N/A
W (tungsten)	N/A
V (vanadium)	0.10
Zn (zinc)	2.0

Site Conditions

Soil texture ranges from sandy loam to clay loam with good internal drainage and shallow water table controllable to within 2 m of land surface. The climate is semiarid to arid with low rainfall. Rainfall does not contribute much to meeting crop water demand or to meeting the leaching requirement of crops. The guidelines are too restrictive when rainfall is high during the growing season..

Methods and Timing of Irrigation

Normal surface or sprinkler irrigation methods are used. Water is applied when available soil water depletion is less than 50% before the next irrigation. LF, the ratio of root zone drainage to infiltrated irrigation water, is 0.15 or greater. These guidelines are too restrictive for drip irrigation or for daily to frequent irrigations.

Water Uptake by Crops

The root water extraction pattern is about 40–30–20–10% of crop reference evapotranspiration (ET_o) from surface root zone quartile to bottom quartile. Each irrigation event results in leaching of salts in the upper root zone and accumulation of salts in the bottom root zone. The average root zone salinity in soil water (EC_{sw}) is estimated to be about three times greater than in the applied water (EC_w), and the average root zone salinity of the soil saturation extract (EC_e) is estimated to be about 1.5 times EC_w. These relationships are based on a steady-state LF of 15 to 20% (or 0.15 to 0.20).

Restriction on Use

The three categories of restrictions on use, which are somewhat arbitrary due to the lack of a clear-cut specific boundary and the gradual occurrence of changes, are based on studies, observations, and experiences in the field. A change of 10 to 20% above or below a numeric guidance value may have little significance for crop yield if other guidance values have no restrictions or less restriction. Moreover, the management skill of the water user could alter the degree of restrictions. For instance, an EC_w of 0.85 dS/m may not necessarily pose a restriction on use if the LF exceeds 15%, because there will be only a small accumulation of salts in the root zone. However, if the water SAR is 9, there may be slight to moderate problems in water intake rates that might be corrected with water or soil amendments containing Ca^{2+}. Moreover, sprinkler-applied water with a SAR of 9 could severely damage Na^+-sensitive plants, such as stone fruits.

The FAO guidelines, though accepted worldwide in irrigated agriculture and widely used since 1976, should be considered part of an initial effort to evaluate the suitability of waters for landscape irrigation. As landscape professionals gain experience in the use of recycled waters to irrigate landscape plants, they may need to consider additional constraints or modifications in addition to potential plugging (Table III.A.1) and RSC (Table III.B.3).

III.C. Quality of Recycled Waters

Generally speaking, if a source water is of acceptable quality to irrigate landscape plants, the recycled water will likewise be of acceptable quality for irrigating landscape plants, since recycled water usually accrues small amounts of dissolved minerals—from 150 to 400 mg of TDS/L (Asano et al., 1985). There are, however, some exceptions:

First, as discussed above, if a significant number of water softeners utilizing sodium chloride are used in the community served by the wastewater treatment plant, there may be significant accumulation of Na^+ and Cl^- ions in the recycled water. This accumulation might pose a specific ion toxicity hazard to sensitive plants, as well as adversely affect soil water infiltration, especially when highly trafficked turf is being irrigated.

Second, recycled waters often contain 15 to 40 mg of nitrogen/L as organic-N, NH_4-N, and NO_3-N (Asano et al., 1985). Since each milligram of N per L equals 2.72 lbs. of N per ac-ft of water, this source of N needs to be taken into account when considering the plant's need for N.

Third, recycled waters are neutralized with bases such as lime or soda ash, because the oxidation of NH_4-N to NO_3-N produces acidity, substantially raising the RSC of the water.

Fourth, recycled waters may contain sufficiently high concentrations of boron to injure boron-sensitive plants.

Fifth, some recycled waters may contain constituents that tend to plug parts of sprinkler irrigation systems, such as the small orifices in drip emitters.

III.C.1. Representative Composition of Recycled Waters

Data were compiled on the composition of Title 22 recycled waters used to irrigate landscapes and agricultural crops at four different sites (Table III.C.1) in three different studies (Sheikh et al., 1990; Shaw et al., 1995; and West Basin Municipal Water District, 2004). The data reported are mean or median values for samples of water obtained at regular intervals: residual chlorine and turbidity were monitored continuously, the pH and EC were monitored daily, SS (suspended solids) were monitored weekly, dissolved minerals were monitored monthly, and

Table III.C.1. Representative composition of recycled waters compiled from various sources.[a]

Description	**Location and values**			
	Torrey Pines, San Diego County, 1992–94 (mean and sd, *n* = 31) Shaw et al., 1995	**Whispering Palms, San Diego County, 1993–94 (mean and sd, *n* = 30) Shaw et al., 1995**	**WBWRF, Los Angeles County, 2001–03 (mean *n* = 36) WBMWD, 2004**	**MC, Monterey County 1980–85, (median, *n* = 91) Sheikh et al., 1990**
pH	7.2	7.3	7.0	7.2
EC, dS/m	1.55 ± 0.23	1.41 ± 0.13	1.03	1.26
TDS, mg/L	989 ± 58	900 ± 83	671	778
Na, mg/L	179 ± 17	185 ± 12	157	166
Ca, mg/L	80 ± 19	63 ± 11	47	52
Mg, mg/L	34 ± 8	26 ± 5	20	21
K, mg/L	14 ± 2	17 ± 4	17	15
Cl, mg/L	226 ± 67	198 ± 52	188	221
SO_4, mg/L	92 ± 21	85 ± 13	110	107
HCO_3, mg/L	90 ± 59	161 ± 32	159	97
Alk., mg/L as $CaCO_3$	148	264	261	159
SAR, meq/L$^{0.5}$	4.2 ± 1.0	4.8 ± 1.0	3.4	4.9
Adj. SAR, meq/L$^{0.5}$	4.5	5.3	4.5	5.1
RSC, meq/L	<0.0	<0.0	1.7	<0.0
B, mg/L	0.4 ± 0.1	0.5 ± 0.07	0.6	0.4
NH_3, mg/L as N	0.24 ± 0.26	0.18 ± 0.23	31.3	1.2
NO_3, mg/L as N	13.9 ± 5.7	11.7 ± 6.2	0.83	8.0
NO_2, mg/L as N			0.23	
Total P, mg/L			(6.2)	2.7
TSS, mg/L			6.0	
Turbidity, JTU			2.2	
Residual Cl_2, mg/L			5.6	
Sulfide, mg/L			(<0.1)	
Iron, mg/L			(0.43)	

[a] WBWRF = West Basin Water Recycling Facility;
MC = including MWRSA = Monterey Wastewater Reclamation Study for Agriculture;

ammonia and nitrate were monitored quarterly. Standard deviations are reported where appropriate.

The recycled water reported for Torrey Pines Golf Course initially originated from the Mission Valley Aquaculture Treatment Plant (later originated from the Whispering Palms Water Pollution Control Facility) and irrigated the Torrey Pines Golf Course in La Jolla. The recycled water reported for Whispering Palms originated from the Whispering Palms Water Pollution Control Facility and irrigated plots of experimental turf in the San Dieguito River basin near the village of Fairbanks Ranch, a site targeted to receive recycled water in the future and located in a floodplain representative of many San Diego County golf courses. Recycled water reported for the West Basin Water Recycling Facility irrigated landscapes at Toyota Motor Sales USA, the Home Depot National Training Center, Goodyear, golf courses such as Victoria Golf Course in Carson, and other landscaped sites. The recycled water reported for Monterey County in a Monterey Wastewater Reclamation Study for Agriculture at Castroville was a demonstration study of recycled water used to irrigate crops of artichokes, broccoli, cauliflower, lettuce, and celery. It is also representative of recycled waters used on golf courses in Monterey County.

As pointed out above, the amount of dissolved minerals in recycled water primarily depends on the quality of the source water, plus the small increase of additional salts, as well as nutrients, from water usage.

III.C.2. Evaluation of Representative Recycled Waters Using FAO Guidelines

The FAO Water Quality Guidelines (Ayers and Westcot, 1985), though based on work with irrigated agricultural crops, are generally applicable to landscape plants (Ayers and Tanji, 1981). However, the FAO guidelines for sodicity may not be applicable for all landscape plants. That is, sodicity is more of an issue in landscape than in agricultural lands since landscape plants, such as turf, are permanent, eliminating the tillage conducted between the growing seasons of most irrigated crops to improve soil tilth and control weeds. Nevertheless, the four representative recycled waters discussed above could be evaluated by using the FAO guidelines and their three classifications regarding the extent of restrictions on the use of waters: no restrictions, slight to moderate restrictions, and severe restrictions (Table III.C.2).

The recycled water from the West Basin Water Recycling Facility in Los Angeles County falls into two categories of severe restriction on use: excess residual chlorine and excess N. It is expected that the 5.6 mg of residual chlorine/L in this recycled water will tend to be dissipated within the distribution system and to be rapidly dissipated at the time of its application. The excess N is more problematic if normal fertilization rates are practiced with this water. The 32.4 mg of N/Lin this recycled water contains about 88 lbs. of N/ac-ft. About 352 lbs. of N would be applied for a seasonal water application rate of 4 ac-ft/acre, a level of application that fulfills the N requirement of most plants. Therefore, commercial N fertilizer would not be needed when one is irrigating with this recycled water. Furthermore, some N is expected to be leached beyond the root zone because plants do not consume 100% of the applied N as either applied fertilizer or as N dissolved in water.

Slight to moderate restrictions on use are expected for each of the four recycled waters discussed above, depending on the species of plants, the types of soil, and the practice of water

Table III.C.2. Evaluation of representative recycled waters based on the FAO Water Quality Guidelines (TP = Torrey Pines, WP = Whispering Palms, WRF = WBWRF, MRS = MWRSA).

Potential problem	Degree of restriction on use		
	None	Slight to moderate	Severe
1. Affects availability of soil water to plants			
EC_w, dS/m	<0.7	0.7–3.0	>3.0
Recycled waters		WRF, MC, WP, TP	
2. Affects soil hydraulic conductivity			
SAR = 3-6, and EC_w in dS/m =	>1.2	1.2–0.3	<0.3
Recycled waters	MC, TP, WP	WRF	
3. Dispersion of soil organic matter and reduced water intake rates			
RSC, meq/L	<1.25	1.25–2.5	>2.5
Recycled waters	TP, WP, MC	WRF	
4. Specific ion toxicity hazard of Na for surface irrigation			
SAR, $meq/L^{0.5}$	<3	3-9	>9
Recycled waters		WRF, TP, MC, WP	
5. Specific ion toxicity hazard of Na for sprinkler irrigation			
Na, mg/L	69	>69	
Recycled waters		WRF, MC, TP, EL	
6. Specific ion toxicity hazard of Cl for surface irrigation			
Cl, mg/L	<142	142–355	>355
Recycled waters		WRF, MC, TP, WP	
7. Specific ion toxicity hazard of Cl for sprinkler irrigation			
Cl, mg/L	<106	>106	
Recycled waters		WRF, MC, TP, WP	
8. Specific ion toxicity hazard of boron			
B, mg/L	<0.7	0.7–3.0	>3.0
Recycled waters	TP, MC, WRF, WP		
9. Excess nitrogen for susceptible plants			
$NH_3 + NO_3$, mg/L as N	<5	5–30	>30
Recycled waters		MC, TP, WP	WRF
10. Carbonate deposition on foliage, flowers, and fruit			
$HCO_3 + CO_3$, mg/L	92	92–518	>518
Recycled waters	TP	MC, WRF, WP	
11. Potential toxicity of chlorine residual			
Chlorine residual for overhead sprinklers, mg/L	<1	1–5	>5
Recycled waters			WRF*

management, among other considerations. First, the EC_w of these waters ranges from 1.0 to 1.6 dS/m and may be too salty for the more salt-sensitive plants while having little or no osmotic effects on the more salt-tolerant plants (refer to Chapter V for salt tolerance ratings). One solution would be to replace salt-sensitive plants with more salt-tolerant plants. Second, the combined effects of EC_w and SAR of the recycled water from the West Basin Water Recycling Facility may reduce permeability for some types of soils, especially those with silt loam texture and that are dominated by smectite clay minerals, which swell upon wetting and shrink upon drying. Third, the recycled water from the West Basin Water Recycling Facility has an RSC of 1.7 mg/L and may disperse soil organic matter and reduce water infiltration, as noted at the Victoria Golf Course in Carson, Calif., where acids are being injected into the water line to ameliorate the problem. Fourth, all four waters are judged to have slight to moderate restrictions on use because of the Na^+ and Cl^- specific ion hazard when irrigated by both sprinkler and surface irrigation methods. A solution to this problem is that plants sensitive to Na^+ and Cl^- could be replaced by more tolerant ones. The recycled waters discussed above (Monterey Wastewater Reclamation Study for Agriculture, Torrey Pines, and Whispering Palms) have from 9 to 14 mg of total N/L and thus may have slight to moderate restrictions on use.

Landscape plants are generally more sensitive to boron than are agricultural crop plants, and the numerical limits presented in Table III.B.5 (Ayers and Branson, 1975) may be more appropriate: i.e., no restrictions, less than 0.5 mg of B/L; slight to moderate restrictions, 0.5 to 2.0 mg/L; and severe restrictions, 2 to 10 mg/L. If the Ayers and Branson (1975) limits are applied, water produced by the West Basin Water Recycling Facility will fall in the slight to moderate restriction in use for landscape irrigation.

In summary, certain characteristics of recycled waters require attention when the waters are used to irrigate landscape plants. Such characteristics include total N, EC, SAR, RSC, B, Na^+, and Cl^- ions. Therefore, wastewater reclamation facilities should ideally be designed and operated so that these constituents in the water produced do not pose a hazard or restrictions on use on landscape irrigation. However, for reclamation facilities that have multiple customers with various end users, it may not be cost effective to install multiple plant modifications to meet specific user requirements.

III.D. A Case Study: Use of Potable and Recycled Waters on Turfgrasses at Whispering Palms Site

Of some concern is the chemical composition of the leachates that result from deep percolation of irrigation drainage into groundwater basins and the load of salts and nitrates that leach from the root zone of landscapes irrigated with recycled waters, especially when the underlying groundwater serves as a source of drinking water. Observed data on the quality of root zone drainage in landscape irrigation are unfortunately scarce. Leachate composition is difficult to predict because of the numerous processes that affect the composition and amount (load) of leachates produced. These processes include the following:

- loss of pure water to the atmosphere from evapotranspiration (ET_o), with salts remaining in the soil solution
- leaching from irrigation and rainfall
- net mineral precipitation from evapoconcentration and mineral dissolution from the chemical weathering of soil minerals
- uptake by plants of such ions as NH_4^+, NO_3^-, Na^+, K^+, Cl^-, etc.
- cation exchange between solution cations and exchangeable cations on the soil exchange complex, e.g., solution Na replacing exchangeable Ca
- transformations such as oxidation of $NH_4 \rightarrow NO_2 \rightarrow NO_3$, mineralization of organic $N \rightarrow NH_4$, and denitrification of $NO_3 \rightarrow NO_2 \rightarrow N_2O \rightarrow N_2$
- adsorption of solution ions onto surfaces of iron and aluminum oxides of soil clays, e.g., boron.

A simplified approach for estimating the leaching of salinity from root zones into the vadose zone, the unsaturated zone above the water table of groundwater basins, is presented in Chapter IV. A case study on observed leaching of salt and nitrates comparing potable and recycled water irrigation on turfgrasses follows.

Shaw et al. (1995) conducted extensive studies in San Diego County of the use of recycled waters to irrigate landscapes. Of particular interest is the field trial using potable and recycled water from the Whispering Palm facility to irrigate plots of turfgrass—an ideal site in that many San Diego County golf courses are similarly located in river basin floodplains and that the drainage of these floodplain soils allows leaching to eliminate the accumulation of salts due to irrigation with moderately saline waters. The soils at this site are identified as Grangeville fine sandy loam and Tujunga sand.

As noted in Table III.D.1, the recycled water used in this study contained concentrations of constituents greater than those found in the associated potable water. Chemical analyses for both waters range quite widely due to changes in blending of imported waters: Colorado River through the Colorado River Aqueduct and northern California water from the California Aqueduct were blended with local surface and well waters in San Diego County. The EC, SAR, and NO_3-N of the recycled water are of particular concern from a water quality perspective (Shaw et al., 1995).

Table III.D.1. The mean and range (parentheses) of water quality of potable and recycled waters used in the Whispering Palms turfgrass study *(Shaw et al., 1995).*

Property measured	Potable water	Recycled water
pH	(6.8–8.0)	(6.8–7.7)
EC, dS/m	0.98 (0.77–1.09)	1.41 (1.24–1.63)
TDS, mg/L	630 (493–685)	900 (736–1043)
SAR, $mM/L^{0.5}$	2.7 (2.2–3.1)	4.8 (4.0–5.5)
Na, mg/L	105 (85–116)	185 (147–212)
Cl, mg/L	117 (75–190)	198 (82–269)
Boron, mg/L	0.15 (0.08–0.23)	0.50 (0.28–0.67)
NO_3-N, mg/L	0.19 (0.05–0.51)	11.2 (2.5–23.7)
NH_4-N, mg/L	0.07 (0.04–0.26)	0.18 (0.01–0.66)

Table III.D.2. Irrigation data for turfgrass from Whispering Palms study *(Shaw et al., 1995).*

Property measured	Cool-season turf		Warm-season turf	
CIMIS ET_o, in.	90.7		90.7	
Calcd. ET_c, in.	74.5		54.1	
Rainfall, in.	25.1		25.1	
	Potable	Recycled	Potable	Recycled
Irrigation, in.	103.4	106.7	78.3	88.7
Total applied water, in.	128.5	131.8	103.4	113.8
Drainage, in.	54	57.3	49.3	59.7
LF, Drainage/total applied water	0.42	0.42	0.48	0.52

The turfgrasses selected for this study included two warm-season varieties, common bermudagrass (*Cynodon dactylon*) and kikuyugrass (*Pennisetum clandestinum*), and two cool-season varieties, tall fescue (*Festuca arundinacea*) and Kentucky bluegrass (*Poa pratensis*)/perennial ryegrass (*Lolium moltiflorum*) mixture, all grasses commonly planted in San Diego County golf courses, parks, and landscapes. Kikuyugrass, not a commonly recommended turfgrass, has become the dominant species in many parks and golf courses due to its adaptability and invasiveness. Warm-season turfgrasses have a higher tolerance of drought and salinity, requiring about 25% less water than do cool-season turfgrasses and achieving peak growth and appearance during the summer. These grasses become dormant in the winter, unlike cool-season grasses, which grow most and are at their aesthetic best in the fall through spring. Consequently, warm-season grasses are being used more often and are overseeded with ryegrass while dormant in the winter to maintain an acceptable appearance.

The experimental design at Whispering Palms involved plots of cool-season and warm-season turfgrasses, randomly assigned, with each having three replicates of irrigation water (potable and recycled waters) and three replicates of turfgrass species. Each plot was 20 ft by 20 ft for water treatment, with each subdivided into two subplots that were 20 ft by 10 ft for cool- and warm-season grasses, for a total of 12 plots with 24 subplots. Irrigation scheduling was conducted by the water budget method and involved real-time data about local weather from the California Irrigation Management Information System (CIMIS) weather station. The duration of irrigation was proportionally adjusted to the changes in reference ET_o. Turfgrass ET_o (ET_c) in inches per day was assumed as approximately equal to 0.6 × ET_o for warm-season grasses and 0.8 × ET_o for cool-season grasses.

Table III.D.3. Soil saturation extract analyses within and below the turfgrass root zone in Whispering Palms study *(Shaw et al., 1995).*

Grass species	LF	Irrigation type	Within root zone			Below root zone		
			0–24-in. depths			24–36-in. depths		
			EC_e	SAR	NO_3-N	EC_e	SAR	NO_3-N
			dS/m	mM/L$^{0.5}$	Mg/L	dS/m	mM/L$^{0.5}$	Mg/L
Bermudagrass	0.48	Potable water	3.3	5.8	0.2	2.5	3.8	2.1
Bermudagrass	0.52	Recycled water	3.0	5.6	1.0	2.2	5.0	3.1
Kikuyugrass	0.48	Potable water	2.7	8.2	0.8	1.7	5.6	3.2
Kikuyugrass	0.52	Recycled water	3.7	10.4	0.4	1.9	6.5	2.2

Table III.D.2 presents the irrigation data. The cool-season grasses received an average of 105 in. of irrigation, and warm-season grasses received an average of 84 in. The total water applied, irrigation plus rainfall, for cool-season grasses averaged 130 in. and for warm-season grasses averaged 109 in. from January 1993 through November 1994. The calculated turf ET_o for cool-season grasses was 74.5 in. and for warm-season grasses was 54.1 in. The difference between total applied water and ET_o is the drainage out of the root zone, which averaged 56 in. for cool-season grasses and 54 in. for warm-season grasses. The LF, the ratio of drainage to total applied water, averaged 0.42 for cool-season grasses and 0.50 for warm-season grasses.

Shaw et al. (1995) determined dissolved mineral constituents within the root zone and below the root zone of the turfgrasses. This database, along with the irrigation data, may be used to estimate mass emission of nitrates and salts from the root zone into the vadose zone, the unsaturated zone above the groundwater table. Table III.D.3 presents soil data on EC, SAR, and NO_3-N determined in the extracts of saturated soil pastes (a standard method of analyzing soil samples [Richards, 1954]). The results show that, with a moderate LF of about 0.5, the EC of extracts of soil paste in both recycled and potable water was comparatively low within the root zone and below, even though the recycled water had an EC of 1.4 dS/m. These soil salinity values are within the acceptable limits of salt tolerance for these turfgrasses. The FAO guidelines indicate that a water of 1.4 dS/m may have slight to moderate restriction on use. The guideline is based on an LF of 0.15 to 0.20 and is not plant specific. With an LF higher than 0.2, the restriction on use may be lessened. At Whispering Palms, the LFs ranged from 0.4 to 0.5, except during the rainy season, when LFs were about 0.7.

The results also show that NO_3-N within the root zone and below for both potable and recycled water treatments was low, although the recycled water had an NO_3-N concentration of 11.2 mg/L. This finding indicates that turfgrasses are heavy feeders of N and can effectively recover N from fertilizer and irrigation water. Clearly, N in the recycled water should be considered for meeting part of the N requirement of grasses. Shaw et al. (1995) believe that excessive nitrate-N leaching losses can be avoided by adjusting fertilizer N applications and lowering the LF. The FAO guidelines suggest that Whispering Palms recycled water would have slight to moderate constraints in use based on the total N content of the water.

Table III.D.4. Estimated mass loading of nitrates and salts from the root zone into the vadose zone at the Whispering Palms study *(after Shaw et al., 1995).*

Loading value	Bermudagrass Potable water	Bermudagrass Recycled water	Kikuyugrass Potable water	Kikuyugrass Recycled water
Applied N fertilizer lbs./acre	544	544	544	544
N content in water lbs./acre	4	225	4	225
Total N applied lbs./acre	548	769	548	769
NO_3-N in drainage mg/L	2.1	3.1	3.2	2.2
LF	0.48	0.52	0.48	0.52
N in drainage lbs./acre	47	84	72	59
N drained %	8.6	10.9	13.1	7.7
TDS in applied water mg/L	630	900	630	900
TDS in applied water tons/acre	5.59	9.05	5.86	9.32
TDS in drainage mg/L	1,412	1,062	1,180	1,294
TDS in drainage tons/acre	8.78	7.19	7.33	8.76
TDS drained %	150[a]	77	125	94

[a] Initial soil salinity (EC_e) was 1.7 dS/m compared to 1.1 to 1.2 dS/m for the others.

The SARs for the plots of kikuyugrass irrigated with both potable and recycled waters were slightly greater than the SARs for the plots of bermudagrass. Shaw et al. (1995) had some concerns about loss of permeability and reduction in infiltration rates, but these were not observed during the 23 months of the study. The sustainability of soil permeability over a longer period has not been ascertained. Contrary to the FAO guidelines, the SAR and EC of the recycled water in this study did not result in slight restrictions on use. If Figure III.A.3 is used as a guide, the Whispering Palms recycled water falls within the no-reduction-in-permeability category. It should be noted that heavy foot and mower traffic on golf courses with fine-textured (clayey) soils sometimes leads to problems with water penetration.

Table III.D.4 presents the estimated mass loadings of nitrates and salts into the vadose zone based on volume of drainage past the root zone (Table III.D.2) and concentrations of nitrates and salts found below the root zone (Table III.D.3). With regard to nitrates, the total N load applied to the grasses was 548 lbs. per acre for the potable water application and 769 lbs. per acre for the recycled water application. Applied N fertilizer was a major source, along with N in the recycled water. The N load discharged with the percolating water below the root zone was only 8 to 13% of the total N applied. This finding confirms that turfgrasses are heavy feeders of N. It should be noted that clippings from mowed grasses remain on site and contribute to organic matter in the soil, a small portion of which becomes bioavailable upon mineralization. In contrast, the mass emission of salts differed from nitrates. The load of salts applied with irrigation water ranged from 5.6 to 9.3 tons per acre. The salt concentration below the root zone ranged from 1,060 to 1,410 mg/L or a discharge load ranging from 7.2 to 8.8 tons/acre. Unlike N, most of the applied salts—77 to 125%— were leached out of the root zone. The calculated deviations from 100% are considered acceptable for salt leaching due to the complex chemical reactivity of salts. The bermudagrass irrigated with potable water was an exception with a 150% salt leaching. A plausible reason for this is that the initial soil salinity in the plots of bermudagrass irrigated with potable water had an EC_e of 1.4 dS/m, while other plots had an initial soil EC_e of 1.1 to 1.2 dS/m.

Shaw et al. (1995) monitored the aesthetic quality of the turfgrasses throughout the study, using a standard turf-scoring procedure that involves a scale from 1, which equals dead turf, to 9, which equals perfect color, texture, density, absence of pests, and overall quality. Both the cool-season and warm-season turfgrasses scored an average of about 6.5, indicating acceptable quality.

Turfgrasses are known to be relatively tolerant of Na^+, Cl^-, and B but are not well documented in the literature. They are mowed at heights ranging from 1.5 to 3.0 in. for cool-season grasses and less than 1.0 in. for warm-season grasses. For both cool-season and warm-season turfgrasses, the concentrations of Na^+ in the soil extracts ranged from about 115 to 345 mg/L and the concentrations of Cl^- ranged from about 106 to 320 mg/L. Concentrations of B ranged from about 0.25 to 0.6 mg/L in the extract of saturated soil pastes. Salts accumulating in the leaf tips are removed during mowing, and consequently leaf tip burns from salts, Na^+, Cl^-, or B are not typically observed. However, there is some concern that leaving mulched mowed clippings on site can cause Na^+, Cl^-, and B to return to the soil, resulting in long-term increases of these constituents in the soil. The FAO guidelines for these specific ions indicate slight to moderate restrictions on use of the recycled water for Na^+ and Cl^- and none for B.

This study demonstrated that recycled water can be beneficially used to irrigate turfgrasses, thus conserving potable waters. Relatively few problems were observed in this 23-month study. Shaw et al. (1995) further state that reliability of the quality of recycled waters is important. Any significant changes should be reported to the user of recycled water or to a professional landscape advisor, so that appropriate agronomic and water management options can be taken to avoid problems. Variations in the quality of recycled water, the types of soil, management practices, patterns of use, climate and expected quality of turfgrass should be noted when evaluating the benefits of using recycled water to irrigate golf courses. This case study demonstrated that the FAO Water Quality Guidelines are a useful guide that is perhaps somewhat conservative for the irrigation of turfgrasses. Nitrate leaching losses at this study's site were kept to a minimum, while salts were extensively leached out.

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Chapter IV. Salinity Control in the Root Zone and Deep Percolation of Salts from the Root Zone into Groundwater Basins

K. Tanji, S. Grattan, and B. Sheikh

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Since soil salinity reduces the availability of soil water to plants due to osmotic effects (Chapter III), salts in the root zone should be kept below the maximum level tolerated by plants for optimal plant performance (Chapter V). When salinity in the root zone exceeds this level, plants experience osmotic stress and their growth is adversely affected. In low-rainfall regions, irrigating plants causes soluble salts to accumulate in the root zone, as most of the salts in the irrigation water remain in the soil after more or less pure water is lost to the atmosphere via evaporation and transpiration (Chapter V). Excessive levels of salinity do not accumulate in the root zone if sufficient leaching occurs: i.e., if rainfall and/or irrigation exceeds the water holding capacity in the root zone and if soil water drains past the root zone, carrying salts with it. Irrigation and drainage water management can play a significant role in keeping soil salinity below the maximum level tolerated by plants. In this chapter, the principles of water and soil salinity management, as well as their practical application, are covered. Included in the appendices are a number of Excel-based hydrosalinity models that can be used to perform some of the calculations that follow. A specific model will be used when appropriate.

IV.A. Root Zone Salinity

IV.A.1. LF and LR—Root Zone as a Whole

Leaching fraction (LF) is defined as the steady state (long-term) ratio of the depth of drainage water (D_{dw}) that drains past the root zone to the depth of irrigation water (D_{iw}) that infiltrates the root zone. The ratio of D_{dw} to D_{iw} was formerly defined as the leaching requirement (LR) by the U.S. Salinity Laboratory (Richards, 1954) but presently is known as LF (LR will be defined later),

$$LF = \frac{D_{iw} - D_{et}}{D_{iw}} = \frac{D_{dw}}{D_{iw}} \qquad \text{(IV-1)}$$

In the absence of rainfall, the depth of drainage water is the difference between D_{iw} and D_{et}, depth of evapotranspiration (ET). D_{et}, which is equivalent to ET_c as defined in Chapter VIII, is defined in this chapter by

$$D_{et} = D_{eto} * K_c \qquad \text{(IV-2)}$$

where D_{eto} is the depth of reference ET or ET_o (obtained, e.g., from a nearby CIMIS weather station) and K_c is the crop coefficient.

The FAO Water Quality Guidelines (Ayers and Westcot, 1985) assumed an LF of 15 to 20%, and if D_{et} can be estimated with Equation IV-2, the amount of water needed for irrigation, D_{iw}, can be obtained by rearranging Equation IV-1,

$$D_{iw} = \frac{D_{et}}{(1 - LF)} \qquad \text{(IV-3)}$$

In some quarters, distribution uniformity of water application (DU) is considered in Equation IV-3 as

$$D_{iw} = \frac{D_{et}}{(1 - LF) * DU} \qquad \text{(IV-4)}$$

The DU with a well-managed irrigation system ranges from 0.70 to 0.95 (Tanji and Hanson, 1990). Correcting for DU will lead to large values of D_{iw} if the irrigation systems are not maintained and operated to achieve high DU, resulting in excessive leaching in much of the irrigated land and root pathogens, such as *Phytophtera*. In some quarters, the DU is ignored in estimating depth of irrigation. Though a small portion of the irrigated land may be underirrigated while ignoring the DU and plant performance may be adversely affected in that portion, ignoring the DU is acceptable with respect to water conservation in irrigated agriculture. If, however, a high, uniform quality of appearance is desired, as in turfgrass and lawns, then the DU may be considered.

Illustrative example IV-1

What is the annual depth of irrigation required for a cool-season turfgrass (such as Kentucky bluegrass) with annual ET_o of 50.6 in. in Los Angeles and annual crop coefficient K_c of 0.80, while assuming an LF of 0.20?

$D_{et} = D_{eto} * K_c = 50.6$ in. $* 0.80 = 40.5$ in.

$$D_{iw} = \frac{D_{et}}{1-LF} = \frac{40.5\,inches}{1-0.20} = 50.6 \quad inches$$

Handbook No. 60 (Richards, 1954) points out that salinity is inversely proportional to water in its LR expression, i.e.,

$$LF = \frac{D_{dw}}{D_{iw}} = \frac{EC_{iw}}{EC_{dw}} \tag{IV-5}$$

Thus, EC_{dw} is

$$EC_{dw} = \frac{EC_{iw}}{LF} \tag{IV-6}$$

The ET process evapoconcentrates soil water as more or less pure water is lost to the atmosphere through transpiration and evaporation, resulting in an increased concentration of salt in the root zone.

Illustrative example IV-2

What is the EC of the water draining past the root zone if the irrigation water has an EC of 1.5 dS/m and if LF is 0.20?

$$EC_{dw} = \frac{EC_{iw}}{LF} = \frac{1.5\, dS/m}{0.20} = 7.5 \quad dS/m$$

The steady-state salinity in the drainage water (EC_{dw}) is 7.5 dS/m, and considering the root zone as a whole, the EC of the soil water (EC_{sw}) in the root zone is somewhere between EC_{iw} in the soil surface and EC_{dw} in the bottom of the root zone. If a simple average between these two is assumed, the average root zone salinity is 4.5 dS/m [(1.5 +7.5 dS/m)/2)]. This EC of 4.5 dS/m represents the average root zone EC_{sw} at field capacity (FC) soil moisture. FC refers to the soil water status after adequate irrigation and when drainage stops or reduces to a low rate. Since salt tolerance threshold values for plants are expressed as EC_e, the EC of the extract from a saturated soil paste, EC_{sw}, needs to be converted to EC_e. The conversion factor used is 0.5, assuming that soil saturation percentage (SP) is twice the soil water content at FC for most soil types. Thus, the average root zone EC_e for this example is 2.25 dS/m (4.5 dS/m * 0.5) for an LF of 0.2 and EC_{iw} of 1.5 dS/m.

LR is a plant-specific parameter. It is a prescribed value of leaching, so that root zone salinity does not exceed the threshold salinity tolerance of the plant in question. This plant-specific LR is defined as

$$LR = \frac{EC_{iw}}{5 * EC_a - EC_{iw}} \qquad \text{(IV-7)}$$

where EC_a is the plant-specific threshold soil salinity, above which yields decrease in the case of crops and above which performance is reduced in the case of landscape plants, and the factor “5” is an empirically derived factor to account for distribution of salts by soil depth (Rhoades, 1974). Threshold salinity values for plants are reported in Chapter V.

Illustrative example IV-3

What is the LR for Kentucky bluegrass that has a threshold salinity value EC_a of 3.0 dS/m and is irrigated with water EC_{iw} of 1.5 dS/m?

$$LR = \frac{EC_{iw}}{5 * EC_a - EC_{iw}} = \frac{1.5 dS/m}{(5 * 3.0 dS/m) - 1.5 dS/m} = 0.11 \qquad \text{(IV-8)}$$

The depth of annual applied water, D_{iw}, to satisfy the LR of this plant is

$$D_{iw} = \frac{D_{et}}{1 - LR} = \frac{40.5 \quad inches}{1 - 0.11} = 45.5 \quad inches \qquad \text{(IV-9)}$$

meaning that 5 in. of water in excess of D_{et} will satisfy the LR.

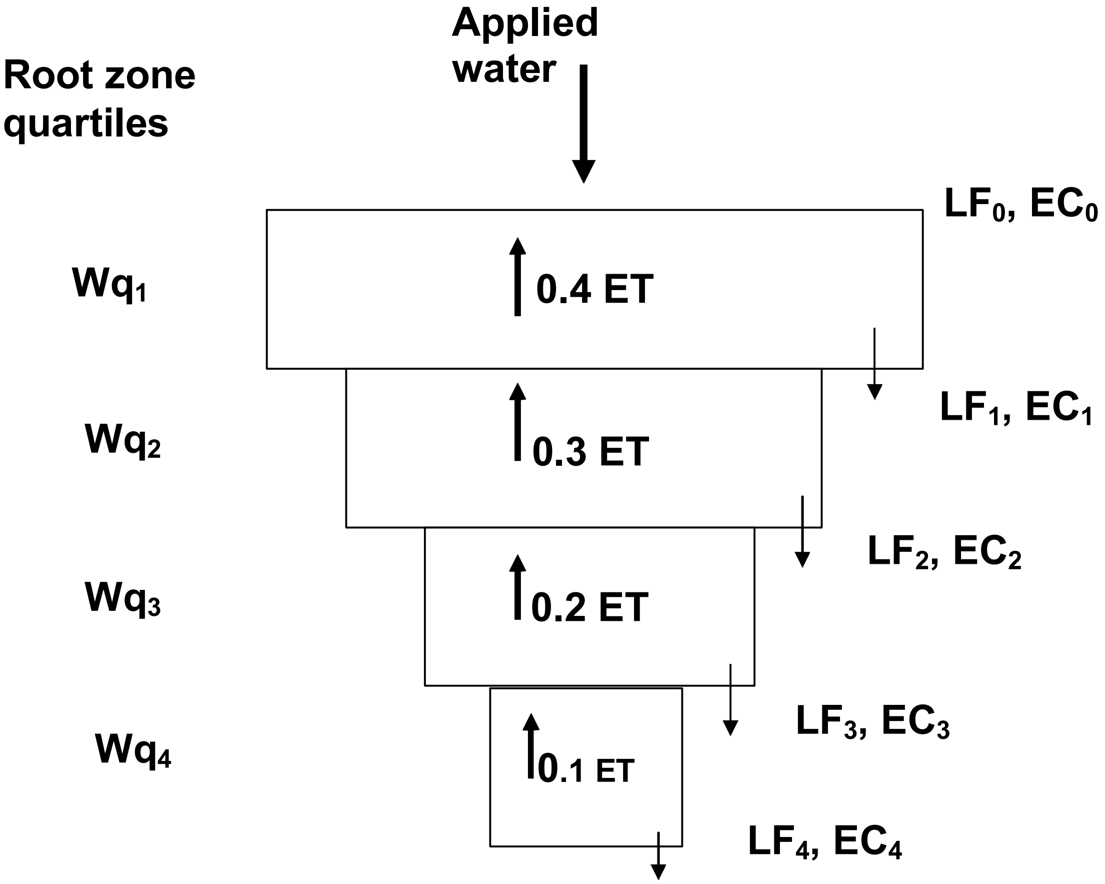

Figure IV.A.1. Crop root zone subdivided into quartiles with specified root water extraction pattern to calculate for quartile LF and EC *(after Ayers and Westcot, 1985).*

IV.A.2. LF and Profile Salt Distribution

The distribution of salts in the root zone as affected by root water extraction patterns, D_{iw}, D_{et}, LFs, and EC_{iw}, will now be examined. Figure IV.A.1 divides the root zone into quartiles (four layers) and assumes that most crop plants extract soil water to meet their seasonal ET with a 40–30–20–10% water extraction pattern (W_q) in the root zone quartiles (Ayers and Westcot, 1985). Based on the previously outlined ET evapoconcentration approach, the LF, the resulting EC at the bottom of each quartile, and the distribution of salts in the root zone can be estimated.

Illustrative example IV-4

What is the long-term salt distribution in the root zone of a cool-season grass uniformly sprinkler irrigated with 52.4 in. of water/year (D_{iw}) at proper intervals to meet the water needs of the grass, with water of 1.5 dS/m (EC_{iw}) and ET of 41.9 in./year (D_{et}), assuming that the root water extraction pattern is 40–30–20–10% of ET (W_q)? Use Hydrosalinity Model 1 in the appendices.

Table IV.A.1 gives the illustrative computation. First, the LF of each root zone quartile (LF_q) is calculated with Eq. IV-10 (given in Table IV.A.1), and then the EC of the soil water leaving the root zone quartile (EC_q) is calculated with Eq. IV-6 (given in Table IV.A.1). As water is extracted in the root zone quartile, the LF decreases and the EC of the water draining from the quartile increases. The overall root zone LF is 0.20, and EC_{dw} is 7.50 dS/m. Within the root zone quartile, the EC of the soil water (EC_{sw}) is assumed to be the average between water entering the quartile and water leaving the quartile; e.g., EC_{sw} in the fourth quartile is the average between 5.34 (EC_3) and 7.50 dS/m (EC_4) or 6.42 dS/m. The average root zone EC_{sw} for the soil profile as a whole is 3.99 dS/m [(1.5+2.21+3.41+5.34+7.5 dS/m)/5].

Figure IV.A.2 is a plot of the calculated values in Table IV.A.1 as the EC_{sw-1} curve with a root water extraction pattern of 40–30–20–10% of crop ET in the root zone quartiles. This cool-season grass is assumed to have a rooting depth of 12 in., and thus each quartile is of 3-in. increments. Curve EC_{sw-2} is for the same case, except the extraction pattern is 60–25–10–5% of ET. Because the extraction in the first root zone quartile is higher (60 versus 40%), the EC_{sw} in the bottom of the quartile is slightly higher in EC_{sw-2} than in EC_{sw-1}. But the EC_{dw} (bottom of the fourth quartile) is the same because the overall LF is the same.

Table IV.A.1. LF and EC by root zone quartiles for surface irrigation.

Root-zone quartile	$LF_q = \frac{D_{iw} - \sum W_q D_{et}}{D_{iw}} \quad (Eq \quad IV-10)$	$EC_q = \frac{EC_{iw}}{LF_q} \quad (Eq \quad IV-6)$
0, surface	$LF_0 = \frac{52.4-(0)41.9}{52.4} = \frac{52.4in}{52.4in} = 1.0$	$EC_0 = \frac{1.5dS/m}{1.0} = 1.5dS/m$
1st	$LF_1 = \frac{52.4-(0.4)41.9}{52.4} = \frac{35.6in}{52.4in} = 0.68$	$EC_1 = \frac{1.5dS/m}{0.68} = 2.21dS/m$
2nd	$LF_2 = \frac{52.4-(0.7)41.9}{52.4} = \frac{23.1in}{52.4in} = 0.44$	$EC_2 = \frac{1.5dS/m}{0.44} = 3.41dS/m$
3rd	$LF_3 = \frac{52.4-(0.9)41.9}{52.4} = \frac{14.7in}{52.4in} = 0.28$	$EC_3 = \frac{1.5dS/m}{0.28} = 5.34dS/m$
4th, bottom	$LF_4 = \frac{52.4-(1.0)41.9}{52.4} = \frac{10.5in}{52.4in} = 0.20$	$EC_4 = \frac{1.5dS/m}{0.20} = 7.50dS/m$

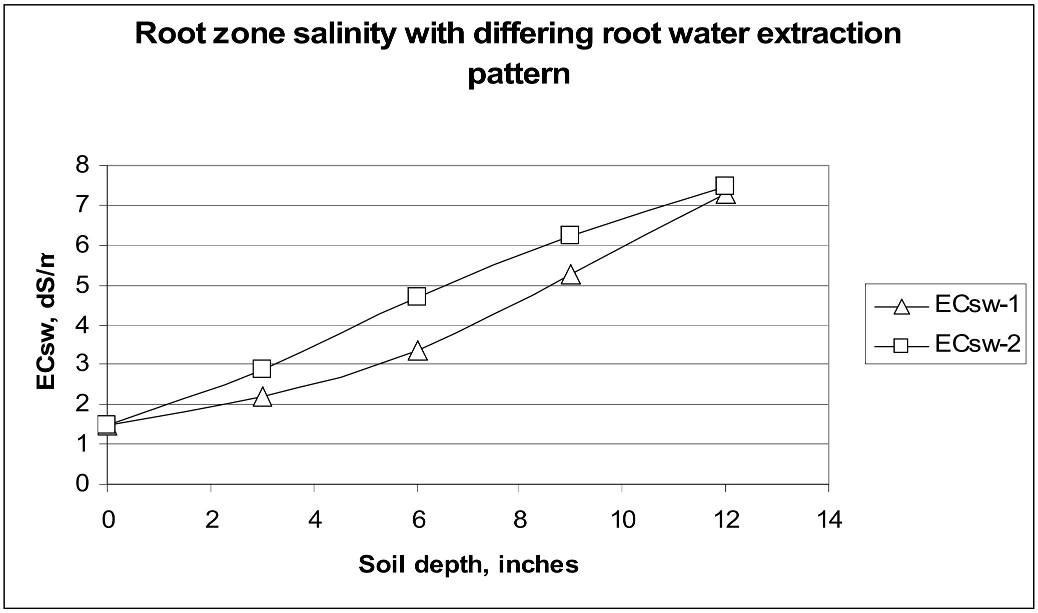

Figure IV.A.2. Calculated distribution of salinity in the root zone of a cool-season grass. Extraction pattern for EC_{sw-1} is 40–30–20–10% and for EC_{sw-2}, 60-25-10-5%.

Figure IV.A.3 contains a plot of salt profiles in which only the LF varies for a cool-season grass that has an annual ET of 41.9 in., is irrigated with water EC of 1.5 dS/m, and has a root water extraction pattern of 60–25–10–5% of ET. This plot clearly shows that root zone salinity is highly regulated by the LF, assuming there is no impediment to root zone drainage.

The threshold salinity of plants is given as average root zone salinity in the extract of saturated soil paste or EC_e in dS/m. The data plotted in Figure IV.A.3 are in terms of EC_{sw}, and the conversion to EC_e is made by multiplying EC_{sw} by 0.5. The average root zone EC_{sw} values for LFs of 0.05, 0.10, 0.20, and 0.30 are 10.62, 6.64, 4.25, and 3.27 dS/m, respectively, which, when converted to average EC_e, would be 5.32, 3.34, 2.12, and 1.64 dS/m, respectively. If the threshold salinity of a cool-season grass is assumed to be EC_e of 3 dS/m, then using an EC_{iw} of 1.5 dS/m will require an LF slightly greater than 0.10—an LF of 0.11 to be exact (see Equation IV-8).

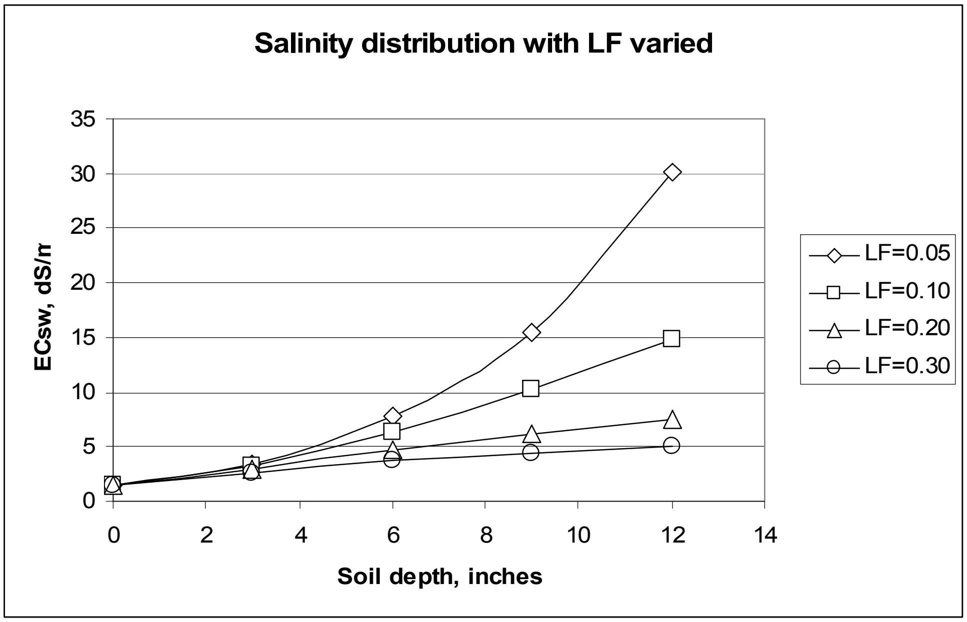

Figure IV.A.3. Salinity profile for a cool-season grass irrigated with EC_{iw} of 1.5 dS/m, ET of 41.9 in./year, and root water extraction pattern of 60–25–10–5% of ET.

IV.A.3. Soil Salinity as Affected by Irrigation and Rainfall

Up to now, the effects of rainfall on root zone salinity and leaching were ignored. The equations on water and salts extended for annual rainfall include one from Richards, 1954:

$$LF_{iw+rw} = \frac{(D_{iw} + D_{rw}) - D_{et}}{D_{iw} + D_{rw}} = \frac{D_{dw}}{D_{iw} + D_{rw}} \qquad \text{(IV-11)}$$

where D_{rw} denotes depth of annual effective rainfall (infiltrated into the soil). The effective annual rainfall is about 50% of annual rainfall for a typical amount of rainfall, ground cover, and topographical slope on irrigated lands of California. In

$$EC_{iw+rw} = \frac{(D_{iw} * EC_{iw}) + (D_{rw} * EC_{rw})}{(D_{iw} + D_{rw})} \qquad \text{(IV-12)}$$

EC_{rw} refers to EC of rainwater and EC_{iw+rw} is the volume-weighted average EC of the mixed supply water. These same equations may apply for a second source of supply water other than rainwater, such as a blend of two irrigation waters of differing water salinities. A more precise treatment can be realized if monthly to weekly values are used instead of seasonal data in equations IV-11 and IV-12.

Illustrative example IV-5

What is the long-term distribution of salts in the root zone of a cool-season grass, assuming the same conditions as in Example IV-4 but with an effective annual rainfall of 8 in. and an EC of rainwater of 0.01 dS/m? Use Hydrosalinity Model 2 in the appendices.

Table IV.A.4 shows that computations similar to those used in Table IV.A.1 are employed to solve this problem. The EC of mixed supply water is

$$EC_{iw+rw} = \frac{(D_{iw} * EC_{iw}) + (D_{rw} * EC_{rw})}{(D_{iw} + D_{rw})} = \frac{(1.5 * 52.4) + (0.1 * 8.0)}{52.4 + 8.0} = 1.31 \quad dS/m$$

Figure IV.A.4 plots the salt accumulation pattern computed in Table IV.A.2 and is compared to that calculated in Table IV.A.1. The average root zone salinity (EC_{sw}) is 4.0 dS/m with irrigation water and 2.68 dS/m with irrigation water plus rainfall. The salt accumulation is less, as rainwater EC is very low. The LF is greater (0.31 versus 0.20), since 8.0 in. of effective rainwater is added to the 52.4 in. of irrigation. Therefore, effective rainfall should be taken into account when it is a significant fraction of the infiltrated water and salt accumulation is of concern. In California, since most rainfall occurs during the winter and most irrigation occurs in the summer, the aforementioned calculations may differ slightly from actual calculations. Winter rains will leach the salts accumulated in the previous summer and fall months. These rains may serve as reclamation leaching, if there is sufficient rainfall.

Table IV.A.2. LF and EC by root zone quartiles for mixed supply irrigation waters.

$LF_{iw+rw} = \dfrac{(D_{iw}+D_{rw}) - \Sigma W_q D_{et}}{(D_{iw}+D_{rw})} \quad (Eq\,IV-13)$	$EC_q = \dfrac{EC_{iw+rw}}{LF_{iw+rw}} \quad (Eq\,IV-14)$
$LF_0 = \dfrac{(52.4+8.0)-0(41.9)}{(52.4+8.0)} = \dfrac{60.4in}{60.4in} = 1.0$	$EC_0 = \dfrac{1.31}{1.0} = 1.31 \quad dS/m$
$LF_1 = \dfrac{(52.4+8.0)-0.4(41.9)}{(52.4+8.0)} = \dfrac{43.6in}{60.4in} = 0.72$	$EC_1 = \dfrac{1.31}{0.72} = 1.82 \quad dS/m$
$LF_2 = \dfrac{(52.4+8.0)-0.7(41.9)}{(52.4+8.0)} = \dfrac{31.1in}{60.4in} = 0.51$	$EC_2 = \dfrac{1.31}{0.51} = 2.57 \quad dS/m$
$LF_3 = \dfrac{(52.4+8.0)-0.9(41.9)}{(52.4+8.0)} = \dfrac{22.7in}{60.4in} = 0.38$	$EC_0 = \dfrac{1.31}{0.38} = 3.45 \quad dS/m$
$LF_4 = \dfrac{(52.4+8.0)-1.0(41.9)}{(52.4+8.0)} = \dfrac{18.5in}{60.4in} = 0.31$	$EC_0 = \dfrac{1.31}{0.31} = 4.26 \quad dS/m$

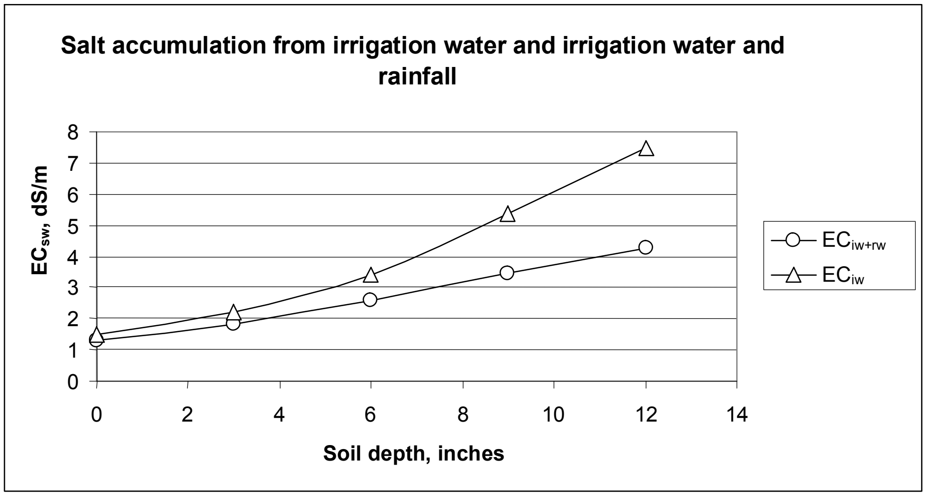

Figure IV.A.4. Comparison of salt accumulation patterns with 52.4 in. of EC_{iw} of 1.5 dS/m and 52.4 of EC_{iw} of 1.5 and 8.0 in. of EC_{rw} (effective rainfall) of 0.01 dS/m.

IV.A.4. Reclamation Leaching

Leaching as a means of salt control in the root zone may take place with each irrigation event or after a crop is harvested and before the next planting. Reclamation salt leaching may be described by a simple mixing cell transport model (Tanji et al., 1967), in which

$$EC_{q,j} = 0.5 * (EC_{q,j-1} + EC_{q-1,j}) \qquad \text{(IV-15)}$$

where q is the space-related increment, such as root zone quartiles or a specified increment in the depth of the soil, and j is the time-related increment or leaching event number. Equation IV-15 states that the concentration of salt in a particular depth of soil and at a particular time is the average of the concentration of salt in that particular depth from a previous time (resident salt) and the concentration of salt entering from a depth above at that particular time (invading salt).

Illustrative example IV-6

Given an initial soil salinity in 6-in. depth increments of a 48-in. clay loam soil profile with EC_{sw} of 10, 12, 18, 12, 6, 4, 4, and 4 dS/m, calculate the degree of reclamation leaching with water having an EC_{iw} of 1.5 dS/m.

Figure IV.A.5 gives the results of using Equation IV-15 with an initial salinity given as curve j-1. If the soil texture is clay loam, it would have a field capacity of about 4 in. of water/ft of soil or in this case 2 in. per 6-in. soil depth. This 2-in. depth of water is the increment of reclamation leaching water applied. After leaching with one increment of EC_{iw} of 1.5 dS/m, the salt profile is given by curve "j," two increments of leaching water by curve "j+1," and so forth. The salt bulge in the 18-in. soil depth is slowly displaced downward with each increment of reclamation leaching. The average EC_{sw} for the initial salt profile for each increment of reclamation leaching is 8.75 (j-1), 8.35 (j), 7.82 (j+1), 7.14 (j+2), 6.37 (j+3), 5.57 (j+4), 4.80 (j+5), and 4.10 dS/m (j+6). This model is applicable to leaching by rainwater or any other EC_{iw} water. Use Hydrosalinity Model 3 in the appendices.

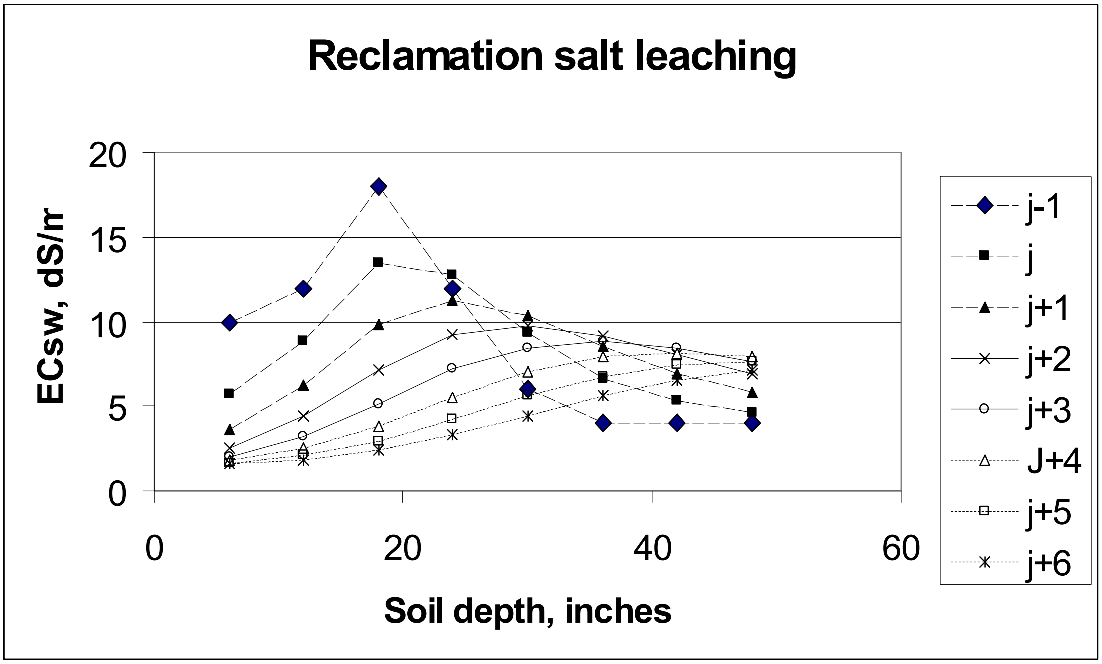

Figure IV.A.5. Results of reclamation leaching for initial salt profile given by curve j-1 with EC_{iw} of 1.5 dS/m. The salt bulge at the 18-in. soil depth is displaced downward with each leaching water increment j, equivalent to a 2-in. depth of reclamation water.

IV.A.5. Pore Volume Reclamation Leaching

Reclamation leaching of constructed root zones established on modern sports fields and golf greens with soil mixes and sand do not often behave in a manner similar to that of native soils. The constructed root zones often incorporate high-sand-content soil mixes of prescribed depths, typically 12 to 14 in., layered profiles designed to perch the water table, and/or confined root zones with impermeable barriers that use a combination of subsurface irrigation/drainage systems. Moreover, common turfgrass management practices such as light and frequent sand topdressing result in an accumulation of high-sand-content root zones over a native soil base lacking subsurface drainage. The low-cation-exchange-capacity, high-sand-content root zone mixtures result in a more rapid development of salt accumulation and stress symptoms than is found in native clay and loam soil profiles and therefore require more frequent leaching events. Thus, adaptation and modification of leaching protocols become necessary.

Carrow et al. (2000) utilize a leaching method based upon pore volume (PV), the total pore space (Rhoades and Loveday, 1990), in the constructed root zone. Table IV.A.1 presents the estimated reclamation needs based on soil texture.

Table IV.A.1. Estimated reclamation leaching needs based on soil texture.

Soil texture	PV in %	No. of in. of water per 12-in. soil to fill to PV
Sand (>95% sand content)	35	4.2
Loamy sand	38	4.56
Sandy loam	42	5.05
Clays	50	6
Soil texture	PV equivalent of water required to leach 70% of total salts[a]	
Sand (>95% sand content)	0.7	
Sandy loam	1.00–1.25[b]	
Loams	1.50–2.50[b]	
Clays	2.50–4.00[b]	

[a] PV equivalent values are adjusted by Carrow, Huck, and Duncan based on experience.

[b] Use higher values for 2:1 lattice shrink swell cracking clays and lower values for 1:1 noncracking clays.

Illustrative example IV-7

What is the depth of water needed to leach salts on a high-sand (>95% sand) golf course or sports field to a depth of 16 in. overlying a subsurface drainage tile lines? This example was contributed by Mike Huck (personal communication).

A sandy soil texture has a PV of 35%, requiring a 4.20-in. depth of water per 12-in. soil depth to fill its PV. Thus, for a 16-in. reconstructed soil depth, 5.60 in. of water (4.20 in. of water × 16 in./12 in.) would be required. For these high-sand greens, a PV equivalent of 0.70 is used to achieve approximately 70% leaching of soluble salts. Therefore, 3.90 in. of water (5.60 in. of water × 0.70) applied would leach 70% of the salts across the 16- in. soil depth.

IV.B. More Complex Treatment of Soil Salinity

In previous sections of this chapter, it has been assumed that salinity in the water is a conservative parameter; i.e., it does not chemically react. Strictly speaking, dissolved mineral salts in waters are chemically reactive. For example, they participate in mineral dissolution, precipitation reactions, and cation exchange reactions. This section describes some common water chemical processes that affect salinity and the use of chemical equilibrium computer models to appraise more quantitatively the chemical reactivity of waters.

IV.B.1. Chemical Reactivity of Salts in Waters in the Soil

The major chemical reactions occurring in the soil that affect salinity are the dissolution and precipitation of such minerals as calcite ($CaCO_3$) and gypsum ($CaSO_4 \cdot 2H_2O$) and the exchange of cations—Na, Ca, Mg, NH_4, and K—between those soluble forms in the soil solution and those forms adsorbed onto the soil exchange complex, which consists of negatively charged clay minerals and soil organic matter.

Figure IV.B.1 depicts this chemistry of soil solutions (Tanji, 1990). Note that interactive chemical reactions involve particular chemical ion species. For example, the dissolution of gypsum ($CaSO_4 \cdot 2H_2O$) produces free calcium ions (Ca^{2+}) and free sulfate ions (SO_4^{2-}). The free Ca ion may replace exchangeable magnesium ion on the soil exchange complex, and SO_4 ions may form the neutrally charged $MgSO_4$ ion pair and monovalently charged $NaSO_4^-$ ion pair. As cation exchange and ion pair reactions occur, they raise the solubility of gypsum to a level higher than that of the solubility of gypsum in distilled water. Because of this complexity and the interactive nature of such soil chemical reactions, chemical equilibrium models are used to evaluate chemical speciation and the equilibrium chemistry of waters and soil solutions.

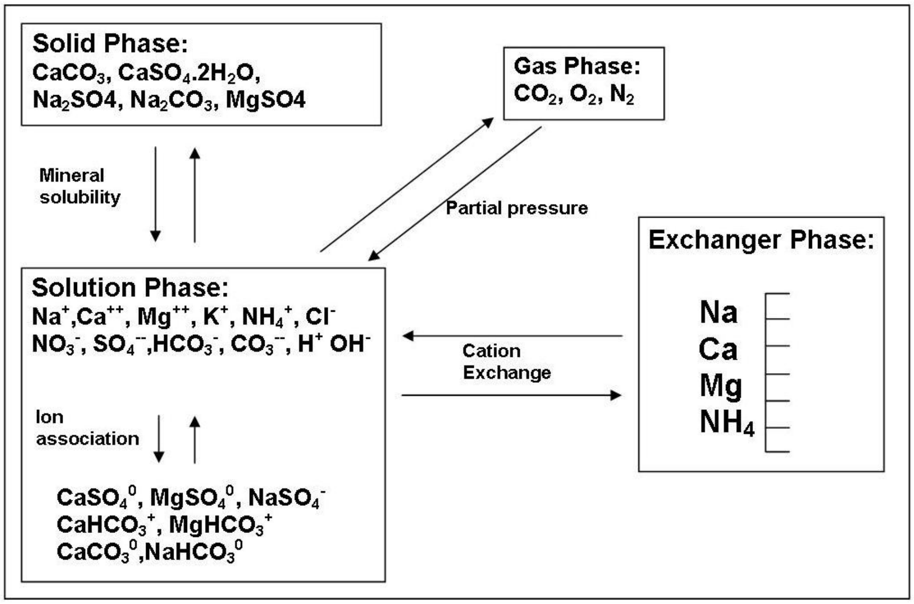

Figure IV.B.1. Interactive chemical reactions in soil water systems (Tanji, 1990). The solution phase consists of completely dissociated ions such as Na^+ as well as incompletely dissociated ion (ion pairs) such as $NaSO_4^-$.

IV.B.2. Equilibrium Chemical Models—WATSUIT

The Water Suitability Determination Model (WATSUIT) by Rhoades and Dell'Osso (1976) will be used first to evaluate equilibrium water chemistry in this section and then to evaluate root zone salt accumulation in the next section.

To illustrate the complex nature of interactive chemistry in soils, changes in water chemistry resulting from the evapoconcentration of Colorado River water will be examined, using WATSUIT. Evapoconcentration of waters in this computer model is evaluated by applying the LF; i.e., an LF of 1.0 will have no evaporation, while an LF of 0.1 means the original volume of water has been evapoconcentrated 10-fold. As a first approximation, the concentration of salt is increased 10-fold.

Table IV.B.1 presents the results of evapoconcentrating Colorado River water from 1- to 20-fold. The column titled "River water" gives the initial concentration in milliequivalents per liter (meq/L) (WATSUIT uses combining chemical concentration units or meq/L), while concentration in milligrams per liter (mg/L) is given in parentheses. The data for an LF of 1.0 are the computed chemical equilibrium concentration with no evapoconcentration. Note that Colorado River water is saturated with respect to calcite ($CaCO_3$) and that this mineral precipitates out of the water under equilibrium

Table IV.B.1. Simulation results from WATSUIT on the chemistry of Colorado River water subjected to various LFs with a fixed CO_2 pressure of 0.01 atm (simulation runs by Tanji, 1999).

Concn^a meq/L	River water^a	LF = 1.0	LF = 0.4	LF = 0.3	LF = 0.2	LF = 0.1	LF = 0.05
Evapoconcn. factor (ECF)		1.0	2.5	3.3	5.0	10.0	20.0
ECw × ECF,^{c} dS/m		**1.03**	**2.58**	**3.40**	**5.15**	**10.3**	**20.6**
Calcd. EC, dS/m	1.27	**1.03**	**2.48**	**3.12**	**4.44**	**7.15**	**12.15**
Ca	6.95 (139)	5.01	14.93	17.56	22.81	25.66	23.42
Mg	3.63 (44)	3.63	9.08	12.10	18.15	36.30	72.64
Na	3.35 (77)						
K	0.22 (9)						
Na + K	3.57 (86)	3.57	8.93	11.90	17.85	35.70	71.10
Cl	1.03 (37)	1.11	2.77	3.70	5.55	11.10	22.20
CO_3		0.44	0.42	0.43	0.43	0.45	0.52
HCO_3	3.73 (228)	1.36	6.46	6.40	6.29	7.03	8.97
SO_4	9.31 (447)	9.31	23.28	31.08	46.55	79.07	135.74
$MgCO_3$							
$CaCO_3^b$		**1.94 (97)**	**2.44 (122)**	**5.61 (280)**	**11.94 (597)**	**29.81 (1,490)**	**65.11 (3,256)**
$CaSO_4$·2H2O^b						**14.03 (1,207)**	**50.47 (4,340)**
pH		8.04	7.09	7.02	7.00	7.03	7.05

[a] All chemical concentrations are in meq/L; except those in parentheses are in mg/L.

[b] The calcite levels and gypsum concentrations given in mg/L may be converted to pounds per acre-foot with a conversion factor of 2.72.

[c] EC_w, evapoconcentration factor assumes salts are not reactive, i.e., no mineral precipitation.

conditions at an LF of 1.0. As the river water is increasingly evapoconcentrated, calcite precipitates in increasing amounts and the chemical speciation also changes. Calcite has a small solubility product constant of 10^{-9} and thus is a very insoluble mineral. In contrast, gypsum has a solubility product constant of 10^{-5} and is a more soluble mineral than calcite. Therefore, gypsum does not precipitate out until about an LF of 0.1, about a 10-fold evapoconcentration of initial Ca^{2+} and SO_4^{2-} ions.

Table IV.B.1 contains data regarding the chemical reactivity of Colorado River water. Assuming salts are not reactive, the difference between the WATSUIT calculated EC and the EC × ECF (initial EC_{iw} × evapoconcentration factor) is due to mineral precipitation. The precipitation of calcite and gypsum with evapoconcentration may be viewed positively because they would decrease salt accumulation in irrigated soils as seen in the next section.

IV.B.3. Application of WATSUIT to Quartile Root Zone Salt Accumulation

Figure IV.B.2 contains EC_{sw} curves in the root zone quartiles when irrigation with Colorado River water at an LF of 0.2 occurs. The curve labeled “EC, nonreactive” assumes that salts in this river water act conservatively as discussed in Chapter IV.B.2, while the curve labeled "reactive" is predicted by WATSUIT, which considers reactive water chemistry. Reduced salt accumulation in the reactive case is caused by the deposition of calcite and gypsum as irrigation water is increasingly evapoconcentrated by root water extraction. The concentrations of calcite forming in the root zone quartiles are plotted in meq/L, a range of values equivalent to about 100 to 600 ppm (mg/L = meq/L × mg/meq = meq/L × 50.04 mg/meq). The LF for the first to fourth quartiles in this case is 0.68, 0.44, 0.28, and 0.20. The average EC_{sw} for the nonreactive case is 3.38 dS/m and for the reactive case is 2.34 dS/m. If one accounts for the natural chemistry of the water and appropriate chemical reactions, the effective salinity in this Colorado River water is reduced by about 30%.

Figure IV.B.3 plots salt accumulation from the use of Colorado River water at LFs that range from 0.05 to 0.40 (5 to 40% of infiltrated water) as calculated by WATSUIT. The average EC_{sw} values for LFs of 0.4, 0.3, 0.2, 0.1 and 0.05 are 1.77, 2.03, 2.34, 3.38, and 4.66 dS/m, respectively. If the threshold salinity of the plants is known, the LFs can be managed to keep soil salinity at a tolerable level during the use of Colorado River water.

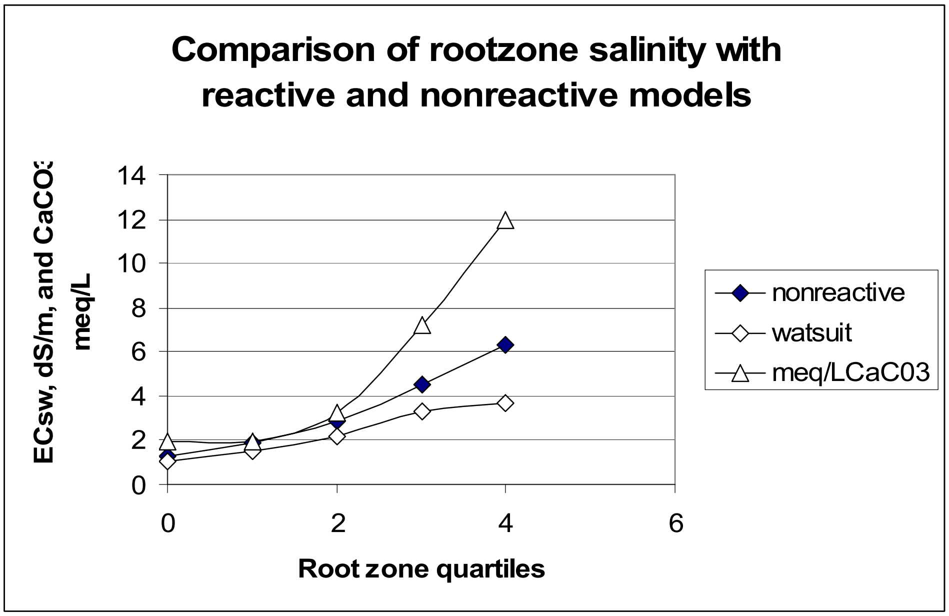

Figure IV.B.2. Comparison of root zone salt accumulation from irrigation with Colorado River water at an LF of 0.2, assuming on the one hand that salts in the water behave conservatively (nonreactive) and on the other hand that they are chemically reactive as predicted by WATSUIT. Also plotted is the concentration of calcite precipitating as its solubility product constant is exceeded. The deposition of calcite reduces salt accumulation in the root zone quartiles.

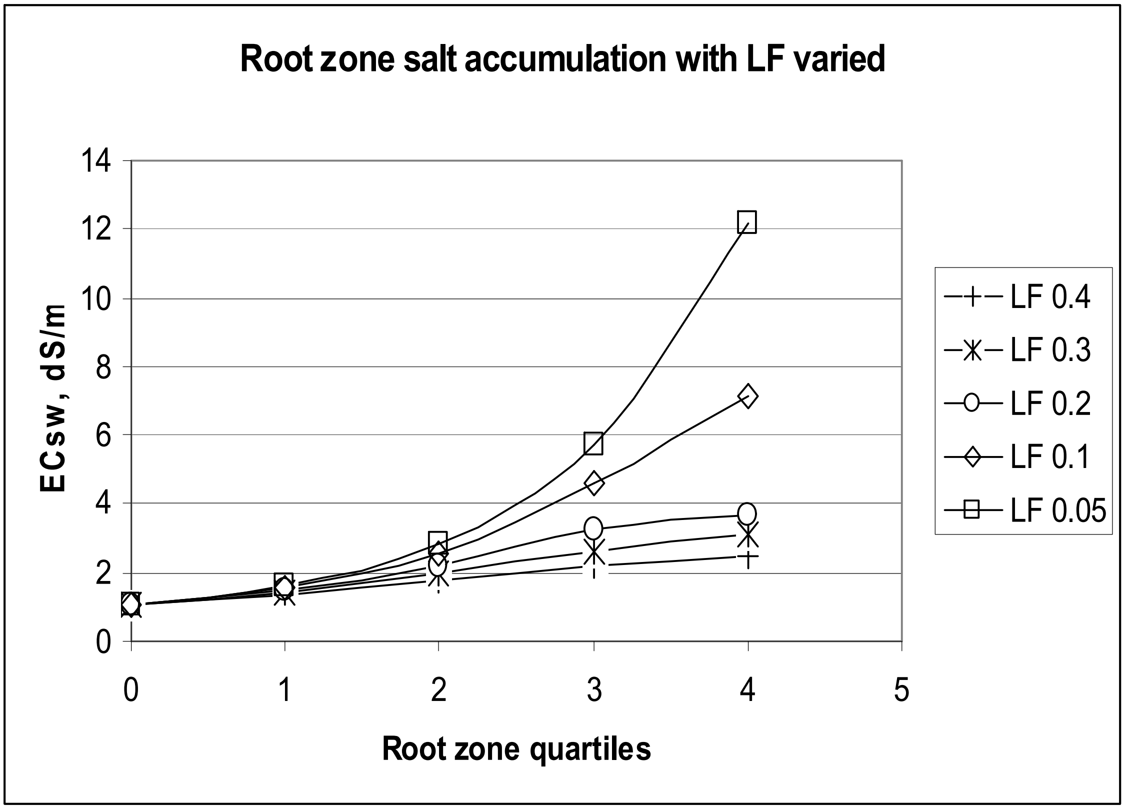

Figure IV.B.3. Salt accumulation from irrigation with Colorado River water at various LFs as predicted by WATSUIT.

IV.B.3. Application of Reactive Mixing Cell Model for Salt Accumulation and Leaching

The reclamation leaching mixing cell model (IV.A.4) can be extended to consider more flexible and dynamic vadose zone conditions (Tanji, 2000) by

$$EC_{q,j} = 0.5 * (EC_{q,j-1} + (EC_{q-1,j} / LF_q)) \qquad \text{(IV-16)}$$

In this model, there is no constraint on the number of increments of soil depth to be considered (such as quartile root zone), and each increment will be of specified length (inches or feet). $EC_{q,j-1}$ is the initial concentration of soil salinity in each soil depth, and accumulated salt may be nonuniformly distributed in the soil profile. The evapoconcentrating effect of root water extraction in each depth increment is considered by LF_q. If there is no root water extraction at that soil depth, LF_q assumes a value of unity (1.00) and salt transport can be calculated below the rooting depth.

Traditional root-water extraction patterns are typically given in root zone quartiles (four depths) in the rooting soil depth. They could be subdivided further into any number of depths, such as eight depth increments instead of four. When water infiltrates the soil surface, the $EC_{q-1,j}$ in Equation IV-16 is the salinity of the applied water of a given source or the salinity of multiple sources of water, which is the volume-weighted average EC_{iw}, as in Equation IV-12. This model is applicable to reclamation leaching, too, should one assume LF_q is unity and reduce Equation IV-16 to IV-15.

Equation IV-16 may be further extended to consider the chemical reactivity of waters. Given the mineral precipitation data of Colorado River water in Table IV.B.1, the reduction in accumulated salts and EC as a function of LF can be estimated. Table IV.B.2 contains calcite and gypsum precipitation data from Table IV.B.1. The precipitation of these minerals will reduce the resulting EC upon evapoconcentration of Colorado River water. For instance, the EC of the water subjected to an LF of 0.1, assuming no chemical reactions, is 10.3 dS/m. The estimated reduction in EC from mineral precipitation is 3.67 dS/m for an LF of 0.1, and the resulting EC after chemical reaction is 6.63 dS/m. The reduction in ECs is quite substantial at smaller LFs.

Figure IV.B.4 plots the reduction in EC in Colorado River water due to mineral precipitation at various LFs. A curve fitting this plot yields $EC_{sw} = -0.0265/LF2$, which is then inserted into Equation IV-16 to account for chemical reactivity of Colorado River water as

$$EC_{q,j} = 0.5*(EC_{q,j-1} + [(\frac{EC_{q-1,j}}{LF_q}) - (\frac{0.0265}{LF^2})] \qquad \text{(IV-17)}$$

Table IV.B.2. Mineral precipitation with evapoconcentration of Colorado River water and estimates of reduction of accumulated salt concentration. The EC_{iw} of water is 1.03 dS/m.

	LF = 1.0	LF = 0.4	LF = 0.3	LF = 0.1	LF = 0.05
Calcite precipitation, mg/L (row 1)	97	122	280	1,490	3,256
Gypsum precipitation, mg/L (row 2)				1,207	4,340
Sum of precipitation, mg/L (row 3 = 1 + 2)	97	122	280	2,697	7,596
Estimated EC reduction from precipitation, dS/m (row 4 = 3/735)[a]	0.132	0.166	0.381	3.669	10.335
Nonreactive evapoconcentration, dS/m (row 5 = EC_{iw}/LF)	1.03	2.575	3.433	10.3	20.6
Reactive evapoconcentration, dS/m (row 6 = 5−4)	0.898	2.409	3.052	6.631	10.265

[a] Reader should assume that 735 mg/L equals 1 dS/m.

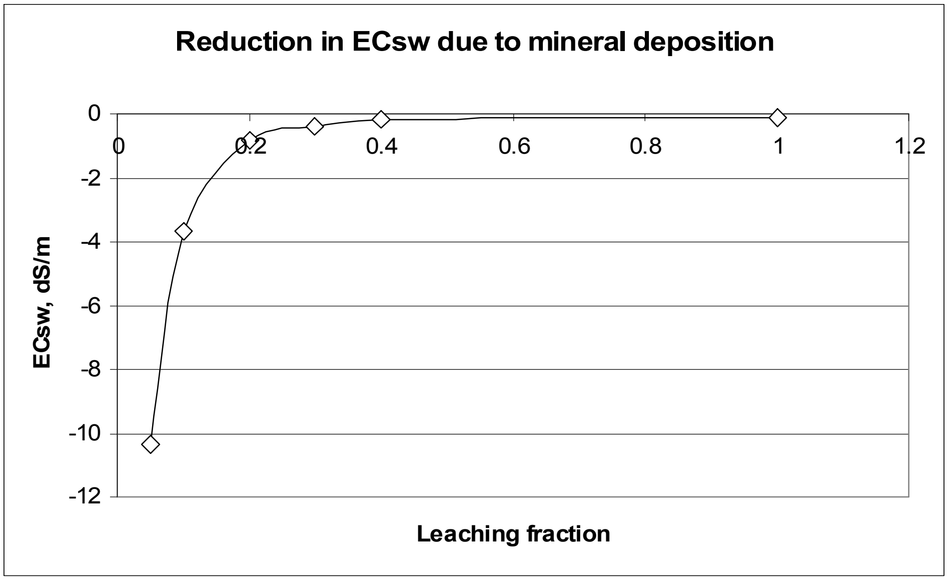

Figure IV.B.4. Reduction in EC due to mineral precipitation with evapoconcentration (decreasing LF) of Colorado River water. Best curve fitting gives EC= –0.0256/LF^2.

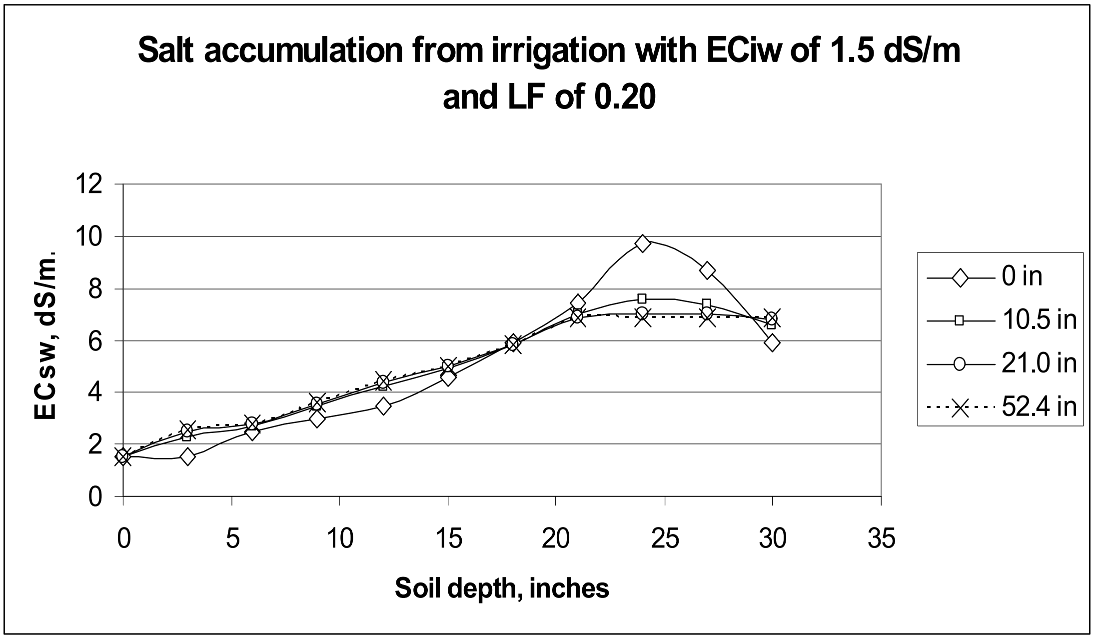

Figure IV.B.5. Salt accumulation in soil irrigated with water of EC 1.5 dS/m having an initial soil salinity given by "0 in" (0 in. of irrigation). Crop ET is 41.9 in,, and total irrigation is 52.4 in., resulting in an LF of 0.20. The rooting depth is 21 in., with a water extraction pattern of 30–30–15–10–5–5–5%.

Illustrative example IV-8

What is the degree of salt accumulation in a 30-in. soil profile in which a cool-season grass is grown with a water EC of 1.5 dS/m? The crop ET is 41.9 in., and total irrigation is 52.4 in., resulting in an LF of 0.20. The rooting depth is 21 in. with root water extraction pattern of 30–30–15–10–5–5–5% of ET. The initial soil salinity values in 3-in. depth increments are 1.5, 2.5, 3.0, 3.5, 4.6, 5.9, 7.4, 9.7, 8.7, and 5.9 dS/m. Use Hydrosalinity Model 4 in the appendices.

Figure IV.B.5 contains the initial soil salinity (EC_{sw}) given by the curve labeled "0 in." The hydrosalinity model calculates salt distribution after each 5.24-in. irrigation in this particular problem. After 10.5 in. of irrigation, the salt bulge below the root zone has been displaced. By 21 in. of irrigation, the salt profile is approaching the final salt profile that one finds after 52.4 in. of irrigation.

IV.C. Concerns about Salt Loading into Regional Groundwater Basins

The Southern California Salinity Coalition is concerned about regional salt balance in California's south coastal region. There is also a Water Replenishment District that is concerned with salt loading into its groundwater basins. This admittedly complex problem will be addressed in this section only relative to the use of recycled water for irrigating landscapes.

Water from irrigation and rainfall not used by plants that infiltrates past the root zone are known as deep percolation. This deep percolation carries salt into the groundwater basin. Such transport of salt into a groundwater basin may or may not be of crucial significance. It is a matter of concern where irrigation occurs above an unconfined aquifer with a relatively shallow water table. This phenomenon is less the case where salt from a farm or from landscaped fields deeply percolates into a salt sink that is used on a limited basis or where the aquifer is confined below a deep aquiclude and there is little seepage across this barrier.

Whatever the site-specific circumstances, it is necessary to address the ability of salt leaching below the root zone to eventually accumulate in the subsoil or in the aquifer underlying it. The length of time it takes for the accumulation of salt in groundwater basins to reach serious levels depends on a number of factors, including natural and artificial recharge to the aquifer, amount of rainfall, extraction of water with wells, interflow to adjoining aquifers, and the effects of such local hydrogeophysical characteristics as vertical faults.

Consequently, deep percolation of salts into regional groundwater basins cannot be straightforwardly determined to always or never be a problem. Under certain conditions, however, it can become a significant problem if not mitigated.

Depending on the flow path and depth to the water table in an unconfined aquifer, deep percolation through the vadose zone may take from months to decades to reach the surface of the saturated zone. The extent of deep percolation may be estimated as the difference between infiltrated water and ET. Deep percolation is usually estimated as the LF, a decimal fraction of the ratio of deep percolation and infiltrated water, where deep percolation is the difference between infiltrated water and ET losses. The amount of deep percolation in landscape irrigation may vary widely. Intensively irrigated turf and lawns with shallow rooting systems may have an LF that ranges from 0.4 to 0.6. Less intensively irrigated landscape covered by deep-rooted trees and shrubs may have an LF ranging from 0.1 to 0.4. When recycled water is used instead of potable water to irrigate a landscape, the LFs are expected to be about the same or slightly higher. A case study presented in Chapter III compared the extents of nitrate and salt leaching for potable water irrigation and recycled water irrigation of turfgrasses.

Assuming that salts are nonreactive in the root zone, under steady-state conditions, the mass of salts present in deep percolation from the root zone would be the same as that introduced by irrigation and rainfall. Due to the concentrating effects of ET, however, the concentration of salt in deep percolation is greater. The degree of evapoconcentration may be approximated from the product of salt concentration in the applied water and the reciprocal of LF, i.e., 1/LF (Tanji, 2002). For instance, if the EC of the water (EC_w) is 1 dS/m, the EC of deep percolation from the root zone for an LF of 0.6 is 1.7 dS/m (1 dS/m × 1/0.6), for an LF of 0.4 is 2.5 dS/m, and for an LF of 0.2 is 5 dS/m (see previous sections of this chapter for further details on soil salinity). If the salts are also assumed to be nonreactive in the vadose zone beneath the root zone, the EC of the water reaching the water table would remain the same as that of the root zone deep percolation. But typically, there is a net accrual of dissolved mineral salts in deeply percolating water through the vadose zone and rarely a net deposit of salts (Tanji et al., 1967).

Salt mass, which is the product of salt concentration and volume of water, may be obtained by converting EC in dS/m to total dissolved solids (TDS) in mg/L and surface depth of water into volume per unit area irrigated. For instance, salt concentration is obtained by a factor of 634 mg of TDS/L per dS of EC/m (sometimes a factor of 735 is used), so that an EC of 1 dS/m contains 634 mg/L. The concentration of salts in deep percolation per acre-foot (ac-ft) of water (C_{dp}) will be the product of salt concentration (634 mg of TDS/L) and the factor 0.00126 ton of salt per ac-ft of water per mg of TDS/L or 634 × 0.00126 or 0.8 ton of salt per ac-ft. The surface depth of deep percolation (D_{dp}) is obtained from the product of LF and infiltrated irrigation water (D_{iw}). If seasonal D_{iw} is assumed to be 5 ft and LF to be 0.4, the D_{dp} is 0.4 × 5 ft or 2 ft and the volume of deep percolation per unit area (V_{dp}) irrigated will be 2 ac-ft/acre. Finally, the mass loading of salts in deep percolation (M_{dp}) is the product of salt concentration (C_{dp}) and volume per unit area (V_{dp}). For this example, if C_{dp} is 0.8 tons per ac-ft and V_{dp} is 2 ac-ft/ac, the seasonal M_{dp} is 0.8 ton salt per ac-ft 2 ac-ft/ac of irrigated land or 1.6 tons per acre.

When landscapes previously irrigated with potable waters are irrigated with recycled waters, the concentration and mass of salt in deep percolation may be slightly higher because of the residual accrual of dissolved mineral salts in recycled water. The concentration of such salts in domestic recycled waters is typically 150 to 400 mg/L higher than in potable water for an EC increase of about 0.2 to 0.6 dS/m (Asano et al., 1985). Hence, the mass loading of salts into the groundwater basin from irrigating with recycled water is slightly greater than the mass loading of salts from irrigation with potable waters. And salt loading into the groundwater basin would increase even more if previously unirrigated land is irrigated. The increase in mass loading is based on the assumption that the salts in irrigation water do not react with the minerals in the strata through which they percolate.

Assuming that all of the salts arriving in irrigation water will ultimately reach the unconfined groundwater aquifer and that complete blending with the aquifer waters occurs, it is possible to compute the equilibrium concentration increase for salts (or any specific constituent) after decades of time during which irrigation with recycled water continues at a constant rate. An Excel-based program was developed for an unconfined aquifer in Santa Clara Valley (B. Sheikh, personal communication), in which characteristics of the aquifer, rainfall, and a range of irrigation acreages were entered to determine the ultimate impact on groundwater quality. This program, for the most conservative scenario, calculates the acreages that can be irrigated for each given recycled water quality without adverse impact.

The quality of deep percolation water from the root zone may, in fact, differ from that of the applied water if salts are reactive, for instance, due to net mineral precipitation or net mineral dissolution. Applied water is evapoconcentrated in the soil solution as more or less pure water is lost to the atmosphere during ET and the salts in the water remain in the soil solution, where they concentrate during the drying phase of irrigation. The solubility product constants of sparingly soluble salts may be exceeded, and mineral precipitation may take place. The minerals that predominantly precipitate in irrigated soils are calcium carbonate ($CaCO_3$) and gypsum ($CaSO_4 \cdot 2H_2O$). Other minerals that might precipitate include magnesium carbonate, calcium phosphate minerals, and silicate minerals. During the wetting phase of irrigation, the more soluble soil minerals present, such as gypsum and calcic feldspars, may dissolve. Reducing the LF generally reduces the mass of salts in deep percolation because of mineral precipitation (Rhoades et al., 1974). Within the flow path of deep percolation into the vadose and saturated zones, the quality of the groundwater may be subject to change, depending on the chemistry of the substratum materials (Tanji et al., 1967). Assessment of mass loading of reactive salts will require a geochemical model coupled to a transport simulation model (Tanji, 2002).

In summary, the mass loading of salts into the groundwater basin from irrigating landscapes with recycled water is expected to be somewhat different from that when irrigating with potable water. Depending on whether salts are reactive in the flow path due to mineral precipitation (a salt sink) or mineral dissolution (a salt source), the mass loading of salts could be less when mineral precipitation dominates and greater when mineral dissolution dominates. Thus, it would be imprudent to predict the combined net effect of salt loading and precipitation or dissolution on the groundwater for all situations without precise site-specific knowledge of geochemistry and recycled water characteristics. Currently, the Santa Clara Valley Water District, in collaboration with the California Department of Water Resources and the University of California–Davis, is conducting a field study to determine the actual impacts of irrigation with recycled water on soil water chemistry as leachate moves beyond the root zone toward an unconfined water table (Ashktorab, 2005). The results of that study are expected to become available in 2007.

IV.D. Summary

Salts tend to build up in the root zone of actively transpiring plants because more or less pure water is lost to the atmosphere through evaporation and transpiration while dissolved mineral salts in the irrigation water remain in the soil solution. One principal means of controlling root zone salinity is by LF, which is defined as the ratio of water draining past the root zone and the applied water. For most waters and most plants, an LF of 0.15 to 0.20 is more than adequate to keep soil salinity at less than harmful levels (Ayers and Westcot, 1985).

This chapter covered the principles and applications of LF. The FAO approach of computing salt accumulation in quartile root zone by considering the root-water extraction pattern, the LF, and the EC of applied water was covered in detail. The impacts of rainfall on salt leaching and/or mixed-quality supply waters as well as reclamation salt leaching were also considered. Simple Excel-based hydrosalinity models were used to demonstrate these concepts and practices. These models assume salinity to be a conservative parameter, i.e., not a chemically reactive parameter. This assumption on salinity may be appropriate for conditions of high LFs (i.e., >0.3) and/or for waters that do not tend to form calcite and gypsum upon evapoconcentration.

More complex aspects of root zone salinity were addressed, including a chemical equilibrium model (WATSUIT) and its use in quartile root zone salt accumulation. WATSUIT was also used to assess precipitation of calcite and gypsum as a function of LF for Colorado River water. This data was used to develop a simplified reactive salt accumulation model, which was incorporated into a mixing cell model, an Excel-based model applicable to more than quartile root zone salt accumulation.

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Appendices: Hydrosalinity Excel Models

Hydrosalinity Excel Model 1. LF and EC_{sw} in root zone quartile FAO model.

Hydrosalinity Excel Model 2. LF and EC_{sw} in root zone quartile FAO model with mixed supply water, e.g., rainwater and irrigation water.

Hydrosalinity Excel Model 3. Reclamation leaching—mixing cell model of a salt-affected soil profile.

Hydrosalinity Excel Model 4. Reactive salt accumulation—mixing cell model for irrigated soil profiles.

Appendix: Hydrosalinity Model 1

Hydrosalinity Model 1 for Illustrative Example IV-4.

Example IV-4:

What is the long-term salt distribution in the root zone of a cool-season grass uniformily sprinkler irrigated with 52.4 in./yr (Diw) at proper intervals to meet the grass's water needs with water of 1.5 dS/m (ECiw) and ET of 41.9 in./yr (Det), while assuming that the root water extraction pattern is 40–30–20–10% of ET?

Computational model Eq. IV-10

LFq = (Diw - ΣWqDet)/(Diw)

Computational model Eq. IV-6

ECq = ECiw/LFq

Computational model Eq. IV-2

Det = Deto * Kc

LF = Leaching fraction
q = Quartile soil depth interval
LFq = Calculated LF in quartile depth
Diw = Depth of irrigation water
Wq = Root water extraction pattern
Det = Depth of evapotranspiration
ECq = Calculated EC in quartile depth
ECiw = EC of irrigation water
Deto = Depth of reference ET (ETo)
Kc = Crop coefficient

Depth of rooting of cool-season grasses
Annual bluegrass = 0.08–0.33 ft
Kentucky bluegrass = 0.5–1.5 ft
Perennial ryegrass = 0.5–1.5 ft
Tall fescue = 1.5–3.0 ft

Root zone divided into 4 soil depth increments (quartile)

Mo.	Kc	ETo (in.)	ET (in.)
Jan	0.61	2.2	1.342
Feb	0.64	2.6	1.664
Mar	0.75	3.7	2.775
Apr	1.04	4.7	4.888
May	0.95	5.5	5.225
Jun	0.88	5.9	5.192
Jul	0.94	6.1	5.734
Aug	0.86	6.1	5.246
Sep	0.74	5.3	3.922
Oct	0.75	3.9	2.925
Nov	0.69	2.6	1.794
Dec	0.6	2	1.2
Avg.	0.7875	4.216667	3.49225
Total			41.907

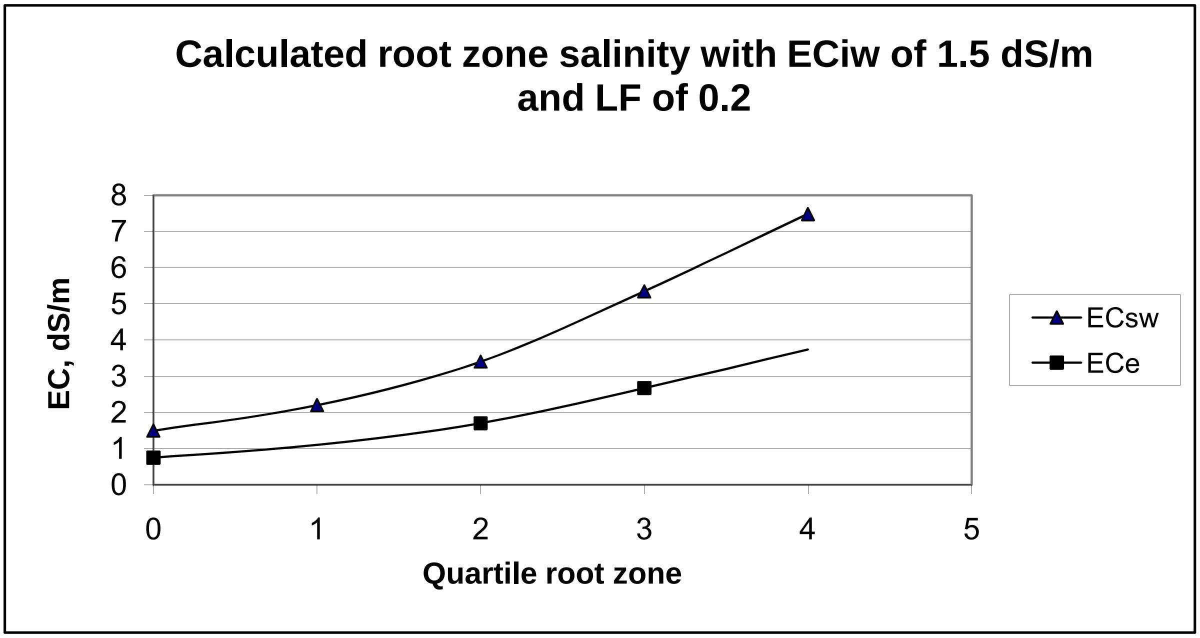
Input data	
Diw	52.4
Det	41.9
Wq0	0
Wq1	0.4
Wq2	0.3
Wq3	0.2
Wq4	0.1
ECiw	1.5

NOTE: Any changes made in the input data will cause new values to be calculated for computations and plottings.

Computations (codings are embedded)

Quartile	LF	ECsw	ECe
0	1	1.5	0.75
1	0.680153	2.205387	1.102694
2	0.440267	3.407022	1.703511
3	0.280344	5.350579	2.675289
4	0.200382	7.485714	3.742857
Avg.		3.98974	1.99487

ECsw = EC in soil water at field capacity
ECe = EC in extract of saturated soil paste


Calculated root zone salinity with ECiw of 1.5 dS/m
and LF of 0.2
EC, dS/m
8
7
6
5
4
3
2
1
0
0
1
2
3
4
5
Quartile root zone
ECsw
ECe

Appendix: Hydrosalinity Model 2

Hydrosalinity Model 2 for Illustrative Example IV-5

Example IV-5:
What is the long-term distribution of salts in the root zone of a cool-season grass, assuming the same conditions as for Illustrative Example IV-4 but with an effective annual rainfall of 8 in. and an EC of rainwater of 0.01 dS/m?

Illustrative Example IV-4:
What is the long-term salt distribution in the root zone of a cool-season grass uniformily sprinkler irrigated with 52.4 in./yr (Diw) at proper intervals to meet the grass's water needs with water of 1.5 dS/m (ECiw) and ET of 41.9 in./yr (Det) and assuming that the root water extraction pattern is 40–30–20–10% of ET?

Computational model: Eq. IV-13
LFiw+rw = ((Diw + Drw) -ΣWq*Det)/(Diw + Drw)

Computational model: Eq. IV-14
ECq = ECiw+rw/LFiw+rw

Computational model: Eq. IV-2
Det = Deto * Kc

Computational model: Eq. IV-12
ECiw+rw = (Diw*ECiw + Drw*ECrw) / (Diw + Drw)

LFiw+rw = LF of combined irrigation and rain waters
Diw = Depth of irrigation water
Drw = Depth of rainwater
Wq = Root water extraction pattern
Det = Depth of evapotranspiration
ECq = Calculated EC in quartile depth q
ECiw = EC of irrigation water
ECrw = EC of rainwater
ECiw+rw = Average EC of mixture of irrigation and rain water
Kc = Crop coefficient
Deto = Depth of Eto

Depth of rooting of cool-season grasses
Annual bluegrass = 0.08–0.33 ft
Kentucky bluegrass = 0.5–1.5 ft
Perennial ryegrass = 0.5–1.5 ft
Tall fescue = 1.5–3.0 ft

Root zone divided into 4 soil depth increments (quartile)

Mo.	Kc	ETo (in)	ET (in)
Jan	0.61	2.2	1.342
Feb	0.64	2.6	1.664
Mar	0.75	3.7	2.775
Apr	1.04	4.7	4.888
May	0.95	5.5	5.225
Jun	0.88	5.9	5.192
Jul	0.94	6.1	5.734
Aug	0.86	6.1	5.246
Sep	0.74	5.3	3.922
Oct	0.75	3.9	2.925

Input data	
Diw	52.4
Det	41.9
Wq0	0
Wq1	0.4
Wq2	0.3
Wq3	0.2
Wq4	0.1
ECiw	1.5
Drw	8
ECrw	0.1

Nov	0.69	2.6	1.794
Dec	0.6	2	1.2
Avg.	0.7875	4.216667	3.49225
Total			41.907

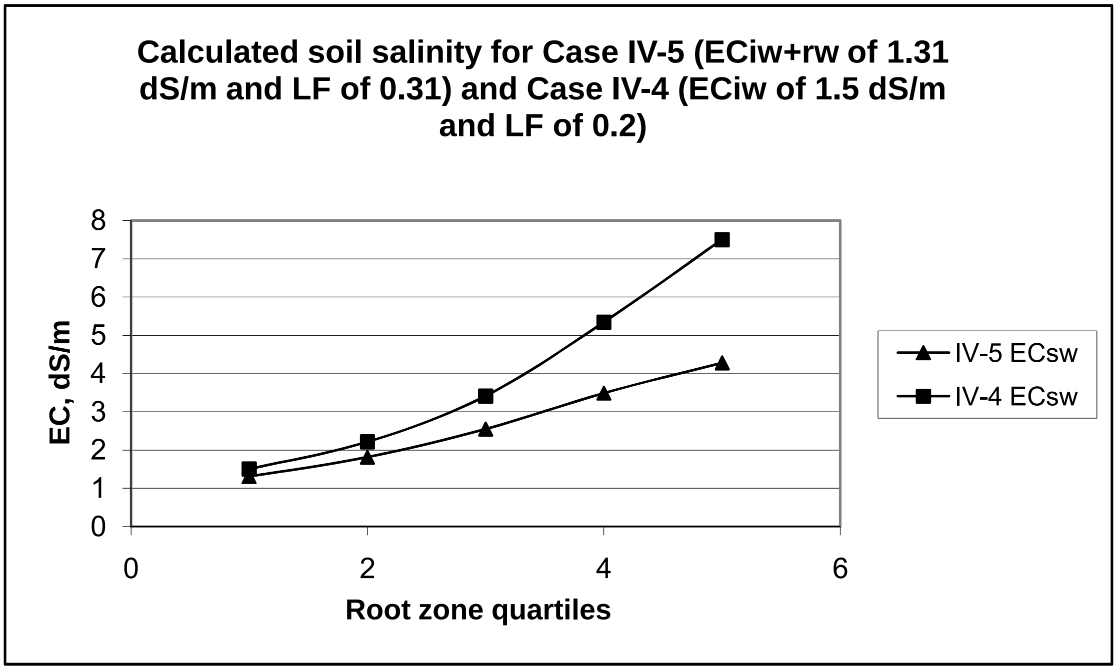
ECiw+rw 1.31

NOTE: Any changes made in the input data will cause new values to be calculated for computations and plottings.

Computations (codings are embedded)

Quartile	LF	IV-5 ECsw	IV-5 ECe	IV-4 ECsw	IV-4 ECe
0	1	1.31	0.655	1.5	0.75
1	0.722517	1.813107	0.906554	2.21	1.105
2	0.514404	2.546637	1.273318	3.41	1.705
3	0.375662	3.487175	1.743587	5.34	2.67
4	0.306291	4.276973	2.138486	7.5	3.75
Avg.		2.686778	1.343389	3.992	1.996

ECsw = EC in soil water at field capacity
ECe = EC in extract of saturated soil paste



Appendix: Hydrosalinity Model 3

Hydrosalinity Model 3 for Illustrative Example IV-5

Example IV-5:
A clay loam soil profile is salt affected and requires reclamation leaching. The ECiw of the water available for reclamation is 1.5 dS/m, and the EC of soil water (ECsw) in the soil profile in 6-in. depth increments is 10, 12, 18, 12, 6, 4, 4, and 4 dS/m. What will be the salinity in this profile if about 1 ft. of reclamation leaching is applied?

Computational model: Eq. IV-15 (mixing cell transport model)

$$ECq,j = 0.5 * (ECq,j-1 + EC\ q-1,,j)$$

EC = EC of soil water
q = Specified space (soil depth) increment in inches
j = Time increment or leaching event number

Eq. IV-15 states that the salt concentration in a particular soil depth q and a particular time j is the average of salt concentration from a previous time (resident salt) and salt concentration entering from a soil depth above (q-1) at that particular time (invading salt). Calculated EC is ECsw or EC at field capacity soil moisture.

Soil texture	Field capacity In. of water per ft of soil
Sand	1.2
Loamy sand	1.9
Sandy loam	2.5
Loamy sand	3.2
Silt loam	3.6
Sandy clay loam	3.5
Sandy clay	3.4
Clay loam	3.8
Silty clay loam	4.3
Silty clay	4.8
Clay	4.8

Assume that this clay loam soil has a field capacity of 4 in. of water per ft of soil or 2 in. of water per 6 in. of soil.

The depth of water applied will be in 2-in. increments for this case.

Initial values

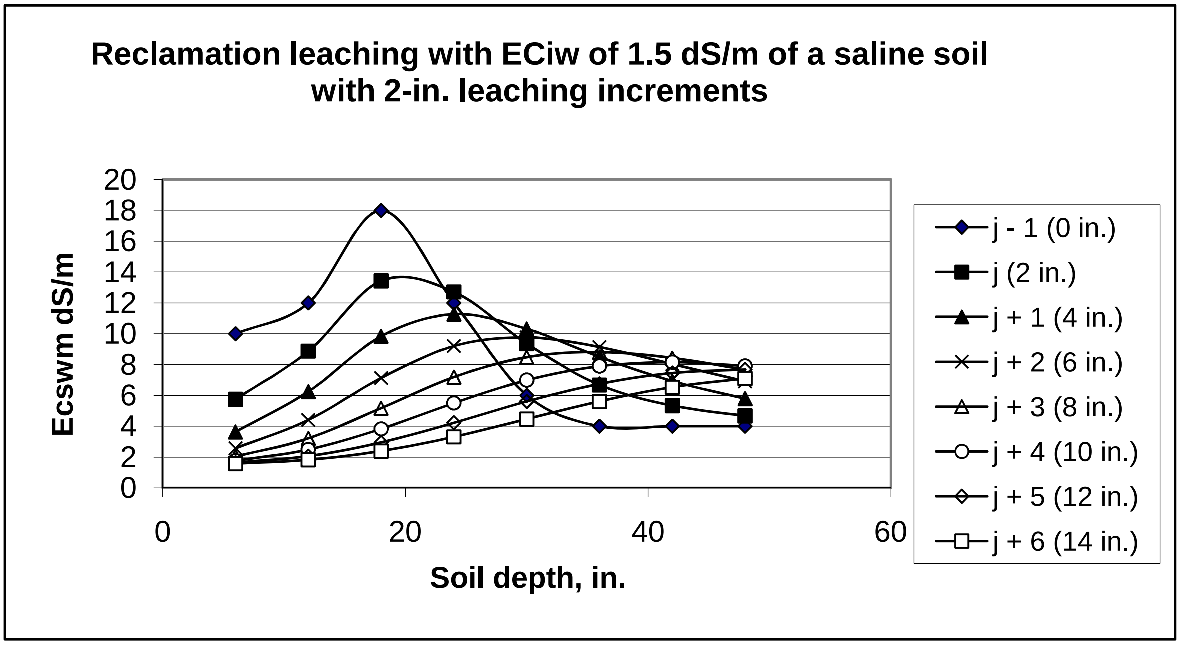
Soil depth	ECsw (dS/m)
0–6 in.	10
6–12 in.	12
12–18 in.	18
18–24 in.	12
24–30 in.	6
30–36 in.	4
36–42 in.	4
42–48 in.	4

NOTE: Any changes made in the input data will automatically cause new values to be calculated in the computations below and the plot.

ECiw 1.5 dS/m

Computations:

Soil depth	j - 1 (0 in.)	j (2 in.)	j + 1 (4 in.)	j + 2 (6 in.)	j + 3 (8 in.)	j + 4 (10 in.)	j + 5 (12 in.)	j + 6 (14 in.)
6	10	5.75	3.625	2.5625	2.03125	1.765625	1.6328125	1.5664063
12	12	8.875	6.25	4.40625	3.21875	2.4921875	2.0625	1.8144531
18	18	13.4375	9.84375	7.125	5.171875	3.8320313	2.9472656	2.3808594
24	12	12.71875	11.28125	9.203125	7.1875	5.5097656	4.2285156	3.3046875
30	6	9.359375	10.320313	9.7617188	8.4746094	6.9921875	5.6103516	4.4575195
36	4	6.6796875	8.5	9.1308594	8.8027344	7.8974609	6.7539063	5.6057129
42	4	5.3398438	6.9199219	8.0253906	8.4140625	8.1557617	7.454834	6.5302734
48	4	4.6699219	5.7949219	6.9101563	7.6621094	7.9089355	7.6818848	7.1060791
Avg.	8.75	8.3537598	7.8168945	7.140625	6.3703613	5.5692444	4.7965088	4.0957489



Appendix: Hydrosalinity Model 4

Hydrosalinity Model 4 for Illustrative Example IV-6

Example IV-6:

What is the degree of salt accumulation in a 30-in. soil profile in which a cool-season grass is grown with a water EC of 1.5 dS/m? Assume that salts in the applied water are reactive using the chemical reactivity function for Colorado River water. The crop ET is 41.9 in., and total irrigation is 52.4 in., resulting in an LF of 0.20. The rooting depth is 21 in., with a root water extraction pattern of 30–30–15–10–5–5–5% of ET. The initial soil salinity in 3-in. soil depth increments is 1.5, 2.5, 3.0, 3.5, 4.6, 5.9, 7.4, 9.7, 8.7, and 5.9 dS/m.

Computational model Eq. IV-17

ECq,j = 0.5*(ECq,j-1+((ECq-1,,j/LFq)-(0.0265/LF^2))

Eq IV-15

ECq,j = 0.5*(ECq, j-1 + ECq-1,j)

Chemical reactivity function for Colorado River water

ECsw = -0.0265/LF^2

Eq. IV-10

LFq = (Diw - ΣWqDet)/(Diw)

Eq. IV-6

ECq = ECiw/LFq

Eq. IV-2

Det = Deto * Kc

Eq. IV-17 is a combination of Eqs. IV-15, IV-10, IV-6, IV-2, and a salt reactivity function to account for mineral precipitation from evapoconcentration of soil water due to ET.

EC = EC of soil water
q = Specified soil depth increment
j = Time increment
LFq = LF in qth depth increment
Diw = Depth of irrigation water
Wq = Root water extraction pattern
Det = Depth of evapotranspiration
ECq = EC of soil water in qth increment
Deto = Depth of ETo
Kc = Crop coefficient

Depth of rooting of cool-season grasses

Annual bluegrass = 0.08–0.33 ft
Kentucky bluegrass = 0.5–1.5 ft
Perennial ryegrass = 0.5–1.5 ft
Tall fescue = 1.5–3.0 ft

Month	Kc	ETo (in.)	ET (in.)
Jan	0.61	2.2	1.342
Feb	0.64	2.6	1.664
Mar	0.75	3.7	2.775
Apr	1.04	4.7	4.888
May	0.95	5.5	5.225
Jun	0.88	5.9	5.192
Jul	0.94	6.1	5.734
Aug	0.86	6.1	5.246
Sep	0.74	5.3	3.922
Oct	0.75	3.9	2.925
Nov	0.69	2.6	1.794
Dec	0.6	2	1.2
Avg.	0.7875	4.216667	3.49225
Total			41.907

Input data

Diw	52.4		
Det	41.9	ECsw1	1.5
ECiw	1.5	ECsw2	2.5
Wq0	0	ECsw3	3
Wq1	0.3	ECsw4	3.5
Wq2	0.3	ECsw5	4.6
Wq3	0.15	ECsw6	5.9
Wq4	0.1	ECsw7	7.4
Wq5	0.05	ECsw8	9.7
Wq6	0.05	ECsw9	9.7
Wq7	0.05	ECsw10	5.9
Wq8	0		
Wq9	0		
Wq10	0		

NOTE: Any changes made in the input data will cause new values to be calculated for computations.

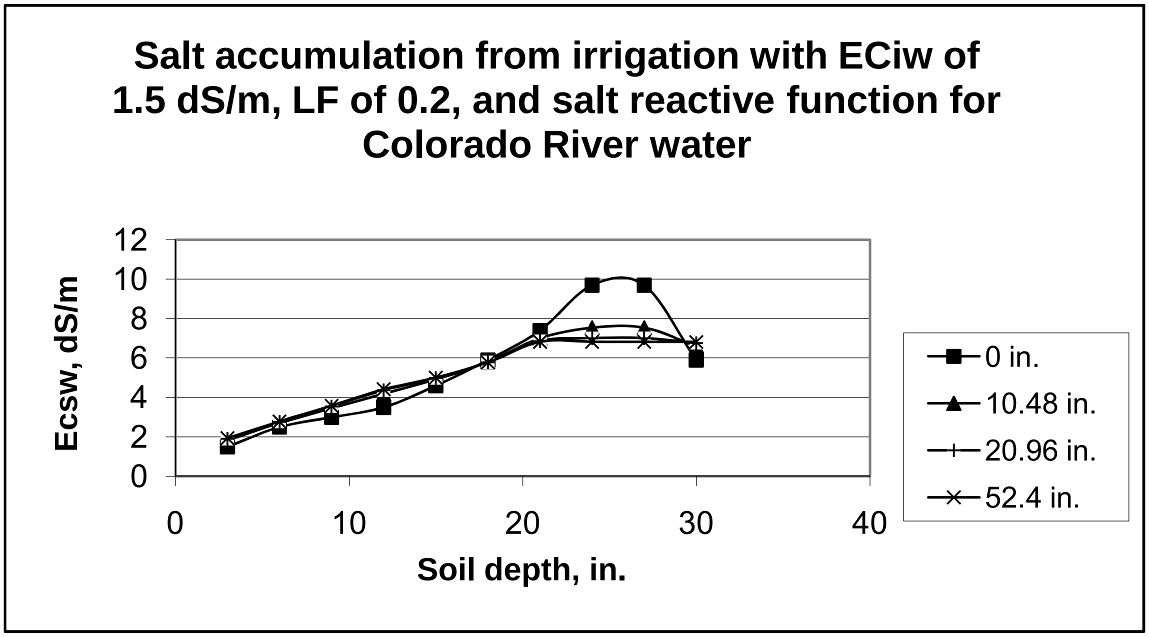
Computations

Depth	LFq
0	1
3	0.760115
6	0.520229
9	0.400286
12	0.320324
15	0.280344
18	0.240363
21	0.200382
24	0.200382
27	0.200382
30	0.200382

	j = 0	j = 1	j = 2	j = 3	j = 4	j = 5	j = 6	j = 7
Depth	0 in.	5.24 in.	10.48 in.	15.72 in.	20.96 in.	26.2 in.	31.44 in.	36.68 in.
3	1.5	1.713761	1.820641	1.874081	1.900801	1.914161	1.920841	1.924181
6	2.5	2.642714	2.714072	2.74975	2.76759	2.776509	2.780969	2.783199
9	3	3.290965	3.436448	3.509189	3.545559	3.563745	3.572837	3.577384
12	3.5	3.962244	4.193366	4.308926	4.366707	4.395597	4.410042	4.417265
15	4.6	4.806698	4.910047	4.961722	4.987559	5.000478	5.006937	5.010167
18	5.9	5.840945	5.811417	5.796653	5.789271	5.78558	5.783735	5.782812
21	7.4	7.112868	6.969302	6.897519	6.861627	6.843681	6.834709	6.830222
24	9.7	8.262868	7.544302	7.185019	7.005377	6.915556	6.870646	6.848191
27	9.7	8.262868	7.544302	7.185019	7.005377	6.915556	6.870646	6.848191
30	5.9	6.362868	6.594302	6.710019	6.767877	6.796806	6.811271	6.818503
Avg.	5.37	5.22588	5.15382	5.11779	5.099775	5.090767	5.086263	5.084011

	j = 8	j = 9	j = 10
Depth	41.92 in.	47.16 in.	52.4 in.
3	1.925851	1.926686	1.927104
6	2.784314	2.784871	2.784871
9	3.579657	3.580793	3.580793
12	4.420876	4.422682	4.422682
15	5.011781	5.012589	5.012589
18	5.782351	5.78212	5.78212
21	6.827979	6.826857	6.826857
24	6.836963	6.831349	6.831349
27	6.836963	6.831349	6.831349
30	6.82212	6.823928	6.823928
Avg.	5.082886	5.082323	5.082364

Depth	0 in.	10.48 in.	20.96 in.	52.4 in.
3	1.5	1.82	1.9	1.93
6	2.5	2.71	2.77	2.78
9	3	3.44	3.55	3.58
12	3.5	4.19	4.37	4.42
15	4.6	4.91	4.99	5.01
18	5.9	5.81	5.79	5.78
21	7.4	7	6.86	6.83
24	9.7	7.54	7.01	6.83
27	9.7	7.54	7.01	6.83
30	5.9	6.6	6.77	6.82



Chapter V. Tolerance by Landscape Plants of Salinity and of Specific Ions

C. Grieve, L. Wu, L. Rollins, and A. Harivandi

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In many communities where recycled water is available, the salinity of the recycled water is somewhat higher than the salinity of municipal drinking water. Therefore, in using recycled water to irrigate golf courses, parks, and other landscapes, it may be beneficial to include salt-tolerant plants, as much as possible, in a landscape's design. The information in this chapter is provided in the hope that it will help park designers, landscapers, maintenance personnel, and others who work with plants to specify, install, and nurture trees, shrubs, ground covers, floricultural plants, and turfgrasses that can thrive when irrigated with recycled water.

Quite a few landscape plants can withstand small or moderate amounts of salt; many are listed in this chapter. Because native Californian plants are favored for park design by the cities of Los Angeles and San Diego and by a number of other communities and individuals in the state, we have included salt tolerance information for native plants to the extent that it is available.

The responses of plants to salts are manifested in two ways. The osmotic effect produced by total salinity decreases the soil water potential, which causes water in the soil to become less available to plants. And when specific constituents (ions) of salts are present in high concentrations, they can disrupt the plant's mineral nutrient status, sometimes becoming toxic. At times, concentrations of ions such as sodium (Na^+), chloride (Cl^-), and boron (B) in soil or irrigation water, or both, can prove to be a major constraint in choosing plants or in deciding where to position plants within a landscape. We describe some of the effects of these salt ions on plants and the concentrations at which the ions can become a problem. In addition, we outline a number of management practices that can be used to minimize salt injury to plants.

When one is preparing for landscape irrigation with recycled water, environmental quality is an important consideration, especially when the landscape is situated within an urban area. To use the lists of plants in this chapter successfully, information regarding water quality, irrigation management, physical and chemical properties of the soil, and any unfavorable environmental conditions should be obtained and thoroughly reviewed.

In addition to choosing plant species that are sufficiently salt tolerant, the landscape professional must select species that adapt well to local climates. California has many different climatic zones ranging from cool, relatively dry, temperate regions in the inland valleys and high mountains to extremely dry, hot deserts to humid, foggy zones along the coast. Since information on the adaptation of plants to climate is readily available elsewhere, we will not further cover the topic in this chapter.

V.A. General Information Regarding Salt Tolerance

V.A.1. Defining Plant Salt Tolerance

The salt tolerance of a plant is often defined as the plant's inherent ability to withstand the effects of high salts in the root zone or on its leaves without significant adverse effects. The actual salt tolerance of a plant will vary, depending on the growth stage at which salinization is initiated and the final level of salinity to which the plant is subjected (Lunin et al., 1963). Another reason for variation is that the genes that determine a plant's salt tolerance function in combination with other genes, some of which influence both quantitative traits and environmentally influenced traits, such as salt tolerance (Shannon, 1997).

A crop's salt tolerance can be described as a complex function of its yield decline in response to salinity. The yield response curve is typically valid for a range of concentrations of salts and is sigmoidal in shape. Mathematical descriptions of these relationships have proven useful for crop simulation modeling (van Genuchten and Hoffman, 1984). However, because crop survival rates tend to be very low at high salinities, the validity of the bottom part of the yield response curve is often in doubt. Maas and Hoffman (1977) proposed a two-piece linear model described by two parameters: the threshold (electrical conductivity of the extract of a saturated soil paste [EC_e] at which significant yield reduction begins), and the slope (percentage of expected yield decline per unit increase in salinity above the threshold value). In landscape plants, aesthetic quality of the plants is more important than yield of crop plants. Nevertheless, the concept of salt tolerance is of value for landscape plants.

V.A.2. Response of a Plant to Salinity

Lauchli and Epstein (1990) conclude that salinity is stressful for many plants because of two concurrent processes: the osmotic effect and specific-ion effects described earlier. The authors examine the various mechanisms by which plants respond to osmotic effects and to the effects of specific ions. They point out that a plant typically responds to the osmotic effects of salinity by absorbing salt from the medium and by synthesizing organic solutes internally so as to make the water potential gradient more favorable for water uptake.

To evaluate what is known about the responses of plants to salinity, Lauchli and Epstein review and then summarize results from a number of studies on the topic. They describe how plants respond during the two successive stages of growth—development and vegetative growth. They conclude the following:

- It is not possible to establish a distinct dividing line between saline stress, on the one hand, and lack of stress, on the other. Instead, a continuum exists between the two.
- The sensitivity of a plant to salinity changes during the development of the plant.
- The integration of responses in the whole plant is critical for the health and survival of a plant under saline conditions.
- Highly salt-tolerant plants (halophytes) tend to absorb salt ions from the medium and sequester them in the vacuoles of cells. Such plants also manufacture organic solutes to balance the osmotic changes that occur in the cell cytoplasm.
- Salt-sensitive plants, referred to as nonhalophytes or glycophytes, tend to exclude sodium and chloride from their shoots and, especially, from their leaves. Consequently, when subjected to salinity, glycophytes must rely more extensively on the synthesis of organic solutes than do halophytes.
- The presence of calcium at elevated concentrations sometimes can help to mitigate the adverse effects of salinity.

The initial and primary effect of salinity, especially at low to moderate concentrations of salt, results from osmotic effects (Munns and Termaat, 1986). Maturity may be delayed or advanced, depending on the species. For example, salt-related stress in wheat accelerates its development and causes early maturity, whereas salt-related stress in rice causes the plants to mature more slowly. The magnitude of a plant's response to salinity depends not only on the species but also on the interactive effects of environmental factors such as relative humidity, temperature, radiation, and air pollution (Shannon et al., 1994).

Depending on the composition of the irrigation water, ion toxicities or nutritional deficiencies may also arise. These result from a preponderance of a certain specific ion or from competitive effects among cations or anions (Grattan and Grieve, 1999). The osmotic effects of salinity contribute to a reduced rate of growth and to changes in the color of leaves. They also can lead to morphological changes such as smaller leaves or shorter stature or, frequently, to fewer leaves and nodes. Ionic effects generally manifest as damaged leaves or formative plant tissue or as symptoms typical of nutritional disorders. Thus, high concentrations of sodium or chloride ions may accumulate in leaves or in portions of leaves and result in the "scorch" or "firing" of leaves, whereas symptoms of nutritional deficiency are often similar to those that occur in the absence of salinity.

Environmental stresses can cause physiological and morphological disruptions in root tissues. Salinity, for example, decreases the integrity and increases the permeability of cell membranes and ultimately results in reduced growth and yield. Such changes may also increase a plant's susceptibility to invasion by pathogens. Chrysanthemum, a relatively salt-tolerant floral species, showed a definite predisposition to infection by *Phytophthora cryptogea* when it was affected by salinity. MacDonald (1982) reported a strong positive relationship between the degree of salt stress and the severity of this root rot.

V.A.3 Symptoms of Salt-Related Stress

The typical observable symptom of a plant injured by salt-related stress is leaf chlorosis (a scorched-like appearance). It is detrimental physically and aesthetically to plants. If subjected to severe salt-related stress, the whole leaf blade may become chlorotic and die. Under moderate salt-related stress, symptoms are similar among salt-sensitive species of plants, although the symptoms on the leaves have a slightly different pattern of distribution.

Species assessed to be "highly tolerant" are unlikely to develop any symptoms of salt-related stress when irrigated with recycled water, even during the dry and warm summer season. Such species include the tree known as Mexican pinon pine (*Pinus cembriodes*), the shrub known as oleander (*Nerium oleander*), the ground cover red apple iceplant (*Aptenia cordifornia*), and the grass known as alkali sacaton *(Sporobolus airoides*). All of these species can tolerate salt spray containing over 1,000 mg of sodium chloride/L, and all are tolerant of soil with a salinity of 10 decisiemens/m (dS/m), or even greater. These plants require only routine management practices.

Plants assessed to be "tolerant" are generally able to tolerate spray with water (i.e., wetted foliage from sprinkler irrigation) that contains concentrations of salt equivalent to those found in most recycled waters and generally do not develop apparent symptoms of salt-related stress if the salinity of the soil remains below an EC_e of 6 dS/m. However, when the foliage of a tolerant plant is exposed to concentrations of salt exceeding 200 mg of sodium/L and 300 mg of chloride/L, symptoms of salt-related stress begin to appear.

Species determined to be "moderately tolerant" can tolerate spray with water containing the concentrations of salts found in most recycled waters. Under such conditions, their aesthetic quality generally remains acceptable, though they may develop symptoms of salt-related stress near the end of the growing season, by which time leaves may have accumulated considerable salt or the salinity of the soil may have exceeded the permissible level. In areas where wet seasons recur cyclically and frequently, moderately tolerant plants will likely do very well through most of the year, even if irrigation is discontinued during the wet seasons.

Plants deemed "sensitive" may develop symptoms of salt-related stress under a spray of water containing a concentration of sodium that reaches or exceeds 200 mg/L and a concentration of chloride that reaches or exceeds 400 mg/L, especially if the weather is warm and dry. One such species is liquidambar (*Liquidambar styraciflua*). Typical symptoms of salt-related and boron-related stresses for plant species are shown in plates 1 and 2 (Gallery), respectively. Plants sensitive to salt spray from sprinkler irrigation tend also to be sensitive to salinity in the soil. For example, roses may develop severe symptoms of salt-related stress if the salinity in the soil reaches or exceeds 3 dS/m. Research with agronomic plants (Benes et al., 1996) has shown that, for some crops, postwashing (finishing an irrigation, then giving a brief, freshwater rinse) can greatly reduce foliar injury from sprinkling.

V.B. Salt Tolerance of Trees, Shrubs, and Ground Covers

V.B.1. Findings from Recent Research

Based on a recent series of experiments, Wu and Dodge (2005) compiled salt tolerance information for over 200 species of trees and palms, shrubs, and ground covers. Reproduced here as Tables V.B.1.1, V.B.1.2, and V.B.1.3, the lists work fairly well as a plant selection guide for decision-makers in the field of landscape management.

These lists were developed by a team of University of California–Davis researchers who used sprinkler and drip irrigation systems and waters with salinities near the upper level found in most recycled waters. The field trials were aimed at differentiating the salt tolerance of landscape plants based on the aesthetic effects of salinity, rather than yield reduction as would be done with agronomic crops (Wu et al., 2001). The response of the plants to saline stress was evaluated visually or measured by using image analysis technology (Lumis et al., 1973; Wu et al., 2001; Wu and Guo, 2005).

The researchers reviewed the relatively scant literature to date on the relationship between the tolerance by plants of salinity in the water applied to leaves, as compared to tolerance of salinity in the water applied to roots. In one study, these two characteristics were found to have evolved independently between different ecotypes for a species of creeping bentgrass, *Agrostis stolonifera L.*, in a seacoast environment (Ashraf et al., 1986). In another study that involved salt-tolerant creeping fescue cultivars (*Festuca rubra L.*), the characteristics of leaf wettability were found to be responsible for tolerance of salt spray (Humphreys, 1986). There appears to exist a positive relationship between the salt tolerance by many landscape plants for saline spray and their tolerance of salinity in the root zone (Wu et al., 2001). In some cases, the tolerance for salts entering the plant via its roots was found to be three to four times higher than the tolerance for salts entering the plant through leaves (Wu et al., 2001). Exceptions were certain fruit trees grafted onto rootstocks of different species. Their tolerance of salt spray and tolerance of soil salinity may be unrelated.

Based on the results of their field trials, which were conducted in the summer months, and information found in the literature, the researchers estimated the salt tolerances of over 200 species of plants for landscapes (Tables V.B.1.1, V.B.1.2, and V.B.1.3).

Although five or six descriptors have been used to categorize the salt tolerance of crop species (Maas and Grattan, 1999), that number was deemed unnecessarily high for differentiating salt tolerance in landscape plants because landscapes often include plants with a wide range of salt tolerance. Instead, these researchers categorized plants using four descriptors for the plants' ability to tolerate salts in irrigation water: highly tolerant, tolerant, moderately tolerant, or sensitive. They concluded that ranking based on the visual quality of the plants was a practical approach.

Table V.B.1.1.Tolerance by selected landscape tree species of salt spray and of soil salinity.[a]

Botanical name	Common name	Tolerance of salt spray[b]	Tolerance of soil salinity[c]
Acer rubrum L.	Red maple	Sensitive	Sensitive
Acer pseudoplatanus L.	Sycamore maple	Sensitive	Sensitive
Albizia julibrissin Durazz.	Silk tree	Sensitive	Sensitive
Araucaria heterophylla (Salisb.)	Norfolk Island pine	Highly tolerant	Tolerant
Averrhoa carambola L.	Carambola, starfruit	Moderate	Moderate
Bauhinia purpurea L.	Orchid tree	Sensitive	Moderate
Callistemon citrinus Curtis.	Lemon bottlebrush	Tolerant	Moderate
Carya illinoinensis Koch.	Pecan	Moderate	Moderate
Cedrus deodara D. Don	Deodar cedar	Moderate	Moderate
Celtis sinensis Pers.	Chinese hackberry	Sensitive	Sensitive
Citrus limon L.	Lemon	Sensitive	Sensitive
Citrus paradisi Macf.	Grapefruit	Sensitive	Sensitive
Citrus reticulata Blanco.	Tangerine	Sensitive	Sensitive
Citrus sinensis Osbeck.	Orange	Sensitive	Sensitive
Coccoloba uvifera L.	Sea grape	Highly tolerant	Tolerant
Cornus mas L.	Cornelian cherry	Sensitive	Sensitive
Cotoneaster microphyllus Lindl.	Rockspray or little-leaf cotoneaster	Tolerant	Moderate
Cupressus sempervirens L.	Italian cypress	Moderate	Moderate
Diospyros digyna L.	Black sapote	Moderate	Moderate
Diospyros virginiana L.	American persimmon	Sensitive	Sensitive
Eriobotrya japonica Lindl.	Loquat	Moderate	Moderate
Euryops pectinatus	Golden marguerite	Sensitive	Sensitive
Ficus carica L.	Edible fig	Tolerant	Tolerant
Forsythia intermedia Zabel	Forsythia	Tolerant	Tolerant
Fraxinus oxycarpa Bieb. Ex Willd.	Raywood ash	Moderate	Moderate
Gingko biloba L.	Gingko	Sensitive	Sensitive
Grevillea robusta Cunn.	Silk oak	Highly tolerant	Tolerant
Jacaranda mimosifolia D. Don.	Jacaranda	Sensitive	Sensitive
Juniperus silicicola Bail.	Southern red cedar	Highly tolerant	Tolerant
Juniperus virginiana L.	Skyrocket juniper	Highly tolerant	Tolerant
Koelreuteria paniculata Laxm.	Golden rain tree	Moderate	Moderate
Lagerstroemia indica L.	Crape myrtle	Sensitive	Sensitive
Ligustrum japonicum Thunb.	Japanese privet	Moderate	Moderate
Liquidambar styraciflua L.	Sweetgum	Sensitive	Sensitive
Litchi chinensis Sonn.	Lychee	Sensitive	Sensitive
Malus sylvestris Mill.	Crabapple	Sensitive	Sensitive
Mangifera indica L.	Mango	Sensitive	Sensitive
Mangnolia grandiflora L.	Southern magnolia	Sensitive	Sensitive
Manilkara zapota	Sapodilla	Tolerant	Tolerant
Musa acuminata Colla.	Banana	Sensitive	Sensitive
Olea europaea L.	Olive	Sensitive	Sensitive
Parthenium argentatum Gray.	Guayule	Highly tolerant	Highly tolerant
Persea americana Mill.	Avocado	Moderate	Moderate
Pinus cembroides Zucc.	Mexican stone pine	Highly tolerant	Tolerant

Pinus clausa Vasey	Sand pine	Highly tolerant	Tolerant
Pinus elliotti Engelm.	Florida slash pine	Moderate	Moderate
Pinus halepensis Mill.	Aleppo pine	Moderate	Moderate
Pinus thunbergii Parl.	Japanese black pine	Moderate	Moderate
Pistachia chinensis Bunge.	Chinese pistache	Sensitive	Sensitive
Platycladus orientalis Franco	Oriental arborvitae	Moderate	Moderate
Plumaria spp. L.	Frangipani	Tolerant	Tolerant
Plumbago auriculata Lam.	Cape plumbago	Tolerant	Moderate
Prunus armeniaca L.	Apricot	Sensitive	Sensitive
Prunus caroliniana Ait.	Carolina laurel cherry	Moderate	Sensitive
Prunus dulcis D. A. Webb.	Almond	Sensitive	Sensitive
Prunus persica Batsch	Peach	Sensitive	Sensitive
Prunus spinosa L.	Blackthorn	Tolerant	Moderate
Psidium guajava L.	Guava	Sensitive	Sensitive
Punica granatum L.	Pomegranate	Moderate	Moderate
Pyrus communis L.	Pear	Sensitive	Sensitive
Pyrus spinosa Forssk.	Almond-leaved pear	Moderate	Moderate
Quercus agrifolia Nee	Coast live oak	Tolerant	Tolerant
Quercus laurifolia Michux	Laurel oak	Sensitive	Sensitive
Quercus suber L.	Cork oak	Moderate	Moderate
Quercus virginiana Mill.	Live oak	Highly tolerant	Tolerant
Sapium sebiferum Roxb.	Chinese tallow tree	Highly tolerant	Tolerant
Schefflera actinophylla Harms	Schefflera, umbrella tree	Moderate	Moderate
Sequoia sempervirens Endl.	Coast redwood Var. Aptos Blue	Sensitive	Sensitive
Sequoia sempervirens Endl.	Coast redwood Var. Los Altos	Moderate	Moderate
Syzgium jambos Alston	Rose apple	Sensitive	Sensitive
Ulmus parvifolia Drake	Drake elm	Moderate	Moderate
Ulmus parvifolia Jacq.	Chinese elm	Moderate	Moderate
Palm			
Butia capitata Becc.	Pindo palm	Tolerant	Tolerant
Chamaerops humilis L.	European fan palm	Tolerant	Tolerant
Phoenix canariensis Chabaud.	Canary Island date	Moderate	Moderate
Phoenix dactylifera L.	Date palmetto	Tolerant	Tolerant
Sabal palmetto Lodd.	Cabbage palmetto	Tolerant	Tolerant
Serenoa repens Small	Saw palm	Tolerant	Tolerant
Washingtonia robusta Wendl.	Washingtonia palm	Tolerant	Tolerant
Chrysalidocarpus lutescens Wendl.	Areca palm	Moderate	Moderate
Caryota mitis Lour.	Fishtail palm	Moderate	Moderate
Rhapis excelsa Henry	Lady palm	Moderate	Moderate
Acoelorrhaphe wrightii Becc.	Paurotis palm	Moderate	Moderate
Phoenix roebelinii O'Brien.	Pygmy date palm	Moderate	Moderate
Phoenix reclinata Jacq.	Senegal date palm	Moderate	Moderate
Syagrus romanzoffiana L.	Queen palm	Moderate	Moderate
Nolina recurvata Hemsle	Ponytail palm (not a true palm)	Moderate	Moderate

[a] Data in the table adapted from Wu and Dodge, 2005 (in press).

[b] Tolerances of salt spray are defined by the degree of salt stress symptoms developed in the leaves of the plants and the salt concentrations in the irrigation water as follows:

Highly tolerant: No apparent salt stress symptoms may be observed when the plants are irrigated with water that contains 600 mg of sodium L^{-1} and 900 mg of chloride L^{-1} and has an EC_{iw} of 2.1 dS/m.

Tolerant: No apparent salt stress symptoms may be observed when the plants are irrigated with water containing 200 mg of sodium L^{-1} and 400 mg of chloride L^{-1}.

Moderate: Less than 10% of symptoms develop when the plants are irrigated with water containing 200 mg of sodium L^{-1} and 400 mg of chloride L^{-1} and having an EC_{iw} of 0.9 dS/m.

Sensitive: More than 20% of the leaves may develop symptoms when the plants are irrigated with water containing 200 mg of sodium L^{-1} and 400 mg of chloride L^{-1} and having an EC_{iw} of 0.6 dS/m.

[c] The definitions of soil salinity tolerance are as follows:

Highly tolerant: Permissible soil EC_e greater than 6 dS m^{-1},
Tolerant: Permissible soil EC_e greater then 4 and less than 6 dS m^{-1},
Moderate: Permissible soil EC_e greater than 2 and less than 4 dS m^{-1}, and
Sensitive: Permissible soil EC_e less than 2 dS m^{-1}.

Table V.B.1.2. Tolerance by landscape shrub species of salt spray and of soil salinity.[a]

Botanical name	Common name	Tolerance of salt spray[b]	Tolerance of soil salinity[c]
Abelia grandiflora Rehd.	"Edward Goucher" Abelia	Sensitive	Sensitive
Acacia redolens Maslin.	Prostrate acacia	Tolerant	Tolerant
Acalypha wilkesiana Muell.	Copper leaf	Sensitive	Sensitive
Agave americana L.	Century plant	Highly tolerant	Tolerant
Arctostaphylos densiflora M.S.Bac	Vine hill manzanita	Tolerant	Tolerant
Bambusa sp. Schreb.	Bamboo	Moderate	Moderate
Buddleja davidii Franch.	Butterfly bush	Sensitive	Sensitive
Buxus microphylla Mull. Arg.	Japanese boxwood	Tolerant	Moderate
Calliandra haematocephala Hassk.	Powder puff tree	Sensitive	Sensitive
Callistemon rigidus R. Br.	Bottlebrush	Moderate	Moderate
Camellia japonica L.	Camellia	Sensitive	Sensitive
Cannax generalis Bailey.	Canna lily	Moderate	Moderate
Carica papaya L.	Papaya	Moderate	Moderate
Carissa macrocarpa A. DC.	Natal plum	Highly tolerant	Tolerant
Ceanothus thyrsiflorus Esch.	Blue blossom	Tolerant	Moderate
Cestrum aurantiacum Lindl.	Orange cestrum	Moderate	Moderate
Codiaeum variegatum Blume.	Croton	Sensitive	Sensitive
Cornus mas L.	Cornelian cherry	Sensitive	Sensitive
Cotoneaster congestus Baker	Pyrenees cotoneaster	Sensitive	Sensitive
Cotoneaster microphylla Lindl.	Rockspray cotoneaster	Moderate	Sensitive
Dracaena deremensis Engler.	Dracaena	Moderate	Moderate
Elaeugnus pungens Thunb.	Silverthorn, silverberry	Highly tolerant	Tolerant
Escallonia rubra Pers.	Escallonia	Tolerant	Moderate
Eugenia unifora L.	Surinam cherry	Sensitive	Sensitive
Euphorbia milii Ch. Des Moulins	Crown of thorns	Highly tolerant	Highly tolerant
Euphorbia pulcherrima Willd.	Poinsetta	Sensitive	Sensitive
Euryops pectinatus L.	Golden shrub daisy	Tolerant	Moderate
Forsythia intermedia Zabel	Hybrid forsythia	Moderate	Moderate
Gamolepis chrysanthemoides DC.	African bush daisy	Highly tolerant	Tolerant
Gardenia augusta Merrill	Cape jasmine, gardenia	Moderate	Moderate
Heliconia sp.	Heliconia	Moderate	Moderate
Hibiscus rosa L.	Rose of China, garden hibiscus	Moderate	Moderate
Hydrangea macrophylla Ser.	Hydrangea	Tolerant	Moderate
Ilex cornuta Burford	Chinese holly	Moderate	Moderate
Ilex vomitoria Ait.	Yaupon holly	Tolerant	Tolerant
Ilex vomitoria Nana	Dwarf Yaupon holly	Highly tolerant	Tolerant
Ixora coccinea L.	Ixora	Sensitive	Sensitive
Jasminum polyanthum Franch.	Jasmine	Moderate	Moderate
Jatropha multifida L.	Coral plant	Sensitive	Moderate
Justicia brandegeana Wassh.	Shrimp plant	Sensitive	Sensitive
Lantana camara L.	Lantana	Highly tolerant	Tolerant
Mahonia aquifolium Nutt.	Oregon grape	Sensitive	Sensitive
Mahonia pinnata Fedde	California holly grape	Sensitive	Sensitive
Murraya paniculata L.	Orange jessamine	Sensitive	Sensitive
Myrica cerifera L.	Wax myrtle	Highly tolerant	Tolerant
Myrtus communis L.	True myrtle	Tolerant	Tolerant
Nandina domestica Thunb.	Heavenly bamboo	Sensitive	Sensitive

Nerium oleander L.	Oleander	Highly tolerant	Tolerant
Opuntia sp. Miller	Opuntia cactus	Moderate	Tolerant
Parthenium argentatum Gray.	Guayule	Highly tolerant	Highly tolerant
Pentas lanceolata Deflers	Pentas, Egyptian star-cluster	Sensitive	Sensitive
Photinia glabra Maxim.	Japanese Photinia	Sensitive	Sensitive
Photinia fraseri Dress	Photinia	Sensitive	Sensitive
Pittosporum tobra Aiton	Mock orange	Highly tolerant	Tolerant
Plumbago auriculata am.	Cape plumbago	Tolerant	Tolerant
Podocarpus macrophyllus D. Don	Yew pine	Sensitive	Sensitive
Pyracantha coccinea Roem.	Red firethorn	Moderate	Moderate
Raphiolepis indica Lindl.	Indian hawthorn	Highly tolerant	Tolerant
Rosa sp. L.	Rose	Sensitive	Sensitive
Russelia equisetiformis Schlecht & Cham.	Firecracker plant	Moderate	Moderate
Sambucus callicarpa Greene	Coast red elderberry	Tolerant	Moderate
Schefflera arboricola L.	Dwarf Shefflera	Moderate	Moderate
Strelitzia reginae Bankses Dryander	Bird of paradise	Moderate	Moderate
Viburnum odoratissimum Ker.	Sweet Viburnum	Moderate	Moderate
Viburnum suspensum Lindl.	Sandankwa Viburnum	Moderate	Moderate
Yucca aloifolia L.	Spanish bayonet	Highly tolerant	Highly tolerant

[a] Data in the table adapted from Wu and Dodge, 2005 (in press).

[b] Tolerances of salt spray are defined by the degree of salt stress symptoms developed in the leaves of the plants and the salt concentrations in the irrigation water as follows:

Highly tolerant:	No apparent salt stress symptoms may be observed when the plants are irrigated with water containing 600 mg of sodium L^{-1} and 900 mg of chloride L^{-1} and having an EC_{iw} of 2.1 dS/m.
Tolerant:	No apparent salt stress symptoms may be observed when the plants are irrigated with water containing 200 mg of sodium L^{-1} and 400 mg of chloride L^{-1}.
Moderate:	Less than 10% symptoms may be observed when the plants are irrigated with water containing 200 mg of sodium L^{-1} and 400 mg of chloride L^{-1} and having an EC_{iw} of 0.9 dS/m.
Sensitive:	More than 20% of the leaves may develop symptoms when the plants are irrigated with water containing 200 mg of sodium L^{-1} and 400 mg of chloride L^{-1} and having an EC_{iw} of 0.6 dS/m.

[c] The definitions of soil salinity tolerance are

Highly tolerant:	Permissible soil EC_e greater than 6 dS m^{-1},
Tolerant:	Permissible soil EC_e greater then 4 and less than 6 dS m^{-1},
Moderate:	Permissible soil EC_e greater than 2 and less than 4 dS m^{-1}, and
Sensitive:	Permissible soil EC_e less than 2 dS m^{-1}.

Table V.B.1.3. Tolerance by various landscape ground covers and vine species of salt spray and of soil salinity.[a]

Botanical name	Common name	Tolerance of salt spray[b]	Tolerance of soil salinity[c]
Adiantum sp. L.	Maidenhair fern	Moderate	Moderate
Ajuga repens	Carpet bugle	Sensitive	Sensitive
Aloe vera Burm. f.	Aloe	Highly tolerant	Tolerant
Alternanthera ficoidea R. Br.	Joyweed	Moderate	Moderate
Aptenia cordifolia N. E. Br.	Red apple iceplant	Tolerant	Tolerant
Arctostaphylos densiflora "Lynne" M. S. Back.	Lynne's vine hill manzanita	Moderate	Moderate
Athyrium filix-femina Rith.	Lady fern	Sensitive	Sensitive
Bromeliaceae sp. L.	Bromeliads	Moderate	Moderate
Caladium sp. Vent.	Caladium	Sensitive	Sensitive
Carissa macrocarpa A. DC.	Natal plum	Highly tolerant	Tolerant
Carpobrotus edulis L. Bolus.	Hottentot fig	Highly tolerant	Tolerant
Catharanthus roseus G. Donf.	Periwinkle	Tolerant	Moderate
Chlorophytum comosum Jacq.	Spider plant	Moderate	Moderate
Cuphea hyssopifolia Kunth.	False heather	Moderate	Tolerant
Cyperus alternifolius L.	Umbrella sedge	Moderate	Moderate
Delosperma "Alba" N. E.	White iceplant	Highly tolerant	Highly tolerant
Dietes spp. Salisb. ex Klatt.	African Iris	Moderate	Moderate
Drosanthemum hispidum Schwantes.	Rosea iceplant	Highly tolerant	Highly tolerant
Ficus pumila L.	Creeping fig	Highly tolerant	Tolerant
Hemerocallis sp. L.	Daylily	Moderate	Moderate
Malephora crocea Schwantes.	Iceplant	Highly tolerant	Highly tolerant
Juniperus chinensis L.	Chinese juniper	Moderate	Moderate
Juniperus conferta Parl.	Shore juniper	Tolerant	Tolerant
Juniperus horizontalis Moench.	Creeping juniper	Highly tolerant	Tolerant
Juniperus procumbens Siebild ex Endl.	Japanese garden juniper	Moderate	Moderate
Kalanchoe sp. Adans.	Kalanchoe	Moderate	Moderate
Lampranthus productus N. E. Br.	Purple iceplant	Highly tolerant	Highly tolerant
Liriope muscari L. H. Bail.	Lilyturf (Liriope)	Moderate	Moderate
Iris hexagona Walter	Iris	Moderate	Moderate
Nephrolepis exaltata Schott.	Sword fern	Highly tolerant	Tolerant
Peperomia obtusifolia Dietr.	Peperomia	Sensitive	Sensitive
Portulaca grandiflora Hook.	Purslane (rose moss)	Moderate	Sensitive
Rosmarinus officinalis L.	Rosemary	Moderate	Moderate
Salvia farinacea Benth.	Mealycup sage	Sensitive	Sensitive
Tigridia pavonia Ker Gawler	Tiger flower	Tolerant	Moderate
Tradescantia pallida Hunt.	Purple queen	Highly tolerant	Tolerant
Tulbaghia violacea Harvey	Society garlic	Moderate	Moderate
Verbena sp. L.	Verbena	Sensitive	Sensitive
Zamia integrifolia L. f.	Coontie	Highly tolerant	Tolerant
Vine			
Allamanda cathartica L.	Allamanda	Tolerant	Tolerant
Allamanda blanchetii A. DC.	Purple Allamanda	Moderate	Moderate
Antigonon leptopus Hookery	Coral Vine	Sensitive	Moderate
Bougainvillea glabra Choisy	Bougainvillea	Highly tolerant	Tolerant
Campsis radicans Seem.	Trumpet creeper	Sensitive	Sensitive
Clerodendrum thomsoniae Balf. f.	Bleeding heart vine	Sensitive	Sensitive
Clytostoma callistegioides Miers ex Bur.	Violet trumpet vine	Sensitive	Sensitive
Cyperus altenifolius L.	Umbrella sedge	Moderate	Moderate

Epipremnum sp. Schott.	Pothos	Moderate	Moderate
Ficus pumila L.	Creeping fig	Highly tolerant	Tolerant
Hedera canariensis Willd.	Algerian ivy	Highly tolerant	Tolerant
Hedera helix L.	English ivy	Moderate	Moderate
Hylocereus undatus Britton & Rose	Night blooming cereus	Moderate	Moderate
Ipomoea pescaprae R. Br.	Railroad vine	Highly tolerant	Tolerant
Ipomoea stolonifera Gmel.	Seafoam morning glory	Highly tolerant	Tolerant
Philodendron williamsii Hook.	Philodendron	Moderate	Moderate
Passiflora incanata L.	Passion flower	Sensitive	Sensitive
Salvia farinacea Benth.	Mealycup sedge	Sensitive	Sensitive
Tecomaria capensis Spach.	Cape honeysuckle	Tolerant	Tolerant
Trachelospermum jasminoides Lem.	Star jasmine	Tolerant	Tolerant

[a] Data in the table adapted from Wu and Dodge, 2005 (in press).

[b] Tolerances of salt spray are defined by the degree of salt stress symptoms developed in the leaves of the plants and the salt concentrations in the irrigation water as follows:

Highly tolerant:	No apparent salt stress symptoms may be observed when the plants are irrigated with water containing 600 mg of sodium L^{-1} and 900 mg of chloride L^{-1} and having an EC_{iw} of 2.1 dS/m.
Tolerant:	No apparent salt stress symptoms may be observed when the plants are irrigated with water containing 200 mg of sodium L^{-1} and 400 mg of chloride L^{-1}.
Moderate:	Less than 10% symptoms may be observed when the plants are irrigated with water containing 200 mg of sodium L^{-1} and 400 mg of chloride L^{-1} and having an EC_{iw} of 0.9 dS/m.
Sensitive:	More than 20% of the leaves may develop symptoms when the plants are irrigated with water containing 200 mg of sodium L^{-1} and 400 mg of chloride L^{-1} and having an EC_{iw} of 0.6 dS/m.

[c] The definitions of soil salinity tolerance are

Highly tolerant:	Permissible soil EC_e greater than 6 dS m^{-1},
Tolerant:	Permissible soil EC_e greater then 4 and less than 6 dS m^{-1},
Moderate:	Permissible soil EC_e greater than 2 and less than 4 dS m^{-1}, and
Sensitive:	Permissible soil EC_e less than 2 dS m^{-1}.

V.B.2. Other Sources of Information

Literature regarding the response of plants to salinity has accumulated so rapidly over the years that a comprehensive bibliography is needed to help search for key references. Fortunately, L. E. Francois and E. V. Maas of the U.S. Salinity Laboratory assembled such a bibliography in 1978. It contains 2,350 literature citations from 1900 to 1977, including citations for papers that describe the effects of salt and boron on whole plants. Key phrases for each citation include plant name, experimental materials and methods, treatments and variables evaluated, and results or data obtained. The bibliography has four sections, one listing common plant names, another listing botanical names, another describing treatments, and yet another organized by results.

An updated version of this bibliography that currently includes over 6,200 literature citations exists on the Salinity Laboratory's website at www.ars.usda.gov/Services

/docs.htm?docid=8908. It is available to everyone, with no password needed to access it, as of 2006.

Researchers at the Salinity Laboratory have written a number of key papers over the years. In one of the earliest papers, "Salt Tolerance of Ornamental Shrubs and Ground Covers" (Bernstein, Francois, and Clark, 1972), the authors describe their experiments on 25 species of plants salinized with sodium chloride and calcium chloride. They discovered that overall salt tolerance does not correlate well with tolerance to injury by chloride or sodium (specific ions). They also concluded that survival of a plant under highly saline conditions is not necessarily a good indicator of overall salt tolerance. The paper includes several tables and one illustration comparing the salt tolerances of various shrubs and ground covers.

Another key reference by Salinity Laboratory researchers is "Salt Tolerance of Ornamental Shrubs, Trees, and Iceplant" (Francois and Clark, 1978). As with the earlier study, the researchers artificially salinized plants with combination of sodium chloride and calcium chloride salts in the water or soil. They evaluated 10 species of shrubs, 2 species of trees, and 4 species of iceplant. Tolerant varieties were reported to include Texas sage (*Leucophyllum frutescens*), brush cherry (*Syzygium paniculatum*), Aleppo pine (*Pinus halepensis*), croceum iceplant (*Hymenocyclus croceus*), purple iceplant (*Lampranthus productus*), rosea iceplant (*Drosanthemum hispidum*), and white iceplant (*Delosperma alba*). Those species were affected little, if at all, by soil with salinities as high as an EC_e (electrical conductivity of the saturated soil paste extract) of 7 dS/m. Sensitive species included glossy abelia (*Abelia grandiflora*), photinia (*Photinia fraseri*), Oregon grape holly (*Mahonia aquifolium*), and Pyrenees cotoneaster (*Cotoneaster congestus*). Each of those was severely damaged, or killed, when the EC_e measured 4 dS/m. Another important finding by these researchers was that leaves typically were injured only at levels of salinity that suppressed growth by 50% or more.

Another pertinent reference by Salinity Laboratory researchers is "Salt Tolerance of Plants" (Maas, 1986). In that journal article, Maas examined the salt tolerance of both crops and ornamental plants, including the criteria for establishing salt tolerance, the factors that influence the salt tolerance of plants, and the relative salt tolerances for herbaceous crops, woody crops, and ornamentals in a series of five tables. Maas pointed out that susceptibility to foliar injury varies considerably among species and depends more on leaf characteristics and the rate of absorption of water than on tolerance of soil salinity. Maas examined the effects of chloride, sodium, and boron on both crops and ornamental plants and provided several tables listing sensitivities of plants to chloride, sodium, and boron.

The Salinity Laboratory's parent organization, the U.S. Department of Agriculture, published a series of leaflets known as Home and Garden Bulletins during the 1960s and 1970s. One of those, the leaflet titled "Reducing Salt Injury to Ornamental Shrubs in the West" (Home and Garden Bulletin No. 95), describes how salinity affects plants, outlines how to diagnose salt injury, and presents a few strategies for coping with salinity (Bernstein, 1964). This leaflet is available at certain libraries: visit www.worldcatlibraries.org on the Internet, click on "Try a search," and enter the leaflet's author and title. The mentioned leaflet has been superseded by another one in the series, "Salt Injury to Ornamental Shrubs and Ground Covers" (Francois, 1980), which includes a table showing the relative tolerances of 41 different trees, shrubs, and ground covers. A PDF of this leaflet can be downloaded from the Internet at www.agnic.msu.edu/hgpubs/modus/morefile/hg231_80.pdf. Though both leaflets were written in earlier decades, they contain pertinent general information.

Bernstein (1980) examined the effects of salinity on fruit trees, such as apple, plum, prune, apricot, and almond, which are occasionally used in landscapes. He relates that the relative importance of osmotic effects and specific ion effects on inhibiting plant growth varies widely, depending on the species. He further states that the yields of some species of fruit tree are relatively unaffected by elevated levels of chloride and sodium ions, even when the leaves are severely injured. However, the yields of certain other species of fruit trees are greatly affected by injuries related to chloride or sodium toxicity. Bernstein outlines several other conclusions, too. First, most fruit trees used as crops are salt sensitive. Second, if the salt tolerance for a particular type of fruit tree tends to vary, it is mainly because different varieties or rootstocks absorb toxic ions at different rates. Third, although salinity generally impairs the quality of fruit, in certain cases it can be beneficial to the fruit quality. Fourth, for sprinkler-irrigated trees, uptake of chloride or sodium by wetted leaves can cause severe leaf burn. And fifth, irrigating infrequently, which is often recommended for ornamental trees and shrubs, can accentuate the effect of salinity on fruit trees.

The book *Abiotic Disorders of Landscape Plants: a Diagnostic Guide* (Costello et al., 2003) provides useful guidelines for assessing the salt tolerance of a plant and diagnosing plant-related problems. The authors list the salinity tolerances and boron tolerances of 610 landscape plants in a table in that book. Entries are listed within categories (shrub, tree, palm, ground cover, vine, herbaceous plant, and turfgrass) and are sorted alphabetically by botanical or scientific name. The list is useful for comparing species and for discovering the salt tolerance or boron tolerance of a particular plant already chosen for a landscape. The authors also provide a table of the same plants sorted according to salt tolerance, as well as a table sorted according to boron tolerance, with each entry appearing in one of three columns: high, moderate, or low tolerance. These tables are helpful when one is seeking a particular plant to satisfy a known salt tolerance or boron tolerance.

Abiotic Disorders of Landscape Plants: a Diagnostic Guide provides several other useful types of information. One table in the book lists 12 different common fertilizers and the relative salinity of each. Another table in the book displays the salt content of seven kinds of commercially available organic soil amendments, including, for example, chicken manure, steer manure, peat, and redwood compost. Another of the book's tables provides guidance for readers who need to interpret chemical data resulting from laboratory tests of soil, water, or plant tissue. Yet another table in the book lists the methodology and criteria used in evaluating the salinity and boron tolerance data for another of the book's tables. Still another table provides a summary of salt-related problems.

Equally useful, if not more so, is information in Chapters 1, 4, 5, and 6 of the aforementioned book on a structured process for diagnosing plant problems caused by salinity or other abiotic agents. Chapter 6 illustrates the process by outlining six case studies.

Salt tolerances for 18 species of eucalyptus—often used in California's landscapes due to their adaptability to the climate, their ability to tolerate little to no irrigation, their relative lack of natural pests, and their fairly high rate of growth—are included in the aforementioned book on abiotic disorders of landscape plants (Costello et al., 2003). A list of 60 species of eucalyptus, plus numerous species of casuarina, acacia, and other Australian shrubs and small trees, appears in an appendix of a book published by the UN Food and Agriculture Organization (Tanji and Kielen, 2002). The list of salt-tolerant plants originated from the Australia Department of Agriculture's farm-revegetation project as part of its sustainable rural development program in 1998.

Many books have been published over the years to help people choose landscape trees, shrubs, and ground covers for California's cool, marine coastal climates and its dry, warm inland climates. Many focus on water-conserving plants because minimizing water usage continues to be one of California's perennial challenges. Very few of the available books contain information about choosing salt-tolerant plants for those same California climate zones. One book that does, by Perry (1981), provides not only a list of plants tolerant of saline soils but also a list of those that do well in the presence of salt spray. Table V.B.2.1 in this chapter, excerpted and adapted from the lists in Perry's book, displays the relative salt tolerance of 36 species of shrubs and trees that are well adapted to the climatic zones of the Los Angeles and San Diego areas.

A number of websites contain helpful information. Currently, the following relevant links are active:

- www.edis.ifas.ufl.edu/EP012 At this site of the University of Florida's Institute of Food and Agricultural Sciences, there are two fairly extensive tables that list the salt tolerances of a number of trees, shrubs, ground covers, vines, and grasses recommended by the institute for landscapes in northern Florida and for southern portions of the state. Many species listed are popular elsewhere in the United States, including California.
- www.denverwater.org At this website of Denver Water, Colorado's largest water utility, click on the side heading "Recycled Water" and then click on the hyperlink "Effects of Recycled Water on Trees and Shrubs" that subsequently emerges on the main window for a number of tips for keeping trees and shrubs healthy when one is irrigating them with recycled water.
- www.sanjoseca.gov/sbwr/Landscape/GuidePlantList.htm This section of the website for the city of San Jose, Calif., has a list of locally available plants for landscapes found to be compatible with irrigation by local recycled water. The list includes 47 species of trees, 29 species of shrubs, 10 species of ground covers, 3 species of vines, 7 species of perennials, and 13 species of native grasses. The vast majority are relatively common varieties that are popular for landscapes elsewhere in California.

In light of the ever-changing and ephemeral nature of websites and their links, the aforementioned may or may not continue to be active. In any case, a search engine can be used to discover alternate relevant links.

V.C. Salt Tolerance of Floricultural Species

Beginning over 50 years ago, researchers at the University of California–Los Angeles, the U.S. Salinity Laboratory in Riverside, and the Metropolitan Water District in La Verne evaluated the salt tolerance of many agronomic and horticultural species. Their legacy—salt tolerance ratings assigned to a number of species and the recommendations for soil, plant and irrigation management practices—is still valid and pertinent today. It should be noted, however, that some varieties and cultivars of major crops have changed and that in some cases there can be significant varietal differences in salt tolerance. This finding is particularly true with perennial crops where rootstock, as well as scion, varieties have changed over the years.

The work of earlier researchers indicated that waters containing 500 parts per million (ppm, or mg/L) of total dissolved solids (TDS) are likely to reduce the growth or cause leaf burn only for the most salt-sensitive plants or for plants grown either in poorly suited soil, along with unfavorable temperature, sunlight, or humidity or with inappropriate irrigation management practices (Pearson, 1949).

They determined that waters containing 800 to 1,000 ppm of TDS also may be used without risk, provided that the kinds of salts contributing to salinity (e.g., sodium, chloride, and sulfate) are considered. Most types of fuchsia (*Fuchsia* spp.), camellia (*Camellia* spp.), and rhizomatous begonia (*Begonia* spp.), for example, grow well in waters of 800 ppm of TDS if sulfate is the principal anion. Yet the same water can cause problems for certain varieties of azaleas and for the Rex begonia. These earlier researchers also found that saline waters dominated by chloride may cause unsightly leaf burn, particularly with sprinkler irrigation.

In the late 1940s, researchers found that calcium-dominated saline waters seemed less detrimental to the growth of plants than did waters containing high concentrations of sodium. Their work suggested that plants may be adversely affected by interactions or imbalances of ions, either in the plant, in the water, or in the soil (Hayward and Wadleigh, 1949). For example, levels of calcium that meet the nutritional requirements of plants not subjected to sodium-based salinity may be inadequate for plants that are exposed to high levels of sodium (Hayward and Bernstein, 1958). Water in the soil that is dominated by sodium not only reduces the availability of calcium but also reduces the mobility and transport of calcium to actively growing tissues. Salinity-induced nutritional disorders may result from the effects of sodium-dominated salinity on nutrient availability, as well as on the uptake, transport, and partitioning of competitive ions within the plant.

In the 1940s and 1950s, researchers examined the effects of specific ions such as boron, chloride, and bicarbonate in soils and irrigation waters on the health of floral species. Azaleas (*Rhododendron* spp.), for example, were found to be relatively sensitive to nutritional imbalances, and even with only slightly saline conditions, calcium deficiency was induced by bicarbonate in the irrigation water (Lunt et al., 1956). Researchers reported that floral species typically respond to salinity by growing less: the length and weight of flowering stems were reduced, or flowers were fewer or smaller. Boron, however, was less detrimental than salinity to the number, size, length, and width of flowering stems of azalea and gardenia (*Gardenia* spp.; Lunt et al., 1957), carnation (*Dianthus caryophyllus*; Lunt et al., 1956), China aster (*Callistephus chinensis*; Kohl et al., 1957), gladioli (*Gladiolus* spp.; Kofranek et al., 1957), and poinsettia (*Euphorbia pulcherrima*; Kofranek et al., 1956). Once the boron tolerance limits for the species were exceeded, injury was characterized by interveinal chlorosis, marginal leaf scorch, and finally, leaf abscission. Refer to Table V.C.1 for boron tolerance limits of selected floral species.

Some researchers in the 1960s and later conducted salt tolerance trials in which they used a single salt, generally sodium chloride, as the salinizing agent. Other researchers, however, have recommended using saline water with sodium/(sodium + calcium) ratio, i.e., $Na^+/(Na^+ + Ca^{2+})$, in the range of 0.1 to 0.7 in experimental studies, as this recommendation better reflects the ion ratios in irrigation water or in the water in the soil for most horticultural crops (Pearson, 1949; Bernstein, 1975). The uncharacteristic salinizing composition of the former may induce ion imbalances that contribute to calcium-related physiological disorders in certain crops (Shear, 1975; Sonneveld, 1988). Furthermore, the use of single-salt solutions in salt tolerance experiments may result in misleading and erroneous interpretations of a plant's response to salinity.

Grattan and Grieve (1999) examined the relationship between a horticultural crop's mineral nutrients and its salinity tolerance. They reviewed the literature that pertains to salinity and mineral nutrition, particularly nitrogen, phosphorus, potassium, calcium, magnesium, sulfur, and boron, and briefly examined the potential interactions between certain micronutrients—copper, iron, manganese, molybdenum, and zinc—and salinity. They concluded that a multiplicity of salinity-nutrient interactions occur simultaneously for many types of plants and that whether those interactions ultimately affect the plant as measured by yield, quality, size or elongation, etc. depends on the levels of salinity, the composition of salts, the species, the nutrients, and a host of other environmental factors.

Even under nonsaline conditions, significant economic losses have been linked to inadequate calcium nutrition of horticultural crops. A number of factors can influence the amount of plant-available calcium, including the total supply of calcium, the nature of the counter-ions, the pH of the substrate, and the ratio of calcium to other cations in the irrigation water (Grattan and Grieve, 1999). Calcium-related disorders may even occur in plants grown on substrates where the calcium concentration appears to be adequate (Pearson, 1949; Bernstein, 1975). Symptoms indicating nutritional deficiency are generally caused by differences in calcium partitioning to the growing regions of the plant. All parts—leaves, stems, flowers, and fruits—actively compete for the pool of available calcium, and each part independently influences the movement of calcium. Organs that transpire more actively are likely to have the highest concentrations of calcium.

In agricultural crop plants that consist of large heads enveloped by outer leaves, such as cabbage and lettuce, excessive transpiration by the outer leaves diverts calcium from the rapidly growing embryonic plant tissue (Bangerth, 1979). A deficiency of calcium manifests as internal browning in the younger tissues of cabbage and lettuce and as “blackheart” in celery. Calcium deficiency may also occur in reproductive tissues and cause decreases in quality such as “blossom end rot” of tomato, melon, and pepper; “soft nose” of mango and avocado; and cracking and “bitter pit” of apple. Artichokes grown under arid, but nonsaline, conditions can exhibit calcium deficiency, with injury appearing as necrosis of inner bracts (Francois, 1995).

Horticultural crops that are susceptible to calcium-related disorders without salinity become even more so under saline conditions. As the concentration of salt in the root zone increases, the plant’s requirement for calcium also increases (Bernstein, 1975). At the same time, the uptake of calcium from the substrate may be depressed because of ion interactions, chemical precipitation, and increases in ionic strength (Grattan and Grieve, 1999). When these susceptible crops are also challenged by salinity, their market quality can decline significantly.

Very little information is available on the differential partitioning of calcium and any resulting patterns of injury in floricultural species. Certain varieties of Asiatic hybrid lilies are susceptible to calcium-related disorders, whereas others are immune. Injury on “Star Gazer,” “Acapulco,” and “Muscadet” manifests as necrosis of the upper leaves (Chang et al., 2004) and on “Pirate,” as white-gray cross bands on the leaves, as well as tip burn (Berghoef, 1986). The varieties “Alliance” and “Helvetia” appear to be resistant to the disorder (Chang et al., 2004). Poinsettia (*Euphorbia pulcherrima*) also exhibits variety-dependent susceptibility to calcium deficiency, with injury usually appearing as marginal necrosis of the bracts. Wissemeier (1993) demonstrated that “Angelika” and “Supjibi” were sensitive. In contrast, injuries do not appear to occur in the varieties “Diva Starlight” and “Lilo.”

The effect of salinity on the sensitivity of floral crops to calcium-related disorders has not been widely explored. One study, however, was conducted with poinsettia, a moderately salt-tolerant crop (Cox, 1991; Dole and Wilkins, 1999). No visible symptoms associated with excess fertilizer salinity were observed in “Red Sails” poinsettia (Cox, 2001) or “V−14 Glory” poinsettia (Ku and Hershey, 1991), although measurements of EC revealed that salinity levels in the root zone exceeded the satisfactory range for the crop (Hartmann et al., 1988).

Other information on the salt tolerance of floral species results from studies of the responses of plants to chloride-dominated saline irrigation waters. Such water typically contains both sodium chloride and calcium chloride. A few researchers evaluated the salt tolerance of floral crops by using irrigation waters prepared to simulate recycled or saline waters typical of a specific location or site. Dutch growers often use solutions with compositions of salts adjusted to the average found in surface waters in the western Netherlands (Bik, 1980; Sonneveld, 1988).

Saline waters (EC = 2.5 to 4.5 dS/m) from local wells in Israel continue to be used successfully for growing floral species on over 700 ha throughout the Negev Desert (Shillo et al., 2002). Arnold and fellow researchers (2003) demonstrated that recycled runoff from a plant nursery and water from a constructed wetland were suitable for irrigating certain bedding plants and flowers. Recent floriculture research at the U.S. Salinity Laboratory involved the use of artificial waters specially prepared to mimic three waters used for irrigation in California: the sodium- and sulfate-dominated drainage effluents from the San Joaquin Valley, various concentrations of Colorado River water, and groundwaters affected by seawater intrusion along the California coast (Grieve et al., 2005; Carter et al., 2005; and Grieve et al., 2006).

An important caveat to bear in mind is that research on the salt tolerance of floricultural species continues to be largely devoted to providing information useful for helping commercial floricultural growers maintain the productivity, quality, and profitability of their plants. The standards of quality for plants in landscapes are far less stringent. For example, because exposure of a plant to salinity generally decreases the length of the stems and the number of florets—two major determinants of quality in commercial flowers—growers of floricultural crops are likely to use the highest quality of water available to maximize the plant's height and number of blooms. However, a slightly shorter flowering plant with somewhat fewer florets would be aesthetically acceptable for use in a landscape—as long as its overall health remains uncompromised, its stems are robust, its leaves and flowers remain true to color, and its flowers and leaves sustain no visible salt injury. Take the specific example of two species of statice grown to be sold as flowers, *Limonium perezii* and *L. sinuatum*, which complete their life cycles in water saltier than seawater (Aronson, 1989). To discover if either could produce marketable cut flowers at lower salinities, both species were grown under irrigation with waters ranging from 2 to 30 dS/m (Grieve et al., 2005). Both species of statice flowered and set seed in all treatments, but their height decreased consistently and significantly as salinity increased, with plants receiving the most saline treatment growing only one-third as tall as those irrigated with nonsaline waters. However, even under severe salt-related stress, both produced healthy plants with attractive foliage and colorful flowers on sturdy, albeit short, stems. The salt tolerance of both species for use as marketable cut flowers is rated as "low" based on stem length (Farnham et al., 1985), but for use in a landscape, they would fall in the "very tolerant" category.

It should also be noted that the effects of salinity on floral crops are not always adverse. Salt-related stress can beneficially affect the yield, quality, and disease resistance of a plant. In some instances, the uptake and accumulation of salinizing ions stimulates growth. Cabrera (2001) and Cabrera and Perdomo (2003) observed a positive correlation between relatively high leaf-chloride concentrations (0.45%) and dry weight for container-grown rose ("Bridal Pink" on *Rosa manetti* rootstock). Yield and quality were unaffected. Salinity imposed early in the life cycle of some cut-flower species tends to limit vegetative growth with favorable results. Salinity-induced reduction in the length of leaf-supporting stems may be beneficial in chrysanthemum, where tall cultivars are treated with growth regulators to keep the plants compact and short. While plant height is often reduced by moderate salinity, the length of time to maturity and the size of developing floral buds generally remain unaffected by stress (Lieth and Burger, 1989).

Application of salinity after some optimal period of vegetative growth tends to enhance reproductive growth and often improves quality. Shillo and coresearchers (2003) reported that salinity imposed on *Eustoma grandiflorum* during its final stages of vegetative growth resulted in significant increases in the number of flowers and in stem weight and diameter. Another benefit of salt treatment was the production of more compact flower clusters, the compactness of which prevents developing buds from drooping. Similar positive effects have been noted with carnation. Salt-related stress during its early reproductive growth resulted in shorter, more robust flower-bearing stalks with larger developing buds (Baas et al., 1995).

Some of the significant varietal differences in salt tolerance reported for cut-flower crops (Table V.C.2) may be due to differences in climate, nutrition, composition of the salinizing medium, and the duration of exposure to salinity. These differences become very important in selecting plants for landscapes irrigated with recycled waters.

In trials conducted under nearly identical cultural conditions, Sonneveld and coresearchers (1987, 1999) reported that the carnation cultivar "Beauty" was significantly more tolerant of soil salinity than were either "Scania" or "Nora Barlo." In the same study, the hybrid lilies "Star Gazer" and "Connecticut King" both produced lighter-weight flowers when the salinity in the soil extract exceeded 1.2 dS/m. Also, the lilies produced 9.6 and 4.6% fewer flowers, respectively, with each unit increase in salinity. Additional information regarding varietal differences in salt tolerance for selected cut flowers is included in Table V.C.3.

The parameters used to assess the salt tolerance of cut flowers need to be considered to accurately assign a tolerance category to a species. Generally, flower quality is less sensitive to salinity than is vegetative growth. For example, once the threshold of "Fabiola" gerbera (*Gerbera jamesonii*) is exceeded, yield based on the number of flower-bearing stalks per plant declines 17% for each unit increase in salinity, but the diameter of the flowers is relatively insensitive, declining only 3% per unit increase. Likewise, the number and weight of flowering stalks in *Anthurium spathes* are more affected by salinity than are the diameter of its flowers. The salt tolerance of the poinsettia variety "Barbara Ecke Supreme" is higher when the rating is based on the diameter of bracts rather than on injury to leaves and an increase in abscissions—the dropping of flowers, fruits, or leaves from the plant (Kofranek et al., 1956).

Salt tolerance ratings of some flower crops as shown in Table V.C.1 are derived from data collected from closely related plants of horticultural and agronomic value. Data regarding the salt tolerance of ornamental *Brassica* species such as kale and cabbage are virtually nonexistent, but it would be reasonable to assume that their salt tolerance would not vary sharply from that of the same leafy vegetables grown under agronomic conditions. Similarly, the *Carthamus tinctorius* varieties of safflower used as cut flowers and bedding plants will likely fall into the same salt tolerance category as the well-known seed oil-producing variety. The commercially important pistachio tree (*Pistacia vera*) and its close relatives are also relatively tolerant of both salt and excess boron stresses (Ferguson et al., 2002). *P. atlantica* and *P terebinthus* are attractive ornamentals, potentially useful for salt-affected sites.

Table V.C.1. Boron tolerance limits for cut flowers.

Sensitivity to boron	**Species**		**Threshold (g/m^3)**	**Reference**
	Botanical name	**Common name**		
Sensitive	*Delphium* sp.	Larkspur	0.5–1.0	Eaton, 1944
	Pelargonium x *hortorum*	Geranium	0.5–1.0	Kofranek et al., 1958
	Viola odorata	Violet	0.5–1.0	Eaton, 1944
	Viola tricolor	Pansy	0.5–1.0	Eaton, 1944
	Zinnia elegans	Zinnia	0.5–1.0	Eaton, 1944
Moderately sensitive	*Calendula officinalis*	Marigold	1.0–2.0	Francois and Clark, 1979
	Callistephus officinalis	China aster	1.0–2.0	Kohl et al., 1957
	Euphorbia pulcherrima	Poinsettia	1.0–2.0	Kofranek et al., 1956
	Gardenia sp.	Gardenia	1.0–2.0	Lunt et al., 1957
	Gladiolus sp.	Gladiola	1.0–2.0	Kofranek et al., 1957
Moderately tolerant	*Dianthus carophyllus*	Carnation	2.0–4.0	Lunt et al., 1956
	Lathyrus odoratus	Sweet pea	2.0–4.0	Eaton, 1944

Table V.C.2. Salt tolerance of selected landscape flower crops.

Botanical name	Common name	Salt tolerance[a]	Reference(s)
Agapanthus orientalis	Lily of the Nile	Sensitive	Skimina, 1980
Ageratum houstonianum	Ageratum	Moderately sensitive	Devitt and Morris, 1987
Alstroemeria hybrids	Inca lily, Peruvian lily	Very sensitive	Sonneveld, 1988
Amaranthus hypochondriacus	Pygmy torch	Tolerant	Aronson, 1989
Amaranthus tricolor	Love-lies-bleeding	Tolerant[b]	Aronson, 1989
Anthurium andreanum	Anthurium	Very sensitive	Sonneveld and Voogt, 1983
Antirrhinum majus	Snapdragon	Moderately sensitive	Carter et al., 2005
Artemesia stelleran	Dusty Miller	Moderately sensitive[c]	Glattstein, 1989
Begonia bunchii	Begonia	Sensitive	Pearson, 1949
Begonia Rex-cultorum	Rex begonia	Very sensitive	Pearson, 1949
Begonia ricinifolia	Begonia	Sensitive	Pearson, 1949
Bouvardia longiflora	Bouvardia	Moderately sensitive	Sonneveld et al., 1999
Brassica oleracea	Ornamental cabbage	Sensitive[b]	Maas and Grattan, 1999
Brassica oleracea	Ornamental kale	Sensitive[b]	Shannon et al., 2000
Calendula officinalis	Pot marigold	Moderately tolerant	Chaparzadeh et al., 2003
Callistephus chinensis	China aster	Moderately sensitive	Kohl et al., 1957
		Moderately tolerant	Sonneveld et al., 1999
Calocephalus brownii	Cushion bush	Moderately sensitive	Costello et al., 2003
Camellia japonica	Camellia	Sensitive	Pearson, 1949
Carathamus tinctorius	Safflower	Moderately tolerant[b]	Beke and Volkmer, 1994
Catharanthus roseus	Vinca	Sensitive	Arnold et al., 2003; Huang and Cox, 1988
Celosia argenta cristata	Crested coxcomb	Moderately sensitive	Devitt and Morris, 1987
Celosia argenta cristata	Chief celosia	Tolerant	Carter et al., 2005
Cereus peruviana	Apple cactus	Moderately sensitive	Costello et al., 2003
Chlorophytum comosum	St. Bernard's lily	Tolerant	Zurayk et al., 1993
Chrysanthemum morifolium	Mum	Moderately tolerant	Kofranek et al., 1953; Pearson, 1949
Clematis orientalis	Clematis	Very tolerant	Krupenikov, 1946
Coleus blumei	Coleus	Tolerant	Zurayk et al., 1993
Codiaeum punctatus	Croton	Moderately tolerant	Farnham et al., 1985
Consolida ambigua	Larkspur	Sensitive	Arnold et al., 2003
Cosmos bipinnatus	Cosmos	Very sensitive	Devitt and Morris, 1987
Coreopsis grandiflora	Coreopsis	Moderately sensitive[c]	Glattstein, 1989
Crassula ovata	Jade plant	Moderately sensitive	Skimina, 1980
Cyclamen persicum	Cyclamen	Sensitive	Bik, 1980
Cymbidium spp.	Orchid	Very sensitive	de Kreij and van den Berg, 1990
Dianthus barbatus	Pinks	Moderately sensitive	Monk and Peterson, 1961
Dianthus caryophyllus	Carnation	Moderately tolerant	Baas et al., 1995
Dianthus chinensis	Carnation	Moderately tolerant	Devitt and Morris, 1987
Eschscholzia californica	California poppy	Moderately tolerant[c]	Glattstein, 1989
Euphorbia pulcherrima	Poinsettia "Red Sails"	Sensitive	Cox, 1991
Euphorbia pulcherrima	Poinsettia "Barbara Ecke"	Very sensitive	Kofranek et al., 1956

Euryops pectinatus	Golden marguerite	Sensitive	Wu et al., 1999
Eustoma grandiforum	Lisianthus	Moderately sensitive	Shillo et al., 2002
Felicia amelloides	Felicia	Sensitive	Farnham et al., 1985; Skimina, 1980
Fuchsia hybrida	Fuchsia	Very sensitive	Pearson, 1949
Gardenia augusta	Gardenia	Sensitive	Lunt et al., 1957
Gazania aurantiacum	Gazania	Moderately tolerant	Costello et al., 2003
Gerbera jamesonii	Gerbera daisy	Moderately sensitive	Sonneveld and Voogt, 1983; Baas et al., 1995; Savvas et al., 2002
Gazania spp.	Treasure flower	Very tolerant	Perry, 1989
Gladiolus spp.	Gladiola	Sensitive	Kofranek et al., 1957
Gomphrena globosa	Globe amaranth	Moderately sensitive	Kang and van Iersel, 2002
Gyposphila paniculata	Baby's breath	Moderately tolerant[c]	Shillo et al., 2002
Helianthus annuus	Sunflower	Moderately tolerant	Ashraf and O'Leary, 1995
Helianthus debilis	Cucumber leaf	Very tolerant	Costello et al., 2003
Hibiscus rosa-sinensis	Hibiscus	Sensitive	Bernstein et al., 1972
Hippeastrum hybridum	Amaryllis	Very sensitive	Shillo et al., 2002; Sonneveld and Voogt, 1983
Hymenocallis keyensis	Spiderlily	Moderately tolerant	Costello et al., 2003
Impatiens × hawkeri	Impatiens	Sensitive	Todd and Reed, 1988
Kalanchoe spp.	Kalanchoe	Moderately tolerant	Costello et al., 2003
Kochia childsii	Kochia	Tolerant	Monk and Peterson, 1961
Lathyrus japonica	Sweet pea	Moderately tolerant	Costello et al., 2003
Lilium spp.	Asiatic hybrid lily	Sensitive	Sonneveld, 1988
Lilium spp.	Oriental hybrid lily	Sensitive	Sonneveld and Voogt, 1983
Limonium spp.	Japanese Limonium	Very tolerant	Shillo et al., 2002
Limonium latifolium	Sea lavender	Very tolerant	Aronson, 1989
Limonium perezii	Statice	Sensitive	Farnham et al., 1985
		Very tolerant	Grieve et al., 2005; Carter et al., 2005
Limonium sinuatum	Statice	Very tolerant	Grieve et al., 2005; Carter et al., 2005
Lobularia maritima	Sweet Alyssum	Moderately tolerant	Monk and Peterson, 1961
Matthiola incana	Stock	Very tolerant	Lunt et al., 1964; Wigdor et al., 1958
Narcissus tazetta	Paperwhite Narcissus	Sensitive	Arnold et al., 2003
Oenthera speciosa	Mexican evening primrose	Moderately tolerant	Costello et al., 2003
Ophiopogon jaburan	Giant turf lily	Moderately sensitive	Skimina, 1980
Ornithogalum arabicum	Arabian star flower	Very sensitive	Shillo et al., 2002
Pelargonium × hortorum	Geranium	Sensitive	Kofranek et al., 1958
Pelargonium domesticum	Geranium	Tolerant	Zurayk et al., 1993
Pelargonium peltatum	Ivy geranium	Moderately tolerant	Costello et al., 2003
Petunia hybrida	Petunia	Tolerant	Devitt and Morris, 1987
Portulaca grandiflora	Moss rose	Very tolerant	Devitt and Morris, 1987
Phalaenopsis hybrid	Orchid	Very sensitive	Wang, 1998
Protea obtusifolia	Protea	Moderately tolerant	Rodrigues-Perez et al., 2000
Rhododendron hybrids	Azalea	Moderately sensitive	Cabrera, 2003

Rhododendron obtusum	Azalea	Sensitive	Pearson, 1949; Lunt et al., 1957
Rosa × *hybrida*	Rose	Sensitive	Cabrera and Perdomo, 2003; Fernández Falcón et al., 1986
Stapelia gigantea	Starfish flower	Moderately tolerant	Costello et al., 2003
Strelitzia reginae	Bird of paradise	Very sensitive	Farnham et al., 1985
Tagetes erecta	Marigold	Moderately tolerant	West et al., 1980
Tagetes patula	Marigold	Moderately tolerant	Devitt and Morris, 1987
Trachelium caeruleum	Blue throatwort	Sensitive	Shillo et al., 2002
Tropaeolum majus	Nasturtium	Moderately sensitive[c]	Glattstein, 1989
Vinca major	Periwinkle	Moderately tolerant	Costello et al., 2003
Vinca minor	Myrtle	Sensitive	Farnham et al., 1985
Viola × *wittrockiana*	Pansy	Sensitive	Arnold et al., 2003
Zinnia elegans	Zinnia	Moderately sensitive	Devitt and Morris, 1987

[a] Criteria for assigning salt tolerance: not more than 50% reduction in growth, no visually observable foliar burn, and maximum permissible $\mathrm{EC_e}$ (dS $\mathrm{m^{-1}}$) as follows:

<2, very sensitive;
2–3, sensitive;
3–4, moderately sensitive;
4–5, moderately tolerant;
5–6, tolerant; and
>6, very tolerant.

[b] Based on salt tolerance classification of related agronomic or horticultural species or variety.

[c] Only qualitative data are available.

Table V.C.3. Varietal differences in salt tolerance for selected cut-flower crops.

Common name	Variety	Threshold EC_e ($dS\ m^{-1}$)	Slope (%)	Reference
Carnation	Adefie	1.1	2.1	Sonneveld et al., 1999
	Beauty	4.3	3.9	Sonneveld et al., 1999
	Princess white	5.0	—	Devitt and Morris, 1987
	Scania	1.2	6.9	Sonneveld and Voogt,1987
	Nora Barlo	1.2	5.5	Sonneveld and Voogt,1987
Chrysanthemum	Indianapolis white	2.4	—	Rutland,1972
	Spider	>0.8	6.8	Sonneveld and Voogt, 1987
	Horim	>0.8	12.1	Sonneveld and Voogt, 1987
	Maghi[a]	>8.0	—	Rahi and Datta, 2000
	Basantika[a]	>8.0	—	Rahi and Datta, 2000
	Bronze Kramer	6.0	9.0	Kofranek et al., 1953
	Albatross	2.0	—	Lunt et al., 1962
Gerbera	Beauty	1.5	9.8	Sonneveld et al., 1999
	Mandarine	<0.6	5.1[b]	Sonneveld and Voogt, 1983
	Fabiola	<0.6	6.5[b]	Sonneveld and Voogt, 1983
Rose	Baccara	1.0	10	Yaron et al., 1969
	Grenoble	2.1	20	Bernstein et al., 1972
	Forever yours	1.8	—	Hughes and Hanan, 1978
	Sonia	1.0	10	Zeroni and Gale, 1989
	Europa	2.1	5.3	Sonneveld et al.,1999
	Madelon	4.8[c]	2.0	Baas and Berg, 1999
	Kardinal	2.2	20	Wahome et al., 2000
	Bridal pink	5.4[d]	—	Cabrera, 2001

[a] Plants grown from cuttings subjected to mutagenesis by gamma irradiation resulted in more salt-tolerant genotypes.

[b] Based on weight of peduncle.

[c] Recirculating irrigation system.

[d] EC of leachate.

V.D. Salt Tolerance of Turfgrasses

The quality of a turfgrass stand is the net result of inherent genetic characteristics of the particular species being grown and the interactions of climate, pests, and the soil. In arid and semiarid regions where rainfall is insufficient to leach salt out of the root zone, excessive amounts of soluble salts may accumulate in the root zone. This phenomenon can impose limits on the production or the management of quality turf (Carrow and Duncan, 1998; Marcum, 2006). Salinity-related stress on turfgrasses is also a serious problem near the seacoast, both because the concentration of salt in the air typically is higher than that found inland and because shallow water tables may be unusually saline.

Wherever salinization of soils occurs, it is a continuous process resulting from various combinations of these factors: insufficient rainfall, inadequate irrigation, poor drainage, irrigation with water of poor quality, and the upward movement of salts from saline shallow groundwater.

As a general rule, if the amount of water applied to the soil (irrigation plus natural precipitation) exceeds evapotranspiration, salt moves downward. Conversely, if evapotranspiration exceeds the amount of water applied, salt movement is upward. In the latter case, salt drawn to the soil surface gradually accumulates to levels toxic to turfgrasses.

Depending on the salinity tolerance of the turfgrass grown, full stands of grass can sometimes be established at low or moderate levels of soil salinity. Turfgrass growth in highly saline soils, however, is restricted (Carrow and Duncan, 1998).

The symptoms of salinity-related stress in turfgrasses are likely to vary somewhat, because existing salt can result in osmotic stress (physiological drought), nutritional imbalances, toxicity, or a combination of these maladies. In general, however, the following symptoms are associated with turfgrass grown under saline conditions:

- Turf is likely to appear blue-green or light bright-green in color during the early stages of salt stress. This coloration is followed by irregular shoot growth.
- Necrotic spots may develop on leaves if toxicity from a specific ion (such as boron) occurs.
- As salinity-related stress increases, the shoots increasingly wilt and become progressively darker green.
- Higher levels of salinity cause burning of the tips of leaves, with the burn eventually extending downward toward the entire leaf surface. At this level, shoot growth is greatly reduced and turfgrass is stunted. As salinity-related stress increases, leaves generally become finer textured and the growth of roots is stunted, often resulting in

shallow roots. If corrective steps are not taken, the growth of grass will be minimal, the density of shoots will decrease, and individual plants will die, thinning the stand. The extent of salt uptake and its consequent effects on the growth of turf are directly related to the concentration of salt in the soil water. Growth of most turfgrasses is not significantly affected by salt levels below an EC_e of 2 dS/m. In soils with salt levels of more than 2 dS/m, the growth of most turfgrasses is gradually restricted. Some notable exceptions, however, would include bermudagrass and seashore paspalum, which can tolerate soil salinities greater than an EC_e of 10 dS/m. Due to pronounced differences among turfgrass species and cultivars in their tolerance to both individual salt ions and total salinity, each turfgrass must be individually evaluated with regard to a specific type of soil salinity.

- Higher levels of salinity cause burning of the tips of leaves, with the burn eventually extending downward toward the entire leaf surface. At this level, shoot growth is greatly reduced and turfgrass is stunted. As salinity-related stress increases, leaves generally become finer textured and the growth of roots is stunted, often resulting in shallow roots. If corrective steps are not taken, the growth of grass will be minimal, the density of shoots will decrease, and individual plants will die, thinning the stand.

Due to many interacting factors, the “absolute” salinity tolerance of a turfgrass species cannot be determined. However, different turfgrasses can be compared, with relative salt tolerance given in terms of the acceptable salt content of the soil root zone, expressed as the EC_e of soil water extract. Table V.D.1 (Harivandi et al., 1992; Marcum, 1990; Marcum, 1999) is a general guide to the salt tolerance of turfgrass species (substantial differences in salt tolerance exist among cultivars within species) and shows, for example, that Kentucky bluegrass (*Poa pratensis*) tolerates soil salinity at EC_e levels up to 3 $dS\ m^{-1}$. As the table indicates, soils with an EC_e below 3 $dS\ m^{-1}$ are considered satisfactory for growing most turfgrasses. Soils with an EC_e above 10 $dS\ m^{-1}$ successfully support only highly salt-tolerant turfgrass species. Salt tolerances of warm-season and cool-season turfgrass cultivars, given in terms of both top growth and root growth, have been summarized by Carrow and Duncan (1998).

Much work has been done in screening existing cultivars or ecotypes for salinity tolerance, including these turfgrass species: *Agrostis stolonifera (*Marcum, 2001), *Buchloe dactyloides* (Wu and Lin, 1994), *Cynodon* spp. (Dudeck et al., 1983; Francois, 1988; and Marcum, 1999), *Distichlis spicata* (Marcum et al., 2005), *Festuca* spp. (Horst and Beadle, 1984; and Leskys et al., 1999), *Lolium perenne* (Rose-Frincker and Wipff, 2001), *Paspalum vaginatum* (Dudeck and Peacock, 1985; Marcum and Murdoch, 1990; and Lee et al., 2004a; 2004b), *Poa* *pratensis* (Qian et al., 2001; Qian and Suplick, 2001; and Rose-Fricker and Wipff, 2001), *Puccinellia* spp. (Harivandi et al., 1982, 1983), *Stenotaphrum secundatum* (Dudeck et al., 1993), and *Zoysia* spp. (Marcum et al., 1998; and Qian et al., 2000). Such work is important and needs to be updated at regular intervals, in order to keep up with the rapid introduction of new cultivars.

The turfgrass industry is expanding rapidly at the same time that pressures from the domestic, agricultural and ecological sectors are placing increasing demands on freshwater resources. Allocation of high-quality waters to high-priority uses has resulted in the transition of landscape sites, parklands, and golf courses to the use of recycled waters. From a survey of golf course superintendents who currently use recycled water for irrigation in the southwestern United States, Devitt et al. (2004) concluded that golf course personnel, while not opposing the switch to reuse water, found that significant changes in turfgrass management practices were required to minimize negative impacts of recycled water.

Table V.D.1. California turfgrass species tolerate various levels of soil salinity.[a]

Sensitive (<3 dS m^{-1})	**Moderately sensitive (3 to 6 dS m^{-1})**	**Moderately tolerant (6 to 10 dS m^{-1})**	**Tolerant (>10 dS m^{-1})**
Annual bluegrassess (*Poa annua*)	Annual ryegrass (*Lolium moltiflorum*)	Course-leaf zoysiagrasses (*Japonica* type)	Alkaligrass (*Puccinellia* spp.)
Colonial bentgrass (*Agrostis tenuis*)	Buffalograss (*Buchloe dactyloides*)	Perennial ryegrass (*Lolium perenne*)	Bermudagrasses (*Cynodon* spp.)
Hard fescue (*Festuca longifolia*)	Creeping bentgrass (*Agrostis palustris*)	Tall fescue (*Festuca arundinacea*)	Fineleaf zoysiagrasses (*Matrella* type)
Kentucky bluegrass (*Poa pratensis*)	Slender, creeping red, and Chewings fescues (*Festuca rubra*)		Saltgrass (*Distichlis* spp.)
Rough bluegrass (*Poa trivialis*)			Seashore paspalum (*Paspalum vaginatum*)
			St. Augustine grass (*Stenotaphurm secundatum*)

[a] Grasses listed here are grouped by their tolerance of soil salinity (expressed as the EC_e of soil paste extract).

V.E. Salt Tolerance of Native Plants

Much information has been published, both in books and on the Internet, to describe California's native plants. However, few sources of information are available regarding the salt tolerances of such plants. *Southwestern Landscaping with Native Plants* (Phillips, 1987) provides relative salt tolerances (as well as other horticultural information) for numerous trees, shrubs, and ground covers that are native to southeastern California, Nevada, Arizona, New Mexico, southern Colorado, southern Utah, and western Texas (see Table V.E.1.1). We have excerpted from that book and then consolidated and edited relevant data for those species of plants reported to be natives of California. The result is Table V.E.1.2, which lists 21 different varieties of shrubs, trees, and ground covers that may be useful for landscape projects in southern California. It is important, however, that the plants featured in this table are arid land varieties; therefore, some may not be particularly well suited for landscapes in Los Angeles or San Diego or elsewhere along the southern California coastal plain. Cross-checking these entries against other sources of horticultural information is recommended.

In the absence of published quantitative data from controlled experiments or field trials involving the salinity of native plants, qualitative salt tolerance information may prove useful. The key is to collect such information with care and to test the information thoroughly for soundness. One method for qualitatively estimating the salt tolerance of a plant is to infer that if the plant originated in an area where saline soils are common, then that plant may do well in other saline environments. Such reasoning is not without risk, however, because many other environmental factors are important during the establishment and growth of a plant and because one or more of those factors may not match between the plant's native origin and the desired site. For example, the microclimate where a plant originally thrived in the wild may not match that of the intended landscape even though the salinity of the soil and perhaps various other factors may be similar.

Another strategy that might work well is to choose several different desirable native species for your landscaping project and then attempt to research those or similar plants in Costello et al. (2003) or other references that list salt tolerance data for "conventional" ornamental plants. It may be that one or more of the California native plants for which information is sought have already become a somewhat popular plant and that their salt tolerance is listed in one of the aforementioned sources.

Table V.E.1.1. Salt tolerance of selected California native trees, shrubs, and ground covers.[a]

Botanical name	Common name	type	Native range	Salt tolerance
Artemesia tridentata	Bigleaf sage	Shrub	Dakotas, Rockies, Sierra Nevada, and Cascades; predominant in Great Basin region	Low to moderate
Atriplex canescens	Fourwing saltbush (Chamiso)	Shrub	New Mexico north to South Dakota and west to California	Excellent
Baccharis emoryii	Broom Baccharis	Shrub	Texas, New Mexico, Arizona, California, Nevada, Utah, Colorado	Good
Baccharis pilularis	Dwarf coyotebush	Ground cover	California coast—Sonoma to Monterey counties	Undocumented; coastal native origin suggests tolerance fair or better
Berberis repens	Creeping Mahonia	Ground cover	Texas, New Mexico, Arizona, California; north to Nebraska and British Columbia	Very poor
Bouteloua gracilis	Blue Grama	Ground cover	Wisconsin to Alberta, Canada; Missouri, Texas, southern California, New Mexico	Fair
Ceratoides lanata	Winterfat	Shrub	Canada south to Mexico, Rocky Mountains west to Pacific Coast	Fair
Chamaebatieria millefolium	Fernbush	Shrub	Idaho south to New Mexico, Arizona, California	Fair
Chilopsis linearis	Desert willow (Flor de Mimbres)	Tree	Central Texas west to California, northern Mexico	Very good
Chrysothamnus nauseosus	Chamisa (Rabbitbrush)	Shrub	Western Canada south to California, Texas, northern Mexico	Moderate
Cowania mexicana	Cliffrose	Shrub	Southern Colorado west to southeastern California, Mexico	Fair
Elaeagnus angustifolia "King Red"	Russian olive	Tree	Southern Europe and southwestern Asia. Naturalized in western U.S.	Excellent
Fallugia paradoxa	Apache plume	Shrub	Texas west to California; Colorado to Mexico	Fair
Fraxinus species	Ash	Tree	Texas to California, Colorado and Utah south to Mexico	Fair to poor
Gaillardia species	Blanketflower	Ground cover	Throughout North America	Good
Linum lewisii	Blue flax	Ground cover	Alaska east to Saskatchewan and south to Kansas, Texas, New Mexico, Arizona, California	Fair to poor
Penstemon ambiguus	Bush penstemon	Ground cover	Kansas, Colorado, Utah, Texas west to California	Fair
Populus tremuloides	Quaking aspen	Tree	Alaska east to Labrador, south to Virginia; Rocky Mountains south to New Mexico and Arizona	Poor
Populus fremontii and subspecies	Cottonwood	Tree	Nevada, Southwestern Utah, northern California, Arizona, New Mexico	Fair
Rhus microphylla	Littleleaf sumac (Lemita)	Shrub	Washington to Missouri, California east to Texas	Fair
Rhus trilobata	Threeleaf sumac (Lemita)	Shrub	Washington to Missouri, California east to Texas	Poor to moderate

[a]Adapted from Phillips (1987).

Table V.E.1.2. Salt-tolerant trees and shrubs for coastal southern California.[a]

Botanical name	Common name	Type of plant	Tolerant of saltwater spray?	Tolerant of saline soil?
Acacia longifolia	Sydney golden wattle	Shrub	Yes	No
Acacia melanoxylon	Blackwood acacia	Shrub	Yes	No
Albizia lophantha	Plume Albizia	Tree	Yes	No
Arctostaphylos edmundsii	Little Sur manzanita	Shrub	Yes	No
Artemisia pycnocephala	Sandhill sage	Shrub	No	Yes
Atriplex species	Saltbush	Shrub	Yes	Yes
Baccharis pilularis	Dwarf chaparral broom	Shrub	Yes	No
Caesalpinia gilliesii	Bird of paradise bush	Shrub or small tree	Yes	No
Callistemon species	Bottlebrush	Shrub or small tree	Yes	Yes
Casuarina species	Beefwood	Tree	No	Yes
Elaeagnus angustifolia	Russian olive	Small tree	No	Yes
Elaeagnus pungens	Silverberry	Shrub	Yes	No
Encelia californica	California Encelia	Shrub	Yes	No
Eriogonum giganteum	St. Catherine's lace	Shrub	Yes	No
Eucalyptus camaldulensis	Red gum	Tree	No	Yes
Eucalyptus rudis	Desert gum	Tree	No	Yes
Eucalyptus torquata	Coral gum	Tree	Yes	Yes
Hakea suaveolens	Sweet Hakea	Shrub	Yes	No
Jasminum humile	Italian jasmine	Shrub	Yes	No
Lavatera assurgentiflora	Tree mallow	Shrub	Yes	Yes
Leptospermum laevigatum	Australian tea tree	Small tree	Yes	No
Melaleuca nesophila	Pink Melaleuca	Tree or large shrub	Yes	Yes
Melaleuca styphelioides	Black tea tree	Tree	Yes	No
Metrosideros tomentosus	New Zealand Christmas tree	Tree or large shrub	Yes	Yes
Myoporum laetum	Myoporum	Shrub or tree	No	Yes
Nerium oleander	Oleander	Shrub	No	Yes
Pinus halepensis	Aleppo pine	Tree	No	Yes
Pinus pinea	Italian stone pine	Tree	Yes	No
Pinus torreyana	Torrey pine	Tree	Yes	No
Pittosporum crassifolium	Pittosporum	Shrub	Yes	Yes
Pittosporum phillyraeoides	Willow Pittosporum	Shrub	Yes	Yes
Prunus lyonii	Catalina cherry	Shrub or tree	Yes	No
Rhus integrifolia	Lemonade berry	Shrub	Yes	No
Schinus terebinthifolius	Brazilian pepper	Tree	No	Yes
Tamarix species	Tamarisk	Tree	No	Yes
Zizyphus jujuba	Chinese jujube	Small tree	No	Yes

[a] All these plants survive well in the climate zones of the Los Angeles and San Diego areas. After Perry, 1981.

V.F. Sensitivity of Plants to Specific Ions

A plant can be salt tolerant yet still be sensitive to and potentially damaged by specific ions. The ions responsible for most of the damage are chloride, sodium ion, and boron. In the paragraphs that follow, some of the effects of chloride, sodium ion, and boron are described.

V.F.1 Sensitivity of Trees, Shrubs, Ground Covers, and Floricultural Species

At the early stages, symptoms of salinity and specific ion toxicities in plants are often difficult to distinguish from each other. Foliage may be off-color green with yellowing of the tips or margins of leaves. These observed symptoms, however, are of little diagnostic value unless accompanied by chemical analysis for specific ions in the tissue.

Chloride Ion

The element chlorine is an essential micronutrient for plants. Its common ionic form of chlorine is chloride (Cl^-). Woody species appear to be more susceptible to chloride toxicity than are herbaceous crops. Tolerances of woody species vary among varieties or rootstocks and are associated with the plant's ability to restrict the accumulation of chloride in the shoot and particularly in the leaves. Tolerances may be significantly improved by selecting varieties or rootstocks that prevent accumulation of chloride.

Moderate chloride toxicity in stone fruit trees may cause reduced vigor and no other visible symptoms. More severe toxicity often results in bleached or bronzed leaves and in scorched margins on leaves. In citrus, bronzing from chloride toxicity is difficult to distinguish from the orange mottling caused by boron toxicity. Proper selection of rootstock helps to avoid the effects of chloride toxicity.

Sodium

Sodium is not considered an essential nutrient for most plants, yet it does aid the growth of plants at concentrations below the salt tolerance threshold. In water, sodium exists as sodium ions (Na^+). Above the salt tolerance threshold, the sodium ion can have both direct and indirect detrimental effects on plants. Direct effects caused by the accumulation of toxic levels of sodium ions are generally limited to woody species. Symptoms of injury do not usually appear immediately after saline water is applied. Initially, the sodium ion is retained in the roots and basal sections of the trunk. After several years, as sapwood is converted to heartwood, stored sodium ion is released and transported to the leaves, causing the burning of leaves and abscission—the separation of flowers, fruits, or leaves from plants at a special separation layer.

Indirect detrimental effects of sodium ions include nutritional imbalances and impairment of the soil's physical condition. The presence of sufficient calcium both in the plant and in the root environment is essential to prevent the accumulation of sodium ions to levels that are injurious to the plant (Maas, 1986). Symptoms of sodium-induced calcium deficiency are weak stems, chlorosis and necrosis of leaves, and leaves distorted by failure to unroll.

Boron

Boron (B) is an essential micronutrient for plants. For most crops, the optimal concentration of plant-available boron falls within a very narrow range and various criteria have been proposed to define those levels necessary for adequate boron nutrition and yet low enough to avoid toxicity that results in injury and reduced yield (Maas, 1986; and Grieve and Poss, 2000). Boron deficiency is more widespread than boron toxicity, particularly in humid climates. In contrast, boron toxicity is more of a concern in arid environments, where salinity problems also exist (Grattan and Grieve, 1999). As with salt tolerance, the tolerance of a plant to boron varies, depending on the climate, the soil's conditions, and the variety of the plant.

Many of the existing data about boron tolerance were obtained from experiments conducted during 1930 to 1934 by Eaton (1944). These experiments provided threshold tolerance limits for more than 40 different crops. While useful, Eaton's data cannot be reliably correlated to the corresponding growth of most crops (Maas and Grattan, 1999). Bingham et al. (1985) demonstrated that the response of plants to excess boron can be described by a two-piece linear response model. Threshold and slope parameters for such a model have been estimated for a limited number of crops.

Francois and Clark (1979) examined the response of 25 species of ornamental shrub to being irrigated with waters containing either high or low concentrations of boron, 7.5 or 2.5 mg/L, respectively. Boron tolerance was based on reduced growth and deterioration of the plant's appearance overall (Table V.F.1.1). The salt tolerance of these species had been established in an earlier study (Bernstein et al., 1972), and no correlation was found between the boron tolerances and salinity tolerances of the species tested. Maas (1984) also studied the boron tolerance limits for a variety of ornamental plants (Table V.F.1.2).

Symptoms of Boron Toxicity

As boron in the root environment increases, characteristic visible symptoms become evident and often sharp boundaries distinctly separate the symptomatic and the unaffected green tissues. Leaves exhibit scorched and necrotic margins, finally dropping prematurely.

Chlorosis followed by necrosis first appears at the end of the veins of leaves. In parallel-veined leaves, such as in grasses and lilies, the necrosis is found at the tips of leaves where the veins end. A similar pattern is found in lanceolate leaves, such as those of stock and carnation, where the principal vein terminates at the tip. In such species as geranium, where veins are more radially distributed, boron toxicity appears as an injured zone all around the margin. In leaves with a well-developed network of veins and with many veins ending in areas between principal side veins, such as the leaves of gerbera, aster, and most citrus species, symptoms first develop as interveinal yellow or red spots. As injury progresses, chlorosis spreads to the margins (Oertli and Kohl, 1961).

Ranges of boron concentrations in healthy, chlorotic, and necrotic plant tissues are shown in Table V.F.1.3. Necrosis of leaves may be expected when concentrations of boron in plant tissue reach 1,500 to 2,000 ppm on a dry weight basis. Differences in the time necessary for the plants to show symptoms of boron toxicity are apparently not caused by differences in tissue tolerance but, instead, are a function of the rate at which boron accumulates (Oertli and Kohl, 1961).

Other symptoms of boron toxicity commonly observed in plants in landscapes include terminal dieback of twigs, necrotic spots on leaves, abnormal forms and textures in leaves, and cracking bark. Necrosis associated with boron is often black and sometimes red such as in eucalyptus, and for most species it is more severe on the older foliage (Chapman, 1966). Characteristic symptoms of boron toxicity in stone fruit trees include reduced bud formation, poor fruit set, and malformed, very poorly flavored fruit (Johnson, 1996). In citrus trees, symptoms often progress from chlorosis and mottling of the leaf tips to the formation of tan, resinous blisters on the underside of leaves (Wutscher and Smith, 1996).

V.F.2 Sensitivity of Turfgrasses

In addition to overall deleterious effects of salinity, several ions comprising the total salinity may have a direct toxic effect on turfgrasses. The most important of those ions are sodium, chloride, and boron.

Sodium

The roots of a turfgrass plant absorb sodium and transport it to the leaves, where it can accumulate and cause injury. The leaf symptoms of sodium toxicity resemble those of salt burn. Because salts can be absorbed directly by leaves, irrigation water with a high level of sodium salts can be particularly toxic if applied to turfgrass leaves via overhead sprinklers. Sodium toxicity is often of greater concern with plants other than turfgrasses, primarily because the accumulated sodium in turfgrass is removed each time the grass is mowed. Of the grasses grown on golf courses, annual bluegrass and bentgrass are the most susceptible to sodium phytotoxicity.

Chloride

Besides contributing to the total concentration of soluble salt in irrigation water, chloride may be directly toxic to plants grown on a golf course, park, or other landscape site. Although chloride is not particularly toxic to turfgrasses, many trees, shrubs, and ground covers are quite sensitive to it.

Chloride is absorbed by the roots of plants and translocated to leaves, where it accumulates. In sensitive plants, this accumulation leads to necrosis: scorched margins of leaves in minor cases and death of the leaves and abscission in severe cases. Similar symptoms may occur on sensitive plants if high-chloride water is applied via overhead sprinklers, since chloride can be absorbed by wetted leaves as well as by roots. As long as they are mowed regularly, turfgrasses tolerate all but extremely high levels of chloride.

Boron

Boron is an essential micronutrient for the growth of plants, though it is required in very small amounts. Even at concentrations as low as 1 to 2 mg/L in the saturation extract of soil, it is harmful to most ornamental plants and capable of causing leaf burn. The most obvious symptoms appear as a dark necrosis on the margins of older leaves. Turfgrasses generally tolerate boron better than do most other plants grown in a landscape—even though they are more sensitive to boron toxicity than to either sodium or chloride toxicity. Most turfgrasses may be grown in soils with levels of boron as high as 5 mg/L.

Table V.F.1.1. Boron injury to leaves and growth reduction in 25 species of shrub.[a]

Sensitivity to boron	Species		Concn of boron[b]	Observed response	Growth reduction (%)
	Common name	Botanical name			
Tolerant	Natal plum	*Carissa grandiflora* (E.H. Mey.) A. DC. cv. Tuttlei)	Low	No injury	0
			High	No injury	0
	Indian hawthorn	*Raphiolepis indica* (l.) Lindl. cv. Enchantress	Low	No injury	0
			High	No injury	0
	Chinese hibiscus	*Hibiscus rosa-sinesis* L.	Low	No injury	0
			High	Slight premature leaf drop	0
	Oleander	*Nerium oleander* L.	Low	No injury	21
			High	Narrow (1–2 mm) marginal chlorosis; slight tip burn	24
	Japanese boxwood	*Buxus microphylla* Siebold and Zucc. var. *japonica* (Mull. Arg.)	Low	No injury	0
			High	General marginal chlorosis with necrotic older leaves	0
	Bottlebrush	*Callistemon citrinus* (Curtis) Stapf	Low	Slight marginal coloration similar to HB	0
			High	Marginal anthocyanin coloration (5 mm from leaf tip) progressed inward in semicircle pattern toward midrib; marginal and tip necrosis developed as leaves matured	0
	Cenisa	*Leucophylum frutescens* (Berland.) I.M. Johnst. cv. Compactum	Low	No injury	15
			High	Older leaves dropped prematurely	24
	Blue dracaena	*Cordyline indivisa* (G. Forst) Steud.	Low	Tip burn, 5–7 cm (1973); 10–13 cm (1975)	0
			High	Tip burn, 7–10 cm (1973); 18–22 cm (1975)	0
	Brush cherry	*Syzgium paniculatum* Gaertn.	Low	Slight anthocyanin spotting on oldest leaves	0

Sensitivity to boron	Species		Concn of boron^{b}	Observed response	Growth reduction (%)
	Common name	Botanical name			
Semitolerant			High	Moderate anthocyanin spotting; oldest leaves dropped prematurely; general appearance chlorotic	11
	Southern yew	*Podocarpus macrophyllus* (Thunb.) D. Don var. Maki Endl	Low	Slight tip burn with narrow chlorotic band between burn and remainder of leaf	0
			High	Moderate to severe tip burn (1 cm) with narrow chlorotic area like LB; leaves on lower 3/4 of plant exhibited burn	8
	Oriental arbivitae	*Platycladus orientalis* (L.) Franco	Low	Slight chlorosis to necrosis on tips of older leaves	27
			High	Severe necrosis of older leaves; only outer perimeter of plant was still green	30
	Rosemary	*Rosemarius officinalis* C	Low	Tip necrosis of older leaves	20
			High	Tip necrosis of all leaves	51
	Glossy abelia	*Abelia* X *grandiflora* (Andre) Rehd.	Low	Bronzing and tip burn on older leaves	56
			High	Bronzing of all leaves; slight leaf drop	70
Sensitive	Yellow sage	*Lantana camara* L.	Low	Tip and marginal leaf burn on intermediate and older leaves; some hastened leaf drop	14
			High	Moderate to severe leaf burn on all leaves; severe leaf drop	82
	Juniper	*Juniperus chinensis* L. cv. Armstrongii	Low	Moderate tip burn on older leaves	20
			High	Severe tip burn all leaves, except perimeter of new leaves; center leaves of plant dead	47
	Chinese holly	*Ilex cornuta Lindl.* and *Paxt.* cv. Burfordii	Low	Some marginal burn and interveinal chlorosis	17

Sensitivity to boron	Species		Concn of boron[b]	Observed response	Growth reduction (%)
	Common name	Botanical name			
			High	Tip and marginal burn on all leaves; premature leaf drop	88
	Japanese pittosporum	*Pittosporum tobira*	Low	Margin burn and tip burn distal half older leaves; premature leaf drop	50
			High	Premature leaf drop all leaves, except very youngest; young leaves chlorotic with moderate to severe marginal and tip burn; small rosettes young leaves at branch tips	50
	Spindle tree	*Euonymus japonica* Thunb. cv. Grandiflora	Low	Slight tip burn; slight leaf drop	4
			High	Severe chlorosis and tip burn all leaves; severe leaf drop	100
	Pineapple guava	*Feijoa sellowiana* O. Berg	Low	Slight tip burn 1st year; moderate leaf drop, moderate tip, and marginal burn 1974 and 1975	13
			High	Severe leaf drop; all leaves showed severe tip and marginal burn; youngest leaves also chlorotic	35
	Wax-leaf privet	*Ligustrum japonicum* Thunb.	Low	No apparent injury symptoms, except reduced growth	17
			High	Terminal 1/2 to 2/3 of branches dead; necrotic spotting older leaves; nearly completely defoliated	100
	Laurustinus	*Viburnum tinus* L. cv. Robustum	Low	Marginal and tip burn intermediate and older leaves; moderate leaf drop	0
			High	Severe tip and marginal burn all leaves, except very youngest	100

Sensitivity to boron	Species Common name	 Botanical name	Concn of boron[b]	Observed response	Growth reduction (%)
	Thorny elaeagnus	*Elaegnus pungens* Tnunb. cv. Fruitlandii	Low	Older leaves interveinal and marginal chlorosis on distal half of leaf	11
			High	Severe chlorosis with marginal necrosis; severe leaf drop nearly all, but youngest, leaves; remaining leaves hypnonastic	70
	Xylosma	*Xylosma congestum* (Lout.) Merrill	Low	Older leaves anthocynanin mottling and tip burn; more severe by mid-summer; severe leaf drop older leaves	23
			High	Many branches dead; anthocyanin mottling and severe tip burn all leaves; nearly complete leaf drop	100
	Photinia	*Photinia* X *Fraseri* Dress	Low	Marginal and tip burn older leaves	0
			High	Severe leaf burn; severe leaf drop; stem tips dead; death mid-1974	100
	Oregon grape	*Mahonia aquifolium* (Pursh) Nutt.	Low	Tip necrosis young leaves; severe leaf drop older leaves	50
			High	Severe leaf drop, except very youngest; severe burn older and intermediate leaves; tip burn young leaves; barely survived 1st year (1973).	100

[a] Excerpted from Francois and Clark (1979).

[b] Boron concentrations were 2.5 mg/L (low) and 7.5 mg/L (high). Control plants were treated with 0.5 mg of boron/L.

Table V.F.1.2. Boron tolerance limits for ornamentals.[a]

Sensitivity to boron	Species[b] Common name	Botanical name	Threshold (g/m^3)
Very sensitive	Oregon grape	*Mahonia aquifolium*	<0.5
	Photinia	*Photinia* X *Fraseri*	<0.5
	Xylosma	*Xylosma congestum*	<0.5
	Thorny elaeagnus	*Elaegnus pungens*	<0.5
	Laurustinus	*Viburnum tinus*	<0.5
	Wax-leaf privet	*Ligustrum japonicum*	<0.5
	Pineapple guava	*Feijoa sellowiana*	<0.5
	Spindle tree	*Euonymus japonica*	<0.5
	Japanese pittosporum	*Pittosporum tobira*	<0.5
	Chinese holly	*Ilex cornuta*	<0.5
	Juniper	*Juniperus chinensis*	<0.5
	Yellow sage	*Lantana camara*	<0.5
	American elm	*Ulmas americana*	<0.5
Sensitive	Zinnia	*Zinnia elegans*	0.5–1.0
	Pansy	*Viola tricolor*	0.5–1.0
	Violet	*V. adorata*	0.5–1.0
	Larkspur	*Delphinium sp.*	0.5–1.0
	Glossy abelia	*Abelia* X *grandiflora*	0.5–1.0
	Rosemary	*Rosemarius officinalis*	0.5–1.0
	Oriental arbivitae	*Platycladus orientalis*	0.5–1.0
	Geranium	*Pelargonium* X *hortorum*	0.5–1.0
Moderately sensitive	Gladiolus	*Gladiolus* sp.	1.0–2.0
	Marigold	*Calendula officinalis*	1.0–2.0
	Poinsettia	*Euphorbia pulcherrima*	1.0–2.0
	China aster	*Callistephus chinensis*	1.0–2.0
	Gardenia	*Gardenia* sp.	1.0–2.0
	Southern yew	*Podocarpus macrophyllus*	1.0–2.0
	Brush cherry	*Syzgium paniculatum*	1.0–2.0
	Blue dracaena	*Cordyline indivisa*	1.0–2.0
	Cenisa	*Leucophylum frutescens*	1.0–2.0
Moderately tolerant	Bottlebrush	*Callistemon citrinus*	2.0–4.0
	California poppy	*Eschscholzia californica*	2.0–4.0
	Japanese boxwood	*Buxus microphylla*	2.0–4.0
	Oleander	*Nerium oleander* L.	2.0–4.0
	Chinese hibiscus:	*Hibiscus rosa-sinesis*	2.0–4.0
	Sweet pea	*Larkyrus odorarus*	2.0–4.0
	Carnation	*Dianthus caryophyllus*	2.0–4.0
Tolerant	Indian hawthorn	*Raphiolepis indica*	6.0–8.0
	Natal plum	*Carissa grandiflora*	6.0–8.0
	Oxalis	*Oxalis bouiei*	6.0–8.0

[a] After Maas, 1984.
[b] Species listed in order of increasing tolerance, based on appearance as well as growth.

Table V.F.1.3. Boron concentration in green, chlorotic, and necrotic leaves of landscape species and time necessary to produce necrosis.[a]

Type	Species		Boron concn (ppm)			Days until necrosis
	Botanical name	Common name	In green leaves	In chlorotic leaves	In necrotic leaves	
Ornamentals	*Begonia* sp.	Begonia	290–380	—	1,560–2,830	20
	Callistephus chinensis	China aster	600–1,000	1,090–1,280	1,100–1,620	4
	Chrysanthemum morifolium	Mum	270–330	370–570	3,080–3,700	12
	Dianthus caryphyllus	Carnation	60–680	1,630–2,200	1,510–5,770	57
	Fuchsia sp.	Fuchsia	640–860	100–1,190	5,050–8,280	22
	Gerbera sp.	Gerbera daisy	410–510	1,880–2,510	2,210–2,500	14
	Gladiolus sp.	Gladiola	200–1,850	—	2,050–3,480	12
	Hedera canariensis	Algerian ivy	80–450	1,210–1,480	1,540–2,120	49
	Hibiscus rosasinensis	Hibiscus	140–200	200–260	—	52
	Hydrangea sp.	Hydrangea	600–950	—	3,510–3,590	20
	Kalanchoe spp.	Kalanchoe	220–990	—	770–2,030	12
	Matthiola incana	Stock	90–340	—	1,840–4,800	12
	Pelargonium X *hortorum*	Geranium	550–780	—	1,800–3,090	7
	Rhododendron hybrids	Azalea	680–1140	—	1,120–3,900	77
	Rosa sp.	Rose	600–810	—	3,780–5,170	20
	Tagetes patula	Marigold	540–820	1,180–1,260	2,100–3,580	12
Grasses	*Cynodon dactylon*	Bermudagrass	40–700	—	1,380–5,770	16
	Festua sp.	Alta fescue	50–760	—	1,510–8,200	8
	Lolium perenne	Perennial ryegrass	100–290	810	950–2,690	8
	Poa annua	Bluegrass	40–960	—	1,860–6,800	12

[a]After Oertli and Kohl (1961). Concentration of boron in external solution was 10 mg/L.

V.G. Effects of Environment and Management

Such factors as weather, the soil's texture, structure, and fertility, management practices, and the interactions between the plants and these factors affect the response of any given species to salts.

Various aspects of weather, including temperature, radiation, humidity, and wind speed, affect the plant's transpiration rate and, therefore, its accumulation of salt and its salt tolerance. Most plants in landscapes can tolerate greater salt-related stress when the weather is cool and humid than when it is dry and warm. Plants may consequently sustain good aesthetic quality in the winter and spring, but when the weather becomes dry and warm in the summer or windy, severe foliar injury may suddenly occur due to increased rates of transpiration and increased salt accumulation in their leaves. This is especially true for salt-sensitive species. Moderately tolerant plants often develop salt injury later—in the fall, for example—when the accumulation of salt in their leaves surpasses threshold levels. For moderately salt-sensitive and salt-sensitive plants, the soil's salinity and irrigation practices need to be closely monitored and well managed.

Any adverse soil conditions inevitably reduce the overall health of plants, causing the plants to become more vulnerable to salt-related stress. Soil with poor structure or impermeable layers can restrict the growth of roots and the distribution of water and salt in the soil. Flooded or poorly drained soils have poor aeration and in some situations can foster the development of a shallow water table. Less fertile, nutrient-deficient soil can reduce the salt tolerance of plants.

The salinity of soil in the field is seldom constant and may indeed be highly variable (see Chapters III and IV). Concentrations of salt near the soil's surface can be nearly equal to that of the irrigation water and many times greater at the bottom of the root zone. If a saline water table exists within 1 m of the surface, and if leaching fractions are low, salts may be transported upward by capillary flow, in which case the highest concentrations of salt will tend to be found at the surface. The salinity of soil also increases between irrigations, due to the transpiration of water withdrawn by the roots and evaporation of water in moist soil surfaces. Water is lost in the vapor form to the atmosphere in both transpiration and evaporation, and soluble salts remain in the soil solution. The growth of plants closely responds to changes in salt concentrations in the root zone because this is where most water absorption is occurring. Modifying the soil's physical condition and improving management practices can reduce the salt accumulation in the root zone and therefore better sustain plants.

The method of irrigation—drip, surface application, or sprinklers—will influence how landscape plants respond to irrigation water of a given salinity. In California, sprinkler irrigation is preferred for most landscapes because it requires less maintenance and is less vulnerable to damage than drip irrigation. Plants irrigated by sprinkling, however, are subject to injury not only from salts in the soil but also from salt absorbed directly through the wetted leaves. Management of the sprinkler irrigation of plants in landscapes can affect the degree of injury to leaves caused by salt deposition. Wherever possible, irrigation should be infrequent and heavy, rather than frequent and light. Slowly rotating sprinklers that allow drying between cycles should be avoided. It is best to sprinkler irrigate at night or in the early morning, avoiding hot, dry, and windy days.

Extra management will be needed to irrigate salt-sensitive and moderately salt-tolerant species of plants with recycled water, if salt concentrations in the recycled water exceed the tolerance levels of the species. Such species are particularly vulnerable in the early stages of growth. For example, the young leaves and buds of salt-sensitive and moderately salt-tolerant trees are more vulnerable to being sprayed with saline water than are mature leaves. Once the trees grow above the height of the spray, there is less need for this type of sprinkler management, though branches at lower levels may still be exposed to the spray of water and develop symptoms of salt-related stress. In irrigation of salt-sensitive shrubs and ground covers, switching to drip irrigation can help prevent the water from coming into contact with the foliage. However, with drip irrigation, the salinity of the soil needs to be monitored (Chapter IX). When one is designing a new landscape or upgrading an older one, much advantage can be gained by grouping plants of similar salt tolerance in the same area. Each such area can then be irrigated accordingly.

Recommendations advanced by researchers for growing ornamental plants and cut flowers with moderately saline waters include the following:

- Water more heavily and less often.
- Keep the soil as moist as possible without retarding the plant's growth or creating disease problems.
- Use soil containing considerable organic matter.
- Select varieties most tolerant of the type of water being used.
- Apply slow-release fertilizers as needed to meet the plant's nutritional requirements, since leaching to control the salinity of the soil may reduce its fertility.
- Confirm suspected salt-related injury to a plant before beginning to correct it, as the causes may be unrelated to salinity. For instance, stunting of growth may result from drought, and leaf burn may be caused by drought or toxic amounts of boron.
- Judge the suitability of a particular water for irrigation not only by considering its salt content but also by evaluating the manner in which the water is applied, as well as the type of soil to which it will be applied.

V.H. Gallery

Two color plates accompany the text of this chapter. Plate 1 consists of two pages displaying 14 color photos of salt-damaged plants and leaves. The species and genera illustrated include the following: liquidambar (*Liquidambar styraciflua*), bottlebrush (*Callistemon* spp.), bougainvillea (*Bougainvillea glabra*), cotoneaster (*Cotoneaster* spp.), crape myrtle (*Lagerstroemia indica*), eucalyptus (*Eucalyptus* spp.), hibiscus (*Hibiscus* spp.), orchid tree (*Bauchinia purpura*), and xylosma (*Xylosma* spp.). Plate 2 consists of a single page displaying images of a boron-damaged liquidambar tree.

Plate 1. Salt-damaged plants and leaves.

Photo VH-1: Hibiscus does not tolerate salt very well, with leaf burn occurring even under the mildest salt treatment. Severe leaf burn is shown above.

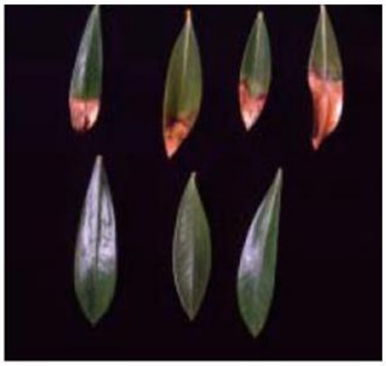

Photo VH-2: Bottlebrush is rated as moderately salt tolerant. Older leaves subjected to salt often exhibit "tip burn", as seen here.

Photo VH-3: Bougainvillea, which is not well-adapted to sand cultures, is highly salt tolerant if grown in soil.

Photo VH-4: Ivy is only slightly salt tolerant. "Bronzing" and curvature of the leaves, as shown here, is likely due to chloride toxicity.

Photo VH-5: Xylosma is moderately salt tolerant. Response to salt often varies from plant to plant.

Photo VH-6: Holly has very poor salt tolerance. This specimen exhibits moderate "bronzing" of leaves.

Photos VH-7, VH-8, VH-9: Cotoneaster has very poor salt tolerance. Shown here, left to right, are: normal plant, plant grown at low salt level (EW$_{iw}$ 3.1 dS/m), plant grown at high salt levels (EC$_{iw}$ 6.2 dS/m).

Photos VH-10, VH-11, VH-12: The tulip tree (*Liriodendron tulipifera*) is very sensitive to salt. Photo above shows, from left to right, a normal leaf, a leaf from plant grown with water of 2,000 ppm TDS, and leaf from plant gown at 4,000 ppm TDS. Photos at left show leaf damage two months after beginning of salinity treatment.

Photos VH-13, VH-14: Shown at right are crape myrtle leaves from plants grown with high-salt water (left, EC$_{iw}$ 6 dS/m), low-salt water (3 dS/m), and the control. Samples shown at far right exhibit "tip burn" and "bronzing".

Plate 2. Boron-damaged eucalyptus tree.

Photos VH-19, VH-20, VH-21: Leaves of the eucalyptus in all of the above photos show signs of boron damage (B=25 ppm; EC_i=2).

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Chapter VI. Selecting Plants for Coastal Southern California Landscapes

L. Rollins and A. Harivandi

VI.A. Selection Based on Zones
VI.B. Guides for Selecting Trees, Shrubs, and Ground Covers
VI.C. Guide for Selecting Turfgrasses
VI.D. Guides Available via the Internet
VI.E. Guides about Native Plant Communities
V.I.F. Selecting Plants for Certain Types of Landscapes
    VI.F.1. General Guidelines
    VI.F.2. Selecting Plants for Golf Courses
    VI.F.3. Selecting Plants for Playing Fields
    VI.F.4. Selecting Plants for Parks
    VI.F.5. Selecting Plants for Medians and Sides of Streets
VI.G. Using Guides Cited
VI.H. References

In this chapter, numerous plant selection guides are described, with a particular focus on guides that pertain to the Los Angeles and San Diego areas, portions of which are served by pipelines conveying recycled water that could be used for landscape irrigation.

The goal is to provide information helpful in choosing plants for relatively large landscapes, such as regional parks, golf courses, city parks, cemeteries, and highway medians. Most of the information is equally relevant for selecting plants for smaller landscapes, such as neighborhood parks or street-side plantings.

Some of the plant species mentioned in this chapter may be less than ideal for sites irrigated with water of moderate or high salinity. For projects that rely on such water, the site designer should screen candidate species by reading about them thoroughly here and in Chapter V (and in the references cited in both chapters), afterward choosing only those species that are relatively salt tolerant. Likewise, some of the plants listed here may be appropriate only for well-drained soil. Others may be considered weeds or invasive species in certain circumstances. Careful screening of candidate species is, once again, the best way to ensure a proper match between plant and environment.

V.I.A. Selection Based on Zones

A plant responds to many different environmental factors, including the following:

- Intensity and daily duration of sunlight
- Quantity of rainfall and of irrigation water
- Quality of available water
- Amount and type of nutrients available
- Temperature
- Physical and chemical properties of the soil
- Physical disturbances, such as wind, flooding, or fire
- Biotic interactions, such as competition by other plants for space or for sunlight, grazing by plant-eating animals, and diseases caused by various microbes.

These various factors, when examined together, can be used to help define a series of geographical and climatological zones or regions for California. This is the approach taken by the authors of some of the more comprehensive plant selection guides described in the following section. The idea is that, by looking at a plant environment map and finding out what zone pertains to a desired project area, one can more reliably determine which species of plants will survive and prosper in the area.

VI.B. Guides for Selecting Trees, Shrubs, and Ground Covers

Seven books are described below, each of which contains information that is helpful when selecting trees, shrubs, and ground covers. Three of the books cover both native and nonnative species. The other four are specifically about species native to California.

Trees and Shrubs for Dry California Landscapes (Perry, 1981)

This book is a comprehensive guide to plants for California landscapes, with an emphasis on species that survive with limited water. The book includes lists of plants that tolerate certain problematic situations in landscapes, such as saline spray and alkaline soil. It also includes detailed descriptions, accompanied by photographs, of 360 different species. Some of the species are native to California. Others are natives of other areas in the world that have Mediterranean-like climates similar to California's: central Chile, South Africa, parts of southern Australia, and, of course, the countries bordering the Mediterranean Sea.

Perry reviews the plants in light of their suitability for specific environments. He then relates that choosing plants for a landscape is specialized work and that the plant selection tables and descriptions of plants he provides should be interpreted with caution. He recommends cross-checking against the lists and information of others.

Perry's book contains four main sections. In the first part, "Regional Plant Environments," he describes nine macroenvironment zones, shown in Figure VI-1. He also includes a detailed plant selection guide consisting of seven lists: ground covers, small shrubs, medium shrubs, large shrubs, small trees, medium trees, and large trees. Each list contains information about the compatibility of the relevant plants with each of the aforementioned zones.

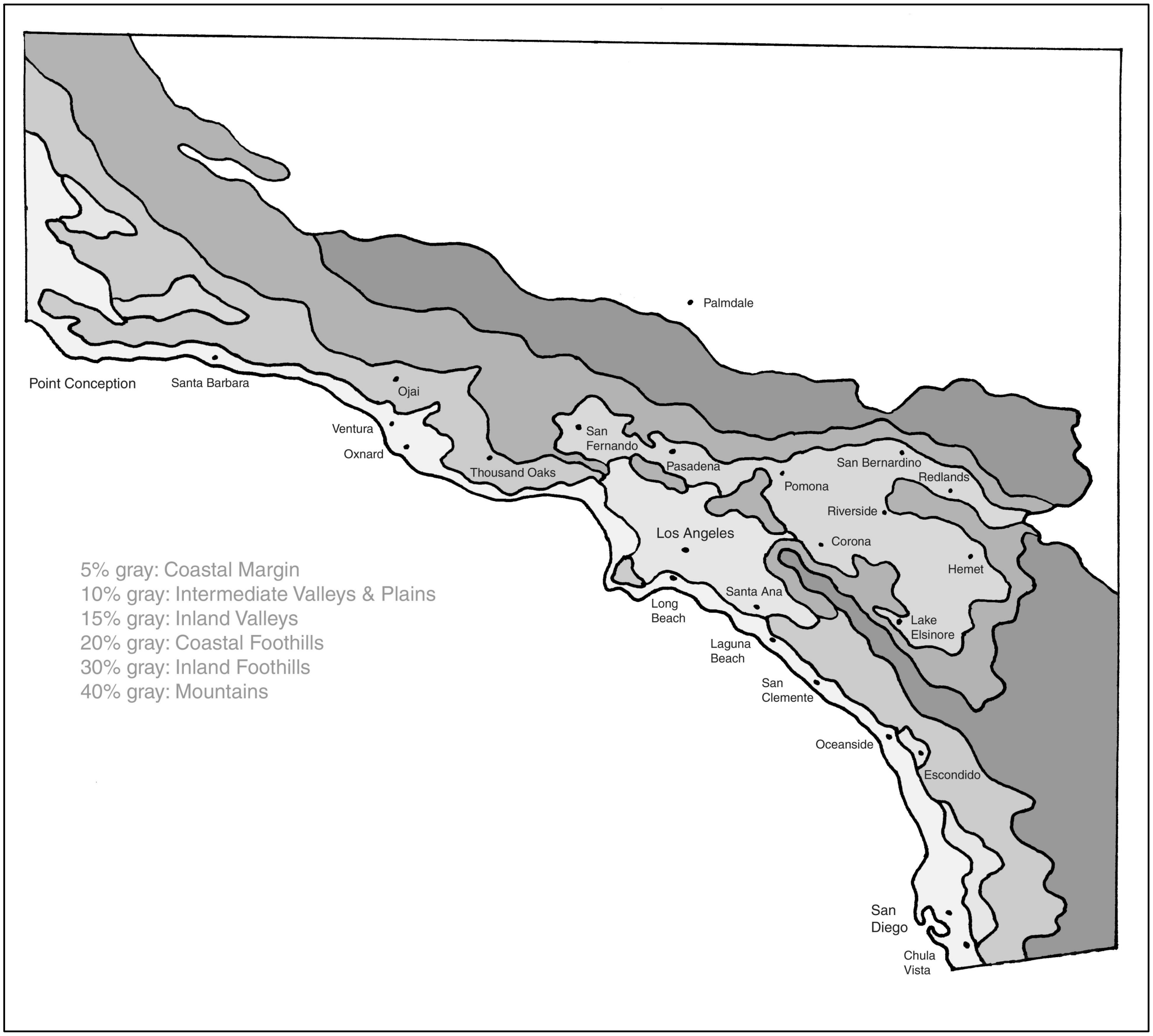

Figure VI-1. Map of plant environments for coastal southern California *(after Perry, 1981)*.

Because Perry's lists represent an invaluable source of information unavailable elsewhere and because his book is now out of print, we have, with his permission, reproduced the lists in this document as Tables VI-1 through VI-7. These tables, when used with the plant environment map, are a highly useful tool for selecting plants during the design of a landscape. The tables and map can be best used in the following stepwise fashion:

(1) Using the map, select the appropriate zone or zones for the area of interest.
(2) Using the tables, choose plants that seem to fit the project.
(3) Cross-check with other relevant guides, such as the *Sunset Western Garden Book* (2001) to make sure that the selected plants truly are optimal for the project's local microclimate.
(4) Gather details about the selected plants from other books and, if possible, from landscape designers or horticultural experts familiar with the area where the project is located.

In the second part of Perry's book, titled "Planting Guidelines," he points out that any landscape project consists of various site-specific conditions and design criteria. The goal, he says, is to establish an appropriate planting concept within the constraints of function, aesthetics, costs, resources, and required maintenance. Several different criteria for design are addressed by the various guidelines provided, including the following: planting from seed, planting on slopes, planting for fire safety, and using species native to California. For each such guideline, Perry lists a number of plants that satisfy the stated criterion. For example, in the guideline for fire-safe landscapes, he defines four zones in the landscape and describes how to use those zones to protect a project's buildings from adjacent fire-prone natural vegetation, such as chaparral.

In the third part of the book, titled "Plant Lists for Landscape Situations," Perry lists plants that can tolerate certain problematic situations that may be encountered in a landscape, such as oak root fungus, alkaline soil, saline spray, and invasive plants.

The fourth, final, and most comprehensive part of Perry's book, titled "Plant Compendium," consists of text and photographs of 360 different species that have proven useful or popular for California landscapes.

Table VI–1. Plant selection guide for coastal southern California: ground covers *(after Perry, 1981).*[a]

Botanical name	**Common name**	**Native? (3 = yes)**	**Coastal margin**	**Intermediate valleys**	**Coastal foothills**	**Inland valleys**	**Inland foothills**
Acacia redolens			•	•	•	•	•
Achillea millefolium	Yarrow	3	•	•	•	•	•
Arctostaphylos densiflora 'James West'		3	•	+	•	+	+
Arctostaphylos edmundsii	Little Sur manzanita	3	•	+	•	+	+
Arctostaphylos hookeri		3	•	+	•	+	•
Arctostaphylos uva ursi	Bearberry	3	•	+	•	+	•
Arctostaphylos "Emerald Carpet"		3	•	+	•	+	•
Arctostaphylos "Indian Hill"		3	•	+	•	+	+
Arctostaphylos "Sea Spray"			•	+	•	+	+
Arctostaphylos "Winter Glow"		3	•	+	•	+	•
Artemisia caucasica	Silver spreader		•	•	•	•	•
Artemisia pyncocephala	Coast sagebrush	3	•	•	•	+	+
Atriplex glauca			•	•	•	•	+
Atriplex semibaccata	Australian sagebrush		•	•	•	•	•
Baccharis pilularis	Prostrate coyote brush	3	•	•	•	+	+
Ceanothus gloriosus	Point Reyes ceanothus	3	•	+	•	+	+
Ceanothus gloriosus porrectus		3	•	+	•	+	+
Ceanothus gloriosus exaltatus "Emily Brown"		3	•	+	•	+	+
Ceanothus griseus horizontalis	Carmel creeper	3	•	+	•	+	+
Ceanothus griseus horizontalis "Yankee Point"		3	•	•	•	+	+
Ceanothus maritimus	Maritime ceanothus	3	•	+	•	+	+
Centaurea cineraria	Dusty Miller		•	•	•	•	•
Cistus salviifolius	Sageleaf rockrose		•	+	•	+	+
Coprosma kirkii	Creeping Coprosma		•	•	•	+	+
Cotoneaster buxifolius	Bright bead cotoneaster		•	•	•	•	•
Cotoneaster congestus			•	•	•	•	•
Eriogonum crocatum	Saffron buckwheat	3	•	+	•	+	+
Eriogonum fasciculatum	Common buckwheat	3	•	•	•	•	•
Gazania species	Gazania		•	•	•	•	+
Grevillea lanigera	Woolly grevillea		•	•	•	•	+
Grevillea "Noelli"			•	•	•	•	+
Grevillea rosmarinifolia	Rosemary grevillea		•	•	•	•	+
Helianthemum species	Sunrose	3	•	•	•	•	•
Hypericum calycinum	Aaron's beard		•	•	•	+	+
Juniperus species	Juniper	3	•	•	•	•	•
Lantana montevidensis	Trailing lantana		•	•	•	•	+
Lippia canescens	Lippia		•	•	•	•	+
Lobularia maritima	Sweet alyssum		•	•	•	•	•
Lupinus nanus	Annual lupine		•	•	•	•	

Mahonia repens	Creeping mahonia		•	+	•	+	+
Myoporum debile			•	•	•	+	+
Myoporum parvifolium	Creeping boobialla		•	•	•	•	+
Osteospermum species	African daisy		•	•	•	•	+
Pyracantha species	Firethorn		•	•	•	•	•
Ribes viburnifolium	Evergreen currant	3	•	+	•	+	+
Rosmarinus officinalis "Prostratus"	Prostrate rosemary		•	•	•	•	•
Salvia sonomensis	Creeping sage	3	•	+	•	+	•
Santolina chamaecyparissus	Lavender cotton		•	•	•	•	+
Santolina virens			•	•	•	•	+
Trifolium frageriferum O'Connor's	O'Connor's legume		•	•	•	•	+
Zauschneria californica	California fuchsia	3	•	•	•	•	•

[a] Most of the information in the table above is from the book *Trees and Shrubs for Dry California Landscapes* (Perry, 1981). Used with permission. •, plant is well suited to this type of landscape; +, plant will do well in this type of landscape if exposure and soil conditions are optimal.

Table VI–2. Plant selection guide for coastal southern California: small shrubs, 3–5 ft *(after Perry, 1981).*[a]

Botanical name	Common name	Native? (3 = yes)	Coastal margin	Intermediate valleys	Coastal foothills	Inland valleys	Inland foothills
Achillea millefolium	Yarrow	3	•	•	•	•	•
Arctostaphylos densiflora "James West"		3	•	•	+	+	+
Arctostaphylos hookeri	Monterey manzanita	3	•	+	•	+	+
Arctostaphylos pumila	Sandmat manzanita	3	•	•	•	+	+
Arctostaphylos "Green Sphere"		3	•	•	•	+	+
Argemone species	Prickly poppy			+	•		•
Artemisia californica	California sagebrush	3	•	•	•	•	•
Calliandra californica		3			•	•	•
Calliandra eriophylla	False mesquite	3		•	•	•	•
Cassia species	Senna	3		•	•	•	+
Ceanothus purpureus	Hollyleaf ceanothus		•	•	•	•	+
Ceanothus rigidus "Snowball"		3	•	•	•	+	+
Ceanothus "Blue Cushion"		3	•	•	•	+	+
Cistus species	Rockrose		•	•	•	•	+
Convolvulus cneorum	Bush morning glory		•	•	•	•	+
Cotoneaster buxifolius	Bright bead cotoneaster		•	•	•	•	•
Cotoneaster congestus			•	•	•	•	•
Encelia californica	California encelia	3	•	•	•	+	
Encelia farinosa	Desert encelia	3		•	•	•	•
Eriogonum arborescens	Santa Cruz buckwheat	3	•	•	•	+	+
Eriogonum cinerium	Ashyleaf buckwheat	3	•	•	•	+	+
Eriogonum crocatum	Saffron buckwheat	3	•	•	•	+	
Eriogonum fasciculatum	Common buckwheat	3	•	•	•	•	•
Eriogonum giganteum	St. Catherine's lace	3	•	•	•	•	•
Eriogonum latifolium rubescens	Red buckwheat	3	•	•	•	•	+
Eriogonum parvifolium	Seacliff buckwheat	3	•	+	•	+	+
Eriophyllum confertiflorum	Golden yarrow	3	•	•	•	•	•
Eriophyllum staechadifolium	Lizard tail	3	•	•	•		
Hypericum beanii			•	•	•	+	+
Juniperus species	Juniper	3	•	•	•	•	•
Lavandula species	Lavender		•	•	•	•	•
Leptodactylon californicum	Prickly phylox	3		•	•	•	•
Leucophyllum frutescens "Compactum"	Texas ranger		•	•	•	•	•
Limonium perezii	Sea lavender		•	•	•	+	
Lotus scoparius	Deerweed		+	•	•	•	•
Lupinus albifrons	Silver lupine	3	•	•	•	•	+
Lupinus arboreus	Tree lupine	3	•	•	•	•	•
Lupinus chamissonis	Dune lupine	3	•	•	•	+	+
Mahonia repens	Creeping mahonia		•	•	•	+	+
Mimulus species	Monkey flower	3	•	•	•	+	+
Osteospermum species	African daisy		•	•	•	+	+

Pennisetum setaceum	Fountain grass		•	•	•	•	•
Penstemon centranthifolius	Scarlet bugler	3	+	•	•	•	•
Penstemon heterophyllus	Blue penstemon	3	+	•	•	•	•
Penstemon spectabilis	Showy penstemon	3	+	•	•	•	•
Pittosporum tobira "Wheeleri"	Wheeler's dwarf pittosporum		•	•	•	•	•
Pyracantha species	Firethorn		•	•	•	•	•
Ribes speciosum	Fuchsia-flowering gooseberry	3	•	•	•	+	+
Ribes viburnifolium	Evergreen currant	3	•	+	•	+	+
Rosmarinus officinalis "Prostratus"	Prostrate rosemary		•	•	•	•	•
Salvia clevelandii	Cleveland sage	3	•	+	•	•	•
Salvia leucantha	Mexican bush sage		•	•	•	•	•
Salvia leucophylla	Coastal purple sage	3		•	•	•	•
Salvia mellifera	Black sage	3	•	•	•	•	•
Santolina species			•	•	•	•	•
Trichostema lanatum	Woolly blue curls	3	•	+	•	+	•

[a] Most of the information in the table above is from the book *Trees and Shrubs for Dry California Landscapes* (Perry, 1981). Used with permission. •, Plant is well suited to this type of landscape; +, plant will do well in this type of landscape if exposure and soil conditions are optimal.

Table VI–3. Plant selection guide for coastal southern California: medium shrubs, 5–10 ft *(after Perry, 1981).*[a]

Botanical name	Common name	Native? (3 = yes)	Coastal margin	Intermediate valleys	Coastal foothills	Inland valleys	Inland foothills
Acacia cultriformis	Knife acacia		•	•	•	•	•
Acacia redolens			•	•	•	•	•
Acacia verticillata	Star acacia		•	•	•	•	+
Arbutus unedo “Compacta”	Dwarf strawberry tree		•	•	•	•	+
Arctostaphylos densiflora ‘Harmony’		3	•	+	•	+	+
Arctostaphylos franciscana			•	•	•	+	+
Arctostaphylos glandulosa	Eastwood manzanita	3			•		•
Arctostaphylos stanfordiana	Stanford manzanita	3		•	•	+	+
Artemisia tridentata	Big Basin sagebrush	3			•	•	•
Atriplex canescens	Four-wing saltbush	3				•	•
Atriplex lentiformis	Quail bush	3	•	•	•	•	•
Atriplex lentiformis breweri	Brewer lenscale	3		•	•	•	
Atriplex nummularia			•	•	•		
Baccharis pilularis consanguinea	Coyote brush	3	•	•	•	•	•
Baccharis viminea	Mulefat		•	•	•	•	•
Bougainvillea species	Bougainvillea		•	•	•	+	+
Caesalpinia species	Bird of paradise bush			•	•	•	•
Calliandra tweedii	Trinidad flame bush		•	•	•	•	•
Callistemon citrinus	Lemon bottlebrush		•	•	•	•	•
Callistemon pallidus			•	•	•	•	•
Callistemon rigidus	Stiff bottlebrush		•	•	•	•	•
Cassia species	Senna	3	•	•	•	•	+
Ceanothus griseus	Carmel ceanothus	3	•	•	•	+	+
Ceanothus “Concha”		3	•	•	•	+	+
Ceanothus “Joyce Coulter”		3	•	•	•	+	+
Ceanothus “Julia Phelps”		3	•	•	•	+	+
Ceanothus “Mountain Haze”		3	•	•	•	+	+
Ceanothus “Sierra Blue”		3	•	•	•	+	+
Cercocarpus ledifolius	Curl-leaf mountain mahogany	3				•	
Chamelaucium uncinatum	Geraldton waxflower		•	•	•	•	+
Cistus corbariensis	White rockrose		•	+	•	+	+
Cistus purpureus	Orchid rockrose		•	•	•	+	+
Cotoneaster lacteus	Red clusterberry		•	•	•	•	+
Cytisus species	Broom					•	
Dendromecon harfordii	Island bush poppy	3	•	•	•	+	+
Dendromecon rigida	Bush poppy	3	•	•	•	•	•
Dodonea viscosa	Hopseed bush		•	•	•	•	•
Echium fastuosum	Pride of Madeira		•	•	+	+	+
Elaeagnus pungens	Silverberry		•	•	•	•	•
Escallonia exoniensis			•	•	•	+	+
Eucalyptus macrocarpa	Desert malee			•	•	•	•
Eucalyptus rhodantha				•	•	•	•
Feijoa sellowiana	Pineapple guava		•	•	•	•	•

Garrya species	Silktassel	3			•		•
Grevillea “Aromas”			•	•	•	•	•
Grevillea lanigera	Woolly grevillea		•	•	•	•	+
Grevillea “Noelli”			•	•	•	•	•
Grevillea rosmarinifolia	Rosemary grevillea		•	•	•	•	•
Grevillea thelemanniana	Hummingbird bush		•	•	•	•	+
Isomeris arborea	Bladderpod	3	•	•	•	•	+
Jasminus humile	Italian jasmine		•	•	•	+	+
Juniperus species	Juniper	3	•	•	•	•	•
Lantana camara	Bush lantana		•	•	•	+	•
Laurus nobilis	Sweet bay		•	•	•	•	•
Leptospermum scoparium	New Zealand tea tree		•	•	•	+	+
Leucophyllum frutuscens	Texas ranger		•	•	•	•	•
Lupinus albifrons	Silver lupine	3	•	•	•	•	+
Lupinus arboreus	Tree lupine	3	•	•	•	•	•
Mahonia amplectans		3	•	•	•	+	+
Mahonia aquifolium	Oregon grape	3	•	•	•	+	+
Mahonia “Golden Abundance”			•	•	•	+	+
Mahonia nevinii	Nevin mahonia	3		•	•	•	•
Mahonia pinnata	California holly grape	3	•	•	•	+	+
Nerium oleander	Oleander		+	•	•	•	•
Penstemon antirrhinoides	Yellow penstemon		•	•	•	•	•
Photinia fraserii			•	•	•	+	+
Pittosporum tobira	Tobira		•	•	•	•	•
Pyracantha species	Firethorn		•	•	•	•	•
Rhamnus californica	California coffeeberry	3	•	•	•	•	•
Rhamnus crocea	Redberry	3		•	•	•	•
Ribes aureum	Golden currant	3		•	•	•	+
Ribes sanguineum	Red flowering gooseberry	3	•	•	•	+	+
Ribes sanguineum “Glutinosum”		3	•	•	•	+	+
Romneya coulteri	Matilija poppy	3	•	•	•	•	•
Rosmarinus officinalis	Rosemary		•	•	•	•	•
Salvia apiana	White sage	3	•	•	•	•	•
Simmondsia chinensis	Jojoba	3		+		•	•
Spartium junceum	Spanish broom			•	•	•	
Tecomaria capensis	Cape honeysuckle		•	•	•	•	+
Viguiera species		3	•		•	•	•
Xylosma congestum “Compacta”			•	•	•	•	•

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Table VI–4. Plant selection guide for coastal southern California: large shrubs, 10–18 ft *(after Perry, 1981).*[a]

Botanical name	Common name	Native? (3 = yes)	Coastal margin	Intermediate valleys	Coastal foothills	Inland valleys	Inland foothills
Acacia baileyana	Bailey acacia		•	•	•	•	•
A. baileyana “Purpurea”	Purple-leaf acacia		•	•	•	•	•
Acacia cultriformis	Knife acacia		•	•	•	•	•
Acacia cyclopis			•	•	•	•	•
Acacia dealbata	Silver wattle		•	•	•	•	•
Acacia decurrens	Green wattle		•	•	•	•	•
Acacia farnesiana	Sweet acacia						•
Acacia greggii	Catclaw acacia	3					•
Acacia longifolia	Sydney golden wattle		•	•	•	•	+
Acacia pendula	Weeping acacia		•	•	•	+	+
Acacia podalyriifolia	Pearl acacia		•	•	•	•	+
Acacia pycnantha	Golden wattle		•	•	•	+	+
Acacia saligna	Willow acacia		•	•	•	+	+
Adenostoma sparsifolium	Red shanks	3			•		•
Aesculus californica	California buckeye	3			•	+	•
Agonis flexuosa	Peppermint tree		•	•	•	+	+
Arbutus menziesii	Madrone	3			+	+	+
Arbutus unedo	Strawberry tree		•	•	•	•	+
Arctostaphylos glauca	Bigberry manzanita	3					•
Arctostaphylos manzanita	Common manzanita	3			+		+
Baccharis viminea	Mulefat		•	•	•	•	•
Bougainvillea species	Bougainvillea		•	•	•	+	+
Calliandra tweedii	Trinidad flame bush			•	•	•	•
Callistemon citrinus	Lemon bottlebrush		•	•	•	•	•
Callistemon viminalis	Weeping bottlebrush		•	•	•	•	+
Ceanothus arboreus	Felt-leaf ceanothus	3	•	+	•	+	+
Ceanothus crassifolius	Hoary-leaf ceanothus	3			•	+	•
Ceanothus cyaneus	San Diego ceanothus	3	•	+	•	+	
Ceanothus griseus	Carmel ceanothus	3	•	+	•	+	+
Ceanothus impressus	Santa Barbara ceanothus	3	•	+	•	+	+
Ceanothus “Frosty Blue”		3	•	+	•	+	+
Ceanothus “Ray Hartman”		3	•	+	•	+	+
Ceanothus “Sierra Blue”		3	•	+	•	+	+
Ceratonia siliqua	Carob tree		•	•	•	•	+
Cercidium species	Palo verde	3	+	+	+	•	+
Cercis occidentalis	Western redbud	3	+	+	+	+	+
Cercocarpus species	Mountain mahogany	3			•		•
Comarostaphylis diversifolia	Summer holly	3	+	+	•	+	+
Cotoneaster lacteus	Red clusterberry		•	•	•	•	+
Dalea spinosa	Smoke tree	3				•	•
Dendromecon harfordii	Island bush poppy	3	•	•	+	+	+
Dodonea viscosa	Hopseed bush		•	•	•	•	•
Elaeagnus pungens	Silverberry		•	•	•	•	+
Eriobotrya deflexa	Bronze loquat		+	•	•	•	•

Botanical name	**Common name**	**Native? (3 = yes)**	**Coastal margin**	**Intermediate valleys**	**Coastal foothills**	**Inland valleys**	**Inland foothills**
Eriobotrya japonica	Loquat		+	•	•	•	+
Escallonia bifida	White escallonia		•	•	•	+	+
Eucalyptus erythrocorys	Red cap gum		•	•	•	+	+
Eucalyptus lehmannii	Bushy yate		•	•	•	+	+
Eucalyptus macrocarpa	Desert malee		+	•	•	•	•
Eucalyptus niphophila	Snow gum		+	•	•	•	+
Feijoa sellowiana	Pineapple guava		•	•	•	•	•
Fremontodendron species	Flannel bush	3	+	+	•	+	•
Grevillea banksii	Crimson coneflower		•	•	•	+	+
Hakea laurina	Sea urchin		•	•	•	+	+
Hakea suaveolens	Sweet hakea		•	•	•	+	+
Heteromeles arbutifolia	Toyon	3	+	+	•	+	•
Jasminus humile	Italian jasmine		•	•	•	+	+
Juniperus species	Juniper	3	•	•	•	•	•
Laurus nobilis	Sweet bay		•	•	•	•	•
Lavatera assurgentiflora	Tree mallow	3	•	+	•	+	+
Leptospermum laevigatum	Australian tea tree		•	•	•	+	+
Leptospermum scoparium	New Zealand tea tree		•	•	•	+	+
Lithocarpus densiflorus	Tanbark oak	3			+		+
Lyonothamnus species	Catalina ironwood	3	•	+	•	+	+
Mahonia higginsae		3	•	•	•	•	•
Melaleuca armillaris	Drooping melaleuca		•	•	•	+	+
Melaleuca elliptica			•	•	•	•	+
Melaleuca nesophila	Pink melaleuca		•	•	•	+	+
Metrosideros excelsus	New Zealand Christmas tree		•	•	•	+	
Myoporum laetum			•	•	•	+	+
Nerium oleander	Oleander		+	•	•	•	•
Photinia fraserii			•	•	•	+	+
Photinia serrulata	Chinese photinia			•	•	+	•
Pistacia vera	Pistachio nut			•		•	
Pittosporum crassifolium			•	•	•	+	+
Pittosporum phillyraeoides	Willow pittosporum		•	•	•	+	+
Pittosporum rhombifolium	Queensland pittosporum		•	•	•	•	+
Pittosporum undulatum	Victorian box		•	•	•	+	+
Pittosporum viridiflorium	Cape pittosporum		•	•	•	+	+
Plumbago auriculata	Cape plumbago		•	•	•	•	+
Prunus species	Prunus	3	•	•	•	+	+
Psidium guajava	Guava		•	•	•	•	•
Psidium littorale	Strawberry guava		•	•	•	+	+
Punica granatum	Pomegranate		+	•	•	•	+
Pyracantha species	Firethorn		•	•	•	•	•
Quercus chrysolepis	Canyon live oak	3		+	•	+	•
Quercus domosa	Scrub oak				•		•
Rhamnus alaternus	Italian buckthorn		•	•	•	•	•

Botanical name	**Common name**	**Native? (3 = yes)**	**Coastal margin**	**Intermediate valleys**	**Coastal foothills**	**Inland valleys**	**Inland foothills**
Rhamnus californica	California coffeeberry	3	•	•	•	•	+
Rhus integrifolia	Lemonade coffeeberry	3	•	+	•	+	+
Rhus laurina	Laurel sumac		•	•	•		+
Rhus ovata	Sugar bush	3	•	•	•	•	•
Sambucus species	Elderberry		•	•	•	•	+
Schinus molle	California pepper		•	•	•	•	•
Schinus terebinthifolius	Brazilian pepper tree		•	•	•	•	+
Tecomaria capensis	Cape honeysuckle		•	•	•	+	+
Xylosma congestum	Shiny xylosma		•	•	•	•	+

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Table VI–5. Plant selection guide for southern California: small trees, 15–25 ft *(after Perry)*.[a]

Botanical name	Common name	Native? (3 = yes)	Coastal margin	Intermediate valleys	Coastal foothills	Inland valleys	Inland foothills
Acacia cyanophylla	Blue-leaf wattle		•	•	•	+	+
Acacia greggii	Catclaw acacia	3				+	+
Acacia longifolia	Sydney golden wattle		•	•	•	•	+
Acacia pendula	Weeping acacia		•	•	•	+	+
Acacia podalyriifolia	Pearl acacia		•	•	•	•	+
Aesculus californica	California buckeye	3			•	+	•
Agonis flexuosa	Peppermint tree		•	•	•	+	+
Arbutus unedo	Strawberry tree		•	•	•	•	+
Arctostaphylos manzanita	Common manzanita	3			+		+
Callistemon citrinus	Lemon bottlebrush		•	•	•	•	•
Callistemon rigidus	Stiff bottlebrush			•	•	•	•
Callistemon viminalis	Weeping bottlebrush			•	•	•	+
Ceanothus arboreus	Felt-leaf ceanothus	3	•	+	•	+	+
Ceanothus “Ray Hartman”		3	•	+	•	+	+
Cercidium species	Palo verde	3	+	+	+	•	+
Cercis occidentalis	Western redbud	3	+	+	+	+	+
Cercocarpus betuloides	Mountain mahogany	3			•		•
Comarostaphylis diversifolia	Summer holly	3	+	+	•	+	+
Dalea spinosa	Smoke tree	3				•	•
Elaeagnus angustifolia	Russian olive			•		•	+
Eriobotrya deflexa	Bronze loquat		+	•	•	•	•
Eriobotrya japonica	Loquat		+	•	•	•	+
Escallonia bifida	White escallonia		•	•	•	+	+
Eucalyptus erythrocorys	Red cap gum		•	•	•	+	+
Eucalyptus lehmannii	Bushy yate		•	•	•	•	+
Eucalyptus niphophila	Snow gum			•	•	•	+
Eucalyptus torquata	Coral gum		•	•	•	+	+
Feijoa sellowiana	Pineapple guava		•	•	•	•	•
Fremontodendron species	Flannel bush	3	+	+	•	+	•
Geijera parviflora	Australian willow		•	•	•	•	+
Hakea laurina	Sea urchin		•	•	•	+	+
Heteromeles arbutifolia	Toyon	3	+	+	•	+	•
Koelreuteria paniculata	Golden rain tree		•	•		•	+
Lagerstroemia indica	Crape myrtle			+		•	•
Laurus nobilis	Sweet bay		•	•	•	•	•
Lavatera assurgentiflora	Tree mallow	3	•	+	•	+	+
Leptospermum laevigatum	Australian tea tree		•	•	•	+	+
Lyonothamnus species	Catalina ironwood	3	•	+	•	+	+
Melaleuca armillaris	Drooping melaleuca		•	•	•	+	+
Melaleuca elliptica			•	•	•	•	+
Melaleuca nesophila	Pink melaleuca		•	•	•	+	+
Metrosideros excelsus	New Zealand Christmas tree		•	•	•	+	
Nerium oleander	Oleander		+	•	•	•	•
Parkinsonia aculeata	Jerusalem thorn	3		+		+	+

Botanical name	**Common name**	**Native? (3 = yes)**	**Coastal margin**	**Intermediate valleys**	**Coastal foothills**	**Inland valleys**	**Inland foothills**
Photinia fraserii			•	•	•	+	+
Photinia serrulata	Chinese photinia			•	•	+	•
Pistacia vera	Pistachio nut			•		•	
Pittosporum crassifolium			•	•	•	+	+
Pittosporum phillyraeoides	Willow pittosporum		•	•	•	+	+
Pittosporum rhombifolium	Queensland pittosporum		•	•	•	•	+
Pittosporum viridiflorium	Cape pittosporum		•	•	•	+	+
Prunus species	Prunus	3	•	•	•	+	+
Psidium littorale	Strawberry guava		•	•	•	+	+
Punica granatum	Pomegranate		+	•	•	•	+
Quercus domosa	Scrub oak				•		•
Rhamnus alaternus	Italian buckthorn		•	•	•	•	+
Rhus integrifolia	Lemonade coffeeberry	3	•	+	•	+	+
Rhus lancea	African sumac		•	•	•	•	+
Rhus ovata	Sugar bush	3	•	•	•	•	•
Sambucus species	Elderberry	3	•	•	•	•	•
Schinus terebinthifolius	Brazilian pepper tree		•	•	•	•	+

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Table VI–6. Plant selection guide for coastal southern California: medium trees, 25–40 ft *(after Perry, 1981).*[a]

Botanical name	Common name	Native? (3 = yes)	Coastal margin	Intermediate valleys	Coastal foothills	Inland valleys	Inland foothills
Acacia baileyana	Bailey acacia		•	•	•	•	•
Acacia decurrens	Green wattle		•	•	•	•	•
Acacia podalyriifolia	Pearl acacia		•	•	•	•	+
Agonis flexuosa	Peppermint tree		•	•	•	+	+
Ailanthus altissima	Tree-of-heaven		•	•	•	•	•
Albizia julibrissin	Silk tree			•	+	•	•
Arbutus menziesii	Madrone	3				+	+
Arbutus unedo	Strawberry tree		•	•	•	•	+
Brachychiton acerifolius	Flame tree			•		•	
Brachychiton populneus	Bottle tree		•	•		•	+
Callistemon viminalis	Weeping bottlebrush		•	•	•	•	+
Casuarina stricta	Beefwood		•	•	+	+	+
Ceratonia siliqua	Carob tree		•	•	•	•	+
Cercidium floridum	Blue palo verde	3				•	+
Cupressocyparis leylandii	Leyland cypress		•	•	•	•	•
Cupressus species	Cypress	3	•	•	•	•	•
Dalea spinosa	Smoke tree	3				•	•
Elaeagnus angustifolia	Russian olive			•		•	+
Eucalyptus niphophila	Snow gum			•	•	•	+
Eucalyptus pulverulenta	Silver mountain gum		•	•	•	•	+
Eucalyptus rudis	Desert gum		+	•	+	•	•
Eucalyptus sideroxylon	Red ironbark		•	•	•	•	•
Geijera parviflora	Australian willow		•	•	•	•	+
Juglans species	Walnut	3		•	•	•	+
Koelreuteria paniculata	Golden rain tree		•	•		•	+
Laurus nobilis	Sweet bay		•	•	•	•	•
Lithocarpus densiflorus	Tanbark oak	3			+		+
Lyonothamnus species	Catalina ironwood	3	•	+	•	+	+
Melaleuca linariifolia	Flaxleaf paperbark		•	•	•	•	+
Melaleuca quinquenervia	Cajeput tree		•	•	•	•	+
Melaleuca styphelioides	Black tea tree		•	•	•	•	+
Myoporum laetum			•	•	•	+	+
Olea europaea	Olive		+	•	•	•	•
Parkinsonia aculeata	Jerusalem thorn	3		+		•	+
Pistacia chinensis	Chinese pistache			•	+	•	+
Pittosporum undulatum	Victorian box		•	•	•	+	+
Prunus caroliniana	Carolina laurel cherry		•	•	•	+	+
Prunus lyonii	Catalina cherry	3	•	•	•	•	•
Quercus chrysolepis	Live canyon oak	3		+	•	+	•
Quercus ilex	Holly oak		•	•	•	•	•
Quercus suber	Cork oak		+	•		•	
Robinia pseudoacacia	Black locust		•	•	•	•	•
Sambucus species	Elderberry	3	•	•	•	•	+
Schinus polygamus	Peruvian pepper tree		+	•		•	+
Schinus terebinthifolius	Brazilian pepper tree		•	•	•	•	+

Botanical name	**Common name**	**Native? (3 = yes)**	**Coastal margin**	**Intermediate valleys**	**Coastal foothills**	**Inland valleys**	**Inland foothills**
Tamarix aphylla	Athel tree			•		•	+
Tristania conferta	Brisbane box		•	•	•	+	+
Zelkova serrata	Sawleaf zelkova			•		•	+
Zizyphus jujuba	Chinese jujube		•	+	•	•	+

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Table VI–7. Plant selection guide for coastal southern California: large trees, 40 ft or taller *(after Perry, 1981).*[a]

Botanical name	Common name	Native? (3 = yes)	Coastal margin	Intermediate valleys	Coastal foothills	Inland valleys	Inland foothills
Acacia decurrens	Green wattle		•	•	•	•	•
Acacia d. dealbata	Silver wattle		•	•	•	•	•
Acacia melanoxylon	Blackwood acacia		•	•	•	•	•
Ailanthus altissima	Tree-of-heaven		•	•	•	•	•
Arbutus menziesii	Madrone	3			+	+	+
Brachychiton acerifolius	Flame tree			•		•	
Casuarina cunninghamiana	Australian pine		•	•	+	•	+
Casuarina equisetifolia	Horsetail tree		•	•	+	•	+
Cedrus atlantica	Atlas cedar		•	•	•	•	+
Cedrus deodara	Deodar cedar		+	•	•	•	+
Ceratonia siliqua	Carob tree		•	•	•	•	+
Cupressocyparis leylandii	Leyland cypress		•	•	•	•	•
Cupressus species	Cypress	3	•	•	•	•	•
Eucalyptus camaldulensis	Red gum		•	•	•	•	•
Eucalyptus catophylla			+	•	•	•	+
Eucalyptus cladocalyx	Sugar gum		•	•	•	+	+
Eucalyptus globulus "Compacta"	Dwarf blue gum		+	•	•	•	+
Eucalyptus leucoxylon	White ironbark		•	•	•	•	•
Eucalyptus polyanthemos	Silver dollar gum		•	•	•	•	•
Eucalyptus rudis	Desert gum		+	•	+	•	•
Eucalyptus sideroxylon	Red ironbark		•	•	•	•	•
Eucalyptus viminalis	Manna gum		•	•	•	•	•
Grevillea robusta	Silk oak		•	•	•	•	+
Lithocarpus densiflorus	Tanbark oak	3			+		+
Lyonothamnus species	Catalina ironwood	3	•	+	•	+	+
Pinus canariensis	Canary Island pine		•	•	•	•	•
Pinus coulteri	Coulter pine	3					•
Pinus halepensis	Aleppo pine		•	•	•	•	•
Pinus pinea	Italian stone pine		•	•	•	•	+
Pinus radiata	Monterey pine	3	•	+	•	+	+
Pinus sabiniana	Digger pine	3					+
Pinus torreyana	Torrey pine	3	•	•	•	+	+
Pistacia chinensis	Chinese pistache			•	+	•	+
Quercus agrifolia	Coast live oak	3	•	•	•	•	•
Quercus chrysolepsis	Live canyon oak	3		+	•	+	•
Quercus douglasii	Blue oak	3			+	+	•
Quercus engelmannii	Mesa oak	3	+	+	•	•	+
Quercus ilex	Holly oak		•	•	•	•	•
Quercus lobata	Valley oak	3		+		•	+
Quercus suber	Cork oak		+	•	+	•	
Robinia pseudoacacia	Black locust		•	•	•	•	•
Schinus molle	California pepper		•	•	•	•	•
Schinus polygamus	Peruvian pepper tree		+	•		•	+
Tamarix aphylla	Athel tree		•	•		•	+

Botanical name	**Common name**	**Native? (3 = yes)**	**Coastal margin**	**Intermediate valleys**	**Coastal foothills**	**Inland valleys**	**Inland foothills**
Zelkova serrata	Sawleaf zelkova		•	+	•	•	+

[a] Most of the information in the table above is from the book *Trees and Shrubs for Dry California Landscapes* (Perry, 1981).

•, plant is well suited to this type of landscape; +, plant will do well in this type of landscape if exposure and soil conditions are optimal.

Sunset Western Garden Book (7th ed., 2001)

One of the best-known and most widely available plant selection guides, this book, like Perry's, is based on a system of climatological zones and related maps. Some horticulturists have stated that the climate zone maps in the Sunset book are more refined and more thorough than any in the other planting references available. Indeed, Sunset is seen as a leader in pointing out that understanding climate conditions is a key prerequisite for the successful selection and growing of plants.

The first part of the book includes maps and descriptions of the climatological zones. Cities and towns in coastal southern California can be found in the map for the San Diego area or in the map for the Los Angeles region. Next in the book is a relatively brief section listing plants for specific landscaping situations—for example, plants for seacoast gardens, shady areas, dry areas, and windy areas. The third and main part of the book consists of an encyclopedia describing several thousand species of plants used for landscapes throughout the western United States. Unfortunately, the text within the book's encyclopedia section describes the *tolerance ranges* of plants for various climate zones. Using those ranges often leads to the selection and use of plants well beyond the climate conditions for which the plants are well suited. Some workers suggest that Sunset should place more emphasis on the *preference ranges* of plants, in addition to reporting the tolerance ranges. Using this book to select plants involves first consulting the appropriate zone map and the lists of plants for specific landscape situations and then consulting the encyclopedia.

Native Plants for Use in the California Landscape (Labadie, 1978)

In this book, author Emile Labadie draws upon his many years of experience as an instructor of ornamental horticulture at a California college to describe 101 species of California native plants. At the front of the book is a key for identifying trees, shrubs, and ground covers. At the back of the book are lists of plants that tolerate particular situations, such as full sun, partial shade, considerable shade, hot and dry weather, and wind, as well as lists of plants that serve a special function, such as providing a visual screen or hedge, a barrier, erosion control, or shade. Table VI-8 is a summary of some information from this book. The notes regarding planting conditions may prove particularly useful.

Table VI–8. Native plants recommended by Labadie (1978) for California landscapes.[a]

Botanical name	Common name	Type	Spread (ft)	Height (ft)	Notes
Arctostaphylos edmundsii	Little Sur manzanita	Ground cover	8+	0.5–2	Sun or partial shade; tolerates salt spray
Arctostaphylos hookeri	Hooker manzanita, Monterey manzanita	Ground cover	6–8	0.5–3	Sun or shade; tolerates salt spray, drought
Arctostaphylos uva-ursi	bearberry, kinnikinnick, creeping manzanita	Ground cover	Up to 15	6–12	Best in sandy soil; drought-tolerant
Artemisia pycnocephala	Coast sagebrush	Ground cover	Up to 2	1.5–2.5	Best where temperature is moderate; drought-tolerant; short-lived
Asarum caudatum	Wild ginger	Ground cover	Wide	0.8	Best in shade in rich, moist soil; needs pure water for irrigation
Baccharis pilularis	Dwarf coyote bush	Ground cover	2–10	0.5–1	Tolerates moisture as well as drought; tolerates moderately saline, somewhat alkali soil
Ceanothus gloriosus	Point Reyes creeper	Ground cover	5+	0.5–1.5	Tolerates wind, salt spray
Ceanothus griseus var. horizontalis	Carmel creeper	Ground cover	5–15	3–5	Needs little water
Ceanothus impressus	Santa Barbara ceanothus	Ground cover	8–10	3–5	Best in well-drained soil
Ceanothus purpureus	Hollyleaf ceanothus	Ground cover	5–6	2–4	Best in well-drained soil
Equisetum hyemale	Horsetail, common scouring-rush	Ground cover	Wide	2–4	Moist, shaded areas from sea level to 8,500 ft
Galvezia speciosa	Island bush snapdragon	Ground cover	3–5	7–8	Moist, well-drained soil; may tolerate moderately saline, somewhat alkali soil
Polystichum munitum	Western sword fern	Ground cover	2–4	2–4	Needs moist, rich soil, partial shade; needs pure water for irrigation
Satureja douglasii	Yerba buena	Ground cover	3+	0.5	Best in moist, rich soil, sun or partial shade; needs pure water for irrigation
Symphoricarpos albus	Snowberry	Ground cover	Wide	2–6	Best in well-drained soil, shade; valuable food plant for wildlife
Woodwardia fimbriata	Giant chain fern	Ground cover	9+	Up to 9	Moist, well-drained soil, partial shade
Zauschneria californica	California fuchsia, hummingbird fuchsia	Ground cover	1.5	1.5–3	Well-drained soil, sun
Washingtonia filifera	California fan palm	Palm	8–20	20–80	Moist, well-drained soil, sun; tolerates drought and saline, alkaline soil; only palm native to Calif.; not good for sites right on the coast
Adenostoma fasciculatum	Chamise, greasewood	Shrub	5	2–10	Best in hot, dry areas; flammable
Arctostaphylos densiflora	Vine Hill manzanita, Sonoma manzanita	Shrub	4–6	1.5–6	Tolerant of dry soil; sun or partial shade
Atriplex lentiformis var. *breweri*	Brewer saltbush	Shrub	6–10	6–10	Tolerates salt spray, alkaline soil
Calycanthus occidentalis	Spicebush, sweet shrub	Shrub	4–12	4–12	Best in moist soil
Carpenteria californica	Bush anemone	Shrub	4–6	6–15	Best in partial shade
Cercis occidentalis	Western redbud	Shrub	Up to 16	8–20	Anywhere except desert
Comarostaphylis diversifolia	Summer holly	Shrub	4–8	6–18	Drought-tolerant
Eriogonum arborescens	Santa Cruz Island buckwheat	Shrub	3.5–4	Up to 3.5	Good for rocky slopes, full sun; tolerates wind
Eriogonum fasciculatum	California buckwheat	Shrub	3–4	2–3	Good for dry slopes

Botanical name	**Common name**	**Type**	**Spread (ft)**	**Height (ft)**	**Notes**
Eriogonum giganteum	St. Catherine's lace	Shrub	4–6	3–6	Drought-tolerant
Fragaria chiloensis	Sand strawberry	Shrub	Wide	0.5–1	Needs fertile, well-drained soil; may tolerate moderately saline, somewhat alkali soil
Fremontodendron californicum	Common flannel bush, leatherwood, Fremontia	Shrub	8–15	6–18	For hot, dry locations
Gaultheria shallon	Salal	Shrub	Wide	1.5–6	Best in moist soil in partial shade; native to coastal redwood region; needs pure water for irrigation
Holodiscus discolor	Cream bush, ocean spray	Shrub	10–12	3–20	Moist slopes, canyons; sun or partial shade; needs pure water for irrigation
Mahonia aquifolium	Oregon grape	Shrub	1–6	1–6	Best in partial shade, in well-drained soil
Mahonia nervosa	Longleaf mahonia	Shrub	Up to 2	0.8–2	Best in moist soil in partial shade
Mahonia nevinii	Nevins barberry	Shrub	3–10	3–10	Best in sun; tolerates any soil, little or much water
Mahonia pinnata	California holly grape	Shrub	5+	2.5+	Tolerates heat, drought; full sun
Physocarpus capitatus	Ninebark	Shrub	6–8	6–8	Partial shade, moist soil
Rhamnus californica	California coffeeberry	Shrub	4–8	4–18	Drought-tolerant; prefers sun, rocky or heavy soil
Rhamnus crocea	Redberry, buckthorn	Shrub	5–8	5	Adaptable, but needs good drainage
Rhododendron macrophyllum	Rhododendron, California rose bay	Shrub	4–10	4–10	Needs moist, rich, well-drained soil, part shade; foliage toxic to livestock; needs pure water for irrigation
Rhododendron occidentale	Western azalea	Shrub	6–10	6–10	Needs moist, rich, well-drained soil, part shade; foliage toxic to livestock
Rhus integrifolia	Lemonade berry	Shrub	3–10	3–10	Best near the coast; may tolerate moderately saline, somewhat alkali soil
Rhus laurina	Laurel sumac	Shrub	5–7	5–7	Best on sunny, dry slopes below 3,000 ft, coastal; may tolerate moderately saline, somewhat alkali soil
Rhus ovata	Sugar bush, sugar sumac	Shrub	2.5–10	3–10	Best on dry slopes below 2,500 ft
Ribes sanguineum var. glutinosum	Pink winter currant, red-flowering currant	Shrub	5–12	5–12	Best in moist soil in partial shade; needs pure water for irrigation
Ribes speciosum	Fuchsia-flowering gooseberry	Shrub	3–6	3–10	Moist, well-drained soil, partial shade
Ribes viburnifolium	Evergreen currant	Shrub	12	3–6	Best in partial shade; drought-tolerant
Romneya coulteri	Matilija poppy, coulter poppy	Shrub	Wide	3–8	Best in sun in well-drained soil; invasive
Rubus parviflorus	Thimble berry	Shrub	3–5	4–6	Likes open woods and canyon areas; needs pure water for irrigation
Salvia leucophylla	Purple sage	Shrub	5+	5+	Best in dry, well-drained soil, sun; tolerates heat
Vaccinium ovatum	California huckleberry	Shrub	3–5	2–8	Best in well-drained acidic soil, part shade; needs pure water for irrigation
Acer circinatum	Vine maple	Shrub or small tree	25–35	5–35	Best in moist, rich soil, partial shade; tolerates heat, cold; needs pure water for irrigation

Botanical name	**Common name**	**Type**	**Spread (ft)**	**Height (ft)**	**Notes**
Amelanchier alnifolia	Western serviceberry	Shrub or small tree	6–8	4–15	Best in dry, rocky soil, sun
Fremontodendron mexicanum	Southern Fremontia	Shrub or small tree	8–15	8–20	Best in dry, well-drained soil
Garrya elliptica	Coast silktassel	Shrub or small tree	8–10	4–30	Likes partial shade, coastal conditions
Abies bracteata	Santa Lucia fir, bristlecone fir	Tree	15-20	30-100	Best in dry, rocky, acidic soil, sun, cool climate
Abies concolor	White fir, silver fir	Tree	40–60	60–100	Best in deep, rich, moist loam in cold areas; tolerates coarse, dry soil
Abies magnifica	Red fir, silver tip	Tree	30–60	60–200	Deep, well-drained soil, sun; high altitude
Acer macrophyllum	Bigleaf maple	Tree	30–50	30–95	Deep, rich, moist soil; sun or partial shade
Acer negundo var. californicum	California box elder	Tree	50+	20–40	Tolerates various soils; box elder bug is a pest
Aesculus californica	California buckeye, horsechestnut	Tree	30–60	15–40	Best in moist, well-drained loam; coastal
Alnus oregona	Red alder, Oregon alder, western alder	Tree	20–30	100–130	Best in deep, well-drained loam with ample water; roots fix nitrogen; needs pure water for irrigation
Alnus rhombifolia	White alder	Tree	Up to 40	40–100	Best in moist soil
Arbutus menziesii	Pacific madrone	Tree	15–75	Up to 80	Best in warm, moist areas, yet tolerates wide climate range; prefers rocky or sandy soil
Calocedrus decurrens	Incense cedar	Tree	Up to 50	50–150	Tolerates extreme heat and cold
Cercocarpus betuloides var. traskiae	Catalina mountain mahogany, Catalina hard-tack	Tree	15+	up to 25	Best on dry slopes or in washes
Cercocarpus ledifolius	Curl-leaf mountain mahogany, desert mountain mahogany	Tree	15+	up to 30	Native to southern Calif. deserts and mountains
Chamaecyparis lawsoniana	Lawson cypress, Port Orford cedar	Tree	30–50	75–200	Best in cool, coastal areas
Cornus nuttallii	Pacific dogwood	Tree	Up to 20	30–50	Best in partial shade, with some moisture; needs pure water for irrigation
Corylus cornuta var. californica	Hazelnut, filbert	Tree	5–12	5–12	Moist slopes, partial shade
Cupressus macrocarpa	Monterey cypress	Tree	up to 75	20–75	Coastal areas; wind-tolerant
Dendromecon harfordii	Island tree poppy	Tree	2–20	2–20	Best in well-drained soil, full sun
Heteromeles arbutifolia	Toyon, Christmas berry, California holly	Tree	5–20	6–25	Best in dry soil, up to 3,500 ft elev.
Juglans hindsii	California black walnut	Tree	20–50	30–70	Best near streams in moist, sandy or gravelly soil; tolerates wind, heat
Lithocarpus densiflora	Tanbark oak, tan oak	Tree	Up to 50	50–150	Best in coastal areas, not for interior valleys
Lyonothamnus floribundus var. asplenifolius	Fern-leaf Catalina ironwood	Tree	15–40	25–50	Best in coastal areas in full sun; doesn't tolerate extreme heat or cold
Myrica californica	Pacific wax myrtle	Tree	15–20	10–35	Best in coastal areas

Botanical name	**Common name**	**Type**	**Spread (ft)**	**Height (ft)**	**Notes**
Pinus contorta	Shore pine, beach pine	Tree	15–30	15–30	Best in sandy, moist soils
Pinus coulteri	Coulter pine	Tree	20–40	40–80	For warm, dry slopes; tolerates heat, wind
Pinus muricata	Bishop pine	Tree	20–40	45–75	Coastal areas; tolerates salty air and wind
Pinus ponderosa	Ponderosa pine, western yellow pine	Tree	30–40	50–200	Best in dry, sandy soil; needs some moisture
Pinus radiata	Monterey Pine	Tree	30–50	40–80	Well-drained, sandy soil, sun; tolerates heat, cold, wind, salt spray
Pinus sabiniana	Digger pine	Tree	25–30	40–80	Best in hot, dry inland valleys and foothills
Pinus torreyana	Torrey pine, Soledad pine	Tree	25–30	20–60	Dry, well-drained soil, sun; moderate temp.; may tolerate moderately saline, somewhat alkali soil
Platanus racemosa	Western sycamore	Tree	50–70	40–90	Deep, rich, moist soil; anthracnose a problem
Prunus ilicifolia	Hollyleaf cherry	Tree	10–25	10–25	Best in well-drained soil, sun; long-lived
Prunus lyonii	Catalina cherry	Tree	15–30	15–45	Best in relatively dry soil, sun or partial shade
Pseudotsuga menziesii	Douglas fir	Tree	30–60	70–250	Best in humid area with well-drained soil, sun or partial shade
Quercus agrifolia	Coast live oak	Tree	60–100	30–75	Needs well-drained soil
Quercus chrysolepis	Maul oak, canyon oak	Tree	Up to 100	25–100	Best in moist soil on slopes below 6,500 ft
Quercus douglasii	Blue oak	Tree	25–50	up to 50	Best in dry, well-drained soil, sun
Quercus kelloggii	California black bak	Tree	25–30	30–80	Dry, gravelly soil, sun
Quercus lobata	Valley oak, California white oak	Tree	70+	70+	Deep soil, sun; tolerates heat
Quercus wislizenii	Interior live oak	Tree	75+	30–75	Tolerates poor, dry soil; best in sun
Sambucus caerulea	Blue elderberry	Tree	15–30	15–30	Best in moist, well-drained soil; bark is toxic
Sequoia sempervirens	Coast redwood	Tree	20–40	100–300	Best in deep, moist, rich, well-drained soil, sun
Sequoiadendron giganteum	Giant sequoia	Tree	75–100	150–250	Deep, rich, well-drained soil, sun; not for areas without winter snow
Thuja plicata	Giant arborvitae, western red cedar	Tree	35–60	up to 200	Best in rich, moist, well-drained soil; tolerates extreme heat and cold
Tsuga heterophylla	Western hemlock, coast hemlock, Alaska pine	Tree	20	125–160	Moist, sandy soil, sun; needs pure water for irrigation
Umbellularia californica	California bay, California laurel, Oregon myrtle	Tree	30–100	20–100	Best in fertile, moist, deep, well-drained soil; sun or partial shade

[a] All plants listed are California natives. Information excerpted from text in Labadie (1978). Some notes in the rightmost column were provided by reviewers of this literature review.

California Native Trees and Shrubs (Lenz and Dourley, 1981)

This book is based on a system of climatological zones and maps similar to those in Perry (1981). The book's subtitle, *For Garden and Environmental Use in Southern California and Adjacent Areas*, makes clear the authors' focus. Basing their book on 50 years of horticultural data from Rancho Santa Ana Botanic Garden, Lenz and Dourley begin by describing the climate and geological environment of southern California. The authors then describe the seven zones in their climatological system. This description is followed by a brief excursion into the realm of native-plant ecology, in which they describe the dominant plant communities of the southern California wildlands: valley grassland, coastal sage scrub, chaparral, creosote bush scrub, Joshua tree woodland, pinion juniper woodland, yellow pine forest, and desert oasis. Key species of each community are outlined in some detail. Next in the book is a chapter that contains detailed descriptions of 361 species of trees and shrubs native to California, including line drawings and photographs for many of them. In subsequent chapters, Lenz and Dourley report on nonnative plants, the survivability of plants without horticultural care, and the development of superior cultivars. At the back of the book, they provide a table listing all species described in the book and the zones for which those species are well suited. Also provided are a relatively comprehensive glossary and a cross-index between common names and scientific names of plants. The book is best used either as an encyclopedic reference or as a map-based guide to selecting plants.

California Native Plants for the Garden (Bornstein, Fross, and O'Brien , 2005)

This recent book covers some of the same ground as Lenz (1956), Lenz and Dourley (1981), and Labadie (1978). Chapter 1 reviews briefly the efforts of those gardeners, nursery workers, landscape designers, and others who sought during the past century to promote the use of native plants in California gardens. Chapter 2 describes the major California plant communities: chaparral, coastal scrub, grassland, woodland, forest, desert scrub, desert woodland, and the high mountain (alpine) regions. Chapter 3 outlines the basics of designing a garden featuring California's native flora: site analysis, selection of a design theme, planning, plant selection, and placement of plants. Chapter 4 describes the best ways to care for native plants. It covers such topics as site preparation, soil management, acquisition of seeds and plants, planting, watering, fertilizing, mulching, pruning, and managing pests and weeds. Next in the book is a fairly lengthy section (176 of the book's 259 pages) titled "Plant Profiles." Here is where the authors describe in detail (and depict with photos) approximately 200 key plants. Along the way they also describe briefly some 300 other native plants. The key plants are ones deemed to be reliable performers that also have high aesthetic value, are readily available, and are resistant to insects and other pests. A final, but no less important, section provides 30 plant selection lists intended to help a gardener choose appropriate plants for a variety of specific site conditions or particular plant characteristics. The site conditions include, for example, moist habitats, seashore conditions, and meadows. The plant characteristics include aromatic foliage, fast growth, slow growth, and fall color.

The chief value of this book, when compared to others mentioned here, is that it features plants widely available now and that it advocates using native species not just as drought-tolerant species (a common use in former years) but also as the featured plants in a variety of more favorable sites.

Landscape Plants for Western Regions (*Perry, 1992)*

This book builds on the body of information provided in Perry's earlier (1981) book. As he explains, "Since the completion of *Trees and Shrubs for Dry California Landscapes* in 1980, I have pursued the study of landscape plants with renewed interest and rigor ... I wanted to have so much information on plants that I could answer any question regarding their needs and tolerances and could give the best advice on the ecological guidelines that influence our use of them. So, I collected better reference materials, made more field observations, and started to travel to other parts of the world in an effort to see some of our ornamental plants growing in their natural environments."

In the book's first section, "Issues and Goals," Perry shares his thoughts regarding the changing nature of landscaping and society's need to keep redefining its landscaping goals and knowledge. Many of the ideas address environmental issues and encourage pursuing the goal of sustainability as part of the process of designing a landscape.

In his book's second section, "Regional Characteristics," Perry defines and depicts on a map a number of landscape regions. He also provides maps outlining intensities of rainfall and the numbers of days of frost per year. They are followed by detailed descriptions and photographs of the various landscape regions—regions that are similar to the ones defined in his earlier book and in Lenz and Dourley's book.

In the third section, "Plants and Environment," Perry introduces a number of ecological concepts helpful when planning and designing landscapes. He also provides illustrative photographs.

The fourth section, "Estimating Water Needs of Landscape Plants," contains an extensive table of 475 trees, shrubs, vines, ground covers, perennials, and succulents, with the water needs of each species indicated for each of the landscape regions described in the book's second section. This is a good place to start when beginning the plant-selecting phase of designing a landscape.

In the fifth section, "Design Checklists," Perry provides an extensive table listing the relevant height, width, flowering season, flower color, and value to wildlife habitat of each species. The table is also another source of information to refer to early in the process of designing a landscape. Perry continues the section by presenting a number of "plant palettes"—groupings of plants that are compatible both aesthetically and in terms of horticultural requirements. The western native palettes include a coast live oak category, a Monterey pine category, and a Western sycamore category. The Mediterranean palette includes olive tree, holly oak, and sweet bay categories. The groupings of Australian species include the sugar gum, the river red gum, the peppermint tree, and the shoestring acacia categories. Other groupings are for Asian species, such as crape myrtle and related plants, and South African species, such as fortnight lily. Also in this fifth section is a list of plants that can help "fix" nitrogen from the air, enhancing the nitrogen content of the plant litter and soil, and a number of planting guidelines aimed at helping to restore native plants or wildlife habitat.

In his book's sixth and final section, "Plant Compendium," Perry describes in detail 475 species of plants. Each description includes a clear, well-composed color photograph of the relevant plant.

Native Plants for California Gardens* (*Lenz, 1956)

Published in 1956 by Rancho Santa Ana Botanic Garden, Claremont, Calif., this book is part of a series of papers devoted to botany and the horticulture of California plants. According to Lenz's foreword, he attempted to select those species of native flora that can be recommended to gardeners and landscape designers. Lenz describes briefly California's various plant communities and early botanical collections. He also provides useful tips for propagating and handling native plants, including germinating seeds, transplanting, rooting, grafting, and preventing disease. The remaining 131 pages of this 166-page book are a detailed compendium of 102 species of plants native to California. Sharp, clear black-and-white illustrative photographs are provided.

VI.C. Guide for Selecting Turfgrasses

Turfgrasses often are valuable components of the environments where people live, work, and play. They can be used to provide an essential base for sports and leisure activities in such settings as baseball fields, football and soccer fields, golf courses, and school grounds. They also prove useful in soothing landscapes in such places as office parks, cemeteries, and home gardens. Yet turf also is seen by some as problematic, for it sometimes contributes to a net loss of oxygen in the atmosphere and often requires considerable water, the conservation of which is a main reason for switching to recycled water in the first place. Also, turfgrass may require the application of fertilizer or other chemical treatments, which may in some instances, foster the contamination of soil or other non-point source pollution problems. The key to avoiding all these potential problems is to use turf only where necessary and to choose a variety of turf that best fits the intended application.

Selecting a turfgrass involves considering a number of factors, including the intended use of the turf, the desired appearance, and the degree of required maintenance. The choice of a turfgrass is also dictated by geography, the soil and biotic conditions under which grass will be grown, and the climate, particularly temperature, rainfall, and the amount of sunlight. Table VI-9 lists all species commonly grown in California, divided into warm- and cool-season species. Warm-season grasses grow predominantly in southern California, in the Central Valley, and along the Pacific coast as far north as San Francisco. Cool-season grasses are grown throughout California, except in the state's deserts and southernmost regions.

Warm-season turfgrasses usually lose their greenness and go dormant in winter if the average temperature drops below 50 to 60 ˚F. Some may die if exposed to subfreezing temperatures for extended periods. Cool-season turfgrasses do not ordinarily lose their greenness unless the average air temperature drops below 32 ˚F for an extended period. They regain their greenness as soon as temperatures rise above freezing and are not usually damaged by subfreezing temperatures. It should be noted that grasses vary in the hue and intensity of their color, from the bright green of Kentucky bluegrass (*Poa pratensis*) to the grayish green of common bermudagrass (*Cynodon* spp.).

The following information applies to the turfgrasses listed in Table VI-9 when such grasses are grown in California:

Bentgrasses (*Agrostis* spp.)

Though they tolerate close mowing and can provide lawns of good quality, bentgrasses require more maintenance than other lawn grasses and extra effort to ward off disease during the summer.

- The colonial variety of bentgrass (*Agrostis tenuis*) may spread very slowly by short rhizomes and, less often, short stolons. Its layer of thatch extends above and below the soil.

This variety is adapted to the northern coastal climate and does not form a dense turf in other areas.

- The highland variety (*Agrostis* spp. cv. "Highland") is adapted to valley climates and will survive extensive droughts. It forms solid patches of grass that turn a frosty blue from morning dew during cool seasons. It may form both short rhizomes and stolons.
- The creeping variety (*Agrostis palustris*) is used for specialized turf, such as golf, bowling and tennis greens. The skill and expense required to maintain it usually preclude its use for home lawns. This variety spreads by stolons to form a mat or layer of thatch above the soil.

***Bluegrasses* (*Poa* spp.)**

Three distinct bluegrasses are grown in California.

- The annual variety of bluegrass (*Poa annua*), considered a weed, is well adapted to the cool, moist conditions of California's Pacific coast from Los Angeles to the Oregon border. It is the predominant species on golf greens, bowling greens, and croquet courts. It also quickly invades the dead and worn areas of a significant number of overused sports fields and parks, as it is very well suited to the coastal climate and is a prolific producer of seeds. This variety often successfully invades golf and bowling greens because it tolerates very close mowing. Shallow-rooted and drought intolerant, this turfgrass is a short-lived perennial in cool, moist climates and persists as an annual in sites with hot, dry summers.
- Kentucky bluegrass (*P. pratensis*) is the standard of quality among turfgrasses in areas where it is well adapted. In areas of marginal adaptation, it suffers from diseases, invasion by weeds, and stress related to high temperatures. Each variety of Kentucky bluegrass has characteristic virtues and faults, with none adapted to hot valley climates. Blending equal portions of several seed varieties usually leads to optimal results. For example, a seed mixture of Kentucky bluegrass and perennial ryegrass is more resistant to disease than is bluegrass alone.
- Roughstalk bluegrass (*P. trivialis*) is a short-lived perennial that is well adapted to moist, shady sites. Due to its superior performance during winter and after close mowing, it is commonly used to overseed dormant bermudagrass on golf putting greens.

***Fescue* (*Festuca* spp.)**

These grasses, which vary considerably by species, are appropriate for a range of purposes.

- Hard and red fescues (*Festuca longifolia* and *F. rubra*) are recognizable by their fine texture and, thus, are also known as "fine-leaf" fescues. They do not prosper in hot climates, except in shady, dry situations, and they do not tolerate being closely mowed or excessively fertilized. Their color, texture, and pattern of growth make them excellent companion grasses for Kentucky bluegrass, as long as these moderately drought-tolerant grasses are grown in moderately shady exposures or dry soil. Fine fescues seldom exceed 8 in. (20 cm) in height, except when in flower, and thus can be useful where a low-maintenance lawn is desired, such as at a summer cabin at cool mountain elevations where a single mowing will remove the seed heads. They can also be used for controlling hillside erosion in urban areas, such as unmowed ground covers along roadsides, and for golf course roughs, parks, and cemeteries.
- Tall fescue (*F. arundinacea*), when densely sown, produces a moderately coarse-textured lawn that is trouble free and uniform in appearance. In a mix with other cool-season grasses, individual tall fescue plants appear as coarse weeds. New selections, known as turf-type and dwarf-type tall fescues, are finer textured and shorter than older selections. Bare or worn spots within tall fescue stands must be reseeded, as these grasses do not produce runners. Tall fescues are quite tolerant of drought and heat and require the least maintenance of all cool-season grasses in California.

***Ryegrass* (*Lolium* spp.)**

Two distinct ryegrass species are commonly planted in California.

- Annual ryegrass (*Lolium multiflorum*), quite coarse textured, is used only to overseed dormant bermudagrass or to provide a temporary annual cover.
- Perennial ryegrass (*L. perenne*), a strong performer in coastal fog belts and adequate elsewhere, is often used in seed mixtures with Kentucky bluegrass. It germinates quickly and provides a rapid turf cover and so is also used to overseed winter-dormant Bermuda grass lawns. It has no rhizomes or stolons, so bare or worn areas should be reseeded.

***Weeping alkaligrass* (*Puccinellia distans*)**

This grass is only marginally adapted to the cool central and northern coast, as well as to mountain regions. Its only use is in areas with severe soil or water salinity problems since it does not produce an attractive, durable lawn. Because weeping alkaligrass tolerates low mowing, it may provide an acceptable alternative for winter overseeding of bermudagrass on salt-affected golf greens.

Bermudagrass (*Cynodon dactylon*)

This grass is well adapted to the warm regions of California. Spreading both by rhizomes and stolons, it can be a troublesome invader of other areas in a landscape. Short mowing helps produce a neat, restrained turf. Bermudagrass does not tolerate shade and turns brown with continued low temperatures. Hybrid bermudagrasses are propagated vegetatively and require a high level of management. If ordinary management is available, common bermudagrass is preferable. Bermudagrasses are highly drought and salt tolerant.

Seashore paspalum (*Paspalum vaginatum*)

This grass grows well near the ocean, where it is subjected to saltwater. It has excellent tolerance of salinity.

St. Augustine grass (*Stenotaphrum secundatum*)

This grass is a coarse-textured, subtropical grass with excellent tolerance of shade, drought, and salinity.

Kikuyugrass (*Pennisetum clandestinum*)

This grass is a weedy grass grown in coastal and some inland areas of California. This native of high-altitude equatorial Africa thrives in climates with moderate, even temperatures. Sometimes mistaken for St. Augustine grass, kikuyugrass forms vigorous stolons and has slightly flattened, hairy leaf sheaths and blades with files of hairs. It tolerates low fertility, drought, and frequent close mowing.

Zoysiagrass (*Zoysia* spp.)

This grass is well adapted only in the warmest areas of California. It is a high-quality, erect turf that forms a dense carpet that may be difficult to mow evenly. Zoysia tolerates moderate shade, though it is slow to become established, even in full sun. The nursery trade uses *Zoysia tenuifolia*, known as mascarengrass or Japanese temple grass, as a ground cover. A fine-leafed, dwarf plant that requires no mowing, this grass slowly yet strongly invades nearby plants. *Zoysia japonica*, known as Japanese lawn grass, is very drought tolerant and the primary zoysia species used as turfgrass in California. The Meyer variety resembles tall fescue in color and texture. El Toro, a variety patented by the University of California, covers faster and is coarser and shorter than other zoysias.

Table VI-9. California turfgrasses.

Common name	Scientific name
Names for cool-season grasses	
Bentgrass (colonial)	*Agrostis tenuis* Sibth.[a]
Bentgrass (creeping)	*Agrostis palustris* Huds.[a]
Bentgrass (highland)	*Agrostis spp.* cv. “Highland”[a]
Bluegrass (annual)	*Poa annua* L.
Bluegrass (Kentucky)	*Poa pratensis* L.
Bluegrass (roughstalk)	*Poa trivialis* L.
Fescue (hard)	*Festuca longifolia* Thuill.
Fescue (red)	*Festuca rubra* L.
Fescue (tall)	*Festuca arundinacea* Schreb.
Ryegrass (Annual)	*Lolium multiflorum* Lam.
Ryegrass (perennial)	*Lolium perenne* L.
Weeping alkaligrass	*Puccinellia distans* (L.) Parl.
Names for warm-season grasses	
Bermudagrass (Common)	*Cynodon dactylon* (L.) Pers.[b]
Bermudagrass (“Hybrid”)	*Cynodon dactylon* (L.) Pers.[b]
Kikuyugrass	*Pennisetum clandestinum* Hochst.
Seashore paspalum	*Paspalum vaginatum* O. Swartz
St. Augustine grass	*Stenotaphrum secundatum* (Walt.) Kuntze
Zoysiagrass	*Zoysia* spp.

[a] This species is not well-adapted for hot summers.

[b] Considered by some to be a weed.

VI.D. Guides Available via the Internet

Many guides for selecting plants for landscapes are available on the Internet. They tend to be narrower in focus than the books cited previously in this chapter. Some useful ones are found on the websites of the Rancho Santa Ana Botanic Garden and the San Diego chapter of the California Native Plant Society. Both sites contain numerous links to many other useful sites.

Rancho Santa Ana Botanic Garden (www.rsabg.org)

The website of Rancho Santa Ana Botanic Garden, Claremont, Calif., hosts a number of useful Web pages and downloadable documents. One of the latter is the California Classics Plant Palette, a 10-page brochure. This document lists the most reliable, garden-worthy, and widely available native plants for southern California gardens and public landscapes. Plants are grouped by ecological community. These include oak woodlands, riparian woodlands, scrubland and chaparral, Mojave Desert, and Colorado Desert. Excerpts from the oak woodland, riparian woodland, and scrubland and chaparral lists are presented here as Tables VI-10, VI-11, and VI-12. All of these groupings are helpful when designing a landscape that includes or consists entirely of plants native to California.

Table VI–10. "Classic" California native plants for oak woodland landscapes.[a]

Type of plant	Botanical name	Common name	Notes
Trees	*Aesculus californica*	California buckeye	
	Quercus agrifolia	Coast live oak	
	Quercus engelmannii	Mesa oak	
Shrubs	*Arctostaphylos bakeri* "Louis Edmunds"	Louis Edmunds manzanita	
	Arctostaphylos "Howard McMinn"	Howard McMinn manzanita	
	Arctostaphylos "Sunset"	Sunset manzanita	
	Carpenteria californica	Bush anemone	
	Ceanothus "Concha"	Concha Ceanothus	
	Ceanothus "Ray Hartman"	Ray Hartman Ceanothus	
	Ceanothus "Wheeler Canyon"	Wheeler Canyon Ceanothus	May tolerate moderately alkaline, somewhat saline soil
	Galvesia speciosa	Island snapdragon	
	Heteromeles arbutifolia	Toyon	
	Mahonia (Berberis) "Golden Abundance"	Golden abundance barberry	
	Prunus ilicifolia	Holly-leaf cherry	
	Rhamnus californica and cultivars	California coffeeberry	
	Rhamnus crocea	Redberry	
	Ribes malvaceum	Chaparral currant	
	Ribes speciosum	Fuschia-flowered gooseberry	
	Symphoricarpos albus var. laevigatus "Tilden Park"	Tilden Park snowberry	
Ground covers	*Arctostaphylos edmundsii*	Edmunds manzanita	
	Baccharis pilularis var. pilularis	Prostrate coyote brush	
	Ceanothus griseus var. horizontalis	Carmel creeper	
	Ceanothus "Joyce Coulter"	Joyce Coulter ceanothus	
	Mahonia (Berberis) repens	Creeping barberry	
	Ribes viburnifolium	Catalina perfume currant	
	Symphoricarpos mollis	Creeping snowberry	
Perennials	*Achillea millefolium*	Yarrow	May tolerate moderately alkaline, somewhat saline soil
	Asclepias fascicularis	Narrow-leaf milkweed	
	Heuchera maxima	Island alumroot	
	Fragaria chiloensis	Beach strawberry	Likes shade
	Monardella villosa	Coyote mint	
	Ranunculus californica	California buttercup	
	Salvia spathacea	Hummingbird sage	
	Sisyrinchium bellum	Blue-eyed grass	
	Thalictrum fendleri subsp. *polycarpum*	Meadow rose	

[a] The first three columns in this table were excerpted from the California Classics Plant Palette (Rancho Santa Ana Botanical Garden, 2005). The notes in the fourth (rightmost) column were provided by a reviewer of this literature review. Unless noted otherwise, all the species in this table are likely to be unsuccessful unless the water with which they are irrigated is relatively low in dissolved salts and alkali.

Table VI–11. “Classic” California native plants for riparian woodland landscapes.[a]

Type of plant	Botanical name	Common name	Notes
Trees	*Alnus rhombifolia*	White alder	A mistletoe magnet
	Platanus racemosa	Western sycamore	
	Populus fremontii	Fremont cottonwood	A mistletoe magnet
	Quercus lobata	Valley oak	
	Umbellularia californica	California bay	
Shrubs	*Calycanthus occidentalis*	Spice bush	
	Carpenteria californica	Bush anemone	
	Cercis occidentalis	Western redbud	
	Cornus sericea	Creek dogwood	
	Lavatera assurgentiflora	Malva rosa	May tolerate moderately alkaline, somewhat saline soil
	Lavatera “Purísima”	Purísima mallow	
	Mahonia (Berberis) “Golden Abundance”	Golden abundance barberry	
	Philadelphus lewisii	Mock orange	
	Ribes speciosum	Fuschia-flowered gooseberry	
	Rosa californica	California rose	
	Rosa nutkana var. nutkana	Nootka rose	
	Rosa woodsii var. ultramontana	Interior rose	
Ground covers	*Ceanothus griseus* var. horizontalis and cultivars	Carmel creeper	
	Iva hayesiana	Hayes iva	Tolerates soil that’s moderately alkaline and somewhat saline
	Arctostaphylos edmundsii	Edmunds manzanita	
	Baccharis pilularis var. pilularis	Prostrate coyote brush	Tolerates soil that’s moderately alkaline and somewhat saline
	Mahonia (Berberis) aquifolium “Compacta”	Compact Oregon grape	
	Mahonia (Berberis) repens	Creeping barberry	
	Ribes viburnifolium	Evergreen currant	
Perennials	*Aquilegia formosa*	Western columbine	
	Asclepias speciosa	Showy milkweed	
	Achillea millefolium	Yarrow	May tolerate moderately alkaline, somewhat saline soil
	Heuchera species and cultivars	Coral bells	
	Iris douglasiana and cultivars	Pacific coast iris	
	Juncus patens	Wire grass	
	Muhlenbergia rigens	Deer grass	
	Thalictrum fendleri subsp. *polycarpum*	Meadow rue	
	Woodwardia fimbriata	Giant chain fern	
Vine	*Vitus californica* “Roger’s Red”	Roger’s red California grape	

[a] The first three columns in this table were excerpted from the *California Classics Plant Palette* (Rancho Santa Ana Botanical Garden, 2005). The notes in the fourth (rightmost) column were provided by a reviewer of this literature review. Unless noted otherwise, all the species in this table are likely to be unsuccessful unless the water with which they are irrigated is relatively low in total dissolved solids.

Table VI–12. "Classic" California native plants for scrubland landscapes.[a]

Type of plant	Botanical name	Common name	Notes
Tree	*Sambucus mexicana*	Elderberry	
Shrubs	*Arctostaphylos bakeri* "Louis Edmunds"	Louis Edmunds manzanita	
	Arctostaphylos glauca	Bigberry manzanita	
	Artemisia californica "Montara"	Montara California sagebrush	
	Ceanothus "Concha"	Concha ceanothus	
	Ceanothus leucodermis	Chaparral whitethorn ceanothus	
	Ceanothus "Sierra Blue"	Sierra blue ceanothus	
	Cercocarpus betuloides	Mountain mahogany	
	Dendromecon harfordii	Island bush poppy	
	Encelia californica	California sunflower	
	Encelia farinosa	Incienso	May tolerate moderately alkaline, somewhat saline soil
	Eriogonum fasciculatum	California buckwheat	
	Eriogonum giganteum	Saint Catherine's lace	
	Heteromeles arbutifolia	Toyon	
	Isomeris arborea	Bladderpod	Tolerates soil that's moderately alkaline and somewhat saline
	Mahonia (Berberis) nevinii	Nevin's barberry	
	Rhus ovata	Sugar bush	
	Salvia apiana	White sage	
	Salvia clevelandii and cultivars	Cleveland sage	
	Salvia leucophylla	Purple sage	May tolerate moderately alkaline, somewhat saline soil
	Salvia mellifera	Black sage	
	Yucca whipplei	Our Lord's candle	
Ground covers and bank plants	*Arctostaphylos hookeri*	Hooker manzanita	
	Arctostaphylos edmundsii	Edmunds manzanita	
	Artemisia californica "Canyon Gray"	Prostrate California sagebrush	
	Eriogonum fasciculatum cultivars	Prostrate California buckwheat	
	Iva hayesiana	Hayes iva	Tolerates soil that's moderately alkaline and somewhat saline
	Romneya coulteri	Matilija poppy	
	Salvia "Bee's Bliss"	Bee's bliss sage	
	Salvia "Dara's Choice"	Dara's choice sage	
	Salvia mellifera "Terra Seca"	Prostate black sage	
Perennials	*Artemisia pycnocephala* "David's Choice"	David's choice sandhill sage	
	Asclepias fascicularis	Narrow-leaf milkweed	
	Erigeron "Wayne Roderick"	Wayne Roderick's daisy	
	Eriogonum crocatum	Sulphur buckwheat	
	Eriogonum grande var. *rubescens*	Red buckwheat	
	Leymus condensatus "Canyon Prince"	Canyon Prince wild ryegrass	
	Mimulus (Diplacus) species and cultivars	Shrubby monkeyflower	
	Zauschneria (Epilobium) species and cultivars	California fuschia	
Vine	*Calystegia macrostegia* "Anacapa Pink"	Anacapa Pink morning glory	

[a] The first three columns in this table were excerpted from the California Classics Plant Palette (Rancho Santa Ana Botanical Garden, 2005). The notes in the fourth (rightmost) column were provided by a reviewer of this literature review.

San Diego Chapter of the California Native Plant Society* (*www.cnpssd.org)

The website of the San Diego chapter of the California Native Plant Society includes a number of brief documents that can be useful when designing a landscape. One, titled "Easy-to-Grow California Native Plants for San Diego County," is a 16-page article that describes 20 species widely appreciated by gardeners. The native ranges and tips for cultivation are provided for each species.

Also on the website is a reprint of a brief 1972 article from the San Diego Natural History Museum, informatively titled "The Twelve Most Wanted Native Shrubs That Succeed in a Garden without Your Really Trying." The growth pattern, leaf color, watering needs, and type of flower and fruit are described for each species. The 12 species described are Hooker's manzanita (*Arctostaphylos hookeri*), quail brush (*Atriplex lentiformus breweri*), dwarf coyote bush *(Baccharis pilularis*), Oregon grape, also known as holly grape (*Berberis aquifolium*), Carmel creeper (*Ceanothus griseus horizontalis*), St. Catherine's lace (*Eriogonum giganteum*), toyon, also known as California holly (*Heteromeles arbutifolia*), hollyleaf cherry (*Prunus ilicifolia*), lemonade berry (*Rhus integrifolia*), sugar bush (*Rhus ovata*), evergreen currant or Catalina currant (*Ribes viburnifolium*), and chaparral yucca (*Yucca whipplei*).

Yet another useful document at this website is a single-page, three-part layout that relates the water tolerances of certain native plants and includes a brief list of native plants that are good substitutes for nonnatives, such as eucalyptus.

California Invasive Plant Council (www.cal-ipc.org)

The website of the California Invasive Plant Council provides a variety of information about plants that are invading California. The subpage titled "Don't Plant a Pest" (www.cal-ipc.org/landscaping/dpp/index.php) provides a handy map that makes it easy to list invasive species for any particular region of California and to list native species that are desirable alternatives to the invasive ones.

VI.E Guides about Native Plant Communities

Numerous scientific papers, reports, and symposium proceedings have been published in the past several decades as part of an attempt on the part of botanists, ecologists, and horticulturists to agree on definitions and concepts related to plant habitats and communities. A useful summary of some concepts and ideas regarding plant communities is provided in the book *Plant Communities of Southern California* (Latting, 1976). It includes papers describing both modern-day plant communities and past (paleontological) plant communities of southern California. Information is provided about the types of vegetation in the San Gabriel, Santa Ana, San Jacinto, and San Bernardino mountains, as well as about the vegetation and plant communities of southern California deserts.

A more recent contribution is the document "A Manual of California Vegetation" (California Native Plant Society, 2000). This document is more botanically inclined than most landscape designers need, but it is relevant for the landscape design process for any large park project that includes native plant communities.

VI.F. Selecting Plants for Certain Types of Landscapes

A city park typically contains a variety of functional elements. It may include, for example, trees and shrubs around its perimeter as visual screens to block the view of nearby buildings. The park might also include meadow-like areas or playing fields covered in turfgrass. And it might include smaller garden areas, each of which might have a particular design theme. A site that is primarily a playing field, on the other hand, might be nearly all turfgrass, with few trees, shrubs, or other ornamental design elements. Golf courses and highway medians have yet other design requirements. The following sections provide a variety of notes that may be useful when designing these types of landscapes and selecting appropriate species of plants.

VI.F.1. General Guidelines

Quite a few different books about landscape design are available. One book that is appropriate and useful for both professionals and for part-time designers charged with designing or redesigning a site is *Landscape Design Guide, Volume 1: Soft Landscapes*, by Adrian Lisney and Ken Fieldhouse, 1990. In it, the authors outline the basic principles of designing with plants and provide practical information about selecting and caring for plants. They emphasize that no two sites are identical and that conducting a thorough visual and physical survey is therefore essential before beginning design work. To achieve the best results, the authors note, the designer draws inspiration from the character of the site: existing trees and buildings, plus the open spaces between those trees and buildings. They also note that principles such as unity and simplicity can help to create effective and practical solutions to the design equation and provide continuity throughout a design scheme.

Chapters 1 through 4 of the book provide a conceptual basis by describing the design process and horticultural and ecological concepts, such as plant communities and climatic conditions. Chapters 5 through 16 provide the specifics of designing with plants, including the particular advantages of trees, shrubs and hedges, climbers, ground cover, grasses, herbaceous plants and bulbs, and woodlands.

VI.F.2. Selecting Plants for Golf Courses

Of greatest importance at golf courses is the turfgrass itself. Yet trees and shrubs make the course a beautiful or desirable place to play, so they, too, are critical to a well-designed, enjoyable environment. A comprehensive, site-based plan is essential if the resulting links are to provide a variety of challenges to professional players and amateurs alike.

Trees

On nearly every golf course hole, trees help to define the course and provide a backdrop against which a ball in flight is more easily seen. They also provide a valuable wind buffer and, on hot days, much-welcomed shade.

Fream (2001) outlines many of the issues that must be explored and addressed to place trees at a course properly and to ensure the trees remain healthy for many years. First, he notes that, before a course is built, a number of decisions must be made regarding clearing of the site. He points out that a more natural and harmonious design will result if the position, size, health, and appearance of existing trees are made part of the design process. He also says, “If you’re going to save it, save it.” By that he means to take care to protect all trees from potential damage while the course is being built. Traffic within the drip line of a tree is to be avoided at all costs, he notes. Regrading the soil within the drip line must also be avoided, as any such changes can, for many species, cause a slow but sure death. Fream also describes the issues of fertilizing, watering, and thinning trees.

Coate (2004) also notes that trees are an important, but often overlooked, component of a golf course. He notes that trees and turf are usually incompatible, because the trees typically do best with infrequent, deep irrigation, whereas turf performs best with frequent, relatively shallow irrigation. He suggests resolving this dilemma by selecting and planting, where possible, species of trees that tolerate the conditions inherent in the turf environment. Tupelo (*Nyssa sylvatica*), swamp myrtle (*Tristanopsis laurina*), and bald cypress (*Taxodium distichum*) all can grow in areas with consistent surface water nearby. Western sycamore (*Platanus racemosa*) also is well adapted to creek side conditions or spring-fed sites.

Coate (2004) mentions a number of difficult planting environments for trees at golf courses. One is the marine coastline, where salt spray often is potentially a problem. Landfills are another, because the soil in such places often is overly compact and, in some cases, contains methane gas. Coates includes a list of 81 species recommended for golf courses. Extensive data are presented for each type of tree, including such parameters as the width of the canopy, preferences regarding amount of sun and shade, requirements regarding drainage and irrigation, tolerance of wind and heat, rate of growth, and expected useful life span.

Sharon Lilly, in her 1999 book *Golf Course Tree Management*, describes in some detail how trees grow. Their growth process is a necessary topic of study, she says, in order to develop sound judgment for choosing and maintaining trees. Lilly examines the same trees-versus-turf dilemma pointed out by Coate (2004) but discusses it in greater detail, devoting an entire chapter to it. She notes that trees and turf tend to be mutually exclusive in nature. As she says, "For the most part, you won't see many trees growing in the prairies or grasslands, and grass is not common on the forest floor." The problem is that a forest or stand of trees produces too much shade for grass to grow, she explains. In open land, the roots of grasses dominate because they are more aggressive than are the roots of trees; they colonize bare expanses of soil faster and establish a dense root system more quickly.

Lilly (1999) describes a number of tree-turf interactions, including competition between the roots of trees and the roots of grass for the same space just below the soil's surface and for infiltrating water. Another conflict, she notes, is exemplified by the many problems that can occur when trees shade grass. A third form of interaction is the phenomenon called allelopathy: inhibition of a plant's growth by another plant that produces chemicals such as terpenes, phenols, organic acids, tannins, steroids, or other compounds. Such chemicals may be leached from the roots into the soil, or volatilized into the air, or exuded from other parts of plants. She points out that species of pine, plane tree, maple, hackberry, eucalyptus, and sumac have all been shown to be capable of allelopathy.

Other issues involving trees on golf courses that Lilly (1999) examines include managing the shade created by trees, controlling roots, fertilizing, controlling debris dropped by trees, protecting turf when the trees are pruned, monitoring the health of plants, planning for and selecting trees, practicing irrigation and drainage, and protecting trees during construction.

Turf

In his comprehensive, 643-page book *Turf Management for Golf Courses*, James B. Beard of Texas A & M University describes how to choose and plant turfgrasses and how to keep turf healthy afterward (Beard, 1982). Chapters in which the turf-related aspects of the different parts of a typical golf course are described are named, appropriately enough, "The Putting Green," "The Tee," "The Fairway," "The Rough," and "The Bunker."

Beard notes that, for tees in such warm-climate regions as southern California, bermudagrass (*Cynodon dactylon*) is most favored. He notes that Tifway and Tifgreen, two cultivars of bermudagrass, perform very well and that common seeded bermudagrass is also used widely with good results. In portions of southern California where air quality is less than pristine, a special smog-tolerant variety known as Santa Ana has proven effective, he adds.

For the fairways of golf courses in southern California, bermudagrass is preferred, though perennial ryegrass is sometimes used instead or in addition. Popular varieties of bermudagrass are common bermudagrass, Santa Ana, and Tifway. According to Beard, the putting greens of most golf courses situated along the Pacific coast consist of bentgrass (*Agrostis* spp.) rather than of bermudagrass. For the roughs along the fairways, golf courses in southern California typically use common bermudagrass (*Cynodon dactylon*), Kentucky bluegrass (*Poa pratensis*), or perennial ryegrass (*Lolium perenne*).

Elsewhere in his book, Beard describes irrigation systems for turf. Yet another section of his book covers typical turf pests, such as nematodes, weeds, viruses and other microbes, and rodents.

VI.F.3. Selecting Plants for Playing Fields

As with golf courses, the primary park element in a playing field or school yard is the turf. In this case, the turf is chosen for its durability and ease of drainage. Soccer fields and baseball fields both must withstand tremendous amounts of foot traffic and, therefore, must be covered with very durable grass.

Trees, shrubs, ground covers, and ornamental plants at a playing field or school yard provide the border landscaping or fringe buffer zones for the main playing areas. The types of plants appropriate for this depend greatly on the microclimate and on the park designer's theme or architectural concept.

Establishing and Maintaining the Natural Turf Athletic Field, a 56-page booklet by Stephen Cockerham, Victor Gibeault, and Deborah Silva (2004), provides a variety of guidelines for designing and maintaining athletic fields. They note that those athletic fields that are well designed, well constructed, and well maintained are most likely to provide optimal safety, playability, aesthetics, and durability.

The authors explore different choices for root zone media. As they put it, “What’s under the turfgrass is very important.” They note that the typical turf is underlain by a mixture of 80 to 100% of sand of various sizes, up to 8% silt, up to 2% clay, and soil amendments such as peat and weathered sawdust.

They also note that, besides looking good, turfgrasses for athletic fields must tolerate foot traffic, must recover from injury, and must provide high playability. Tolerance of sports traffic—the scuffing, compaction, and tearing of grass by shoes, particularly cleated shoes—requires turfgrasses that have considerable lignin and cellulose in the shoot and hardened or sclerified plant cells, providing strength and rigidity. Such characteristics typically are found in perennial ryegrass, tall fescue, and bermudagrass. Tolerance of foot traffic and recovery from foot-traffic-related damage are also higher in species of turfgrass that produce rhizomes, stolens, or tillers, or all three. The authors note that Kentucky bluegrass has tillers and rhizomes; perennial ryegrass and tall fescue have tillers; kikuyugrass has tillers and stolens; and bermudagrass and zoysiagrass have all three.

The method of planting and maintenance practices are important for all turfgrasses. The authors provide a number of suggestions in these areas.

VI.F.4. Selecting Plants for Parks

Aside from turf, it is difficult to identify the primary plant typically used in a municipal park in southern California. That difficulty arises because the purposes and designs of parks vary so widely. Whether constructing a new park or upgrading an old one, perhaps the best guideline to bear in mind is that, ideally, the park’s design should exhibit unity and simplicity (Lisney and Fieldhouse, 1988). Also, it is essential that any desired species of plants be checked thoroughly against reference materials to ensure that they will survive in the expected microclimate(s) that will be created by the project.

VI.F.5. Selecting Plants for Medians and Sides of Streets

Street-tree programs for residential neighborhoods help to define the types of trees that are beneficial along automotive rights of way. The ideal tree has a canopy shaped somewhat like an inverted cone; the branches go outward as they go upward. The tree develops a tapered profile as it matures, with most of its branchlets up high, not down low. The area near the base of the tree is relatively clear, helping to ensure that the view along the street remains unobstructed (Grey, 1996).

VI.G. Using Guides Cited

In selecting plants for nearly any landscape, the best place to begin is one of Perry's books. The 1981 book is the simpler of the two, and the tables presented here will get you started. The 1992 book is more comprehensive, though it may require a greater investment of time to be used effectively.

The next step is to consult the *Sunset Western Garden Book* and any other guides that seem relevant. If a landscape is intended to consist partially or totally of plants native to California, refer in particular to the book by Labadie and to the one by Lenz and Dourley.

For a golf course, a playing field, or highway median, consult the references cited previously.

Copies of all aforementioned books are available in numerous libraries throughout southern California. To find a library near you that has the book or books you are looking for, visit www.worldcatlibraries.org on the Internet, click on "Try a Search," and enter the book's title, author, or ISBN (tip: the Yahoo search function within Worldcat appears to work more reliably than do the other search options).

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Chapter VII. Irrigation Systems for Recycled Water

D. Shaw, S. Grattan, and A. Harivandi

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VII.G. References

This chapter summarizes literature relevant to the types of irrigation systems used to deliver recycled water to turf and landscape plants. The literature consists of many trade magazine articles on irrigation systems and their maintenance and use for distributing recycled water, as well as a few irrigation manuals considered to be peer reviewed that were developed by the University of California (Shaw and Pittenger, 2005) and California Polytechnic State University–San Luis Obispo (Irrigation Association, 2004). Information on irrigation systems is also available in manufacturers' catalogs, which contain product specifications and describe intended uses for virtually any landscape application. Publications on irrigation design, including books with theories and formulas used in the process of designing an irrigation system as well as computer-aided design (CAD) programs, contain information used by landscape architects and irrigation designers to determine flow and precipitation rates (PRs), pipe sizes, and equipment specifications in designing an irrigation system. Planning codes and regulations, which are developed and published by municipalities and water districts, set standards for the needed equipment, design of irrigation systems, and specifications for installation. These regulations are relevant to all irrigation systems, regardless of the type of water used. With the increase in use of recycled water, the regulations have been expanded to include systems that use recycled water. The response from manufacturers has included a full line of components for use specifically in irrigation systems to deliver recycled water.

Recycled water purveyors, water-reuse organizations and associations, and the Irrigation Association have also published guidelines about irrigation systems that deliver recycled water and about retrofitting existing irrigation systems to deliver recycled water (American Water Works Association, 1997; Terry, 1994; and San Diego County Water Authority, 1999).

Articles in such trade magazines as *Grounds Maintenance* and various manufacturers' data sheets cover topics from the design of irrigation systems to their installation, operation, and maintenance. They are intended for landscape designers, irrigators, and maintenance personnel (Vinchesi, 2000; and Zupancic, 1999).

Peer-reviewed scientific literature pertinent to components of irrigation systems is limited. However, there are a number of published papers regarding the use of subsurface drip systems, the uniformity of irrigation with various nozzles and sprinklers, and materials for valves and other hardware (Greene et al., 1994; and Suarez-Rey et al., 2000).

Clearly, there is a wide and varied array of information available on landscape irrigation systems and hardware relevant to irrigation with recycled, as well as potable, water. This chapter will focus on basic requirements for all irrigation systems, while expanding on needs and strategies for systems delivering recycled water.

What is the function of an irrigation system?

- **The irrigation system delivers water to the plants in a way suitable for fostering the growth and performance of the landscape. The system should have the capacity to meet the landscape's peak water demands.**
- **The system should have the ability to apply enough water to leach salts through the root zone.**
- **The system may also be used to control frost or to provide other cultural needs.**

What is a hydrozone?

Plants and their irrigation systems are organized into areas known as hydrozones according to water-related factors, such as water need, exposure to sun or shade, and salinity tolerance. Multiple valves and system control allow for different types of systems, such as spray and drip, to be independently operated as part of a larger irrigation system to apply the correct amount of water to each hydrozone.

VII.A. Function of the Irrigation System

The irrigation systems used in almost all irrigated landscapes in California provide several functions. The major function is to provide water to plants during spring, summer, and fall because little to no rainfall occurs during these seasons. Irrigation systems also are used during the winter in dry years, when rainfall is inadequate to meet landscape water demands.

As emphasized in Chapter VIII of this document, irrigation systems provide water to meet the evapotranspiration (ET) needs of plants, which is a major component contributing to the health and aesthetic value of turfgrass and the landscape. However, this objective becomes complex because different species of plants have different water needs, different growth patterns, and different rooting characteristics (Meyer and Camenga, 1985; Shaw and Pittenger, 2005; and Vinchesi, 2000). Moreover, planted areas can be irregular in size and shape due to property boundaries, buildings, and hardscape and may have differences in slope, exposure to sun and shade, and exposure to wind. Usually, different irrigation systems or separate valves are used to factor in and accommodate these differences. Hence, different irrigation systems are used for turfgrass and ground covers; for shrubs and trees; for areas with different watering requirements in terms of timing, amount, or both; and for certain situations that warrant their use, including irregularly shaped areas, median strips, and plants in containers. These areas where the irrigation system must be matched to the particular plant materials, microclimate, or other specific need are called hydrozones.

Since all irrigation water contains some salts, irrigation systems must have the capability for applying enough water to effectively leach salts from the root zone. Recycled water usually contains from 140 to 400 parts per million (ppm) more salts than does potable water (Chapter III of this document), so an irrigation system's leaching ability becomes more important. Where drainage is limited, precise management to leach salts while preventing water logging must be practiced.

A landscape's irrigation system can also be used to fulfill the landscape's cultural needs other than watering, such as providing frost control, cooling the landscape, and applying fertilizer.

VII.B. Performance of the Irrigation System

An irrigation system's performance is usually measured in terms of its irrigation efficiency, its distribution uniformity (DU), its PR, and the integrity of its components (Shaw and Pittenger, 2005). These criteria are used to evaluate each valve and associated distribution system within an overall irrigation system. The most important considerations with regard to performance are the irrigation efficiency and/or DU and the PR, which together with an assessment of the plant material involved, provide the information necessary for irrigation scheduling.

A system's irrigation efficiency equals the ratio of the amount of water used beneficially divided by the total amount applied. This value is less than 100% because, in order to irrigate all plants adequately, some plants are overwatered. In the overwatered areas, water is lost to runoff or deep percolation or both. While the total water applied is determined easily from a water meter reading or water bill, the beneficial use is often determined from an estimate of the landscape ET because runoff and deep percolation are very difficult to measure. Irrigation efficiency can be assessed on an irrigation event or a monthly or even yearly basis. It is not uncommon to have a significant range in values because efficiency is a function of both equipment and management. Only through deficit or underirrigation can efficiency reach 100%.

DU is a measure of how evenly water is delivered to the landscape. This performance measure is related more to system hardware than to management. In the field, DU is easily assessed from data collected in a catch can test. It is the average of measurements of water applied to the low quarter (25% of the area receiving the least water) divided by the overall average. Systems with high DU are usually easier to manage. With such a system, the irrigator can easily determine when to irrigate based on soil moisture or the condition of plants. In other words, if all areas receive about the same amount of water, there will be less variability in the landscape's moisture level and health. Less variability speeds the decision-making process for the irrigation manager. In addition, through improvements in uniformity alone, water waste can be reduced and the quality of the landscape increased. Leaching salts delivered in the recycled water is also much easier with high DU since a more uniform wetting front can be maintained throughout the soil profile. High DU helps prevent drier areas of coverage from not receiving their intended leaching fraction and becoming salinized as well as wetter areas from becoming saturated and resulting in runoff or deep percolation.

Runoff can be caused by high rates of water application (PR), poor DU, broken components, and/or mismanagement. The PR of an irrigation system is expressed in number of inches per hour and can range from 0.1 to greater than 3.0. Lower rates are helpful in reducing runoff by matching the PR to the soil infiltration rate. Alternatively, the cycling on and off of systems has been successful in allowing adequate water penetration while reducing runoff. The elimination of runoff is mandated by most recycled water regulations and by water quality regulations in most localities (San Diego County Water Authority, 1999).

The performance characteristics of the irrigation system are influenced by the design process and installation of the system. Often the PR and DU are specified in the landscape irrigation system design. However, field verification of PR and DU is necessary to provide for accurate irrigation scheduling. The performance of each valve and distribution system cannot be assumed to be similar without testing or verification in the field.

The performance of an irrigation system also depends on the integrity of the system's components. Components of poor quality, those installed incorrectly, and those inadequately protected from breakage, vandalism, or other damage will ensure a poorly performing system. Repairs take time and expense and can leave the landscape in need of water. A well-performing irrigation system is critical for aesthetically pleasing and functional landscapes. To achieve and maintain good performance, irrigation systems need to be properly designed, installed, operated, and maintained.

VII.C. Major Phases of Successful Irrigation

For successful landscape irrigation, four major phases must be addressed and coordinated: the design, construction and installation, operation, and maintenance phases.

VII.C.1. Design, Layout, and Staking

The design phase of an irrigation system encompasses the conception and artistic application of landscape components, the necessary engineering and planning, and the specification of materials. This process includes selecting plants that are tolerant of the soil and water conditions at the site. It also includes developing hydrozones and appropriate irrigation and drainage systems for the plants, as well as specifying construction details, irrigation schedules, and maintenance requirements for the landscape. The designer must also meet regulatory guidelines, including plumbing codes, local and state ordinances, permits, and any regulations required by the recycled water purveyor, and submit plans to be approved by local regulators. The designer also determines the water budgets and irrigation schedules to use during the landscape's establishment and as the landscape matures.

VII.C.2. Installation and Construction

The installation and construction phase includes installing the irrigation system, as well as coordinating with other construction operations, such as land grading, preparing the soil, and installing hardscape, plants, lighting, signage, and other components of the landscape. Proper layout and staking of the system are critical so similar sprinklers are installed at uniform spacing distances to maintain uniform PRs and high DU and maximize potential irrigation efficiency within each hydrozone. Often substitutions and variations from the design can occur during construction. The irrigation designer should approve changes and substitutions related to the irrigation design to maintain optimum efficiency of the final product. Plans that depict the landscape “as built,” including any changes in design, are of tremendous value to operation and maintenance personnel.

VII.C.3. Operation

The operation phase of an irrigation system involves managing the landscape’s irrigation scheduling and water budgeting. As mentioned in Chapter VIII of this document, this requirement varies according to locations in the landscape and time of the year.

VII.C.4. Maintenance

During the maintenance phase, activities that maintain and maximize the effectiveness of the irrigation system are conducted. The proper cultural treatment of plants and other components of the landscape not only improve the landscape’s appearance and value but can also affect the use of water in the landscape. Maintenance personnel also play an important role by either sustaining the integrity of the system as designed by replacing failed sprinklers or nozzles with “like” equipment of the same PR or making intelligent and sound modifications to the system as the landscape matures. Proper maintenance also includes precise pruning, fertilization, and other cultural practices to promote the most efficient use of water for the aesthetic need of the landscape.

Maintenance personnel may need to diagnose problems affecting system flow and pressure. In general, if the entire system is affected, the point of connection and main filter and pressure regulator should be checked. In areas undergoing new development, the purveyor’s water pressure and flow may be reduced due to new service activity or other reasons. Pressure and flow will also drop if too many valves are operated simultaneously or if modifications are made, such as adding sprinklers or increasing nozzle size, that change the system’s hydraulics. If pressure losses occur in one valve station or along one lateral line, the valve may be faulty or there may be a broken or constricted pipe. Clogging of lines or individual devices can also be caused by flow back into the system. For example, dirt or contaminants can enter pop-up sprinkler nozzles placed below grade when the valve is turned off.

Strategic planning, coordination, and competency among all phases—design, installation, operation, and maintenance—are important for sustaining the health and aesthetic appearance of turfgrass and all landscape plants. For example, the landscape architect and irrigation designer—often one and the same—must select trees and shrubs that are suitable to the site and purpose and then design an irrigation system that will supply water to them without saturating their root crown areas. Sometimes a temporary system is installed to keep root balls moist, while the plants are becoming established. The designer may also specify a drainage system to handle excess water or storm water.

In the construction and installation phase, the contractor must achieve a functional landscape from the plans. This task includes following plans for selecting and installing pipes and other components. It also includes properly locating selected plants and planting them at the proper depths. If trees are planted too deeply, water will pond near the root crown and create conditions favorable to *Phytophthora* species and other "water mold" fungi (Chapter X of this document). These diseases can devastate a landscape very rapidly. In addition, the plants cannot be placed where they will deflect the application of water, such as directly in front of a sprinkler. Hence, installing the irrigation system must be well coordinated with installing plants.

The operator must follow and refine irrigation schedules that allow for adequate irrigation, while avoiding runoff or oversaturation of the root crowns. Continuing with the aforementioned example, the operator may overirrigate or underirrigate or may continue to use the temporary irrigation system specified for wetting the root balls while the plants become established and consequently overirrigate the plant's crown area. Either of these actions would also tend to result in diseases and a poorly performing landscape.

The process of applying water to trees and shrubs demonstrates the amount of coordination and the level of competency needed among the design, installation, operation, and maintenance phases of landscape irrigation.

What constitutes a good irrigation system for distributing recycled water?

- **The system selected should be compatible with the landscape being irrigated. It should be well designed and constructed and easily repaired and maintained.**
- **The irrigation system and its components are easily identified as conveying recycled water.**
- **The system must be completely independent of potable water systems. Most water purveyors require separation of buried pipes and cross-connection testing to verify the integrity of the recycled water system.**

Table VII-1. Performance characteristics of sprinkler systems.

Type	Radius of throw (ft)	PR (in/h)	DU (%)
Geared rotor	20–100	0.1–1.5	70–80
Impact rotor	30–150	0.1–1.5	60–70
Fixed spray	3–15	1.0–2.5	40–80

VII.D. Types of Irrigation Systems for Distributing Recycled Water to Landscapes

Irrigation systems for landscapes consist of sprinkler, drip, and bubbler systems (Irrigation Association, 2004). Within the category of sprinkler systems, there are gear-driven or impact-driven rotor sprinkler heads, which are commonly used for large areas of turf or ground cover, and fixed spray heads, which are commonly used for irrigating shrubs, flower beds, and small or irregularly shaped areas. Sprinklers can be individually valved or connected to a lateral line governed by one valve (Meyer and Camenga, 1985; Rainbird Corporation, 2005; Smith et al., 1985; and Terry, 1994). The irrigation of golf courses and other large areas of turf may involve the use of rotors, where a valve is integrated into large rotor heads, i.e., a valve in head design (Balogh and Walker, 1992).

The PR of any irrigation system will depend on the spacing and flow rate of the sprinklers used. Flow rate will depend on the size of the nozzle's orifices and the water pressure (Irrigation Association, 2004).

VII.D.1. Rotor Sprinklers

Geared rotor sprinklers usually have an arrangement of gears that moves water through one to three nozzles in a predetermined arc. Impact rotors usually have one or two nozzles that rotate by the action of a reciprocating spoon that interrupts the water stream (Irrigation Association, 2004).

VII.D.2. Fixed Spray Sprinklers

Fixed spray sprinklers usually have no moving parts. The water is directed through orifices in a fixed pattern of spray over the irrigated area. However, some have adjustable arcs and adjustable flow rates.

VII.D.3. Sprinkler Distribution Profiles and Matched PRs

The irrigation industry has made many improvements in sprinkler design to facilitate the uniform distribution of water to the irrigated area. Most sprinkler manufacturers publish specifications, which include water distribution profiles—graphically, the amount of water distributed versus distance from the nozzle—for different nozzle sizes and water pressures. This information is used during the design phase to specify sprinkler spacing and operating pressure to achieve precise, uniform application of water to the irrigated area. This information is used to design systems with what are known as matched PRs. The Center for Irrigation Technology at California State University–Fresno provides testing and data for many available products.

Matched PR is the practice of matching the rate of sprinkler flow with the area or arc covered. This objective can be achieved in two ways: sprinklers with different patterns or arcs (360°, 180°, or 90°

or full, half, or quarter) should use differently sized nozzles (for differing gallons per minute [gpm]) to compensate for the different size of area being covered if they are operated together on the same valve. Alternatively, the same nozzles can be used in both full-circle and part-circle sprinklers if they are on separate valves. In this case, the run time is adjusted; e.g., full circle heads are operated twice as long as half-circle heads, etc., to achieve matched PRs and higher uniformity (Irrigation Association, 2004).

Fixed spray heads are also being produced with matched PRs (Rainbird Corporation, 2005), which allow a more even distribution of water with heads with different arcs. Also, new technology, such as small rotor heads that replace fixed spray nozzles, is available.

VII.D.4. Drip Irrigation

Drip systems, both aboveground drip systems and subsurface drip systems, are also used to distribute recycled water. These systems distribute the water through many small orifices or emitters at rates of 0.5 to 5.0 gal/h. They are commonly used to irrigate areas with trees and shrubs where it is not necessary to wet the entire root zone of the plants. Filtration is more important in drip systems due to the smallness of the emitters' orifices. In addition, injection systems are commonly used with drip systems to inject sanitizing agents, such as chlorine, or acids to eliminate emitter-clogging biotic growth and carbonate deposits. Injection systems can also be used to apply fertilizer or other materials through the irrigation system.

Suarez-Rey et al. (2000) make a strong argument for specifying the use of subsurface drip irrigation for areas of turfgrass, as well as for other areas of the landscape. Use of these systems avoids exposing maintenance personnel to recycled water and enables irrigation at any time or day. Also, runoff potential is reduced, and water does not contact the leaves of plants. This benefit would be particularly important if plants are sensitive to foliar absorption of sodium or chloride. On the other hand, increased maintenance is often necessary and subsurface turf irrigation designs can become complex, if not impractical on sites with significant land contours and elevation changes. Subsurface turf irrigation is best suited to relatively flat or uniformly sloped turf areas such as athletic fields and residential lawns.

Advantages and disadvantages of drip irrigation systems

Advantages	*Disadvantages*
Precise placement of water	**Relatively more maintenance**
Retention of foliage's dryness	**Difficulty of access to buried system**
Fewer time-of-day restrictions	**Limited access in thorny plants**
Use of nearby water fountains	
Compensation of pressure for topography	
Attainability of high irrigation application efficiencies	

VII.E. Components of Irrigation Systems

Irrigation systems vary tremendously, depending on the size and complexity of the landscape irrigated, the type or types of systems used, the amount of sophistication in the systems' design, and the number of control and monitoring options used (American Water Works Association, 1997; Hunter Industries, 2004; and Rainbird Corporation, 2005). For example, a simple system may require only a backflow prevention device, a controller, several valves, and a distribution system. A complex system may be controlled by a computer; be capable of sensing and metering flow; incorporate sensors monitoring soil moisture or other relevant aspects; and consist of rotor, spray, and drip distribution systems. Depending on its complexity, an irrigation system may include backflow prevention devices, flow meters, pressure regulators, master and station valves, check valves, valve and equipment enclosures, pipe and fittings, emission devices (sprinklers, emitters, etc.), quick couplers, pumps, reservoirs, and flush-out valves. Control systems may vary in the degree of sophistication and cost and may include sensing devices to determine flow rates or soil moisture, operate injection systems, or operate backwash systems for filters. While irrigation systems for delivering recycled water contain many of the same components as systems delivering potable water, the components of the system using recycled water are usually colored purple or have signs, so that they are easily recognizable as conveying recycled water (Chapter II).

VII.E.1. Backflow Devices and Point of Connection

Water purveyors require that irrigation systems have backflow devices to prevent water from returning to and possibly contaminating their distribution system. While most potable water purveyors require a reduced pressure backflow device at the point of connection with the purveyor's system, recycled water purveyors usually only require a check valve or one-way gate valve to prevent backflow. If a lake or water feature is used to store recycled water, the delivery should have an air gap to prevent backflow.

In addition to the backflow prevention device, a meter, filter, booster pump and/or pressure regulator may be present at the point of connection.

How to Eliminate Runoff from Landscape Irrigation

Design and use an irrigation system with a PR that is lower than or equal to the infiltration rate of the soil.

Operate the irrigation system in cycles or "cycle and soak" periods to maximize water penetration into the soil.

Use antisiphon valves and check valves within an irrigation system to eliminate low head drainage caused by the landscape's changes in elevation.

Immediately repair leaks and broken components. Flow sensors and control systems can readily identify lines with excessive flow due to broken components and shut the valve off. Inline components are available that restrict or close orifices with excessive flow.

Provide cultural needs to maximize water distribution to the landscape, such as minor grading, aeration of turf areas, application of mulch, and/or application of wetting agents or gypsum.

VII.E.2. Filters

To maintain the integrity of irrigation systems, filters are used to trap particulates, algae, and other contaminants from entering the systems (Chapter III). Contaminants can lodge in pipes and fittings and valves and emission devices and restrict water flow. If flow is reduced, the system will not perform up to its design potential. If flow is changed significantly, the engineered hydraulics of the system will be compromised, resulting in nonuniform distribution of water. In severe cases, the landscape will receive inadequate water or the affected lines and devices, such as drip emitters, may be permanently damaged. Generally, if water is properly filtered, clogging of valves, screens, and emission devices is minimized.

The filters to use depend on the quality of the recycled water, the amount used, the type of irrigation system used, and cost (Smith et al., 1985). For large systems, sand or medium filters are used. Often, an automatic reverse flushing system is used with media filters, especially if the recycled water contains high suspended solids. The flushing system may be actuated by a timer or by pressure sensors. Screen or disk filters are useful in systems where the water quality is relatively good and less cleaning is necessary. The degree of filtration necessary depends on the size of the orifices in the system's components. For example, a drip system will require a finer filtration than does a typical sprinkler system. The filter selected should be properly matched to the system's components for both the system's flow and the size of particles involved. Finer filtration may seem advantageous, but if the filter is too small or filtration too fine, frequent cleaning may be necessary. For systems with different types of distribution systems, one filter may be used for the mainline service and additional filters used for drip or microirrigation systems. These filters are finer and may be inline or Y-type screen filters.

Filter maintenance is important to sustain the integrity and performance of the irrigation system. Although self-cleaning filter systems are also available, maintenance personnel need to know where the filtration devices are and when they need to be cleaned. Mainline filters and inline screen filters may be quite obvious. However, most backflow prevention devices, pressure regulators, and sprinkler heads all contain a screen or basket type of filter. In addition, it is not uncommon to find screened washers or gaskets placed inline or at hose connections. A system flow sensor or pressure gauges placed before and after the filter will show reduced flow or significant pressure drop through the filter, indicating that cleaning is necessary.

VII.E.3. Pressure Regulators

Pressure regulators are used to adjust the water pressure at the point of connection to the level specified during the design phase. While excessive pressure can cause components of the system to burst and destroy rubber and plastic parts, low pressure can cause reduced flow and uneven distribution of water along lateral lines. The most common signs of excessive pressure are the overatomization of water droplets, excessive drift, and loss of the sprinkler distribution profile. The irrigation designer determines the pressure and flow needed at each sprinkler head, determines the pipe size required by calculating the friction loss in the pipe, and accounts for differences in pressure caused by changes in topographical elevation.

There are several types of pressure regulators: positive shutoff; regulating valves; inline regulators; and diaphragms or flow constrictors within the sprinkler, emitter, or other emission device. Positive shutoff regulators are usually adjustable and maintain the set pressure regardless of the flow rate. These can be located at the point of connection to district lines and may be integrated with a backflow prevention device. In general, these regulators are positioned before valve manifolds. Regulating valves that incorporate an adjustable pressure regulation device within the valve are available from most major irrigation manufacturers.

Inline regulators are usually inexpensive and preset for desired pressure within a range of flow, e.g., 20 lbs./sq. in. (psi) at 1 to 5 gpm. These are often used in drip systems or in lateral lines where topography is a concern or at individual sprinkler heads to reduce lateral pressures to the sprinkler and prevent atomization. Manufacturers have incorporated nozzle screens or flow constrictors within sprinkler heads that adjust the pressure within sprinklers. Pressure-compensating drip emitters contain a flexible diaphragm to maintain the same flow over a range of pressures.

There are many different valves available for virtually any application in irrigation systems. They include ball valves and gate valves for manually closing flow and solenoid valves for automatically controlled systems. Most designers will specify “dirty water” or “contamination-proof” valves for irrigation with recycled water. These valves have self-cleaning screens (internal “scrubbers” that clean screens inside the valves), scouring systems that operate when the water is flowing to keep particulates from accumulating, or filtered pilot flow, i.e., flow that actuates the diaphragm.

VII.E.4. Quick Couplers and Hose Bibs

Quick couplers allow fast connection of a hose line to the recycled water lines to facilitate syringing of dry areas in the landscape. Quick couplers specifically designed for use with recycled water systems are now available. These devices do not allow connection between potable and recycled systems.

VII.E.5. Components of Recycled Water Systems

Irrigation manufacturers have incorporated various materials into diaphragms, seals, and other flexible components of valves and sprinklers used for recycled water in order to prolong the life of these components. These improvements have helped to address the effects of scaling and corrosion from salinity, pH, chlorine, and other constituents present in recycled water. Valve diaphragms can be fabric reinforced and made of more resistant rubber. The industry standard for rubber used in seals and valves has been Buna-N rubber. It is being replaced by ethyelene propylene diene monomer, because of its resistance to corrosion and chlorine and chloramine (a by-product that forms in recycled water when chlorine and ammonia combine). Manufacturers are also experimenting with polyester materials suitable for recycled water.

VII.E.6.Injection Systems

Injection systems are used to inject fertilizers, wetting agents, acids, gypsum, sanitizing agents, and other materials into and through an irrigation system (Schwankl and Prichard, 2001; and Burt et al., 1998). Injection equipment, materials, and best management practices are addressed in *Chemigation in Tree and Vine Micro-Irrigation Systems* (Schwankl and Prichard, 2001) and *Fertigation* (Burt et al., 1998) and are applicable to systems delivering recycled water to landscapes. Schwankl and Prichard discuss batch tank systems, venture injection systems, and positive displacement pump systems and their relative cost. Schematics are provided for incorporating an injection system into the irrigation system, including the proper placement of valves, check valves, and filter screens for the various systems.

In addition, best management practices are suggested to achieve a uniform distribution of the injected material. With proper design, installation, and management, a microirrigation system can apply water very uniformly throughout a hydrozone. Application of chemicals through the irrigation system can also be very uniform if an appropriate injector is selected, the correct amount of material is injected, and the material is injected for the correct length of time. If the injection time is too short, orifices nearest the injection point receive the most injected material. Injection practices must also be compatible with irrigation scheduling in order to keep the injected material, e.g., fertilizer, from running off or percolating below the root zone. Best management practices involve determining the length of time required for the injected material to travel to the emitter farthest away hydraulically from the injection point. Once the system is fully pressurized, inject the chemical over a period at least as long as the travel time. Once injection is stopped, continue running the system for a period at least as long as the travel time to the furthest emitter. Schwankl and Prichard also discuss selection of materials and use of chlorine for sanitizing drip or microirrigation systems.

VII.F. Retrofit of Potable Systems to Recycled Water Systems

Retrofitting an existing irrigation system for use with recycled water involves assessing the site, the condition of the landscape, and the condition of the irrigation system. Components of the system are evaluated for wear and effectiveness at providing water to the landscape without significant runoff. Potential cross-connections, any water supply or existing pipelines nearby, the locations of hose bibs and quick couplers, and the locations of water fountains or other features that should not be in contact with recycled water all need to be identified. Components of the irrigation system need to be visibly distinguishable as parts of a system that delivers recycled water. This goal can be achieved by purchasing new components, e.g., sprinklers, etc., by installing purple recycled water caps or tags onto existing equipment, or by painting components.

VII.F.1. Cross-Connection Testing

Once the recycled irrigation system is installed or a system is retrofitted to use recycled water, a cross-connection test is performed to verify the independence of recycled and potable water systems. These tests, usually performed by the health department or the water purveyor, involve shutting off each system while the other is charged. Pressure or flow recorders are connected to the system mainlines to determine if there are any connections between the two. This requirement is especially important in retrofitted systems, where numerous modifications to the system may have occurred over time. Also, during the cross-connection testing, the recycled water system is inspected for leaks, overspray to nonlandscape areas, and contact with drinking fountains or other potable water components.

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Chapter VIII. Estimating Water Needs and Scheduling Irrigation for Landscapes

S. Grattan, D. Shaw, B. Sheikh, and A. Harivandi

- VIII.A. Estimating the Water Needs of Plants
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Proper irrigation management ensures that plants in landscapes receive adequate water to grow well and sustain aesthetic appeal. This task involves applying the correct amount of water at the right time as efficiently as possible. The focus of this chapter is on determining the water needs of plants in landscapes and scheduling their irrigation. Refer to Chapter VII for information regarding how to irrigate efficiently and uniformly with various types of irrigation systems.

Most methods developed over the past several decades for estimating the water needs of plants in California's landscapes are modeled after those used for estimating the water needs of agricultural crops, which is where most of the research has been conducted. These methods estimate the water need of a crop by using historical water use records or by using atmospheric data, such as statistics for humidity, solar radiation, temperature, and wind speed.

It should be noted that the goal in irrigating landscape plants differs from the goal in irrigating crops. In landscapes, the goal is to maximize the intended utility or, by implication, usually to sustain healthy, attractive plants and sometimes also to control erosion or fire hazards. In agriculture, the goal is to optimize profitability or, by implication, to maximize the crops' growth and yield. Regardless of these differing goals, it is important to accurately estimate the amount of water needed by plants in a landscape to improve the landscape's quality while at the same time conserving water and ultimately reducing costs (Costello et al., 2000).

V.III.A. Estimating the Water Needs of Plants

Considerable research has been conducted over the past century regarding how to estimate the amount of water needed by agricultural crops. In the most widely accepted method to date, which is described by Allen and others in a paper prepared for the UN Food and Agriculture Organization (1998), the water needs of crops are referred to as crop evapotranspiration (ET_c). This concept includes both evaporation, the physical process by which water vaporizes from the soil at the surface, and transpiration, the movement of water from inside the crop's leaf to the atmosphere.

Though water is likewise transpired by landscape plants and evaporated from the soil in which they grow, adopting this method to estimate the water needs of landscape plants involves taking into account the wider range of variables in landscapes, such as types of plants, ground covers, mulches, shading, and structures.

VIII.A.1. Evaporation and Transpiration

Most evaporation from the soil occurs in its top 6 in. When the surface of the soil dries out, the rate of evaporation diminishes rapidly, even though the soil beneath the surface remains moist. Water evaporates more rapidly from wet, fine-textured, or compact soils than it does from wet, coarse-textured, sandy, or loose soil. Bark and other mulches applied to the soil surface reduce evaporation.

Transpiration in a plant is important for cooling it and for transporting nutrients from the soil (American Society of Plant Biologists, 2005). Over 99% of the water absorbed by the roots of most mature plants is transpired to the atmosphere. Most of this water is transpired through the plant's stomata, pores with openings controlled by guard cells, all located on the surface of the plant's leaves. When guard cells expand with water, the stomatal pores open and water is transpired. At the same time, the carbon dioxide needed for photosynthesis enters.

When the guard cells contract, the stomatal pores close, reducing transpiration and conserving water within the plant.

The shape, location, density, and opening and closing of stomata vary according to species. Most species open their stomata during the day and close them at night. This process allows the plant to cool and carbon dioxide to enter the leaf for photosynthesis. If the plants undergo stress, such as when the soil becomes completely dry, some plants will close their stomata in the middle of the afternoon as a means of conserving water. Others, such as many succulent species in the family *Crassulaceae*, close their stomata during the day and open them at night. Their special type of sugar metabolism allows carbon dioxide to enter the leaf at night and be fixed into an organic acid—a feature that makes these types of plants more water efficient.

VIII.A.2. Determining ET

The processes of evaporation and transpiration combine to become evapotranspiration (ET), a term synonymous with the water use of plants.

In agricultural water management, an ET_c is measured indirectly by using a reference grass. In this method, ET_c is related to the use of water by a healthy, unstressed cool-season grass uniformly cut to a height of 4 to 6 in. (Allen et al., 1998). The use of water by this unstressed reference grass is referred to as reference evapotranspiration (ET_o). As the reference grass's ET increases, so in direct proportion does the crop's consumptive use. ET_c can be calculated as

$$ET_c = ET_o * K_c \tag{VIII-1}$$

where K_c is defined as the crop coefficient(s), a factor that simply adjusts the ET_o to ET_c and varies according to the type and maturity of the plant, the extent to which the plant covers the soil at the surface, and water management.

A plant's use of water is affected by the amount of sunlight, the temperature and humidity of the air, and the speed of the wind (Doorenbos and Pruitt, 1984). Increases in the amount of sunlight, the temperature, and wind speed raise the ET. An increase in humidity reduces the ET.

Four primary factors contribute to differences in the ET of a crop and the ET of a reference grass (Allen et al., 1998). One is the height and roughness of the canopy, which influences the amount of aerodynamic resistance. Taller, rougher canopies lose more water under the same conditions than do shorter, smoother canopies. A second factor is the reflective power of the surfaces of the crop and the soil at the surface. The higher the reflective power, the less the total energy enters the crop and soil and thus the lower the ET. A third factor is the resistance of canopies, which depends on the architecture of the plants and leaves, the density of leaves and stomata, and the opening and closing of stomata. A fourth factor is the extent to which evaporation from the soil at the surface contributes to the overall ET. Dry surfaces and those heavily shaded by taller nearby plants or buildings lose considerably less water than surfaces that are exposed to the sun and frequently wetted. All four of these factors integrate and are reflected in the resulting K_c.

The K_c implies that the crop in question is nonstressed—adequately watered, free from pests and diseases, etc.—and this factor usually varies between 0.3 and 1.2, depending on the type of crop, the architecture of the canopy, and the extent to which it covers the ground, the location, and management practices (Allen et al., 1998).

VIII.A.3. ET_o and CIMIS

Over the years, several formulas for estimating ET_o have been developed (Doorenbos and Pruitt, 1984). Some more effectively predicted the ET_o along coastal environments. Others were better suited for predicting the ET_o of hotter, drier inland areas. The Penman–Monteith formula has recently been recommended as the standard method for defining and calculating ET_o (Allen et al. 1998). This formula has proved to be reasonably accurate at estimating ET_o in a variety of climates throughout the world. The method requires the use of real-time data including solar radiation, temperature, humidity, and speed of the wind. To learn more about this method and the parameters used with this method, refer to the paper of Allen et al. (1998) or visit www.fao.org/docrep/X0490E/X0490E00.htm on the Internet.

California has developed a statewide, computer-based network of weather stations that generates daily ET values. Known as the California Irrigation Management Information System (CIMIS), this statewide network of nearly 120 weather stations provides daily and hourly estimates of ET_o. The weather stations collect data on the key meteorological parameters used to calculate ET_o, which include the amount of solar radiation, the temperature, the humidity, and the speed of the wind, as well as data regarding rainfall. These ET_o values are referred to as "real-time" ET_o estimates and differ from those where historical averages are provided. These weather stations (refer to photograph VIII-1) were developed by the University of California under a grant from the California State Department of Water Resources and are now owned,

Photo VIII-1. A typical CIMIS weather station used to collect and transmit meteorological data used to calculate ET_o.

operated, and maintained by the Department of Water Resources. These computer-based weather stations estimate ET_o by using the modified Penman method, a method that differs slightly from the Penman–Monteith formula. CIMIS weather stations and their ET_o estimates provide irrigation managers, growers, and irrigation districts with valuable information for real-time irrigation scheduling. This information is available at the CIMIS website at wwwcimis.water.ca.gov/cimis/welcome.jsp.

The ET_o estimates of the CIMIS, usually reported as a depth of water per unit of time, such as inches per month or millimeters per day, can vary dramatically over time and at different locations. In a given year, particular variation occurs during the spring and fall months, when the weather changes dramatically from day to day. Such variation is shown in Figure VIII-1, which illustrates real-time ET_o values in two California locations: Davis, which is located inland in the Sacramento valley, and San Luis Obispo, which is located in the south-central part of the state along the coast.

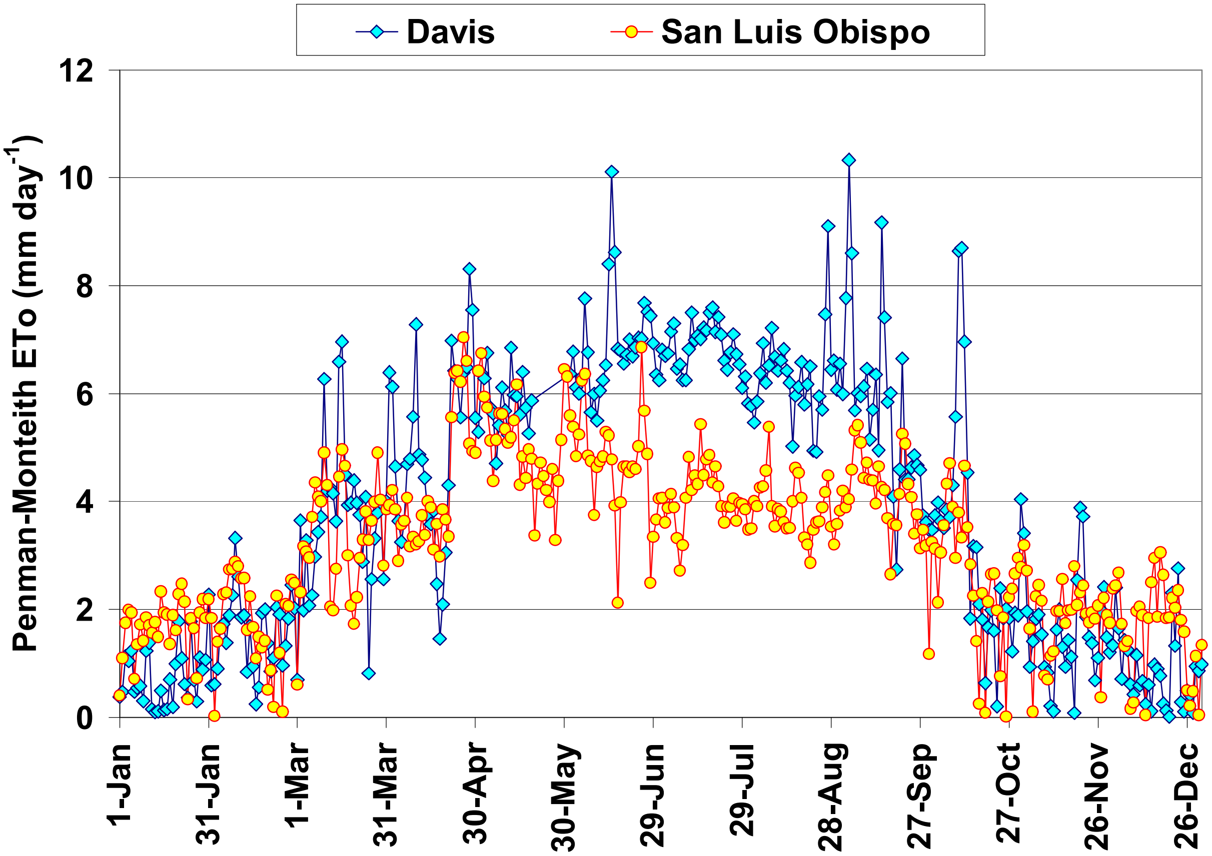

Figure VIII-1. Variations of real-time ET$_o$ values in two different locations in California.

Historical values are used instead of real-time estimates to adjust for the high variation that occurs during transition months in a particular year. When this adjustment is done for the same locations, it can easily be seen that the maximal use of water occurs in both locations between May and September, when the days are long and the amount of solar radiation is greatest (Figure VIII-2). During the summer months, the ET$_o$ in the inland areas is substantially higher than the ET$_o$ in cooler, more humid coastal areas. In the winter months, the reverse is true, with the ET$_o$ in inland areas less than the ET$_o$ of coastal areas, since the inland areas receive more fog and less sun than do the coastal areas.

The historical ET$_o$ values are particularly useful for planning the allocation of water, for designing an irrigation system, and for estimating the water needed by a plant, using generalized irrigation schedules. Though the water needed by a plant can be estimated with reasonable accuracy by using historical ET$_o$ data, it is important to recognize that these figures are averages for 30 and 40 years and that actual daily data can vary significantly from a 30- or 40-year average (Shaw and Pittenger, 2005). For example, a historical ET$_o$ value for a day in

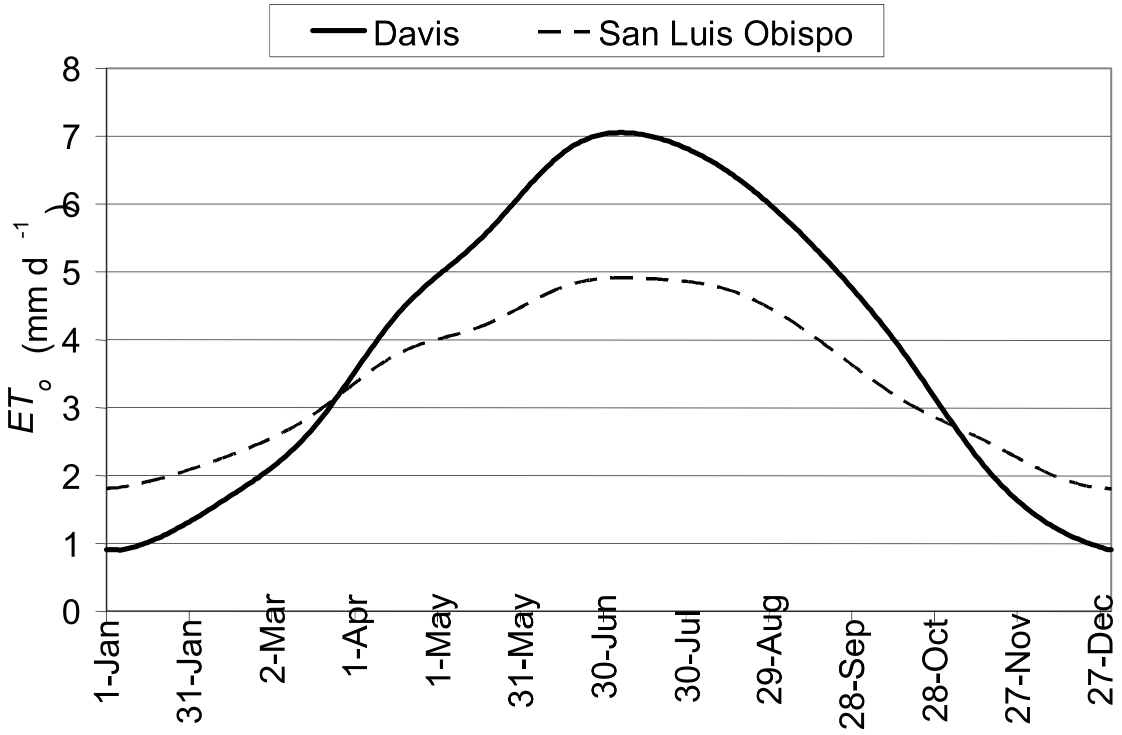

Figure VIII-2. Historical average ET_o values in two different locations in California.

February in Oceanside is 0.09 in., but the actual ET_o was 0.04 in. on February 14, 1992, and soared fivefold to 0.20 in. on February 23, 1992. In such instances, the "real-time" ET_o from CIMIS weather stations would provide a much more accurate estimate for operating an irrigation system than would the use of historical ET_o values.

VIII.A.4. K_c

In agriculture, K_c have been developed for a number of crops (Allen et al., 1998). They were developed to estimate the water needed by a crop when the crop is not subjected to stress. K_c are usually presented in relation to the time of the year rather than as a stage of developmental growth, even though the latter system provides less error (Grattan et al., 1998). They have been developed for annual crops, as well as for perennial crops (Figure VIII-3). The K_c for annual crops and deciduous orchards earlier in the growing season, when the crop covers less than 20% of the soil at the surface, depends on management practices, such as how often the soil is wetted. This finding occurs because most of the ET_c comes from evaporation from the soil. Generally, the K_c is low during the early season, unless the soil is frequently wetted. Later, when the crop covers more than 70% of the soil at the surface, most of the ET_c is due to transpiration and the type of crop determines the K_c. Unlike for annual and deciduous crops, the

K_c of evergreen species is relatively constant over the year. For a complete list of the K_c for numerous agricultural crops, as well as methods for adjusting the K_c to account for off-season values, irrigation frequency, and plants grown in suboptimal conditions, refer to Allen et al. (1998).

VIII.A.5. Modeling Coefficients for Landscape Plants after K_c

A plant's overall architecture, size, and location in the landscape, as well as the climate, are the primary factors that affect ET. For example, when grown under the same conditions, bluegrass uses more water than does juniper or ivy. More water would have to be applied to bluegrass and juniper growing in the desert region of Palm Springs than to the same plants growing on the coast in Long Beach due to the higher ET_o of the hotter, drier Palm Springs climate (refer to Figure VIII-1).

The amount of water needed by a plant varies according to species and its location in the landscape. Most plants for landscapes, such as turfgrass, ground covers, shrubs, and trees, need less water than does the standard reference grass ET_o (Shaw and Pittenger, 2005). For example, since actively growing bermudagrass (*Cynodon dactylon*) needs about 60% of the water estimated as ET_o, if information from a CIMIS weather station indicates that the ET_o for a day was 0.20 in., then bermudagrass would need 0.12 in. of water a day.

As previously noted, K_c for agricultural crops were developed to estimate the water needed by a crop when the crop is not subjected to stress. Coefficients for landscapes may not need to be this stringent. It is perfectly acceptable, if not encouraged in many instances, to induce stress, particularly with drought-tolerant plants, as a way to control excessive vegetative growth, thereby minimizing the need for maintenance (Costello et al., 2000). The extent to which this practice can be done without fatal consequences to the plant remains unclear. When irrigating with recycled water, which may be somewhat more saline than potable water, and particularly when other conditions facilitate the accumulation of salts in the root zone, such strategies may be unwise and caution is advised.

VIII.A.6. Coefficients for Turfgrasses

Since lawns, sports fields, golf courses, and other such places with turfgrass consist mostly of turfgrass and since the ET of turfgrass closely reflects the ET_o of the reference grass (Shaw and Pittenger, 2005), the use of water by such landscapes can be more confidently estimated than can the use of water in more heterogeneous types of landscapes. Turfgrass coefficients have

Table VIII-1. K_c for cool-season and warm-season turfgrasses in California[a] *(from Shaw and Zellman, 2005).*

Month	Cool-season crop coefficient[b]	Warm-season crop coefficient[c]
January	0.61	0.55
February	0.64	0.54
March	0.75	0.76
April	1.04	0.72
May	0.95	0.79
June	0.88	0.68
July	0.94	0.71
August	0.86	0.71
September	0.74	0.62
October	0.75	0.54
November	0.69	0.58
December	0.6	0.55
Annual avg.	**0.8**	**0.6**

[a] See Meyer et al. (1985).

[b] Species include tall fescue, ryegrass, bentgrass, and Kentucky bluegrass.

[c] Species include bermudagrass, zoysiagrass, and St. Augustine grass.

.been developed to estimate the water needed by common species of turfgrass to perform optimally (Table VIII-1). Though annual K_c averages are commonly used to schedule irrigation, it is important that monthly values generate irrigation schedules that more precisely match the needs of turfgrass (Shaw and Pittenger, 2005).

VIII.A.7. Coefficients for Other Types of Landscape Plants

Arriving at the coefficients for other types of plants for landscapes is not as simple as arriving at coefficients for turfgrass. Research-based data regarding the water needed by plants in landscapes with a heterogeneous variety are limited. Hundreds of species with differing needs for water exist, and those needs are influenced by their location in the landscape and their interaction with the surrounding environment. This complexity severely limits the ability to accurately estimate water needs by using the ET_o-K_c approach. Estimating the water needed by species in a heterogeneous landscape is even more difficult (Costello et al., 2000; and Shaw and Zellman, 2005).

Despite these limitations, several approaches for estimating water needed by a landscape have been proposed. One popular method, the Water Use Classification of Landscape Species (WUCOLS), introduces a landscape coefficient adjusted with the use of inputs that take into account differences in microclimates, densities, and species (Costello et al., 2000; or visit

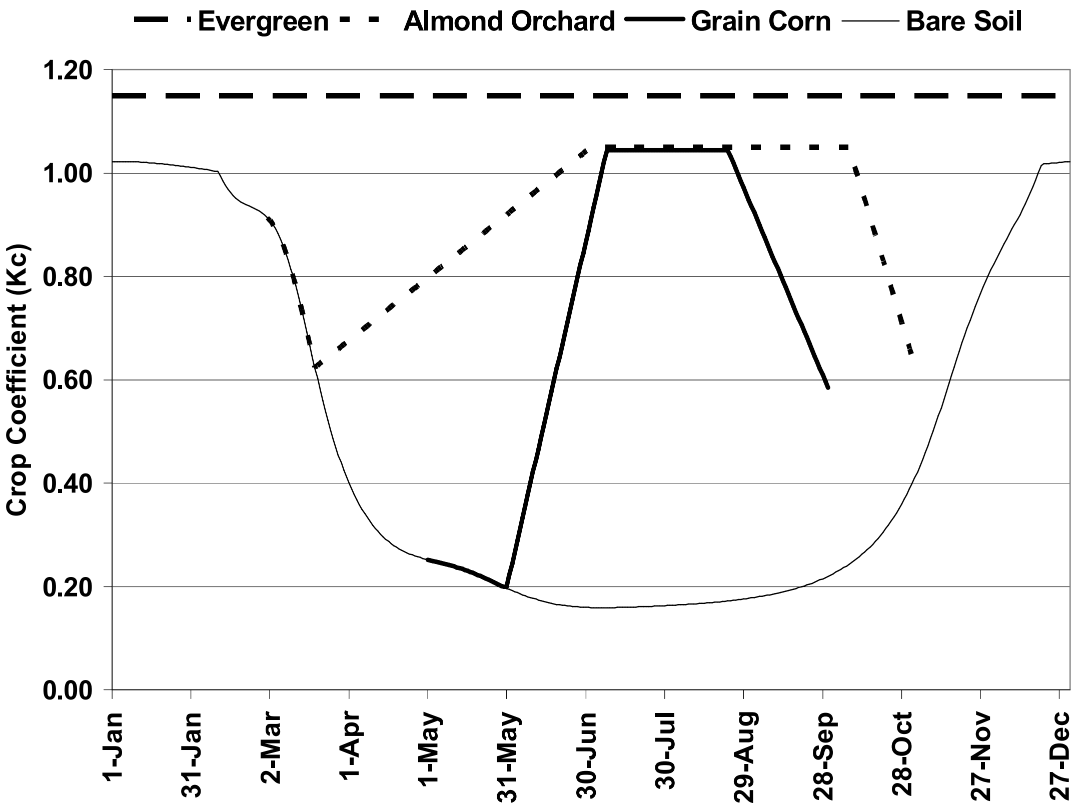

Figure VIII-3. Typical K_c and their variation over the year for four different types of crops ***(courtesy of R. L. Snyder, UC–Davis).***

www.owue.water.ca.gov/docs/wucols00.pdf). In this approach, the landscape coefficient, K_L, is used rather than K_c, and K_L is calculated as

$$K_L = K_s * K_d * K_{mc} \tag{VIII-2}$$

where K_s is a species coefficient, K_d is the plant density coefficient, and K_{mc} is a coefficient that accounts for the microclimate. Refer to Costello et al. (2000) for detailed information about the water needed by various plants within landscapes and the qualitative approaches for adjusting estimates to take into account the mixtures of types of plants, the density of plants, and other site-specific conditions. Though this method takes into account factors that affect the K_L, each individual coefficient adds an additional level of uncertainty, resulting in an uncertain K_L. This method produces rough, initial estimates of ET that will probably need to be adjusted after first estimates are used.

A simple and somewhat qualitative approach in adjusting the K_c may be suitable to take into account differences related to aspect, shade, microclimate, densities of plants, stress, and

Table VIII-2. Initial K_c values or irrigation amount required (as percent ET_o) for selected landscape ground covers and shrubs to provide acceptable landscape performance after establishment.[a]

Scientific name	Common name	Initial K_c
Arbutus unedo "Compacta"	Compact strawberry tree	18–36
Arctostaphylos uva-ursi "Pacific mist"	Bearberry	18–36
Artemisia "Powis Castle"	Wormwood	0–36[b,d]
Baccharis pilularis "Twin peaks"	Twin Peaks coyote bush	20
Calliandra haematocephala	Pink powder puff	18–36
Cassia artemisioides	Feathery cassia	0–36[b,c]
Cistus x *purpureus*	Orchid spot rock rose	0–36[b]
Correa alba "Ivory Bells"	White Australian correa	18–36
Drosanthemum hispidum	Pink iceplant	20
Echium fastuosum	Pride of Madeira	0–36[b]
Escallonia x exoniensis "Fradessii"	Frades escallonia	18–36
Galvezia speciosa	Bush snapdragon	0–36[b,c]
Gazania rigens var. *leucolaena*	"Yellow Cascade" trailing gazania	50–80
Grevillea "Noelii"	Noel grevillea	0–36[b]
Hedera helix "Needlepoint"	Needlepoint English ivy	20–30
Heteromeles arbutifolia	Toyon	0–36[b]
Hibiscus rosa-sinensis	Rose of China	40–60
Lantana montevidensis	Trailing lantana	18–36
Leptospermum scoparium	New Zealand tea tree	18–36
Leucophyllum frutescens	"Green Cloud" Texas ranger	0–36[b,c]
Ligustrum japonicum "Texanum"	Texas privet	40–60
Myoporum "Pacificum"	Prostrate myoporum	0–36[b]
Otatea acuminata	Mexican bamboo	18–36
Phormium tenax	New Zealand flax	18–36
Pittosporum tobira	Mock orange	18–36
Potentilla tabernaemontanii	Spring cinquefoil	70–80

Scientific name	**Common name**	**Initial K_c**
Prunus caroliniana	Carolina laurel cherry	0–36[b]
Pyracantha koidzumii	“Santa Cruz” firethorn	0–36[b]
Rhaphiolepis indica	Indian hawthorn	18–36
Teucrium chamaedrys	Germander	18–36
Vinca major	Periwinkle; myrtle	30–40
Westringia rosamarinaformis	Rosemary bush	18–36
Xylosma congestum	Shiny xylosma	18–36

[a] See Pittenger et al. (1990), Pittenger et al. (2001), Shaw and Pittenger (2004), and Staats and Klett (1995).

[b] Acceptable landscape performance with no summer irrigation shown only on the immediate coast. Inland plantings may require summer irrigation up to the maximum amount listed.

[c] Species typically provides unacceptable landscape performance in summer and fall months regardless of irrigation amount.

[d] Requires renovation every 3 years to maintain acceptable performance.

frequency of irrigation. The standard or “initial” K_c can be adjusted according to the site’s conditions and the desired amount of water-related stress. For example, the K_c may need to be adjusted downward for plants partially shaded by a building or taller nearby trees. Or the K_c may need to be adjusted higher when plants are irrigated with more-saline water or exposed to excessive wind or heat from a nearby street or parking lot. The degree of adjustment is somewhat arbitrary since a heterogeneous group of plants with different needs for water, tolerances to salinity, and microclimates makes rigid numerical adjustments to the K_c impractical. Nevertheless, such adjustments need to be made to the initial K_c either upward or downward, depending on the outcome of the first adjustment.

The range of K_c provided in Table VIII-2, which has been developed by University of California scientists based on research and field experiences, is a sound starting point (Shaw and Zellman, 2005). The higher K_c is relevant for maintaining actively growing plants in good aesthetic condition, such as the turf in a sports field. Lower K_c apply to keeping plants alive under minimal irrigation, such as during periods of restricted water use, and do not maximize aesthetic quality. The K_c typically chosen by irrigation managers falls somewhere in the middle of the range of values listed in Table VIII-2. When one is irrigating with relatively more-saline water, using the higher-end K_c or possibly even a higher value is likely to be advisable.

For species with unknown needs for water, it is currently recommended to set initial irrigation schedules at 50% ET_o for established nonturf plants for landscapes (Shaw and Zellman, 1995). Subsequently adjusting the K_c is the easiest way to handle differences in aspect, shade, microclimate, densities of plants, stress, frequency of irrigation, and water quality. Costello et al. (2000) provide a table listing hundreds of plants and their relative needs for water, i.e., high, moderate, or low. Though no quantitative values are provided, referring to this table is a useful first step.

VIII.B. Scheduling Irrigation

Scheduling irrigation involves determining how long and how often to irrigate. It can be done by hand or by computer.

To develop a schedule for irrigating a landscape, it is critical to first estimate the water needed by the landscape based on the type of plant, the ET_o, and the K_c selected in Table VIII-2. The landscape's ET is estimated from both the ET_o—either historical or "real-time" from weather stations—and the K_c.

Example VIII-1

What is the water needed by a cool-season turfgrass, such as Kentucky bluegrass, in Los Angeles in July with a monthly ET_o of 6.2 in.? Assume that the K_c is 0.80 and does not change during the year.

$ET_c = ET_o * K_c = 6.2$ in. $* 0.80 = 5.0$ in. for July

VIII.B.1. Duration of Irrigation

Using either a hand-held calculator or such scheduling software as TURFIMP on a computer, the duration of irrigation can be calculated on a daily, weekly, or monthly basis with the use of the following information:

1) The irrigation system's application rate (AR) in inches/hour.

2) The irrigation system's distribution uniformity (DU), which has been described in Chapter VII and is an estimate of how uniformly water is applied. The DU will account for the losses due to nonuniformity of irrigation. Irrigation efficiency (IE) accounts for losses due to uniformity, runoff, and deep percolation. If runoff is minimal and the average depth of water applied to the low quarter is equal to the landscape's use of water, then the DU is a viable estimate of IE.
3) Historical or real-time ET_O.

4) Initial or adjusted K_C.

With a hand-held calculator or scheduling software on a computer, the aforementioned information is used in the following formula to calculate how long each irrigation should last:

$$\text{Run time (minutes)} = \frac{ET_o \text{ in./day} \; * \; K_c \; * \; 60 \text{ min/h}}{AR \text{ in./h} \; * \; DU} \qquad \text{(VIII-3)}$$

The duration of irrigations for successive days can be determined by adding daily run times or using the cumulative ET_o value. The weekly duration of irrigations can be determined by multiplying the average daily ET_o by 7.

Example VIII-2

What is the daily run time for irrigating shrubs in a landscape in the southern coastal area with a K_c of 0.50, a daily ET_o of 0.18 inches, and a water application rate (AR) of 0.75 in./h? Assume that the irrigation system's DU is 80% (0.80).

$$\text{Daily run time} = \frac{0.18 \text{ in./day} * 0.50 * 60}{0.75 \text{ in./h} * 0.80} = 9.0 \text{ min/day} \qquad \text{(VIII-4)}$$

This particular example above works best for sprinkler irrigation. Under drip irrigation, the system run time will be based on the number of emitters and emitter discharge rates (gallons per hour) for the area being irrigated. Usually there are numerous plant types, plant sizes, and emitter discharge rates on a particular station. In these instances, it is best to have flow meters installed. In example VI-2, the amount of water that needs to be added each day during this time of year is 0.11 in. ($ET_o * K_c/0.8$). For an acre of landscape, the meter would have to run for about 400 ft^3 (about 3,000 gal).

VIII.B.2. Frequency of Irrigation

Since the approximate amount of water that a plant needs can be calculated on a daily basis, that amount of water theoretically could be applied daily, but applying small amounts of water on a daily basis is an inefficient and unsound practice in most cases (Hanson et al., 1994).

A more practical and effective method is to wait for a period of time—usually several days—and then to apply the accumulated amount.

The following should be considered in determining how often to irrigate:

Factors that necessitate frequent irrigation are as follows:

- Plants that use water at a high rate
- Plants with shallow roots
- Sandy soils with little capacity for retaining water
- High probability of runoff due to sloping land or compacted soil
- Poor rate of infiltration due to compacted or clay soils.

Factors that allow for infrequent irrigation are as follows:

- Low rates of ET
- Additional water from rain, dew, or fog
- Plants with deep roots and dense roots
- Plants that are drought tolerant
- No problems with runoff
- A site able to maintain acceptable quality or use with infrequent irrigation
- More-saline waters used to irrigate, requiring deep watering with a higher leaching fraction.

Observations in the field including appearance of plants, the depth of their roots, the penetration of water into the soil, the type of soil, and the estimated available water-holding capacity will help in determining how often to irrigate. Often, a field estimate of the amount of water in the soil or the amount of visible water-related stress being sustained by the plants is used to decide when to irrigate and ET data are used to determine how long to irrigate or with how much water. If conditions at the site limit the rate of infiltration, the length of time that elapses before runoff occurs will determine the longest possible run time at that site. Multiple cycles should be programmed if additional run time is needed for water to infiltrate to a desired depth in the soil.

Three common methods for deciding when to irrigate include the flexible method, which is based on an estimate of the allowable depletion of moisture from the root zone; the fixed-day calendar method, which accommodates weekly cultivational practices and weekly activities involving use of the site; and soil moisture sensors. Many irrigation controllers provide programming functions for all three methods, using a 7- or 14-day calendar, features for skipping a day, and sensor inputs. Each method is acceptable, as long as the proper amount of water is applied and runoff is minimized.

VIII.B.3. Using the Flexible Method

With the flexible method, the duration of each irrigation remains the same and the frequency of irrigation varies during the year according to an estimate of the allowable depletion of moisture from the soil and the daily use of water by plants.

The amount of water in the soil available to the plant depends on the type of soil and the depth of the roots of the plant in question. Tables exist that provide estimates of available water for soils of various textures (Goldhamer and Snyder, 1989). Coarse-textured soils—sands to sandy loams—typically have 0.5 to 1.25 in. of available water/ft of soil. Medium-textured soils—fine-sandy loams to silt loams—generally have 1.0 to 2.0 in. of available water per ft. Fine-textured soils—clay loams to clays—have 1.5 to 3.0 in. of available water per ft. The total available water is the available water multiplied by the effective root depth. For example, a plant with an effective root depth of 2 ft grown in a soil with 1.5 in. of available water/ft has 3 in. of total available water.

It should be noted that all of what is termed total available water is not all readily available to the plant. Its roots can readily extract water when the soil is relatively wet, but this process becomes progressively more difficult as the soil dries. Consequently, instead of scheduling a irrigation after the total water is extracted, it is recommended that an allowable depletion of the total available water in the soil be selected to prevent potentially fatal stress to the plant. This allowable depletion can vary between 20 and 70%. An allowable depletion of 20 to 30% may be appropriate for more drought-sensitive plants. More drought-tolerant plants may be able to handle an allowable depletion of 70%. If the lesser allowable depletion is selected, more frequent irrigations will obviously be required.

The frequency of irrigation is determined by summing up the values for daily use of water by plants ($ET_O \times K_C$), until the total water use equals the desired depletion of water in the soil (Figure VIII-4). The effect of rainfall and fog, which may contribute to moisture in the soil, can be assessed only by observation in the field.

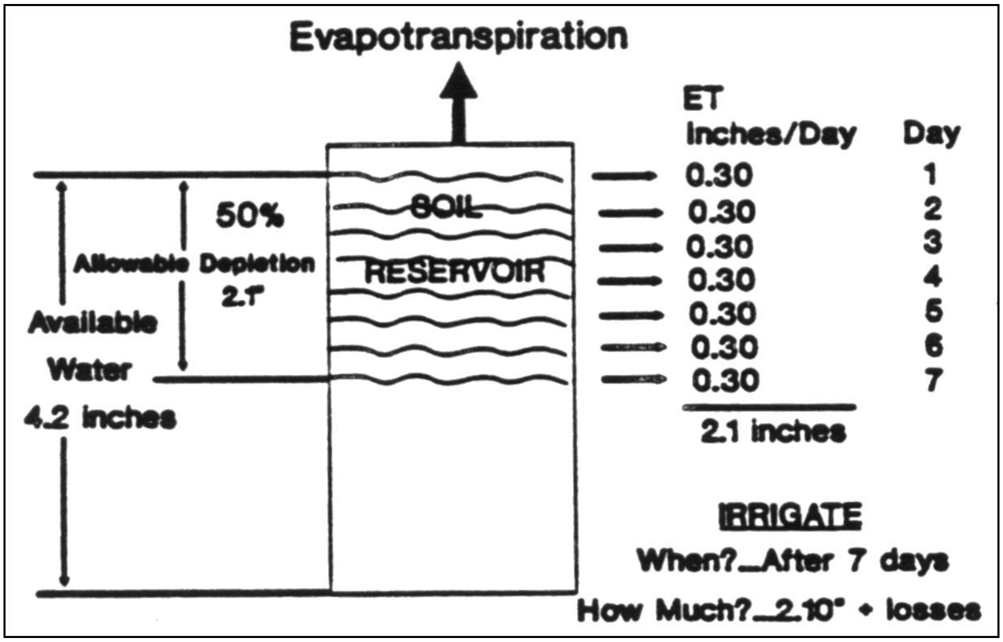

Figure VIII-4. Soil water depletion (flexible) method.

VIII.B.4. Using the Calendar Method

With the calendar method, the frequency of irrigation is fixed to specific days of the week that generally accommodate the site's activities. Since the water needs of plants vary according to the time of year and evaporative demand, the run time per irrigation will vary during the year. The calendar method involves taking the following steps: First, determine the number of minutes of run time per week. Second, determine the number of irrigation days per week. Third, calculate the run time per day:

$$\text{Run time per day} = \frac{\text{minutes per week}}{\text{irrigation days per week}} \qquad \text{(VIII-5)}$$

If runoff occurs during this run time, then the run time will need to be divided into more cycles of irrigation. If the soil permits a high rate of application, then only one cycle per day is needed.

VIII.B.5. Using Soil Moisture Sensors

Soil moisture sensors are sometimes used in landscapes to determine when to start irrigating and, in some cases, when to stop irrigating. It is very important that these sensors be located in the active root zone and that they be properly calibrated for the specific conditions of the site's soil. Sensors should be read and recorded in a routine and timely way. When one is using soil moisture sensors, uniformity of irrigation remains an important factor and information about ET plays a limited role in water management, but irrigation may be scheduled based on data about historical ET_o and sensors can be used to shut down the irrigation system when water is not needed.

VIII.B.6. Components of Efficient Irrigation Scheduling Programs

As with all irrigation practices, the plant's observed response, measurements of the moisture in the soil, and the irrigation manager's judgment will help to verify the appropriateness of the irrigation schedule. Modifying the K_c or analyzing data about the irrigation system's performance and subsequently recalculating the run times will be needed to fine-tune the schedule.

A high-quality, efficient system for irrigating a landscape is the product of good design, high-quality hardware, professional installation, and timely maintenance. Each component depends on the others for success. The failure of any one component may result in the entire system's demise. An efficient program for irrigating a landscape combines a high-quality irrigation system with knowledgeable people performing proper scheduling and monitoring.

VIII.C. Conserving Water by Irrigating with Recycled Water

Irrigating a landscape with recycled water instead of with water that has never been previously used constitutes a major water-conserving measure. Such a conservation-oriented water management policy does not necessarily involve an irrigation water of lesser quality. Not all recycled water is of poor quality, and not all potable water is necessarily of low salinity. If the recycled water used to irrigate has a higher salt content than did the water used before, then care should be taken when simultaneously adopting deficit irrigation, as the combination could create excessive accumulation of salinity in the root zone, which could adversely affect sensitive plants. Under most circumstances, however, irrigating with recycled water may not involve the need for any special management practices above and beyond those needed for irrigating with high-quality potable water. It depends on the recycled water's source. Recycled water from municipalities with potable water of low salinity would be superior to that derived from communities with potable water of a higher salt content.

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Chapter IX. Soil-Related Problems

K. Tanji, B. Sheikh, and S. Grattan

- IX.A. Saline Soils
- IX.B. Sodic Soils
- IX.C. Slowly Permeable Soils
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  - IX.D.3. Nutrients Required by Landscape Plants
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The soil is the medium supporting the growth of plants. It is here where the roots draw water and absorb essential nutrients. Consequently, any soil-related problem will markedly affect the health and viability of plants. Problems involving soils include excessively saline soils, excessively sodic soils, insufficiently fertile soils, those that are less penetrable to water, those that contain toxic amounts of trace elements, and those that are steeply sloped—a condition that contributes to the runoff of irrigation water and the erosion of soil.

IX.A. Saline Soils

In soils with an excessive amount of salinity, i.e., greater than an electrical conductivity of extract of soil paste (EC_e) of 4 dS/m (Table IX.A.1), the availability of water in the soil to plants is reduced by osmotic effects. Saline soils are typically dominated by Na, Mg, Cl, and SO_4 ions, which typically form highly soluble salts and consequently accumulate to high concentrations. Their pattern is in contrast with that of Ca, HCO_3, and CO_3 ions, which form less soluble salts and thus less readily accumulate soluble salts (Chapter IV). Symptoms of excessive salinity to plants include wilting and other signs of stress induced by

Table IX.A.1. Classification of salt-affected soils and distinguishing properties *(after Richards, 1954).*[a]

Class	EC_e dS/m	ESP %	pH_s
Nonsaline	<4	<15	<8.5
Saline	>4	<15	<8.5
Sodic	<4	>15	>8.5
Saline-sodic	>4	>15	<8.5

[a] EC_e = EC of extract of saturated soil paste;
ESP = (exchangeable Na/CEC) × 100, with both Na and CEC in number of milliequivalents/100 g of soil;
CEC = cation exchange capacity (negatively charged sites) in number of milliequivalents/100 g of soil; and
pH_s = pH of saturated soil paste.

insufficient water, as well as stunted growth, and, in severe cases, damaged leaves and death (Chapter V).

Soils become salinized either through nature, which is known as primary salinization, or via human activity, known as secondary salinization. The primary natural source of salinity in soils is the geochemical weathering of rocks, sediments, and soil minerals, which produces dissolved mineral salts. Elevated salinity is naturally present in soils derived from saline marine sedimentary rocks. Some soils in coastal zones are saline due to seawater intrusion or being sprayed by seawater. Salinity in soils introduced by human (anthropogenic) activity includes salts from applied irrigation water, from such amendments to soil and water as gypsum and sulfuric acid, from animal manures, and from biosolids.

Though measuring salinity in waters is straightforward and though the result is expressed as EC or total dissolved salts (TDS), measuring the salinity of a soil presents more of a challenge due to the dynamic changes that occur within a soil over time and space. The concentration of dissolved mineral salts generally does not change in direct proportion to changes in soil water contents because of mineral solubility, cation exchange, and ion association (Paul et al., 1966). Soil water content undergoes cyclical wetting and drying. Soil water content is replenished by irrigation and rainfall and depleted by evapotranspiration. Moreover, dissolved mineral salts are highly mobile in the soil due to chemical diffusion (ion diffusion) and to convective and dispersive transport by soil water flow. Therefore, plant roots are exposed to dynamic temporal and spatial changes in soil salinity, and these changes pose a challenge in measuring soil salinity.

Methods to measure the salinity of a soil include (1) collecting samples of the soil and measuring the EC_e, (2) collecting water in the soil in situ with ceramic suction cups when the soil is moist and measuring soil salinity (EC_{sw}), and (3) using the time domain reflectometry device (TDR) or electromagnetic devices (EM-38 probe) to remotely sense EC_{sw} in situ.

Figure IX.A.1 illustrates the dynamic changes in a lysimeter with soil depth of 120 cm, in which a crop of alfalfa was grown. It specifically depicts changes in the salinity of soil in two depths and in the water potential of the soil in one depth (Rhoades, 1972). Note that the EC_{sw} at a depth of 40 cm is less than the EC_{sw} at a depth of 80 cm in this lysimeter. This result occurs because salts are leached at the surface and tend to accumulate in the lower depths. The EC_{sw} was measured with salinity sensors embedded in the soil column. Irrigation water was applied when the water pressure in the soil at a depth of 60 cm reached about 0.5 bars as measured with tensiometers. When irrigation water was applied, the EC_{sw} abruptly decreased and then slowly increased, as plants extracted water in the soil, with salts remaining residually. The time-integrated EC_{sw} at a depth of 40 cm was 7.4 and 12.4 dS/m at a depth of 80 cm. Roots of the plants were consequently exposed to various amounts of water and salinity in the soil over time and space. The alfalfa example is given because the authors did not find a similar data set for turfgrasses.

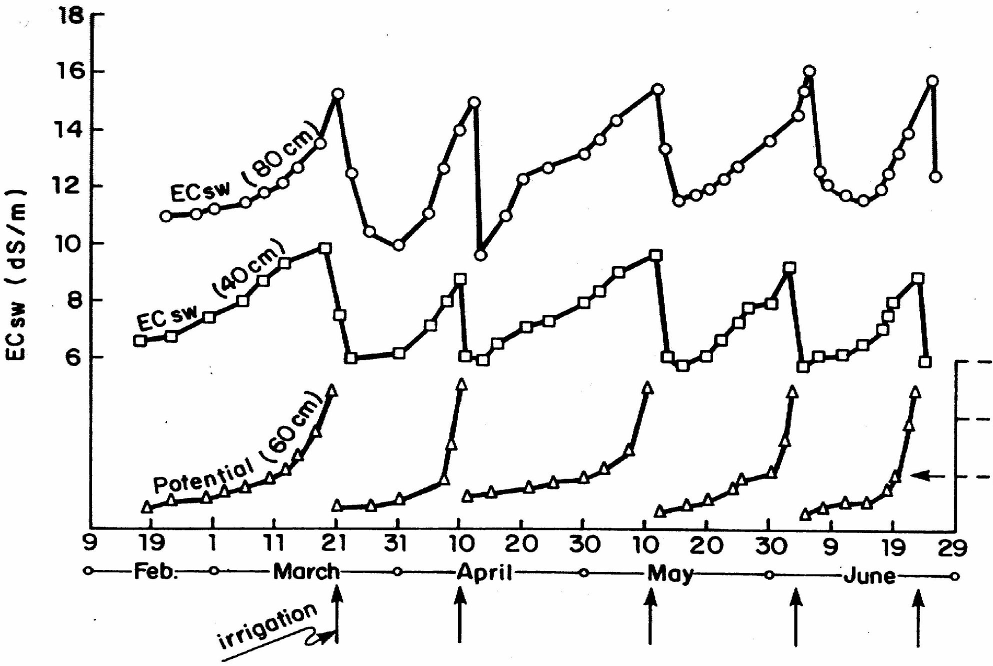


Figure IX.A.1. Dynamic changes in soil salinity in two soil depths and soil water potential in one soil depth as influenced by irrigation and evapotranspiration of alfalfa grown in a lysimeter *(after Rhoades, 1972).*

The salinity of a soil depends on the salinity of the water that irrigates it and the leaching fraction (LF) provided with each irrigation event or seasonally (Chapters III and IV). It is assumed that the soil profile is permeable: i.e., no restrictions on drainage. The seasonal LF is defined as

$$LF = \frac{D_{iw} - D_{et}}{D_{iw}} = \frac{D_{dw}}{D_{iw}} \tag{IX-1}$$

where D_{iw} denotes the depth to which irrigation water has infiltrated, D_{et} denotes the depth of plant ET, and D_{dw} the depth of drainage water leaching past the root zone. The distribution of salts in the soil varies according to the pattern of root water extraction and the depth of rooting (Chapter IV). If the rainfall that infiltrates the soil contributes substantially to meet the plant's ET requirements, fewer salts accumulate in the root zone than with irrigation alone, since rainwater contains a very low level of salts—approximately from 5 to 20 ppm of TDS.

A root zone's average salinity may be sustained within a plant's known threshold for tolerating salt (Chapter V) with the leaching requirement (LR). The seasonal LR is defined as

$$LR = \frac{EC_{iw}}{5 * EC_a - EC_{iw}} \tag{IX-2}$$

where EC_a is the plant-specific threshold soil salinity, above which plant performance is impaired and "5" is an empirical factor to account for the distribution of salt in the soil (Rhoades, 1972).

The way in which salt is eventually distributed in irrigated soils depends greatly on the type of irrigation system and the extent of leaching. Figure IX.A.2 illustrates the wetting patterns with several methods of surface and subsurface irrigation (FAO, 1997). Salts tend to accumulate in the wetted perimeter of soils. Figure IX.A.3 illustrates the gravimetric soil moisture contents around two surface drippers in a strawberry field and the pattern of soil salinity (Hanson and Bendixson, 2004).

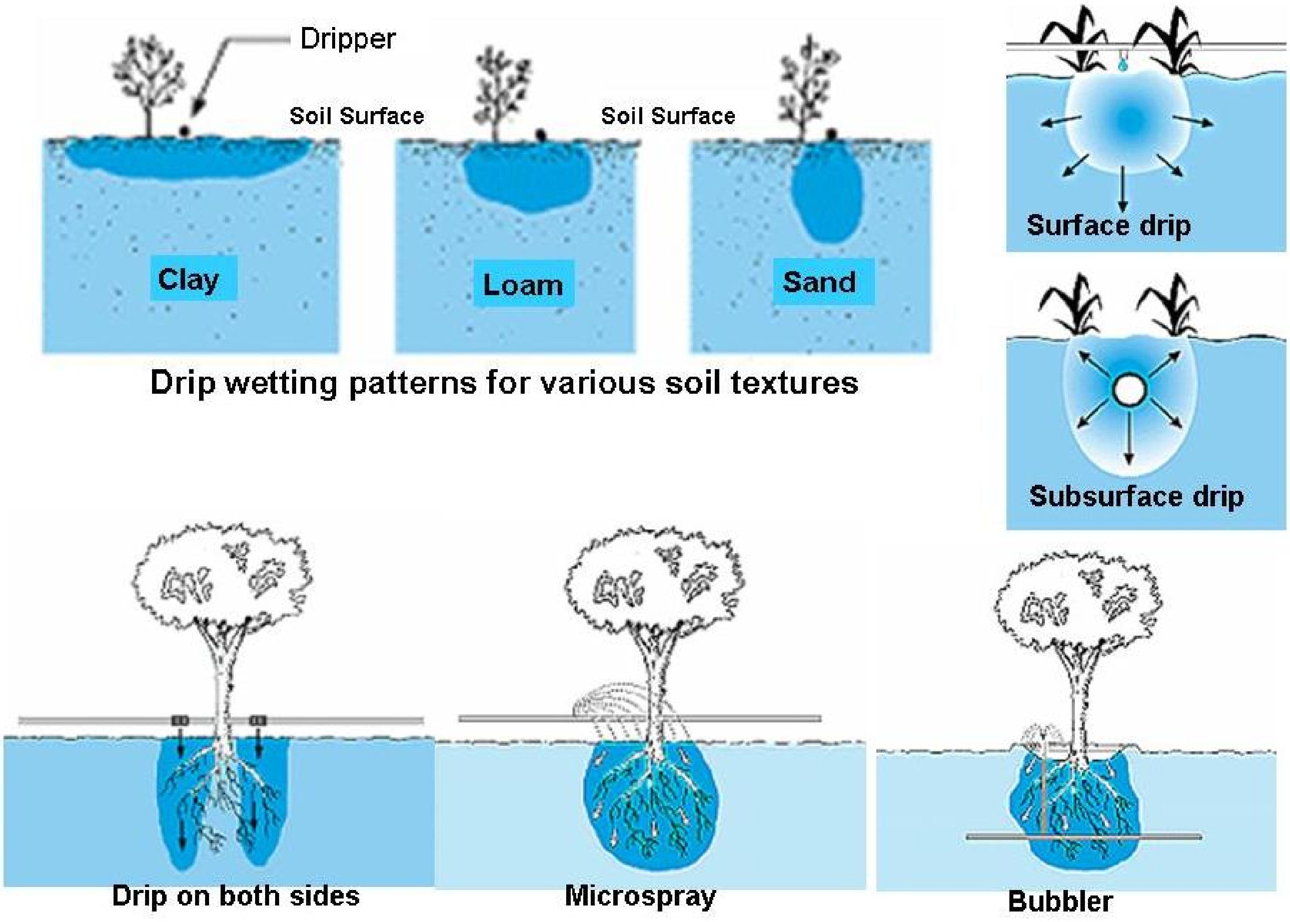
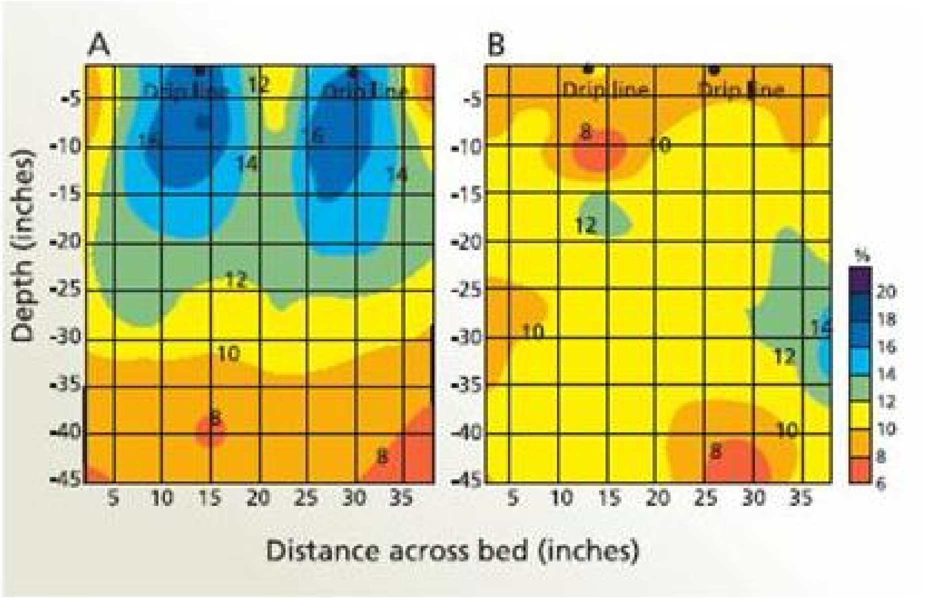
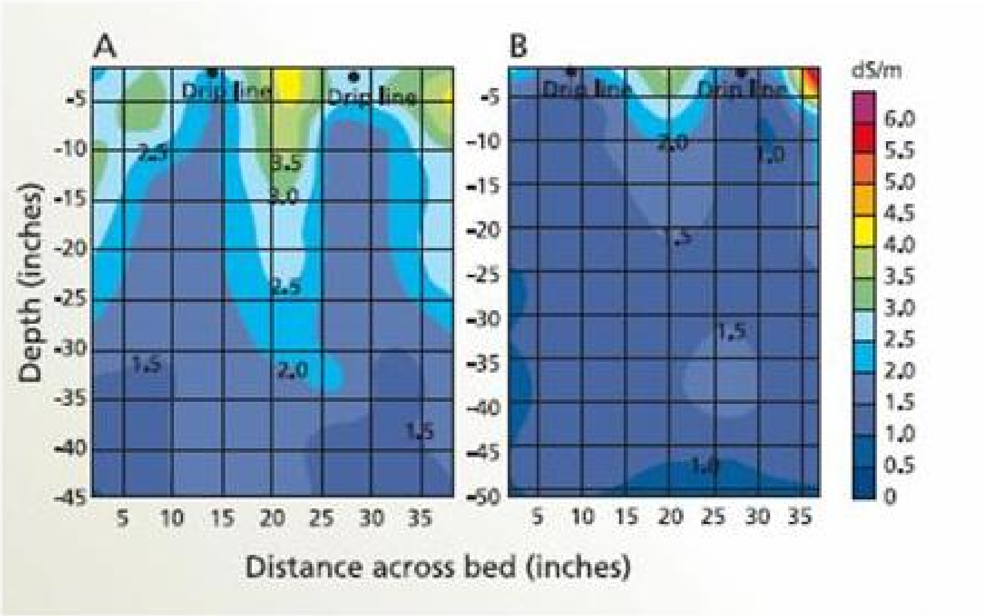


Figure IX.A.2. Wetting patterns for surface drip, subsurface drip, microspray, and bubbler irrigation application systems *(from FAO, 1997)* .



Pattern of moisture contents for two drippers just after irrigation (A) and several days after drying (B)



Pattern of EC for two drippers with relatively low (A) and high (B) leaching fraction

Figure IX.A.3. Moisture and salinity distribution patterns for two surface drippers *(from Hanson and Bendixson, 2004).*

With drip irrigation, the wetted zone is somewhat ellipsoidal in shape and salts accumulate in the outer wetted edges, as shown in Figure IX.A.3. Though the LF principle does not apply directly to this wetted zone, a greater application of drip irrigation will result in the accumulation of salt farther away from the roots of the plant. After drip irrigating with saline waters for a prolonged period in agricultural crops, it is common to carry out reclamation leaching by using the sprinkler irrigation method to leach soil salts before the planting of the next crop. Such a practice could be adopted for annual landscape plants. Heavy rainfall on drip-irrigated soil with a high accumulation of salt will redistribute the salts vertically and laterally. Since this redistribution of salts may adversely affect salt-sensitive plants, it is suggested that drip irrigation be conducted during rainfall to reduce the influx of salts into the root zone.

IX.B. Sodic Soils

Sodic soils contain excessive levels of exchangeable (adsorbed) Na, causing such unfavorable physical conditions in the soil as a reduced rate of water infiltration (Chapter III). High exchangeable sodium percentage (ESP) and soil pH result in the dispersion of clays and organic matter in the soil. High ESP may be toxic to sensitive plants (USSL, 1954). Sodic soils have a pH greater than 8.5 due to the presence of sodium in the form of Na_2CO_3 or NaOH.

The genesis of sodic soils is more complex than that of saline soils. Some sodic soils may be formed by leaching of saline soils rich in Na, resulting in excess ESP. Other sodic soils may result from the chemical weathering of igneous rocks, forming $NaHCO_3$ under nonsaline conditions and being subjected to evapoconcentration from transpiration of plants and evaporation from bare soils. Another pathway of sodicity involves the biological formation of Na_2CO_3 by the reduction of sulfate to sulfide ions in wetland environments (Whittig and Janitsky, 1963).

In sodic soils, the ratio of exchangeable Na to cation exchange capacity (CEC) multiplied by 100—the ESP—exceeds 15% (Table IX.A.1). Analytical determination of ESP involves extraction of exchangeable and soluble Na, as well as the determination of CEC. Since determining the ESP requires a lengthy and complex process, a proxy sodicity parameter known as the sodium adsorption ratio (SAR) is commonly used. The SAR is calculated from the soluble Na, Ca, and Mg in the extract of soil saturated paste. It is defined as

$$SAR = \frac{Na^{+}}{[Ca^{++} + Mg^{++}]^{0.5}} \qquad \text{with all ionic concentrations in mmoles/liter} \qquad \text{(IX-3)}$$

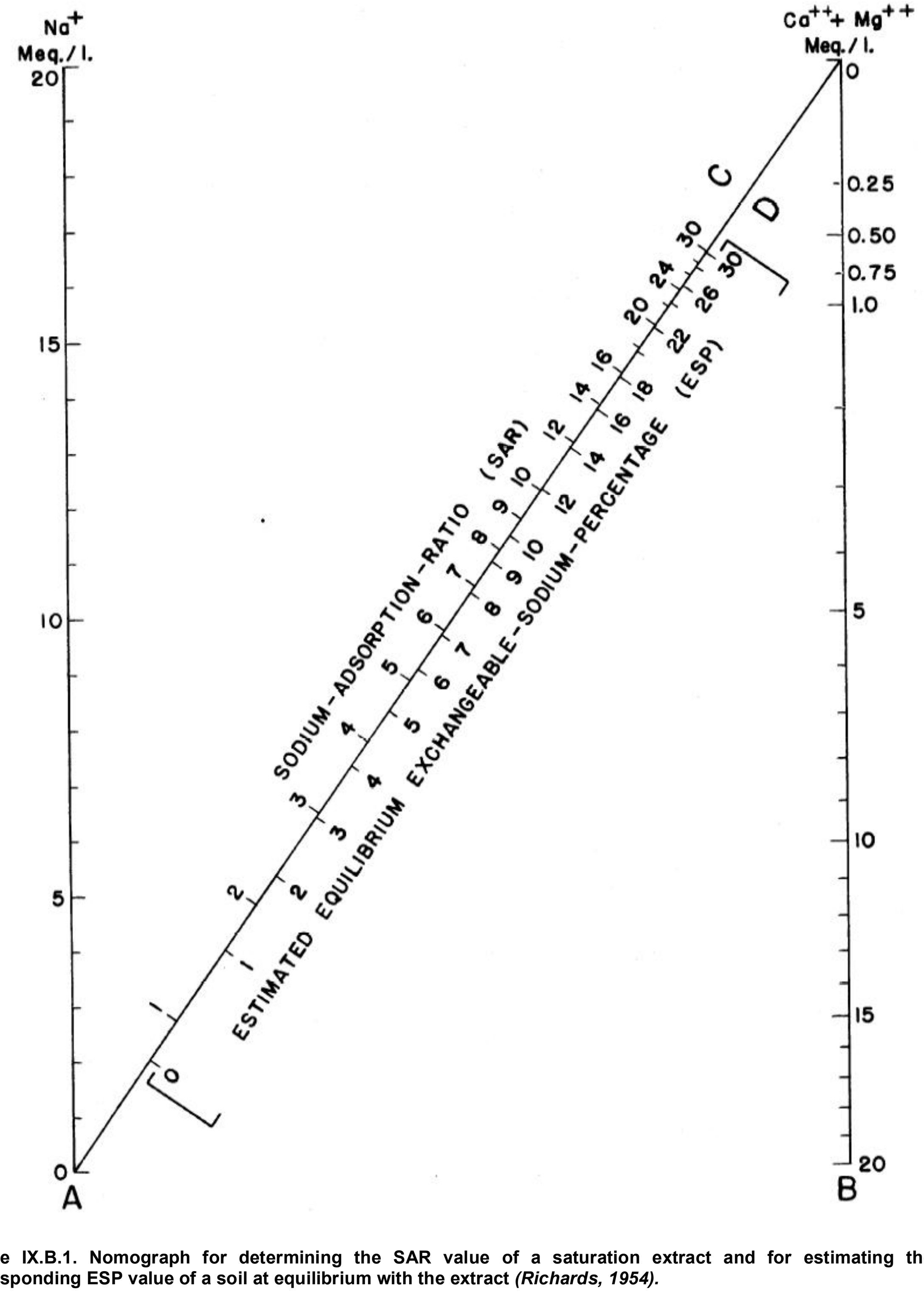


Figure IX.B.1. Nomograph for determining the SAR value of a saturation extract and for estimating the corresponding ESP value of a soil at equilibrium with the extract *(Richards, 1954).*

or $SAR = \frac{Na^{+}}{[0.5 * (Ca^{++} + Mg^{++})]^{0.5}}$ with all ionic concentrations in number of milliequivalents/liter (IX-4)

The SAR in the soil solution may be empirically related to the ESP on the soil exchange complex by a nomogram (Figure IX.B.1) found in Richards (1954) or calculated from

$$ESP = \frac{100(-0.0126 + 0.01475 * SAR)}{1 + (-0.0126 + 0.01475 * SAR)} \qquad \text{(IX-5)}$$

A high ESP or SAR adversely affects a soil's structure, especially at the surface. It results in the breakdown of soil aggregates and the dispersion of clays and organic matter, reducing rates of water intake. S. Miyamoto (personal communication) has found that the ESP in turf irrigated with saline-sodic waters is affected by LF as much as by the SAR of the irrigation water. This discussion of sodic soils is considered more fully in the next section.

The dispersion of clays and organic matter is also affected by salt (electrolyte) concentration. The combined effects of EC and SAR in the water on the permeability of soil are commonly evaluated with the approach shown in Figure IX.B.2.

Another water sodicity parameter that was frequently used in the past is residual sodium carbonate (RSC). It is defined as

RSC = (HCO_3 + CO_3) – (Ca + Mg) in number of milliequivalents/liter
(IX-6)

When the RSC exceeds 1.25 meq/L, clays and organic matter in the soil may disperse, resulting in reduced permeability (Richards, 1954). Although the use of RSC is somewhat dated, many testing laboratories for soils and horticulture still use this parameter and find it to be a useful sodicity parameter.

Excessive levels of sodicity are commonly ameliorated by adding Ca amendments into the soil's surface or to the water used to irrigate. This topic will be further discussed in the next section.

Figure IX.B.3 shows the SAR-EC combinations for a number of sources of recycled water, as reported by some of California's major water recycling agencies (B. Sheikh, personal communication). As can be seen, many of these waters fall within the zone of no reduction in the infiltration rate, several waters in the zone of slight to moderate reduction in the infiltration rate, and no water in the zone of severe reduction in the rate at which water infiltrates the irrigated soil. Some agencies whose recycled water reduces the rate slightly to moderately have begun to add gypsum, so that irrigating with the amended water does not cause infiltration problems. For example, Carmel Area Wastewater District, which provides recycled water to

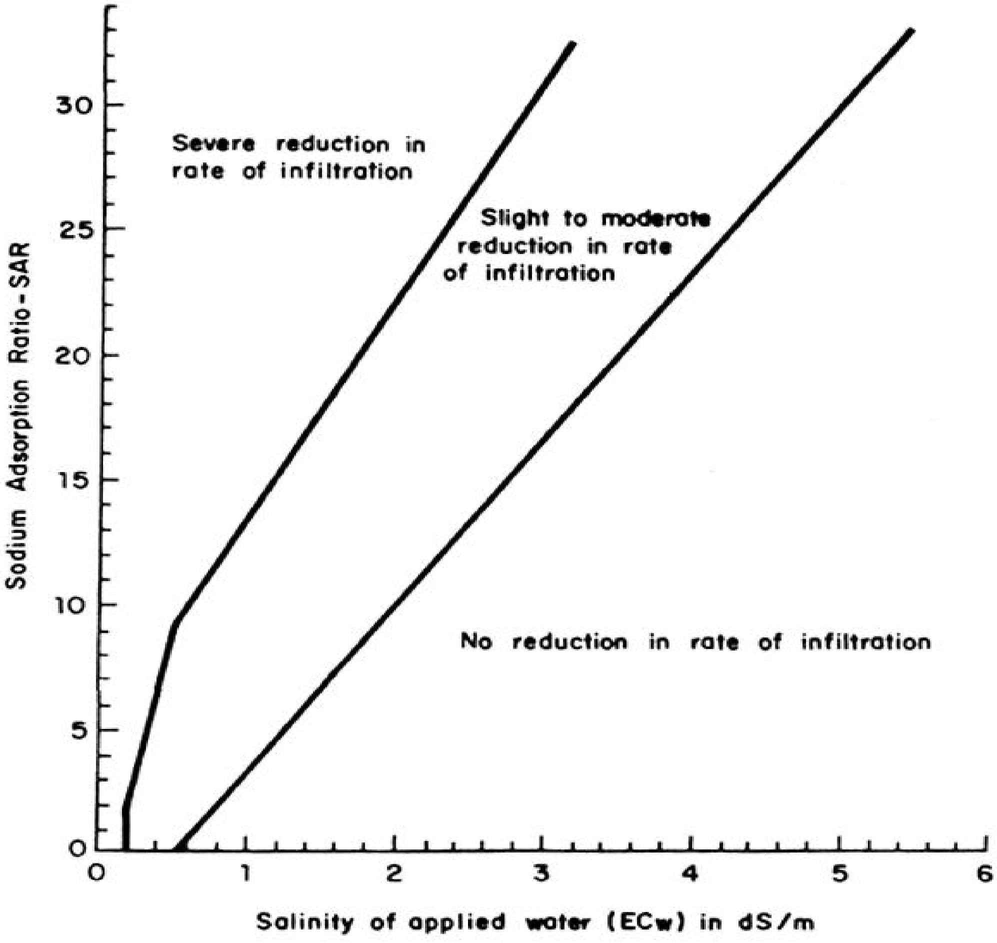


Figure IX.B.2. An approach for evaluating the combined effects of water salinity and sodicity on soil permeability ***(from Ayers and Westcot, 1985).***

seven Pebble Beach golf courses, is planning to desalinate its recycled water enough to meet certain criteria for concentrations of TDS. Ironically, meeting these criteria may cause the recycled water to move from the no-impact zone to a slight reduction in the irrigated soil's rate of infiltration, unless gypsum continues to be added.

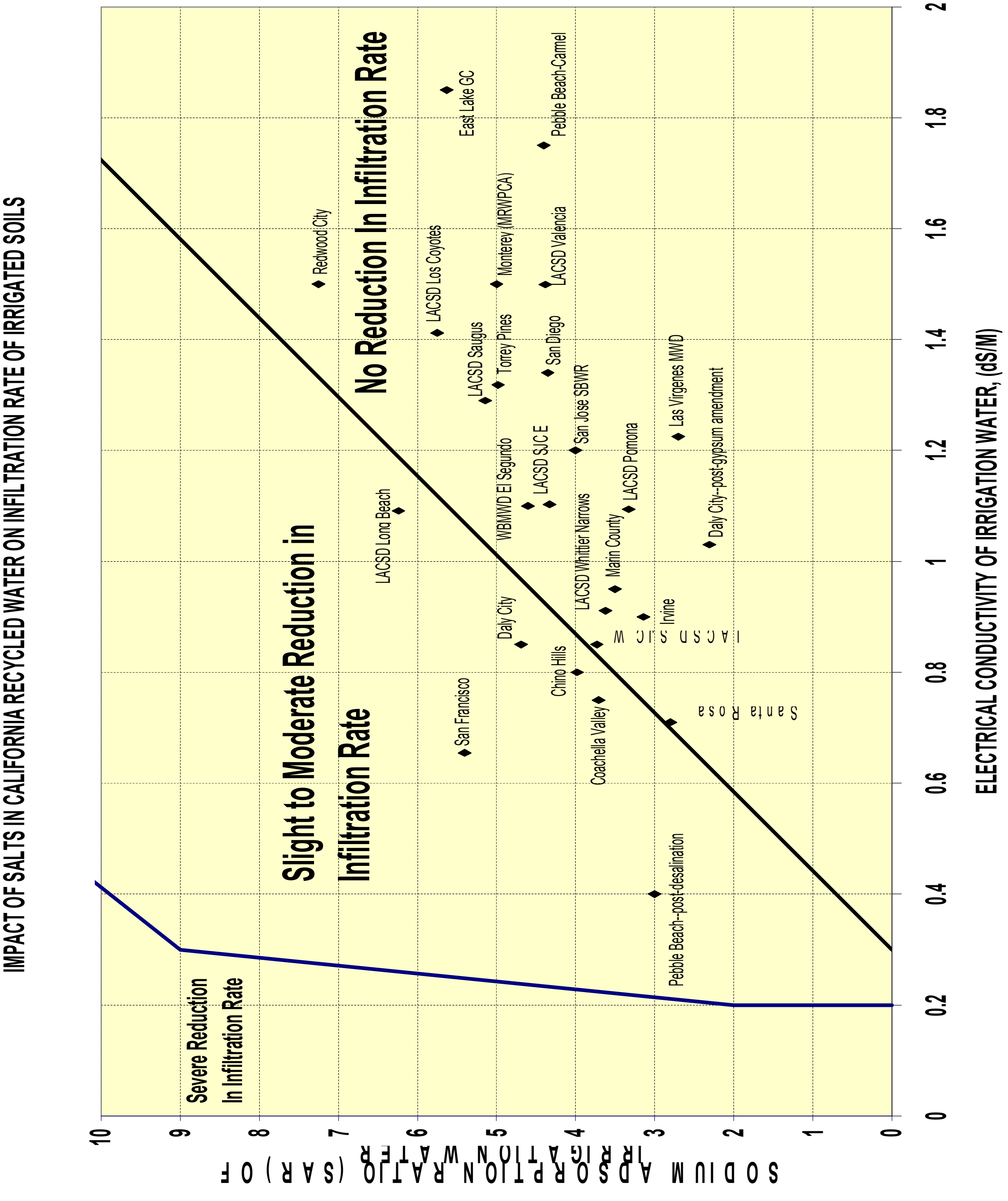


Figure IX.B.3. EC-SAR combinations of major sources of recycled water in California ***(from personal communication by B. Sheikh with personnel at the respective agencies featured in the graphic)*****.**

IX.C. Slowly Permeable Soils

If a soil is slowly penetrated by water, that low penetration rate may be caused by conditions at the surface that slow the intake of water, as well as by the sluggish movement of water below the surface. Symptoms include plants stunted by lack of water, soil dryness even after prolonged irrigation, excessive ponding and/or runoff during irrigation and rainfall, poorly aerated soil, increased incidence of root diseases, excessive wilting of plants during hot summer months, and the need to irrigate for an excessively long time, which, in turn, can prevent or interfere with other cultural practices such as weeding, fertilization, etc. (Oster et al., 1984). In landscapes, prolonged wetness from the prolonged need to irrigate may also interfere with the mowing of turf and with the public use of the landscapes.

IX.C.1. Causes

Solving the problem of slow soil penetration by water depends on its cause. It could be the quality of the water used to irrigate, coupled with the types of clays in the soil. A water with an EC exceeding about 0.5 dS/m will tend to promote the aggregation of particles of soil. A far less saline water, e.g., one with an EC of less than 0.2 dS/m, will tend to disperse them. If a soil is dominated by kaolinite and illite clays, which do not swell, the soil's particles will tend to aggregate. If the soil is dominated instead by smectite clays, which swell, the soil's particles will tend to swell, separate, and disperse.

A second cause could be that crusting of the soil is impeding the water intake rate. The two kinds of crusts that cause water to penetrate a soil poorly are structural crusts and depositional crusts (Oster et al., 1984). Structural crusts are formed when drops of rain and water from sprinklers wet and beat the soil, collapsing its structure. When the soil dries, the thin crust that forms decreases the number and size of larger water-conducting pores. Depositional crusts are formed when sediment-laden water infiltrates the soil, leaving a residual layer of sediment on the soil's surface that is usually thicker than structural crusts.

A third cause could be that sodicity, which is reported as SAR, is impeding water infiltration. This potentiality was discussed previously in IX.B.2. Note that the criteria for sodicity developed for agricultural soils may not be directly applicable to soils in heavily trafficked landscapes, particularly those that are moist and clay rich, as they can become compacted.

This discussion brings up a fourth cause: compaction of the soil by the traffic of machines and humans, especially when the soil is moist. The applied force of such traffic rearranges particles of soil, increasing its dense bulk and decreasing its number of larger water-conducting pores.

A fifth cause could be that stratification of the soil below the surface is impeding water movement in the soil profile. Possible strata may include clay pan, cemented hardpan, and bedrock. A clay pan is formed when the soil's clays are leached into the subsoil, accumulating at depths of 12 to 24 in. A hardpan is a layer of subsoil strongly cemented with silica and calcium carbonate. Dropping a sample of the pan into a bucket of water helps to distinguish a clay pan from a hardpan: if it softens and falls apart, it is a clay pan; if it does not, it is a cemented hardpan.

A sixth cause of slowly permeable soil is abrupt textural stratifications in alluvial soils. Such stratifications can prevent the uniform flow of water in the soil. Clay layers can restrict the movement of water and cause a perched water table and poor aeration. Sandy layers can cause the same problems as clay layers, since overlying layers of soil must become saturated with water before water will flow into the sandy layers.

IX.C.2. Solutions

Management options can be divided into solutions for such problems as crusting and compaction. They may be addressed at the soil's surface with the addition of chemical amendments, the addition of organic matter and/or tillage; solutions for subsurface problems, and remedies that involve a change in irrigation systems. The following solutions have proven effective over decades of agricultural practice with natural sources of water and should work just as effectively with recycled water. These amendments may not be as effective for recycled waters having an EC of 1.5 to 3.5 dS/m as used in the landscapes of the southwestern United States (Miyamoto, 1998). Mechanical means of improving soil permeability tend to give better results than do chemical amendments in the Southwest.

Gypsum

A chemical amendment—mainly either calcium or an acid-producing amendment that yields calcium—can improve both the soil and the quality of water used to irrigate. Gypsum ($CaSO_4 \cdot 2H_2O$), a relatively inexpensive and easily applied soil and water amendment, is widely used. The calcium released from gypsum reduces the SAR of the water and soil. It enhances the stable aggregation of soil and increases the concentration salt in water with low salinity, which would otherwise poorly penetrate soil. Gypsum is applied to the soil at a rate of 1 to 4 tons per acre by being spread on the soil's surface and is then tilled into the soil. It is applied to water with a device that dissolves gypsum into a slurry and injects it into water. Doing so increases the concentration of calcium by 2 to 4 meq/L (40 to 80 mg/L). Sometimes phosphogypsum, a by-product in the manufacture of phosphorus fertilizer, is used instead of gypsum with equally good results.

Acidification

Such acid-forming amendments as sulfur, sulfur dioxide gas, lime sulfur, sulfuric acid, ammonium polysulfide, and ammonium thiosulfate may also be used. These amendments produce hydrogen ions, which dissolve the soil's calcium carbonate, releasing soluble calcium ions. A conversion table outlining the number of tons equivalent to pure gypsum or elemental sulfur is available (California Fertilizer Association, 1998), as is a conversion table with the number of pounds required per acre-foot of water to obtain 1 meq of calcium/L or that required per acre to replace 1 meq/100 g of exchangeable sodium in the top 6 in. of soil (Oster et al., 1984).

Soil Conditioners

Soil conditioners consisting of synthetic organic polymers are used to bind smaller aggregates of soil into larger ones. Polyacrylamide (PAM) applied at a rate of 30 lbs. per acre in the irrigation water improves water intakes. PAM is also used to reduce sediment load in tailwater (runoffs) from furrow irrigated fields.

Organic Matter

Such organic matter as residues of crops, cover crops, manure, and biosolids generated from the treatment of municipal wastewater, when added to soil, improves the rate at which water infiltrates that soil. Polysaccharides in the organic matter appear to bind particles of soil, promoting their aggregation and maintaining the structure of the soil.

IX.D. Infertile Soils

IX.D.1. Essential Plant Nutrients

Maintenance of adequate plant nutrition is important in landscape settings to keep plants healthy and attractive. Plants require 17 nutrients to metabolize or to complete their life cycle. These 17, known as essential nutrients, are extracted by plants from the air, the water, and the soil. Three of them—carbon (C), hydrogen (H), and oxygen (O)—are readily available from the atmosphere and water (California Plant Health Association, 2002). Another three—nitrogen (N), phosphorus (P), and potassium (K)—are known as primary nutrients and are the most commonly deficient. Plants need the secondary plant nutrients of calcium (Ca), magnesium (Mg), and sulfur (S) in the same amounts as N, P, and K. These secondary nutrients are less frequently deficient, particularly in California's soils. The remaining eight nutrients are required in small amounts. Referred to as micronutrients, they consist of zinc (Zn), iron (Fe), manganese (Mn), copper (Cu), boron (B), molybdenum (Mo), chlorine (Cl), and nickel (Ni). The roots and some leaves of plants take up these nutrients in the form of ions and in the form of simple molecules, excluding larger molecules, including nearly all organic molecules (Epstein and Bloom, 2004).

IX.D.2. Symptoms of Deficiencies

When plants are lacking in these 17 essential nutrients, they exhibit such visually apparent symptoms as discolored leaves, spotting, marginal leaf necrosis, and injured buds and leaves (Table IX.D.1.). Some symptoms may resemble another deficiency or disorder. For instance, symptoms of a deficiency in Mn closely resemble those of a deficiency in Fe, as well as symptoms of damage sustained from applying herbicides to the soil before weeds have emerged (Costello et al., 2003).

A symptom's location on the plant can be useful in figuring out the nutrients that are lacking. For example, deficiencies of the three most frequently limiting elements—i.e., N, P, and K—and deficiencies of magnesium and Mo first become noticeable on older leaves. Deficiencies in S, Fe, Mn, Zn, and Cu first become noticeable in young, newly emerging leaves. Deficiencies in B and Ca manifest themselves as dead buds and as the dieback of growing tips. It is important to corroborate the particular nutrient deficiency deemed to be the culprit by collecting and analyzing samples of leaf tissue and soil. The symptoms of some deficiencies in nutrients may appear similar to symptoms stemming from other causes, such as toxicity from boron or chloride or injury from ozone in the air.

IX.D.3. Nutrients Required by Landscape Plants

The nutrients required by plants in landscapes vary as widely as the number of types of plants found in landscapes. For example, turfgrasses require a large amount of N to promote vegetative growth, whereas many flowering plants require higher proportions of P and K. A proper balance of nutrients is desired for optimal plant performance. Inorganic and organic forms of fertilizer are available for nutrient-deficient soils. The rates and times to apply fertilizers may be obtained from local landscape horticulturists and testing laboratories. Excess fertilization with one nutrient can induce the deficiency of another nutrient. For instance, a heavy application of P may induce deficiencies in Fe, Zn, and Cu (Merhaut, 2001).

IX.D.4. Soil Analysis

Results from collecting samples of soil from the landscape and subjecting them to analysis in the laboratory can be used to determine the kinds and amounts of fertilizer that need to be added by indicating the existence of mineral deficiencies.

Coarse-textured (sandy) soils with relatively little soil organic matter are typically less fertile and require regular fertilization. Heavily graded landscapes without topsoil may also be nutrient deficient. The availability of nutrients varies with the pH of the soil.

The primary and secondary plant nutrients are generally readily available when the soil has a pH of 6 to 8. An exception is P, which is less available when its pH is alkaline due to complexation with calcium (California Plant Health Association, 2002). Fe, Mn, Zn, and Cu are also less available when the soil has an alkaline pH. Often deficiencies in micronutrients can be corrected by adjusting the pH of the soil.

Soil tests can be conducted at any time, but the best time is early spring. Such timing allows for corrective measures if analyses indicate that a nutrient deficiency may be likely to occur before the plant begins to grow. Though scant information exists regarding the fertility of soil required for specific ornamental plants, local extension advisors in ornamental horticulture can help interpret the results of tests.

Table IX.D.1. Symptoms of deficiency in plants ***(after California Plant Health Association, 2002; Costello et al., 2003; and Merhaut, 2001).***

Nutrient	Typical symptoms indicating deficiency of nutrient in plants
Nitrogen	Overall decrease in vigor in all plants, chlorosis (yellowing) especially in citrus and conifers, necrosis (death) of tips and margins of leaves, delayed blooming of flowering plants, uniform yellowing and senescence of older leaves to chlorotic canopy, stunted plants in severe cases
Phosphorus	Slow growth and stunted growth, purplish discoloration on older leaves of some plants, fewer flowers in flowering plants
Potassium	Slow growth, tip and marginal chlorosis, necrosis of older leaves, weak stem and stalks, dieback of tips of new growth, yellowish and reddish brown conifer leaves
Calcium	Death of growing tips, abnormal dark green appearance of foliage, premature shedding of blossoms and buds, leaf necrosis, death of meristem
Magnesium	Interveinal chlorosis of older leaves, curling of leaves upwards along margins, marginal yellowing, yellowing of palm leaves with midrib green, necrotic older leaves
Sulfur	Retarded growth, small and spindly plants, light green to yellowish young leaves, necrotic leaf tips
Zinc	Mottled, interveinal chlorosis, rosetting of terminal leaves, decreased stem growth, reduced fruit bud formation, stunted and chlorotic conifer needles, leaf drop
Iron	Interveinal chlorosis of young leaves, chlorosis of young leaves with green spots, twig dieback, stunted and chlorotic new conifer needles, caused by high-pH calcareous soils
Manganese	Interveinal chlorosis of young leaves with green bands along veins, gradual pale green leaf coloration, withered and scorched older leaves, frizzletop in palms
Copper	Stunted growth, dieback of terminal shoots in trees, wilting and eventual death of leaf tips, young leaves turn white in monocots
Boron	Death of terminal growth, thickened, curled, wilted and chlorotic leaves, reduced flowering, cracked roots
Molybdenum	Yellow spotting of citrus, marginal scorching, undergoing of chlorosis by older then younger leaves, rolling/cupping of leaves
Chlorine	Spotting of older leaves first, delayed maturity
Nickel	Chlorosis of young leaves, death of the meristem

IX.D.5. Plant Analysis

Collecting and analyzing samples of leaf tissue are often recommended in conjunction with collecting and analyzing samples of soil. This requirement is particularly critical for many species of trees and other woody plants with deep root systems. In these instances, it is difficult to sample the soil that fully represents the active root system where the plants absorb nutrients. Also, analyzing leaf tissue helps to more accurately gauge the amount of nutrient actually available to the plant. Again, it is recommended that local advisors in ornamental horticulture be consulted to interpret results from analyses.

IX.D.6. Nutrients in Recycled Water

Many recycled waters contain significant concentrations of nitrates and/or ammonia. A concentration of 20-mg/L nitrate as N contains 54.4 lbs. of N (20 mg/L × 2.72) in an acre-ft of water. A seasonal irrigation of 4 acre-ft/acre equals an application rate of about 218 lbs. of N/acre. Hence, the amount of nitrogen in recycled waters used to irrigate should be considered in fertilizing with N. Based on the assumption that NH_3-N will be eventually oxidized to NO_3-N, the conversion factor of NH_3-N to NO_3-N is 0.82. Plants can also take up NH_3-N usually in the form of NH_4 ions. In most analyses of water, the N species are reported as number of milligrams of N per liter (e.g., NH_3 as number of milligrams of N per liter) and so conversions are not needed if the total amount of N is of interest.

Another nutrient present in recycled waters is phosphorus (P), which occurs as inorganic (mainly as Ortho-PO_4) and organic species. Frequently, the total amount of P is reported. Unlike NH_4 and NO_3, inorganic phosphorus is immobile in soils because it is held tightly by particles of soil. Organic P may be mineralized by microbes similar to the mineralization of organic N but at much lower concentrations.

IX.E. Other Soil-Related Problems

Boron

Boron is an essential nutrient required especially at the early stages of the plant's growth. At slightly higher concentrations—more than about 0.3 mg/L in the irrigation water—boron can be toxic to boron-sensitive plants, especially ornamentals (Chapter V). Boron-tolerant plants may not be harmed at 2.0 mg/L or less. Boron is adsorbed by the oxide surfaces of particles of soil and is not readily leached and may accumulate to toxic levels in the root zone. Most recycled water in California contains less than 0.5 mg of boron/L. In rare cases, where the soil parent material contains boron minerals or hot springs contribute water to a wastewater treatment plant, higher concentrations may be observed. In such situations, control at the source would be the best remedy, as boron is not removed in wastewater treatment short of reverse osmosis.

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Chapter X. Diagnosing and Solving General and Plant-Specific Problems

K. Tanji, A. Harivandi, L. Wu, C. Grieve, B. Sheikh, S. Grattan, and D. Shaw

X.A. Challenges of Accurate Diagnosis
X.B. Diagnostic Checklist and Strategy
X.C. General Symptoms, Diagnoses, and Potential Solutions
X.D. Problems with Turfgrasses and Lawns
X.E. Problems with Trees and Shrubs
X.F. References

Salinity-related problems encountered in irrigating landscapes with recycled water should not be viewed in complete isolation, since associated causes may be contributing to these problems. The quality of recycled waters used to irrigate landscapes may have broader impacts on the plants, soils, and irrigation system (Chapter III). It can affect the performance of plants due to salinity (osmotic) and the toxic effects of specific ions (Chapter V). It can affect the salinity, sodicity, and permeability of the soil (Chapters IV and IX). It can also lead to small orifices in irrigation systems such as drip emitters and sprinkler heads becoming clogged with suspended matter and precipitated chemicals (Chapters III and VII).

This chapter gives an overview of diagnosing and solving problems that may arise when irrigating plants in landscapes with recycled water, drawing upon the contents of previous chapters of this literature review.

X.A. Challenges of Accurate Diagnosis

Costello et al. (2003) presents a highly informative approach to accurately diagnosing abiotic disorders of plants in landscapes and solving those problems. Dreistadt et al. (2004) presents a companion publication on appraising biotic problems—pests and diseases—of trees and shrubs. In this chapter, the primary focus will be on abiotic problems.

Some problems such as stunted growth, moderate to severe foliar injury, waterlogging and standing water, and plugging of drip systems are visually obvious. Other problems, such as inadequate plant performance caused by insufficient irrigation or an imbalance in mineral nutrition, are subtler and less easily discerned. A problem may be due to multiple causes, rendering accurate diagnosis more challenging (Costello et al. 2003). In any case, problems need to be addressed punctually and comprehensively to avoid high maintenance costs and sustain the quality of landscapes.

Accurately diagnosing problems depends on the following (Harris, 1983):

- observing subtle differences from the norm in the appearance of the plants or of the surrounding environment
- becoming well informed about the relevant plants, soil, climate, growing practices, pests, diseases, and their interactions
- obtaining accurate information about the recent history of affected plants, the site, the climate, and growing practices
- using a few simple tools to diagnose the problems
- analyzing the results from testing samples of plant tissue, soil, and water to diagnose certain problems.

A familiarity with what constitutes normal in the appearance and growth of plants and in the environmental setting is essential for accurately diagnosing problems. Inexperienced observers may think they have encountered a serious problem, when the supposed symptom may merely be a plant's normal feature, a seasonal change in its appearance, or the sign of a nonparasitic agent (Harris, 1983). Recognizing the appearance of healthy plants at different stages of growth and during different seasons is important to differentiate disorders from the norm. A change in the color of leaves may indicate nutrient deficiency or waterlogging. However, the leaves of some plants may normally change color. For example, the leaves of maturing conifers may change from green to yellow to brown before they drop and the new leaves of Chinese photinia (*Photinia serrulata*) may be copper or reddish before turning green with maturity.

Certain nonnative plants chosen for a landscape based on aesthetic appeal may be grown at the limit of their tolerance to the prevailing climate, soil, and water and require special growing practices to promote good performance. Several types of plants grown at the same site may have differing water and other requirements, unlike monoculture systems found in agriculture. Plants may be mechanically injured by high winds and infestations of insects, chemically injured by the drift of herbicide or excessive salt, and thermally injured by low temperature. Table X.A.1 includes abiotic and biotic causes of injury or disease to plants (Harris, 1983).

Table X.A.1. Abiotic and biotic causes of injury and disease in plants *(after Harris, 1983)*

Causes of injury		Causes of disease	
Abiotic	**Biotic**	**Abiotic**	**Biotic**
Salt	Insects	Mineral deficiencies and excesses	Bacteria
Air pollutants	Mammals	Salt	Fungi
Herbicides	Birds	Air pollutants	Nematodes
Moisture extremes		Moisture extremes	Viruses
Temperature extremes		Pesticides	Higher plants
Wind		Radiation	
Snow and ice			
Lightning			
Radiation			

The conditions of a landscape's site can significantly affect its vitality. If a site is located near buildings, then the soil is likely to be compacted and suffer from poor drainage. Such a site will need to be prepared before planting to promote the healthy growth of plants subsequently placed there. If a landscape has been graded to a moderate to severe extent, then topsoil will have been removed, which could lead to poor soil fertility, inadequate rooting depth due to shallow soil, and poor drainage. If a landscape has been established on a landfill with infertile fill soils obtained from construction sites, then the site needs to be adequately covered with topsoil of good quality to minimize problems with poor soil fertility. The soil should be sufficiently deep to minimize the upward movement of toxic gases from the buried landfill into the root zone of plants. If a landscape is established on a steep slope, then the soil there may be highly eroded by rainfall and irrigation without the establishment of ground cover or without the mulching of soil to prevent such erosion and promote adequate infiltration of water into the soil.

X.B. Diagnostic Checklist and Strategy

Harris (1983) provides a detailed diagnostic checklist for diagnosing problems with trees and woody shrubs by assessing conditions at the site—soils, plant species, cultural practices, weather, air quality, pests, and diseases—to ascertain the following: the number of plants affected; the species affected; the existence of a pattern related to space, if any; the occurrence of depressions, if any, indicating problems with frost and drainage; the amount of moisture in the soil; any unusual color to the soil; any unusual odor emanating from the soil; and, if there is one, any recent occurrence that might account for it, such as construction, paving, excavation, or soil filling and the location of gas, water, sewer, and septic fields. Harris (1983) delves into further detail about examining the various affected parts of trees and woody shrubs, such as leaves, shoots, dormant twigs, the trunk, the main branches, and the roots. He also recommends certain tools and equipment useful for diagnosis and explains how to collect samples of plants and soils to verify or disconfirm on-site diagnosis.

Costello et al. (2003) also outlines a similar step-by-step strategy for diagnosing problems with not only trees and woody shrubs but with other plants as well. They point out that a systematic approach provides a thorough, accurate diagnosis that could lead to corrective actions that are specific to the problem. The diagnostic steps that they recommend are as follows:

1. Identify the injured plant or plants. Determining the genus, the species, and, if appropriate, the cultivar is an essential first step. Such determination will provide an understanding of the plant's origin, characteristics of its growth, and its growing requirements. Identifying the plant's family may provide further useful information. If you are unable to identify the plant, ask a colleague. Or submit a sample of the plant to a local botanical garden, arboretum, nursery, or University of California Cooperative Extension office for identification. If you inaccurately identify a plant, you may misdiagnose a problem. What appears to be a disorder may be normal for the particular plant. Once the plant is accurately identified, refer to horticultural manuals for information regarding the specific plant's cultural requirements.

2. Identify symptoms. After examining the plant's injured part or parts, list all symptoms as thoroughly and accurately as possible. Look for discoloration, distortion, signs of chlorosis and necrosis, and abnormal size and development. For a description of common symptoms, see Tables X.C.1, X.C.2, and X.C.3 of this chapter.

3. Inspect the whole plant. If symptoms of injury are uniformly evident throughout, the cause is often found in the root zone, though there are some exceptions, such as anthracnose on leaves of London plane (*Platanus* × *acerifolia*). If symptoms are limited to certain areas, the cause is likely linked to the injured part or parts of the plant. Check for signs of delayed growth such as no new leaves or flowers; signs of infestation by insects such as droppings or cast skins; and signs of disease, such as foaming caused by bacteria.

4. Inspect the site. Search for conditions that may be contributing to injury. Evaluate the soil's physical and chemical properties, which may require a laboratory analysis of

samples. Try to identify all of the factors that may have contributed to the identified symptoms. Check the terrain for slopes; the soil for its drainage, textural layers, and compacted zones; irrigation of the area and its scheduling; the existence of wet or dry areas; exposure to wind, heat, and cold; limitations to the development of plants imposed by the infrastructure or nearby buildings, walkways, and such; and adjacent vegetation that could be contributing to injury by shading or by competing for water and minerals.

5. Look for patterns. Are symptoms evident throughout the plant, scattered, on one side only, or on old or young foliage? Is one plant affected, or are many? Is one species affected or several? Lack of soil oxygen due to overwatering, for example, is likely to affect all of the species in a landscape, whereas diseases are more likely to affect a single species or only species within one family. Do the symptoms form a pattern in the landscape that correlate to topography? Frost, for instance, may more adversely affect plants in low areas of the landscape where cold air accumulates.

6. Investigate the history of the landscape's management: contact a person knowledgeable about the site and its plants. Collect as much information as possible. Find out if any records of the landscape's installation and maintenance exist. Bear in mind that available information may not be comprehensive or, in some cases, such as when negligence contributed to injury, inaccurate. Obtain, if possible, such details as the following: the date when the site was planted; the size or age of the plants at the outset; any occurrence of previous problems and any similarity to current problems; the irrigation, fertilization, soil amendment, mulching, pruning, and pest management practices of the site; the site's source of water; the existence of any previous analyses of water quality; the use, if any, of plant growth regulators or other chemicals; the occurrence of construction in the area, if any; the use of deicing salts on adjacent walkways or roadways, if any; and any other changes that may affect the plants in the landscape.

7. Integrate all collected information. Once information about the plant and site has been gathered, thoroughly and comprehensively identify possible causes of the problem. Zero in on the most likely causes, listing reasons that support each diagnosis.

8. Test for likely causes. To arrive at an accurate diagnosis, samples of soil, water or tissue from the plant may need to be obtained and submitted to a horticultural or agricultural

Table X.C.1. Problem description, diagnosis, and potential solution: general aspects *(after California Plant Health Association, 2002; Harivandi et al., 1992; and Costello et al., 2003).*

Symptom or condition	Diagnosis	Potential solution
Plants showing signs of water stress, e.g., wilting	Insufficient irrigation	Increase duration and/or rate of irrigation to satisfy plant evapotranspiration
	Excessive soil salinity	Increase leaching fraction to leach out excessive soil salts
	Excessive water salinity	Replace plants with more salt-tolerant ones, blend with less saline water
Plants suffering foliar injury/damage	Plants sensitive to specific ions	Replace plants with more-tolerant plants, change from sprinkler to drip irrigation to prevent foliar wetting, reposition sprinkler heads to avoid spraying foliage
	Herbicide damage	Reduce and/or eliminate applications of herbicides and minimize drift
	High air temperature	Replace plants with more heat-tolerant plants
	Excessive exposure to sunlight	Replace shade-loving plants with more sunlight-tolerant plants
Presence of dry or wet areas	Poor uniformity of water application system	Improve uniformity with change in spacing of lateral lines and sprinkler heads, adjustments in water pressure
	Variability in soil texture and water holding capacity	Adjust sprinklers and nozzle heads, install separate lines
Excessive ponding, waterlogging	High sodium adsorption ratio and low electrical conductivity	Add Ca source like gypsum to water and/or soil to increase soil permeability
	High residual sodium carbonate (RSC)	Inject acid into irrigation water or add gypsum to soil to reduce RSC
	Soil compaction	Reduce machine traffic and tillage when soils are moist, use soil aerators
	Soil stratification	Deep tillage to break up stratified layers
Excessive soil runoff	Slow water penetration	Decrease irrigation application rate and/or duration
	Runoff on steep slopes	Improve infiltration rates with dense vegetation such as ground cover and mulching
Plugging of drip emitters and low volume sprinklers	Sediments	Install sand filtration system for drip irrigation
	Water chemistry (carbonate deposition)	Inject acids into water supply line to reduce calcium carbonate deposits
	Microbial slimes and iron precipitates	Inject biocides into water supply line to suppress microbial growth

laboratory for analysis. This task is particularly essential if nutrient deficiencies, specific ion toxicities, salts, or pH-related problems are suspected. With results in hand, create a list of likely causes. If an abiotic disorder is suspected, refer to such sources as Costello et al. (2003). If a disorder caused by an organism, such as an insect, fungus, or bacterium, is suspected, refer to such sources as Dreistadt et al. (2004). Check to see if the description of the problem in the reference corroborates your tentative diagnosis. If not, then the list of most likely causes will need to be reevaluated, perhaps with the help of specialists. According to Costello (2003), hallmarks of a good diagnostician include an educational background in plant biology and horticulture, field experience for a better understanding of the conditions of the site and growing practices, and experience with use of diagnostic techniques. Bear in mind that multiple causes may be involved. Or entirely new problems may arise that occurs more commonly with biotic disorders than with abiotic disorders. Some disorders cannot be remedied, which though unfortunate from a management perspective, at least precludes unnecessary, inappropriate, or ineffective actions.

X.C. General Symptoms, Diagnoses, and Potential Solutions

Table X.C.1 contains a summary of plant symptoms or other problems, diagnoses, and potential solutions generally applicable to plants in landscapes. Common plant symptoms cited include plants suffering water stress and foliar injury. Other related irrigation problems include the presence of wet or dry spots, excessive ponding and waterlogging, excessive soil runoff, and plugging of drip emitters and low-volume sprinklers. Potential solutions are suggested for each problem. The information can be used in conjunction with the diagnostic steps recommended by Costello et al. (2003) and Harris (1983). The module in the compact disk on “Solve a Problem Related to Plants, Water or Soil” contains numerous images accompanied with a text on symptoms, diagnosis, and recommended solutions.

X.D. Problems with Turfgrasses and Lawns

By far the largest amount of recycled water used in California’s south coast region goes to irrigate golf courses, sport fields and lawns in playgrounds, school yards, greenbelts, and industrial parks. Table X.C.2 contains a summary of problems with turfgrasses and lawns, as well as their potential causes and solutions. The first group of problems cited is related to salinity and to irrigation and drainage. The second group of problems cited is related to the mineral nutrition of turfgrasses and lawns.

X.E. Problems with Trees and Shrubs

After turfgrasses and lawns, trees on golf fairways, in playgrounds, school yards, industrial parks, and roadways are the biggest recipients of recycled irrigation water. Trees and woody shrubs in landscapes adjacent to buildings, roadways, walkways, greenbelts, and the like are also

Table X.C.2. Problem description, diagnosis and potential solution: turfgrasses and lawns *(after Beard, 2002; Merhaut, 2001; Harivandi, 2002; and Harivandi et al., 1992).*

Symptom or condition	Diagnosis	Potential solution
Tip burning, bluish-green leaves	Excess salinity in water and/or soil	Increase leaching fraction and/or replace with more salt-tolerant turf, blend with less saline water
Extensive vegetative desiccation	Insufficient irrigation	Increase duration and/or rate of water application
Localized dry and wet spots	Nonuniform irrigation patterns	Improve uniformity of application
	Surface soil compaction	Carry out soil core aeration, add organic matter such as compost
	Subsoil impermeable layers	Improve drainage with installation of subsurface drainage
	Water-repellent sand-based turf	Add wetting agents and clay colloids like zeolites
Difficulties in seed germination and early seedling growth	Excessive salinity in water and/or soils	Select and plant more salt-tolerant turf, blend saline water with less saline water or conduct reclamation leaching before seeding
Spotty bare spots with salt crust	Excessive salinity in soils	Conduct localized leaching to remove salts
Spotty bare spots with no salt crust	Excessive sodicity in soils	Add calcium amendments like gypsum to soil and/or water
Bare spots with dispersed organic matter	Excessive RSC in water	Inject acids to source water, add calcium amendment to soil or water
Uniform yellowing and senescence of older leaves	Nitrogen deficiency	Apply N fertilizers, improve drainage, aerate to relieve compaction
Uniform chlorosis of younger and older leaves, leaf tips necrotic, stunted growth	Sulfur deficiency	Rare but resembles N deficiency symptoms. Apply S-containing fertilizer.
Yellowing of younger leaves and new leaves white or necrotic in severe cases	Iron deficiency	Add acid-forming materials to calcareous soils, apply iron chelate or other iron fertilizers
Dark green discoloration of older leaves	Phosphorus deficiency	Apply P fertilizer appropriately broadcasting or by injection into water supply; P will tend to precipitate in calcareous soils and high-bicarbonate waters
Drooping of leaves, chlorosis, and leaf rolling	Potassium deficiency	Broadcast K fertilizer, incorporate in ground as much as possible
New leaves chlorotic, deformed, and stunted or necrotic	Calcium deficiency	Rare in alkaline and neutral soils
Interveinal chlorosis of older leaves or necrosis of older leaves	Magnesium deficiency	Rare in alkaline and neutral soils

irrigated with recycled waters. Presented in Table X.C.3 is a summary of problems with trees and woody shrubs, as well as their potential causes and solutions. The first group of problems cited is related to salinity, specific ions, and irrigation and drainage. The second group of problems cited is related to the mineral nutrition of trees and woody shrubs.

Table X.C.3. Problem description, diagnosis and potential solution: trees and shrubs *(after Costello et al., 2003; Dreistadt et al., 2004; Harris, 1983; and Harris et al., 2004).*

Symptom or condition	Diagnosis	Potential solution
Stunted growth, chlorosis, leaf tip burn, marginal burn, defoliation, death	Excess salinity in soil and/or water	Leach soil, increase leaching fraction, select more salt-tolerant plants, correct drainage problem, blend with less saline water
Stunted growth, chlorosis, necrosis, black salt crust on soil surface, water ponding	Excess sodicity in soil and/or water	Add gypsum, acid or acid-forming materials to soil or water, and leach
Stunted growth, chlorosis, necrosis, white salt crust on soil surface	Excess salts and sodicity	Leach salts, add gypsum, acid, or acid-forming materials
Stunted growth, necrosis of leaf tips and margins, bronzing, leaf drop	Excess chloride in water and/or soil	Leach or increase leaching fraction, correct drainage problem, reduce foliar wetting, select more chloride-tolerant plants
Yellowing of leaf tip, necrosis of leaf margins and between veins	Excess boron in water and/or soil	Avoid foliar wetting, leach soil, select boron-tolerant plants
Mottled and interveinal chlorosis leaves, burning of growing tips	Excess sodium in water and/or soil	Avoid foliar wetting, leach soils, plant more sodium-tolerant plants, inject acid into water, apply gypsum to soil
Yellowing foliage and leaf drop, damage to buds, limbs and shoots, root crown diseases	Excess irrigation and/or poor drainage	Decrease irrigation, improve drainage and aeration
Excessive growth and succulent tissue, dark green foliar margins	Excess N fertilization	Decrease N fertilization
Uniform yellowing of leaves, light green coloring, yellowish and short needles in conifers	Nitrogen deficiency	Apply N fertilizer; nutrient deficiency in woody plants is usually not caused by deficiency of soil nutrients except for container plants. Sometimes N deficiency confused with symptoms caused by restricted root growth
Bronzing of lower leaves with purple or brown spots, dieback of needles in conifers	Phosphorus deficiency	Add P fertilizer. P deficiency in woody plants is normally rare; symptoms may look like herbicide damage
Leaf spotting and sparse leaf growth, older leaves yellow, marginal necrosis along leaflets, necrosis at needle tips in conifers	Potassium deficiency	Apply K fertilizer, K deficiency is rare among conifers and broadleaf species but occurs in palms and fruit and nut trees; P deficiency may resemble leaf spot damage from sucking insects and certain pre-emergence herbicides
New foliage yellowish and undersized with green veins, causes curling and burning in palms, stunted and chlorotic needle tips in conifers	Iron and/or manganese deficiency	Noted especially in acid-loving plants grown in calcareous soils; reduce the soil pH with acidic amendments; apply iron chelate and improve drainage and aeration
Uniformly yellow and stunted new growth may turn purplish and die, small leaves, branches and needles extremely stunted, and die back of terminals in conifers	Zinc deficiency	Apply zinc chelates or zinc sulfate; may be confused with systemic herbicide (glyphosate) damage
Yellowing of leaves, premature leaf drop, wilting, stunted growth	Poor aeration or soil aeration deficit	Improve drainage, reduce excess irrigation, conduct appropriate site preparation before planting
Dieback of youngest foliage, damage to lower leaves and canopy dieback, dieback of limbs. Rapid onset of foliar symptoms	Low-temperature injury	Select more cold-tolerant trees and shrubs. Protect sensitive plants during periods of low temperature
Leaf discoloration and necrosis, damage to bark and trunk	Sunburn or scalding damage	Select more tolerant plants, shade plants, irrigate adequately
Trees appears to be under water deficit, leaf necrosis and leaf drop, tattering of leaves, fewer leaves on windward side	Wind damage	Select wind-tolerant species, provide windbreaks
Leaves or needles turn yellow to brown, foliage dieback, stippling or specking of leaves	Air pollution injury	Select trees more tolerant to ozone, sulfur dioxide, etc.

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Appendix. Acronyms and Abbreviations

ac = Acre

ac-ft = Acre-feet

AR = Application rate

B = Boron

Ca = Calcium

$CaCO_3$ = Calcium carbonate

$CaSO_4•2H_2O$ = Gypsum

CIMIS = California Irrigation Management Information System

Cl = Chloride

Cl_2 = Molecular chlorine

CO_3 = Carbonate

Cu = Copper

D_{dw} = Surface depth of drainage water

D_{et} = Surface depth of evapotranspiration

D_{eto} = Surface depth of reference evapotranspiration

D_{iw} = Surface depth of irrigation water

DS = Dissolved solids (same as TDS)

dS/m = Decisiemens per meter

DU = Distribution uniformity

EC = Electrical conductivity, specific conductance

EC_a = Plant-specific threshold soil salinity in electrical conductivity

EC_{dw} = Electrical conductivity of drainage water

EC_e = Electrical conductivity of extract of saturated soil paste

EC_{iw} = Electrical conductivity of irrigation water

EC_{rw} = Electrical conductivity of rainwater

EC_{sw} = Electrical conductivity of soil water at field capacity soil moisture

EC_w = Electrical conductivity of water

ECF = Evapoconcentration factor

ESP = Exchangeable sodium percentage of soil cation exchange capacity

ET = Evapotranspiration

ET_c = Crop (plant) evapotranspiration

ET_o = Reference evapotranspiration

FAO = Food and Agriculture Organization of the United Nations

Fe = Iron

HCO_3 = Bicarbonate

IE = Irrigation efficiency

K = Potassium

K_c = Crop coefficient

K_d = Plant density coefficient

K_L = Landscape coefficient

K_{mc} = Plant microclimate coefficient

K_s = Species coefficient

LF = Leaching fraction

LR = Leaching requirement

meq/L = Milliequivalents per liter

Mg = Magnesium

mg/L = Milligrams per liter

mmol/L = Millimoles per liter

Mn = Manganese

mS/cm = Millisiemens per centimeter

N = Nitrogen

Na = Sodium

NH_3 = Ammonia

NH_4 = Ammonium

NO_3 = Nitrate

P = Phosphorus

PAM = Polyacrylamide

pH_s = pH of saturated soil paste

PO_4 = Phosphate

ppb = Parts per billion

ppm = Parts per million

RSC = Residual sodium carbonate

S = Sulfur

SAR = Sodium adsorption ratio

SAR_{adj} = Adjusted sodium adsorption ratio

SO_4 = Sulfate

TDS = Total dissolved solids

WATSUIT = Water Suitability Determination Model

Zn = Zinc

Appendix. Conversion Factors

Table of conversion factors for SI and non-SI units

To convert Column 1 into Column 2, multiply by	Column 1 SI unit	Column 2 Non-SI unit	To convert Column 2 into Column 1, multiply by
	Length		
0.621	kilometer, km	mile, mi	1.609
3.28	meter, m	foot, ft	0.305
0.00394	millimeter, mm	inch, in.	25.4
0.394	centimeter, cm	inch, in.	2.54
	Area		
2.47	hectare, ha	acre, ac	0.405
247	sq. kilometer, km^2	acre, ac	0.00405
0.000247	sq. meter, m^2	acre, ac	4,047
10.76	sq. meter, m^2	sq. foot, ft^2	0.0929
	Volume		
0.00973	cubic meter, m^3	acre-inch, ac-in.	102.8
0.00081	cubic meter, m^3	acre-foot, ac-ft	1,234
0.81	cubic kilometer, km^3	millions of acre-feet, maf	1.234
0.265	liter, L	gallon, gal	3.785
	Mass		
0.0022	gram, g	pound, lb.	454
0.0011	kilogram, kg	ton (U.S.), ton	907
2.205	kilogram, kg	pound, lb.	0.454
1.102	ton, t	ton (U.S.), ton	0.907
	Yield		
0.893	kg/ha	pounds per acre, lb/ac	1.12
893	tonne/ha	pounds per acre, lb/ac	0.00112
	tonne/ha	U.S. tons per acre, ton/ac	
	Rate		
264×10^{-6}	m^3/day	millions of gallons per day, mgd	3,785
0.107	L/ha	gallons per acre, gal/ac	9.35
2.24	m/s	miles per hour, mi/h	0.447
	Pressure		
9.9	megapascal, MPa	atmosphere, atm	0.101
10	megapascal, MPa	bar	0.1
0.0209	pascal, Pa	pounds per sq. foot, lb./ft^2	47.9
0.000145	pascal, Pa	pounds per sq. inch, psi	6,900
0.00987	kilopascal, kPa	atmosphere, atm	101.3

To convert Column 1 into Column 2, multiply by	Column 1 SI unit	Column 2 Non-SI unit	To convert Column 2 into Column 1, multiply by
	Electrical conductivity		
10	siemen/m, S/m	millimho/cm, mmho/cm	0.1
1	decisiemen/m, dS/m	millimho/cm, mmho/cm	1
0.001	decisiemen/m, dS/m	micromho/cm, umho/cm	1,000
1	millisiemen/cm, mS/cm	micromho/cm, umho/cm	1
	Water measurement		
0.00973	m^3	ac-in.	102.8
0.00981	m^3/h	cfs	101.9
35.59	m^3/s	cfs	0.028
4.4	m^3/h	gal/min	0.227
8.11	ha-m	ac-ft	0.1233
0.00081	m^3	ac-ft	1234
97.28	ha-m	ac-in	0.0103
0.0821	ha-cm	ac-ft	12.33
0.000328	m^3/ha	ac-ft/ac	3,047
3.279	m^3/m^2	ac-ft/ac	0.305
0.264	L/min	gpm	3.788
	Concentration		
1	centimole/kg	meq/100 g	1
0.1	g/kg	%	10
1	mg/kg	ppm (weight basis)	1
1	mg/L	ppm (volume basis)	1
1	µg/kg	ppb (weight basis)	1
1	µg/L	ppb (volume basis)	1
0.1335	g/L	oz/gal	7.489
0.00835	g/L	lb./gal	119.8

Table for Chemical Conversion Units

To convert Column 1 into Column 2, multiply by	Column 1 Milligrams/liter	Column 2 Milliequivalents/liter	To convert Column 2 into Column 1, multiply by
0.0499	mg/L Ca	meq/L Ca	20.04
0.0823	mg/L Mg	meq/L Mg	12.15
0.0435	mg/L Na	meq/L Na	22.99
0.0256	mg/L K	meq/L K	39.1
0.0164	mg/L HCO_3	meq/L HCO_3	61.02
0.033	mg/L CO_3	meq/L CO_3	30
0.0282	mg/L Cl	meq/L Cl	35.45
0.0208	mg/L SO_4	meq/L SO_4	48.03
0.0161	mg/L NO_3	meq/L NO_3	62
0.0554	mg/L NH_4	meq/L NH_4	18.04

To convert Column 1 into Column 2, multiply by	Column 1 Milligrams/liter	Column 2 Millimoles/liter	To convert Column 2 into Column 1, multiply by
0.025	mg/L Ca	mmol/L Ca	40.08
0.0411	mg/L Mg	mmol/L Mg	24.31
0.0435	mg/L Na	mmol/L Na	22.99
0.0256	mg/L K	mmol/L K	39.1
0.0164	mg/L HCO_3	mmol/L HCO_3	61.02
0.0167	mg/L CO_3	mmol/L CO_3	60
0.0282	mg/L Cl	mmol/L Cl	35.45
0.0104	mg/L SO_4	mmol/L SO_4	97.06
0.0161	mg/L NO_3	mmol/L NO_3	62.01
0.0554	mg/L NH_4	mmol/L NH_4	18.04

Other Useful Conversions

mg/L TDS = EC dS/m × 640
mg/L TDS = EC dS/m × 735 (preferred for Colorado River water)
mg/L TDS = EC dS/m × 800 (for saline waters)
lbs/ac-ft TDS = mg/L TDS × 2.72
tons/ac-ft TDS = mg/L TDS × 0.00136

atm osmotic pressure = EC dS/m × 0.36

1 ac = 43,560 sq. ft
1 mi = 5,280 ft

1 ac-ft soil = 4 million lbs. (approx.)
1 ton/ac = 20.8 g/sq. ft
1 g/sq. ft = 96 lbs./ac
1 lb./ac = 0.0104 g/sq. ft

1 cu. ft = 7.48 gals
1 gal = 8.345 lbs.
1 cfs = 448.8 gpm
1 cfs/24 h = 1.98 ac-ft
1 mgd = 3.07 ac-ft/24 h
1 mgd = 1.547 cu ft/s
1 mgd = 694.4 gpm
1 ac-ft = 325,851 gals

1 atm = 14.7 psi
1 psi = 14.22 kg/sq. cm
1 bar = 14.5 psi
1 bar = 1,023 cm of water

Table for Soil Water

Soil texture	Field capacity or water holding capacity (inches of water per ft of soil)	Available soil moisture (inches of water per ft of soil)
Sand	1.2	0.7
Loamy sand	1.9	1.1
Sandy loam	2.5	1.4
Loam	3.2	1.8
Silt loam	3.6	1.8
Sandy clay loam	3.5	1.3
Sandy clay	3.4	1.6
Clay loam	3.8	1.7
Silty clay loam	4.3	1.9
Silty clay	4.8	2.4
Clay	4.8	2.2

Appendix. Glossary

Abiotic. Pertaining to processes that involve physical or chemical mechanisms not influenced by living organisms; nonliving.

Abiotic disorder. A disease caused by factors other than a pathogen such as adverse nevironmental conditions or inappropriate cultural practices.

Abscission. The dropping off of a leaf, fruit, or flower.

Acid soil. Soil for which the pH is less than 7.0.

Acidic. Having a high concentration of hydrogen ions; pH less than 7.0.

Acre-foot. Amount of water that would cover 1 acre to a depth of 1 ft; equivalent to 43,560 cu. ft or 325,851 gal (1 acre-ft of water is considered enough water to meet the needs of two families of four for a year).

Action level. The level of a contaminant in drinking water that is considered not to pose a significant health risk to people ingesting that water on a daily basis. Action levels (ALs) are health-based advisory levels established by DHS for chemicals in drinking water that lack maximum contaminant levels (MCLs).

Activated sludge process. A treatment process that removes (by biological assimilation and decomposition) organic matter from wastewater by using a biological floc in an aerobic environment.

Adsorption. The combination of physical and chemical processes by which atoms, molecules, or ions bind to the surfaces of solids.

Adsorption complex. Collection of various organic and inorganic substances in soil that are capable of adsorbing ions and molecules.

Advanced wastewater treatment. Additional treatment provided to remove suspended and dissolved substances after conventional secondary treatment. Often this term is used to mean additional treatment after tertiary filtration and disinfection treatment for the purpose of further removing contaminants of public health or other water quality concern. This process may include membrane filtration and advanced oxidation.

Aerobic. Occurring in the presence of molecular oxygen, as in certain chemical or biochemical processes (for example, aerobic respiration).

Aggregation. The process whereby primary soil particles (sand, silt, and clay) are bound together, usually by natural forces and substances derived from root exudates and microbial activity.

Agricultural drainage. (1) The process of directing excess water away from root zones by natural or artificial means, such as by using a system of drains placed below ground surface level; also called subsurface drainage. (2) The water drained away from irrigated farmland.

Agronomy. The theory and practice of crop production and soil management.

Alkali soil. Soil in which sodium is the primary cation and is present in large enough quantities to adversely affect plant growth; a soil with a pH of 8.5 or higher and with exchangeable sodium percentage greater than 15%; now called sodic soil.

Alkaline. Having a high concentration of hydroxyl ions (OH^-); pH greater than 7.0.

Alkaline soil. Soil for which the pH exceeds 7.

Alkalinity. The capacity of water to neutralize acids, a property resulting from the presence of carbonates, bicarbonates, hydroxides, and occasionally of borates, silicates, and phosphates. Expressed in milligrams of equivalent calcium carbonate per liter.

Allowable depletion. That part of soil water stored in the plant root zone managed for use by plants, usually expressed as equivalent depth of water in inches (acre-inches per acre, or inches).

Amendment. Any material such as gypsum, fertilizer, and soil conditioners added to water and soils to improve soil properties.

Ammonia. A form of nitrogen gas, highly soluble in water and extremely toxic to aquatic organisms. At alkaline pH values, ammonia exists as ammonium ion in waters.

Ammonium. An inorganic ion formed from the microbial oxidation of organic nitrogen. This cation may be adsorbed to soil exchange complex.

Anaerobic. Occurring in the absence of molecular oxygen, as in certain biochemical processes.

Angiosperm. A plant that produces seeds inside an enlarged ovary, which at maturity is called a fruit (synonymous with the term flowering plant.)

Anions. Negatively charged ions such as chloride, sulfate, bicarbonate, carbonate, and nitrate.

Annual. A plant that germinates, flowers, fruits, and dies within a year.

Anoxia. The condition of being without oxygen or of receiving a reduced supply of oxygen (e.g., tissues within a plant).

Anoxic environment. An environment without oxygen.

Apical meristem. The tissues at the tip of roots and shoots where cells divide, giving rise to new growth.

Application efficiency (E_a). The ratio of the average depth of irrigation water infiltrated and stored in the root zone to the average depth of irrigation water applied, expressed as a percentage.

Application rate. Rate that water is applied to a given area. Usually expressed in units of depth per time such as inches per hour.

Aquifer. A geologic formation that holds and yields useable amounts of water. Aquifers can be classified as confined or unconfined.

Arid. A term describing a climate or region in which precipitation is so deficient in quantity or occurs so infrequently that intensive agricultural production is not possible without irrigation.

Artificial recharge. (1) The addition of surface water to a groundwater reservoir by human activity, such as putting surface water into a spreading basin. (2) The designed (as per human activities as opposed to the natural or incidental) replenishment of groundwater storage from surface water supplies such as irrigation or induced infiltration from streams or wells.

Available soil water. (See **available water capacity**.)

Available water. The portion of water in a soil that can be readily absorbed by plant roots. Considered by most workers to be that water held in the soil against a pressure of up to approximately 15 bars.

Available water capacity (AWC). The portion of soil water that can be readily absorbed by plant roots of most crops, expressed in millimeters of water per millimeter of soil (inches per inch, inches per foot, or total inches) for a specific soil depth. It is the amount of water stored in the soil between field capacity (FC) and permanent wilting point (WP). It is typically adjusted for salinity (electrical conductivity) and rock fragment content. Also called available water holding capacity (AWHC) or available soil water.

Average annual precipitation. The long-term or historic arithmetic mean of annual precipitation (rain, snow, and dew) received by an area.

Average daily use rate. Calculated or measured water used by plants in 1 day through evapotranspiration, expressed as an equivalent depth in millimeters per day (inches per day).

Backflow. (1) The backing up of water through a conduit or channel in the direction opposite to normal flow. (2) The undesirable flow of water from a plumbing system back into the community potable water supply. (3) A reverse flow condition created by a difference in water pressures that causes water to flow back into the distribution pipes of a drinking water supply from any source other than the intended one. Backflow prevention assemblies prevent contamination and are required by city and state laws. Also referred to as back siphonage.

Bacteria (singular: bacterium). (1) Microscopic one-celled organisms, which live everywhere and perform a variety of functions. While decomposing organic matter in water, bacteria can greatly reduce the amount of oxygen in the water. They also can make water unsafe to drink. (2) Microscopic unicellular organisms, typically spherical, rodlike, or spiral and threadlike in shape, often clumped into colonies. Some bacteria cause disease, while others perform an essential role in nature in the recycling of materials, for example, decomposing organic matter into a form available for reuse by plants. Some forms of bacteria are used to stabilize organic wastes in wastewater treatment plants, oil spills, or other pollutants. Disease-causing forms of bacteria are termed "pathogenic."

Bacterium (plural: bacteria). A microscopic, single-celled organism that does not produce chlorophyll. Most bacteria obtain nitrogen and energy from organic matter. Some bacteria cause plant and animal diseases.

Bare-root plant. A plant grown in the open ground and then lifted, without soil around its roots, for replanting elsewhere.

Basic intake rate. Rate at which water percolates into soil after infiltration has decreased to a low and nearly constant value.

Beneficial use (of water). A use of water resulting in appreciable gain or benefit to the user, consistent with state law, which varies from one state to another. In California, beneficial uses of waters of the state that may be protected against quality degradation include, but are not necessarily limited to, "domestic, municipal, agricultural and industrial supply; power generation; recreation; aesthetic enjoyment; navigation; and preservation and enhancement of fish, wildlife, and other aquatic resources or preserves." (Water Code, Section 13050(f)).

Best management practices (BMP). (1) A generally accepted practice for some aspect of natural resources management to protect or achieve the best use of the resources, such as water conservation measures, drainage management measures, or erosion control measures. Typically incorporates conservation criteria. (2) A set of field activities that provide the most effective means for reducing pollution from a nonpoint source.

Biochemical oxygen demand (BOD). (1) A measure of the quantity of dissolved oxygen, in milligrams per liter, necessary for the decomposition of organic matter by microorganisms, such as bacteria. (2) A measure of the amount of oxygen removed from aquatic environments by aerobic microorganisms for their metabolic requirements. Measurement of BOD is used to determine the level of organic pollution of a stream or lake. The greater the BOD, the greater the degree of water pollution. Also referred to as biological oxygen demand.

Biodegradation. The metabolic breakdown of materials into simpler components by living organisms. A more specific form of biotransformation.

Biofouling. The gradual accumulation of waterborne organisms (as bacteria and protozoa) on the surfaces of engineering structures in water that contributes to corrosion of the structures and to a decrease in the efficiency of moving parts. Biofouling contributes also to the clogging of membranes and filters.

Biogas. Methane gas produced during the anaerobic decomposition of the remains of plants or animal wastes by bacteria.

Biological oxidation. Decomposition of complex organic materials by microorganisms. Occurs in the self-purification of water bodies and in activated sludge wastewater treatment processes.

Biological wastewater treatment. The use of bacteria to degrade and decompose organic materials in wastewater.

Biosolids. A nutrient-rich organic material that is a by-product or waste resulting from the treatment of wastewater. Biosolids contain nitrogen and phosphorus along with other supplementary nutrients in smaller doses, such as potassium, sulfur, magnesium, calcium, copper, and zinc. Soil that is lacking in these substances can be reclaimed with biosolid use. The application of biosolids to land improves soil properties and plant productivity and reduces dependence on inorganic fertilizers. The terms biosolids, sludge, and wastewater sludge can be used interchangeably.

Biotic. Pertaining to living organisms; alive.

Black alkali soil. A soil with a pH of 8.5 or higher or with an exchangeable sodium percentage greater than 15%. Dissolved organic matter may be deposited on the soil surface as soil water evaporates (now known as sodic soil).

Blackwater. Water that contains animal, human, or food wastes; wastewater from toilet, latrine, and agua privy flushing and sinks used for food preparation. Compare to **graywater**.

Blade. The flat, expanded portion of a leaf or petal.

Blending. The mixing or combination of one water source with another, typically a finished source of water with raw water to reuse water while still satisfying water quality standards, for example, mixing of product water from a desalting plant with conventional water to obtain a desired dissolved-solid content or mixing brine effluents with wastewater treatment plant effluents in order to reduce evaporation pond size.

BOD. See **biochemical oxygen demand (biological oxygen demand)**.

BOD_5. The amount of dissolved oxygen consumed in 5 days by biological processes breaking down organic matter. This is the common standard of measurement of BOD. Also see **biochemical oxygen demand (BOD)**.

Brackish water. Water containing dissolved minerals in amounts that exceed normally acceptable standards for municipal, domestic, and irrigation uses but that are less than the amounts found in seawater. Typically, water containing from 1,000 to 10,000 mg of dissolved solids/L.

Bubbler irrigation. The application of water to flood the soil surface using a small stream or fountain. The discharge rates for point-source bubbler emitters are greater than for drip or subsurface emitters but are generally less than 225 L/h (1 gpm). A small basin is usually required to contain or control the water.

Bulb. In horticulture, the term “bulb” is used for plants that produce their leaves and flowers directly from an underground storage organ.

Bulk density. The mass of dry soil per unit volume, expressed as grams per cubic centimeter.

Calcareous soil. Soil containing sufficient free $CaCO_3$ to effervesce visibly when treated with cold 0.1 M hydrochloric acid.

Calcium ion. A positively charged inorganic ion that contributes to the hardness of water; forms calcite ($CaCO_3$) and gypsum ($CaSO_4{\cdot}2H_2O$).

Carbon filtration. The passage of treated wastewater or domestic water supplies through activated charcoal to remove low concentrations of dissolved chemicals.

Cations. Positively charged ions such as calcium, sodium, magnesium, potassium, and hydrogen**.**

Cation exchange capacity (CEC). The sum of exchangeable cations (usually Ca, Mg, K, Na, Al, and H) that negatively charged soil constituents (clay and organic matter) can adsorb at a specific pH, usually expressed in centimoles of charge per kilogram of soil ($cmol_c$/kg), millimoles per charge per kilogram ($mmol_c$/kilogram), or milliequivalents per 100 g of soil at neutrality (pH = 7.0) (meq/100 g).

Centrifugal pump. Pump consisting of rotating vanes (impeller) enclosed in a housing and used to impart energy to a fluid through centrifugal force.

cfs (cubic feet per second). A unit of measurement of flowing liquid equal to a rate of 1 cu. ft/s past a given section. A rate of flow equivalent to 448.83 gal/min. Also called second-foot. Also written as C.F.S. and cfs.

Chaparral. Low-growing, woody vegetation composed of rigidly branched shrubs that have small, hard leaves and extensive roots. Plant cover is nearly 100%, and leaf area index is twice that of desert scrub. The shrubs within chaparral typically are 1 to 3 m in height.

Check valve. A type of backflow preventer.

Chelates. Certain organic chemicals known as chelating agents forming ring compounds with a metal ion like iron such as EDTA (ethylenediaminetetraacetic acid).

Chemical oxygen demand (COD). (1) A measure of the chemically oxidizable material in water, which provides an approximation of the amount of organic and inorganic oxygen reducing material present. The determined value may correlate with **biochemical oxygen demand** (BOD) or with carbonaceous organic pollution from wastewater or industrial wastes. Nonbiodegradable and recalcitrant (slowly degrading) compounds, which are not detected by the test for BOD, are included in this measurement.

Chemical weathering. The breakdown of rocks and minerals due to the presence of water and other components in the soil solution.

Chemigation. Application of chemicals to plants through an irrigation system by mixing them with the irrigation water.

Chlorination. The application of chlorine or one of its compounds to water or wastewater, often for disinfection or oxidation purposes.

Chlorine residual. The concentration of chlorine remaining in water or wastewater at the end of a specified contact period that will react chemically and biologically. May be present as either combined or free chlorine or both.

Chlorophyll. The green plant pigments that absorb light energy in the process of photosynthesis.

Chlorosis. Yellowing of green portions of a plant, particularly between the leaves.

Christiansen's uniformity coefficient. A measure of the uniformity of irrigation water application. The average depth of irrigation water infiltrated minus the average absolute deviation from this depth, all divided by the average depth infiltrated.

Clarification. A process or combination of processes where the primary purpose is to reduce the concentration of suspended matter in a liquid.

Clarifier. A device or tank in which wastewater is held to allow the settling of particulate matter.

Coagulant. (1) An agent that causes a liquid or solid to coagulate. (2) A chemical compound, such as Alum (aluminum sulfate), used to produce coagulation.

Coagulation. The process of destabilization and initial aggregation of colloidal and finely divided suspended matter by the addition of a floc-forming chemical (coagulant) or by biological processes.

Coliform (bacteria). (1) A group of bacteria (*Colon bacilli*) predominantly inhabiting the intestines of humans or animals but also found in soil. While typically harmless themselves, coliform bacteria are commonly used as indicators of the possible presence of pathogenic organisms or fecal material. Generally reported as bacterial colonies per 100 mL of sample.

Coliform count. Number of coliforms present in a sample of water (usually reported per 100 mL).

Coliform index. An index of the bacteriological quality of water, based on a count of the numbers of coliform bacteria.

Coliforms. Bacteria that colonize the gastrointestinal tracts of mammals and are present in fecal material, among other sources. Coliforms are used as indicator organisms in testing water for microbial contamination.

Collector sewers. Pipes used to collect and carry wastewater from individual sources to an interceptor sewer that will carry it to a treatment facility.

Community. (1) Public at large including, but not limited to, local ethnic groups, political or social or economic groups, environmental justice advocates, and environmentalists. (2) A group of plants and animals that often occurs together within a particular habitat. The group can be described by the presence of one or more characteristic species.

Community water system. Water treatment and conveyance facility that serves at least 25 residents year-round or has at least 15 water connections.

Compensating emitter. Microirrigation system emitters designed to discharge water at a near-constant rate over a wide range of pressures.

Competition. Occurs when plants vie for available light, water, or nutrients.

Complete fertilizer. A fertilizer containing nitrogen, potassium, and phosphate.

Composite sample. A representative water or wastewater sample made up of individual smaller samples taken at periodic intervals.

Conifers. Trees that bear cones. Leaves of conifers are usually needle-like or scale-like, with parallel veins, and most conifers are evergreen.

Consumptive use. The total amount of water taken up by vegetation for transpiration or building of plant tissue, plus the unavoidable evaporation of soil moisture, snow, and intercepted precipitation associated with vegetal growth. Synonymous with **evapotranspiration**.

Constituents. Any of the chemical substances found in water. Typically, measurements of such constituents in sampled drinking water may consist of **total dissolved solids** (TDS), hardness (concentrations of calcium and magnesium, specifically), sodium, potassium, sulfate, chloride, nitrate, alkalinity, bicarbonate, carbonate, fluoride, arsenic, iron, manganese, copper, zinc, barium, boron, and silica.

Contact recreation (water). Recreational activities involving a significant risk of ingestion of water, including wading by children, swimming, water skiing, diving, and surfing.

Contaminant. (1) In a broad sense, any physical, chemical, biological, or radiological substance or matter in the environment. (2) In more restricted usage, a substance in water of public health or welfare concern. Also, an undesirable substance not normally present or an usually high concentration of a naturally occurring substance in water, soil, or other environmental medium.

Contamination (water). Impairment of the quality of water sources by wastewater, industrial waste, or other matters to a degree that creates a hazard to public health. Also, the degradation of the natural quality of water as a result of human activities. There is no implication of any specific limits because the degree of permissible contamination depends upon the intended end use, or uses, of the water.

Continuous flushing emitter. Microirrigation system emitter designed to continuously permit passage of large solid particles while operating at a trickle or drip flow, thus reducing filtration requirements.

Controlled reuse. The use of recycled water under legal and physical control or restraint even though the recycled water may be comingled with water in a natural water body.

Conventional wastewater treatment. Well-established wastewater treatment processes typically consisting of primary and secondary treatment and excluding advanced or tertiary treatment.

Cool-season turfgrass. Turfgrass species adapted to favorable growth during cool portions of the growing season; may become dormant or injured in hot weather.

Cooling water. Water used for cooling purposes by electric generators, steam condensers, large machinery or products at industrial plants, and nuclear reactors. Water used for cooling purposes can be fresh, recycled, or saline water and may be used only once or recirculated multiple times.

Crop coefficient (K_c). The ratio of the crop evapotranspiration (ET_c) to its reference crop evapotranspiration (ET_o).

Crop evapotranspiration (ET_c). The amount of water used by the crop in transpiration and building of plant tissue and that evaporated from adjacent soil or intercepted by plant foliage. It is expressed as depth in millimeters (inches, or as the volume-depth ratio of acre-inches per acre) and can refer to daily, peak, design, monthly, or seasonal quantities. Sometimes referred to as consumptive use (CU).

Crop irrigation requirement. Quantity of water, exclusive of effective precipitation, that is needed for crop production. It also may include water requirements for germination, frost protection, prevention of wind erosion, leaching of salts, and plant cooling.

Crop water use. Calculated or measured water used by plants, expressed in millimeters per day (inches per day). Same as ET_c except it is expressed as daily use only.

Cross-connection. A physical connection between two water systems, typically between a potable water system and any source or system of water or other substance that is not approved for drinking

Crown. The base of an herbaceous perennial, where stem and root meet and from which fresh shoots and roots arise. Also, the topmost limbs on a tree or shrub.

Cultivar. A garden variety of a plant found in the wild but which does not breed true from seed, instead being maintained in cultivation by vegetative propagation.

Cumulative intake. The depth of water infiltrated into the soil from the time of initial water application to the specified elapsed time.

Deciduous plant. A plant that sheds all its leaves each year, typically in the autumn.

Deep percolation. Water that moves downward through the soil profile below the root zone and cannot be used by plants.

Deficit irrigation. An irrigation water management alternative where the soil in the plant root zone is not refilled to field capacity in all or part of the field.

Denitrification. The biological conversion of nitrate or nitrite to gaseous N_2 or N_2O.

Desalting (or desalination). A process to reduce the salt concentration of seawater or brackish water.

Desert scrub. Scrub (shrub land) that occurs where annual rainfall is less than 25 cm and where a pronounced dry season exists every year.

Dew point. The temperature to which a given parcel of air must be cooled at constant pressure and at constant water vapor content until saturation occurs or the temperature at which saturation vapor pressure of the parcel is equal to the actual vapor pressure of the contained water vapor.

Digester. In a **wastewater treatment plant**, a closed tank that decreases the volume of and stabilizes raw biosolids or sludge by bacterial action.

Digester gas. The gas produced as a result of the microbial decomposition of particulate organic matter under anaerobic conditions. Methane and hydrogen are major components.

Digestion. The biochemical decomposition of organic matter, resulting in partial gasification, liquefaction, and mineralization of pollutants. In wastewater treatment, the biological decomposition of organic matter in sludge. See **digester**.

Dilution. The reduction of the concentration of a substance in air or water by mixing with additional air or water.

Direct reuse. The planned and deliberate use of treated wastewater for some beneficial purpose such as irrigation, recreation, industry, or potable reuse without first being discharged to a body of water or into the ground. (See, for comparison, **indirect reuse**.)

Discharge. (1) The volume of water (or more broadly, the volume of fluid including solid- and dissolved-phase material) that passes a given point in a given period of time. (2) The flow of water from an opening into another body of water, like the release of treated wastewater from a treatment plant into a stream or the ocean. The flow of surface water in a stream or the flow of groundwater from a spring, ditch, or flowing artesian well. (3) (Hydraulics) The rate of flow, especially fluid flow; the volume of fluid passing a point per unit time, commonly expressed as cubic feet per second, millions of gallons per day, gallons per minute, or cubic meters per second.

Discharge permit. A permit issued by the state to discharge effluent into waters of the state.

Discharge point. A location at which effluent is released into a receiving stream or body of water.

Disinfection. The killing of waterborne fecal and pathogenic bacteria and viruses in water or wastewater by chlorination, ozonation, ultraviolet (UV) radiation, or other processes. When one is quantifying the effectiveness of disinfection, a statistical limit must be specified; for example, a wastewater effluent might be disinfected such that not more than 200 colonies of fecal coliform remain per 100 mL of water.

Disinfection by-products (DBPs). (1) Chemicals that are formed when a disinfectant such as chlorine is added to water that contains organic matter, usually from decaying plant or animal material. (2) Compounds that form when chlorine combines with naturally occurring or pollution-derived organic, carbon-based materials, such as the acids from soils or decaying vegetation and bromide (salt). Some of such by-products are suspected to be human carcinogens. One typical such disinfection by-product for which the U.S. Environmental Protection Agency (EPA) has established maximum contaminant levels (MCLs) as part of its enforcement of the Safe Drinking Water Act (SDWA) is total trihalomethanes (TTHMs).

Dissolved organic carbon (DOC). A measure of the organic compounds that are dissolved in water. In the analytical test for DOC, a water sample is first filtered to remove particulate material, and the organic compounds that pass through the filter are chemically converted to carbon dioxide, which is then measured to compute the amount of organic material dissolved in the water.

Dissolved oxygen (DO). (1) Concentration of oxygen dissolved in water and readily available to fish and other aquatic organisms. (2) The amount of free (not chemically combined) oxygen dissolved in water, wastewater, or other liquid, usually expressed in milligrams per liter, parts per million, or percentage of saturation. The content of water in equilibrium with air is a function of atmospheric pressure, temperature, and dissolved-solid concentration of the water. The ability of water to retain oxygen decreases with increasing temperature or dissolved solids, with small temperature changes having the more significant offset. Photosynthesis and respiration may cause diurnal variations in dissolved-oxygen concentration in water from some streams. Adequate concentrations of dissolved oxygen are necessary for the lives of fish and other aquatic organisms and the prevention of offensive odors. Dissolved-oxygen levels are considered the most important and commonly employed measurement of water quality and indicator of a water body's ability to support desirable aquatic life. The ideal dissolved-oxygen level for fish is between 7 and 9 mg/L; most fish cannot survive at levels below 3 mg of dissolved oxygen/L. Secondary and advanced wastewater treatment techniques are generally designed to ensure adequate dissolved oxygen in waste-receiving waters.

Dissolved solids. (1) Minerals, chemical compounds, and organic matter dissolved in water. They form the residue that remains after evaporation and drying. Also known as **total dissolved solids** (TDS). Excessive amounts of dissolved solids make water unfit to drink or use in industrial processes.

Distribution uniformity. Measure of the uniformity of irrigation water distribution over a field.

DO. See **dissolved oxygen (DO)**.

DOC. See **dissolved organic carbon (DOC)**.

Domestic sewage. Wastewater and solid waste that are characteristic of the flow from toilets, sinks, showers, and tubs in a household. Also referred to as domestic waste.

Domestic wastewater facility. Refers to those facilities that receive or dispose of wastewater derived principally from residential dwellings, business or commercial buildings, institutions, and the like. May also include some wastewater derived from industrial facilities. Also referred to as **municipal wastewater facility**.

Dominant species. The species in a plant community that determine, by virtue of size or abundance, the characteristics of that community. Sometimes, two species are co-dominant and the community is so named; for example, oak-ash woodland.

Dormant period. A period of greatly reduced metabolism, during which a plant, or parts of the plant, are alive but not actively growing.

Drain. Any closed conduit (perforated tubing or tile) or open channel, used for removal of surplus ground or surface water.

Drainage. Process of removing surface or subsurface water from a soil or area.

Drainage system. Collection of surface and/or subsurface drains, together with structures and pumps, used to remove surface or ground water.

Drinking water. Water that does not contain objectionable pollution, contamination, minerals, or infective agents and is considered satisfactory for domestic consumption (drinking). The term is used synonymously with **potable water** and refers to water that meets federal drinking water standards of the Safe Drinking Water Act (SDWA) (Public Law 93-523) as well as state and local water quality standards and is considered safe for human consumption. Fresh water that exceeds established standards for chloride content and dissolved-solid limits is often referred to as slightly saline, brackish, or nonpotable water and is either diluted with fresher water or treated through a desalination process to meet drinking water standards for public supply.

Drinking water standards. Regulations established by state agencies and the U.S. Environmental Protection Agency (EPA) for drinking water.

Drinking water supply. Water provided for use in households. The most common sources are surface supplies (rivers, lakes, and reservoirs) or subsurface supplies (aquifers). The distribution of water to households is regulated under the Safe Drinking Water Act (SDWA) of 1974, as amended, as well as state regulations.

Drip irrigation. (1) A system in which piping is laid out so that each plant is watered individually, at its roots. Typically, lesser quantities of water are necessary with this method than for furrow or sprinkler irrigation. (2) A method of microirrigation wherein water is applied to the soil surface as drops or small streams through emitters. Discharge rates are generally less than 8 L/h (2 gal/h) for single-outlet emitters and 12 L/h (3 gal/h) per meter for line-source emitters.

Drought. Hydrologic conditions during a defined period when rainfall and runoff are much less than average.

Drought-deciduous shrub. A shrub that retains its leaves during the wet season and sheds the leaves during the dry season to conserve water. Roots of such plants typically are relatively shallow. Leaves are thin, requiring relatively little energy (from the plant) to be remade.

Dual-distribution piping (or dual plumbing). The plumbing of a facility to provide two sources of water in separate piping systems; for example, a water distribution system that uses one set of pipes for the distribution of potable water and a separate set for the distribution of **reclaimed water**.

EC. See **electrical conductivity**.

E. coli **(*Escherichia coli*).** A bacterial species that inhabits the intestinal tract of humans and other warm-blooded animals. Although it poses no threat to human health, its presence in drinking water does indicate the potential presence of other, more dangerous bacteria. Also see **bacteria**.

Ecology. The study of the interrelationships among plants, animals, and their environment.
ecosystem. A group of interdependent plants and animals and their environment.

Effective precipitation. That portion of total precipitation which becomes available for plant growth.

Effluent. Wastewater or other liquid, treated or in its natural state, flowing from a treatment plant or process.

Effluent limitation. An amount or concentration of a water pollutant that can be legally discharged into a water body by a point source, expressed as the maximum daily discharge, the maximum discharge per amount of product, and/or the concentration limit in the wastewater stream, as a 24-h or 30-day average.

Electrical conductivity (EC). A measure of the ability of the water to transfer an electrical charge. Used as an indicator for the estimation of salt concentration, measured in decisiemens per meter (dS/m, equivalent to mmhos/cm) or millisiemens per centimeter (mS/cm or micromhos/cm, 10^{-3} dS/m), at 25 °C (77 °F).

EC_e = electrical conductivity of saturated soil water extract
EC_i, EC_{iw}, EC_w = electrical conductivity of irrigation water
EC_{sw} = electrical conductivity of soil water

Emission uniformity. An index of the uniformity of emitter discharge rates throughout a microirrigation system. Takes account of both variations in emitters and variations in the pressure under which they operate.

Emitter. A small microirrigation dispensing device designed to dissipate pressure and discharge a small uniform flow or trickle of water at a constant discharge, which does not vary significantly because of minor differences in pressure head. Also called a “dripper” or “trickler.”

Endocrine-disrupting compounds (EDCs). Chemicals that can interfere with the normal hormone function controlling metabolism, growth, and reproduction in humans and animals.

Environment. The combination of all biotic and abiotic elements that surround and influence an organism.

Environmental water. The water for wetlands, the in-stream flow for a major river (based on the largest flow specified in an entire reach of that river for maintenance of fish) or, for wild and scenic rivers, the amount of water based on unimpaired natural flow. Also referred to as dedicated natural flows.

Epiphyte. A plant that grows upon another plant for position or support but which does not parasitize it.

Erosion. The wearing away of the land surface by detachment and transport of soil and rocks through the action of water, wind, or other geologic agents.

Evaporation. The physical process by which a liquid is transformed to the gaseous state, which in irrigation is restricted to the change of water from liquid to vapor.

Evaporation pan. (1) A standard U.S. Weather Bureau Class A pan (48-in. diameter and 10-in. depth) used to estimate the reference crop evapotranspiration rate. Water levels are measured daily in the pan to determine the amount of evaporation. (2) A pan or container containing water. Water evaporated from the device is measured and adjusted by a coefficient to represent estimated crop water used during the period.

Evapotranspiration. The combination of water transpired from vegetation and evaporated from the soil and plant surfaces. Synonymous with **consumptive use**.

Evergreen plant. A plant that remains green during the dormant season and persists for two or more seasons.

Exchangeable cation. A positively charged ion held on or near the surface of a solid particle by a negative surface charge of a soil or colloid and which may be replaced by other positively charged ions in the soil solution.

Exchangeable sodium percentage (ESP). The fraction of the cation exchange capacity of a soil occupied by sodium ions determined as exchangeable sodium (meq/100 g of soil) divided by CEC (meq/100 g of soil) times 100. It is unreliable in soil containing soluble calcium silicate minerals or large amounts of gypsum.

Exchange capacity. The total negative charge of the soil exchange complex.

Feedwater. Water input into a desalting or water treatment plant or an industrial water-using facility.

Fertigation. Application of fertilizer materials through the irrigation system.

Field capacity. Amount of water remaining in a soil when the downward water flow due to gravity becomes negligible. Usually it is assumed that this condition is reached about 2 to 3 days after a full irrigation or heavy rain.

Filtration. A process in which suspended matter is removed from a liquid through a medium that is permeable to the liquid but not to the suspended material. The medium may be sand or a human-made filter. The objective is often to remove particles that contain pathogens.

Fire-type climate. Places in which a combination of low rainfall, high evaporation, frequent wind, and other climatic factors favor the onset of fires, such that the probability is high that wildfire will reoccur on the same hectare of land every 1 to 3 years.

Fixation. The process by which available nutrients such as potassium and phosphorus are rendered unavailable or fixed in the soil.

Flocculate. To aggregate individual small clusters or aggregation of soil particles that creates structure such as crumbs and clods.

Flowering plants. See **angiosperm**.

Flow augmentation. The addition of water to a stream especially to meet in-stream flow needs.

Flow rate. Speed at which water moves, usually measured in terms of volume per time period (for example, liters per minute).

Forb. Any herbaceous plant that is neither a grass nor grass-like.

Fresh water (freshwater). Water that is not brackish or saline and is obtained from rainwater, surface waters such as lakes and streams, and groundwater.

Gallons per day (gpd). A measure of the rate of flow or the rate of water withdrawal from a well. Typically used when the rate of flow in cubic feet per second (cfs) is too low to be useful.

Geographic information system (GIS). Computer data base management system for spatially distributed attributes.

Giardia lamblia. A flagellate protozoan that causes the severe gastrointestinal illness giardiasis when it contaminates drinking water.

Grassland. A vegetation type dominated by herbaceous species, including forbs and grasses, and occupying an area too dry to support trees. Trees may be present, but typically they occur only in localized areas, such as on rocky ridges where soil is thin, or along waterways.

Gravimetric (oven dry) soil water method. A method of measuring total soil water content by sampling, weighing, and drying to constant weight in an oven at 105 °C. Percent water, usually on the basis of dry soil weight, is calculated.

Graywater (or gray water, or greywater). Wastewater from a household or small commercial establishment that does not include water from a toilet, kitchen sink, dishwasher, or water used for washing diapers.

Ground cover. Plants which, by their natural habit of low, close growth, are suitable for covering the ground surface and discouraging weeds.

Groundwater. Water occurring in the zone of saturation in an aquifer or soil. Sometimes referred to as “ground water.”

Groundwater basin. A groundwater reservoir, defined by an overlying land surface and the underlying aquifers that contain water stored in the reservoir. In some cases, the boundaries of successively deeper aquifers may differ and make it difficult to define the limits of the basin.

Groundwater overdraft. The condition of a groundwater basin in which the amount of water withdrawn by pumping exceeds the amount of water recharging the basin over a period of years during which water supply conditions approximate average conditions.

Groundwater recharge. The natural or artificial infiltration of surface water or injection of water into the zone of saturation (i.e., into groundwater aquifer).

Groundwater table. The upper surface of the zone of saturation in an unconfined aquifer.

Growing season. The period, often the frost-free period, during which the climate is such that crops can be produced. In the case of annual plants, it approximates the time interval between planting and crop maturity; for perennial crops, it is the period between certain temperature conditions that establish growth and dormancy. This growing season is sometimes restricted to the period between killing frosts.

Gymnosperm. A plant that produces seeds exposed to the environment rather than seeds enclosed in a fruit. All conifers are members of this group, as are gingkos and cycads.

Gypsum. A mineral used in the fertilizer industry as a source of calcium and sulfur. Widely used to reclaim sodic soils and improve water infiltration.

Habitat. The natural environment in which a plant or animal lives.

Halophyte. A plant that can tolerate, or even thrive in, saline water or saline soil.

Hardpan. A hardened or cemented soil horizon or layer cemented by iron oxide, silica, or calcium carbonate.

Hard water. Water with a high concentration of minerals, principally calcium and magnesium ions.

Herb. A seed plant that does not develop woody tissues.

Herbaceous perennials. Perennial plants that die back each winter, shedding leaves and stems and leaving only the plant's underground organs, such as a bulb, corm, root, or rhizomes. Examples: iris, gladiolus, onion (Allium).

Herbaceous plant. A plant having the characteristics of an herb.

Herbicide. A pesticide for controlling weeds.

Humus. The well-decomposed, more or less stable portion of the organic matter in soils.

Hybrid. A plant produced by the crossing of two other, genetically distinct plants. Hybrids may be between varieties (referred to as a varietal hybrid), between species (specific hybrid), or, more rarely, between genera (generic hybrid). Such plants may show a blending of characteristics from each parent or may display the characteristics of one parent more than of the other.

Hydraulic conductivity. The rate of water flow in soil per unit gradient of hydraulic head or potential.

Hydrologic cycle. The continuing process by which atmospheric water condenses, falls to the surface of the earth in any of various forms of precipitation, runs through the surface or subterranean passages toward the sea, and again returns to the atmosphere by evaporation from either the sea or land surface.

Hydrozone. Refers to areas where the irrigation system must be matched to the plant material, microclimate, or other needs like watering requirement and leaching requirement.

Impermeable layer (soil). Layer of soil resistant to penetration by water, air, or roots.

Incidental reuse. Unplanned use of treated wastewater effluent after disposal.

Incidental runoff. Unintended, but perhaps unavoidable, runoff of water from a site where water is used, such as overspray from sprinkler irrigation.

Indigenous. Plants originating in a particular locality, district, or country.

Indirect reuse. The use of reclaimed water indirectly after it has passed through a natural body of water after discharge from a wastewater treatment plant.

Infiltration. The downward entry of water through the soil surface into the soil.

Infiltration opportunity time. The time that water inundates the soil surface, with opportunity to infiltrate.

Infiltration rate. The quantity of water that enters the soil surface in a specified time interval. Often expressed in volume of water per unit of soil surface area per unit of time.

Inflorescence. The arrangement of fruits on a floral axis.

Influent. Water, wastewater, or other liquid flowing into a reservoir, basin, or treatment plant.

Inorganic fertilizer. Fertilizer manufactured from mineral-based chemicals.

Instantaneous application rate. The maximum rate that a sprinkler application device applies water to the soil, expressed in millimeters per hour (inches per hour).

Intake characteristic curves. Curves reflecting cumulative water intake versus time for irrigation systems.

Intake rate. The rate at which irrigation water enters the soil at the surface (see **infiltration**). Expressed as millimeters per hour (inches per hour).

Ion. Chemical constituent that has an electrical charge, either positive like sodium or negative like chloride.

Ion exchange. Process in which ions of one mineral are replaced by ions of another mineral. In water-softening processes, magnesium and calcium ions are replaced by sodium ions.

Iron chlorosis. A yellowing or loss of greenness in leaf tissue, commonly between veins, due to an insufficient concentration of iron in the plant.

Irrigate. To distribute water to land through artificial means, especially to enhance crop production either where natural water sources are so deficient as to make crop production impossible otherwise or where it is advantageous to supplement the natural water supply at certain critical stages in the development of crops.

Irrigation frequency, interval. The time between irrigation events.

Irrigation scheduling. The process of determining when to irrigate and how much water to apply, based upon measurements or estimates of soil moisture or water used by the plant.

Irrigation set. The area irrigated at one time within a field.

Irrigation set time, irrigation period. The amount of time required to apply a specific amount of water during one irrigation to a given area.

Irrigation system. Physical components and configuration used to apply water by irrigation. May include pumps, pipelines, valves, nozzles, ditches, gates, siphon tubes, turnout structures, land shaping, furrows, etc.

Irrigation (system) efficiency. The ratio of the volume of irrigation water that is beneficially used to the volume of irrigation water applied, expressed as a percentage. Beneficial uses include satisfying the soil water deficit and any leaching requirement to remove salts from the root zone. It is commonly interpreted as the volume of water stored in the soil for evapotranspiration compared to the volume of water diverted for this purpose but may be defined and used in different ways.

Irrigation water management (IWM). Managing plant, soil, and water resources (precipitation, applied irrigation water, humidity, etc.) to optimize water use by the crop.

Irrigation water requirement. The calculated amount of water needed to replace soil water used by the crop (soil water deficit), for leaching undesirable elements through and below the plant root zone, plus other production needs, less effective precipitation.

Land application. The reuse of reclaimed water or the utilization or disposal of effluents on, above, or into the surface of the ground through spray fields or other methods.

Land capability. Classification of soil units for the purpose of showing their relative suitability for specific uses without permanent damage, such as crop production with minimum erosion hazard.

Land grading. The operation of shaping the surface of land to predetermined grades. Also called “land shaping” (see **land leveling** for a special case).

Land leveling. Process of shaping the land surface to a level surface. A special case of land grading.

Land smoothing. Shaping the land to remove irregular, uneven, mounded, broken, and jagged surfaces without using surveying information.

Landscape impoundment. A body of water that is used for aesthetic enjoyment or that otherwise serves a function not intended to include contact recreation.

Langley. A unit of energy per unit area commonly used in radiation measurements that is equal to gram calorie per square centimeter.

Laser leveling. Land leveling in which a stationary laser transmitter and a laser receiver on each earth-moving machine are used for grade control.

Leaching. Refers either to a process by which substances are dissolved into water flowing over a surface or through a medium or to the movement of salts, nutrients and other solutes down through the soil along with percolating rainwater or irrigation water.

Leaching fraction (LF). The ratio of the depth of subsurface drainage water (deep percolation) to the depth of infiltrated irrigation water.

Leaching requirement (LR): Quantity of irrigation water required for leaching salts through the soil profile to maintain a soil salinity level in the root zone that gives maximum crop yield or salinity level below the threshold salinity of plants.

Leaf litter. A layer of rotting leaves that eventually decays to form humus.

Lime. A mineral such as calcium carbonate (ground limestone), calcium hydroxide (hydrated lime), or calcium oxide (burned lime).

Limited irrigation. Management of irrigation applications to apply less than enough water to satisfy the soil water deficiency in the entire root zone. Sometimes called “deficit” or “stress irrigation.”

Line source. Continuous source of water emitted along a line.

Low elevation spray application (LESA). Irrigation method using a low-pressure spray applicator designed to operate near the ground, 0.3 to 0.6 m (1.0 to 2.0 ft), from drop tubes, on either a center-pivot or a lateral-move sprinkler system (see **low pressure in canopy**).

Low pressure in canopy (LPIC). A system that may or may not include a complete water, soil, and plant management regimen as required in LEPA. Application devices are located in the crop canopy with drop tubes mounted on low-pressure center pivot and linear-move sprinkler irrigation system (see **low elevation spray application**).

Lysimeter. An isolated block of soil, usually undisturbed and in situ, for measuring the quantity, quality, or rate of water movement through or from the soil. A device such as a tank or large barrel that contains a mass of soil and vegetation similar to that in the immediate vicinity, which is isolated hydrologically from its surroundings. It is commonly used in research to determine the water use of various crops in field conditions.

Macroclimate. The climate of a large geographical area; for example, the southwestern United States.

Macroenvironment. That part of a plant’s environment that is determined by the general climate, elevation, and latitude of the region.

Magnesium ion. A positively charged inorganic ion that contributes to the hardness of water.

Maintenance. Routine operations necessary to keep a landscape in good order—for example, pruning, mowing, and weeding.

Management-allowed depletion. The desired soil-water deficit at the time of irrigation.

Manufacturer's coefficient of variation. A measure of the variability of discharge of a random sample of a given make, model, and size of microirrigation emitter, as produced by the manufacturer and before any field operation or aging has taken place; equal to the ratio of the standard deviation of the discharge of the emitters to the mean discharge of the emitters.

Maximum contaminant level (MCL). The highest drinking water contaminant concentration allowed under federal and state Safe Drinking Water Act regulations.

Meadow. Grassland that occurs within a climate capable of supporting forest vegetation. Forbs often dominate, with grasses secondary.

Mediterranean climate. A climate zone similar to that of the Mediterranean rim of southern Europe. Four other areas worldwide (besides Europe) have such climates: southern Australia, central Chile, the Cape region of South Africa, and California. All five regions are located between 32 and 40 degrees north or south latitude and occupy the southern or southwestern edges of the continents of which they are part. Other common characteristics include precipitation of 27 to 90 cm per year, mainly during the winter; minimal frost; and episodic wildfires**.** Hot, dry summers and cool, wet winters are the norm. Vegetation in these areas is diverse, ranging from forest (in the wetter locations) to woodland or scrub (in the dry locations). Plant cover is relatively high, with broad-leaved, woody, evergreen flowering plants the dominant vegetation type.

Mesoclimate. The climate of a local area, which may differ from that of the region as a whole; for example, the climate within a river basin or along a coastal strip.

Microclimate. Climate of a small area, such as an isolated hilltop or walled garden or within a group of plants.

Microenvironment. The part of a plant's environment that is modified by nearby abiotic or biotic surfaces and structures. The microenvironment in the vicinity of a plant surrounded by bare soil, for example, is much greater than the ambient air temperature, because the bare soil absorbs solar radiation and radiates heat.

Microirrigation. The frequent application of small quantities of water as drops, tiny streams, or miniature spray through emitters or applicators placed along a water delivery line. The microirrigation method encompasses a number of systems or concepts, such as bubbler, drip, trickle, line source, mist, or spray.

Micronutrients. Nutrients that plants need in small amounts such as boron, copper, zinc, manganese, molybdenum, and nickel.

Milliequivalent (meq). The combining weight of chemicals equal to millimoles divided by their valence or charge.

Millimolar (mM). A chemical concentration unit that is 1/1,000 of a molar concentration. A molar concentration is the atomic weight of the element (or formula weight of the molecule or compound) dissolved in 1 L of water.

Minerals (in water). Soluble inorganic ions in water.

Mist irrigation. A method of microirrigation in which water is applied in very small droplets.

Moisture deficit, soil moisture depletion. The difference between soil water at field capacity and the actual soil water.

Montane. A midelevation mountain zone, above the foothills and below the subalpine zone.

Montane scrub. Scrub that occupies rocky ridges or south-facing mountain slopes. Sometimes this type of vegetation develops after wildfire has passed through an area; in such cases, trees may eventually reclaim the site by growing through the scrub and shading it out.

Mulch. Forest bark, compost, leaf mold, well-rotted farmyard manure, or similar organic material, spread over the soil surface around plants to conserve moisture and inhibit weed growth by restricting the light. Stones, gravel, and synthetic sheet material can also be used.

Municipal discharge. The discharge of effluent from wastewater treatment plants that receive wastewater from households, commercial establishment, and industries. Wastewater from combined sewers carrying both wastewater and collected storm water is included in this category.

Municipal sewage. Wastewater (mostly liquid) originating from a community, which is composed of domestic wastewater and possibly commercial and industrial wastewater.

Municipal wastewater. Wastewater derived from domestic, commercial, and industrial sources.

Municipal wastewater facility. A facility that receives and treats wastewater derived principally from residential dwellings, business or commercial buildings, institutions, and the like. May also include some wastewater derived from industrial facilities. Also referred to as domestic wastewater facility.

Native plant. A plant indigenous to a specific area.

Natural regeneration. Regrowth of vegetation on an area of disturbed land.

Necrosis. Localized death of living tissues such as plant leaves.

Necrotic. Appearance of dead tissues on leaves.

Needle. A long, slender leaf blade common in pines and some spruce.

Net irrigation. The actual amount of applied irrigation water stored in the soil for plant use or moved through the soil for leaching salts. Also includes water applied for crop quality and temperature modification, i.e., controlling frost or cooling plant foliage and fruit. Application losses, such as evaporation, runoff, and deep percolation, are not included. Generally measured in millimeters (inches) of water depth applied.

Net irrigation water requirement. The depth of water, exclusive of effective precipitation, stored soil moisture, or ground water, that is required for replacing that lost to crop evapotranspiration for crop production and other related uses. Such uses may include water required for leaching, frost protection, cooling, and chemigation.

Nitrification. The formation of nitrates and nitrites from ammonia or ammonium compounds in soils or waters through microbial activity.

Noncontact cooling water. Water used for cooling that does not come into direct contact with any raw material, product, by-product, or waste.

Noncontact recreation. Recreational pursuits not involving a significant risk of water ingestion, including fishing, commercial and recreational boating, and limited body contact incidental to shoreline activity.

Nonpoint. Not from a specific location.

Nonpotable reuse. The use of treated wastewater in water supplies that are not intended for drinking or ingestion, such as certain industrial uses or the irrigation of certain types of farm crops.

Nonpotable water. Water that is not suitable for drinking because it contains pollutants, contaminants, minerals, or infective agents.

Nonsaline-alkali soil. (See **sodic soil**.)

Nutrient cycle. The uptake of nutrients by plants and the subsequent use of such nutrients and eventual return of nutrients to the environment.

Nutrients. Mineral elements and ions that are essential for plant growth.

Opportunity time. The time that water inundates the soil surface with opportunity to infiltrate.

Organic chemical. Molecules made up of carbon along with other elements. All living organisms consist of organic molecules.

Organic fertilizer. Fertilizer derived from living matter; for example, fishmeal or bone meal.

Osmotic hazards. Salinity hazard to plants causing soil water to become less available to plants. Plants need to expend more energy to extract soil water in saline than in nonsaline soils.

Outfall. The place where a sewer, drain, or stream discharges; the outlet or structure leaving a treatment plant through which reclaimed water or treated effluent is finally discharged to a receiving water body.

Overdraft. See **groundwater overdraft**.

Pan coefficient. A factor to relate actual evapotranspiration of a crop to the rate water evaporates from a free water surface in an evaporation pan. The coefficient usually changes by crop growth stage.

Pan evaporation. Evaporation from a class A or similar pan. The U.S. Weather Bureau class A pan is a cylindrical container fabricated of galvanized iron or Monel metal with a depth of 10 in. and a diameter of 48 in. The pan is accurately leveled at a site that is nearly flat and well sodded and free of obstructions. The pan is filled with water to a depth of 8 in., and periodic measurements are made of the changes of the water level with the aid of a hook gauge set in the stilling well. When the water level drops to 7 in., the pan is refilled.

Pathogen. A disease-producing agent. Term usually refers to a living organism (i.e., biological). Generally, any viruses, bacteria, or fungi that cause disease.

Penman-Monteith method. A method for estimating reference crop evapotranspiration (ET_o) using current climatic data including air temperature, relative humidity, wind speed, and solar radiation.

Percolation. The downward movement of water through soil. Also called deep percolation past the root zone of plants.

Perennials. Plants that live for many years and usually flower repeatedly.

Permanent wilting point. Soil water content below which plants cannot readily obtain water and permanently wilt. Sometimes called “permanent wilting percentage.”

Photosynthesis. The process by which green plants combine water and carbon dioxide to form carbohydrates in the presence of sunlight. Chlorophyll is required for the conversion of light energy into chemical energy.

Phreatophyte. A woody plant that has deep roots permanently in contact with groundwater. Such a plant is well supplied with water throughout the dry season and experiences stress mainly during winter. (To avoid winter stress, many such plants shed their leaves during the wintertime.)

Planned reuse. The deliberate direct or indirect use of recycled water without relinquishing control over the water during its delivery.

Plant community. All the plant populations within a given habitat; usually, such populations are considered to be somewhat interdependent.

Plant succession. A gradual process in which a plant community changes over time at the population level in a particular place.

Pollution. An alteration of the quality of waters of the state by wastes to a degree that unreasonably affects (1) such waters for beneficial use or (2) facilities that serve such beneficial uses. Pollution may include contamination.

Population. A group of freely interbreeding individuals belonging to the same species and occupying the same habitat.

Potable reuse. The use of treated wastewater in water supplies intended for drinking or ingestion. Usually involves careful treatment of the wastewater with advanced processes, followed by piping of the resulting water directly to a water treatment plant.

Potable water. Water that is drinkable. Specifically, fresh water that generally meets the standards in quality as established in the U.S. Environmental Protection Agency (EPA) Drinking Water Standards for drinking water throughout the United States. Potable water is considered safe for human consumption and is often referred to as **drinking water**.

Pot-bound. Said of a pot-grown plant whose roots have grown to fill its pot to the extent that further development is inhibited. Also known as "root-bound."

Prairie. See **grassland**.

Precipitation intensity. Rate of precipitation, generally expressed in units of depth per time (see **rainfall intensity**).

Pre-plant irrigation. Irrigation applied prior to seeding. Sometimes called "preirrigation."

Pressure regulator. It is used to adjust the water pressure at the point of connection to the level specified in the irrigation design.

Primary plant nutrients. Nitrogen, phosphorus, and potassium needed in large amounts by plants.

Primary wastewater treatment. The removal of particulate materials from domestic wastewater, usually done by allowing the solid materials to settle as a result of gravity. Typically, the first major stage of treatment encountered by domestic wastewater as it enters a treatment facility. The wastewater is allowed to stand in large tanks, termed **clarifiers** or primary settling tanks. Primary treatment plants generally remove 25 to 35% of the **biochemical oxygen demand (BOD)** and 45 to 65% of the total suspended matter. Also, any process used for the decomposition, stabilization, or disposal of sludges produced by settling. The water from which solids have been removed is then subjected to **secondary wastewater treatment** and possibly **tertiary wastewater treatment**.

Puddled soils. Dense, massive soil compacted when wet and having no regular soil structure, commonly caused by machine and heavy foot traffic.

Pumping plant or station. A complete installation of one or more pumps together with all necessary appurtenances such as power units, sumps, screens, valves, motor controls, motor protection devices, fences, and shelters.

Purification (water). Steps taken to eliminate impurities and pollution from water.

Pyranometer. A general name for instruments that measure the combined intensity of incoming direct solar radiation and diffuse sky radiation.

Radiation. Process by which electromagnetic radiation is propagated through space.
Net radiation is the difference of the downward solar and long-wave radiation flux and upward solar and long-wave radiation flux passing through a horizontal plane just above the ground surface (R_n).

Rainfall intensity. Rate of rainfall for any given time interval, usually expressed in units of depth per time.

Raw water. Untreated surface water or groundwater.

Reasonable-use rule. A concept of water law in which a landowner is given the right to the reasonable use of water for domestic or similar needs.

Recharge. Process by which water is added to the zone of saturation to replenish an aquifer.

Recharge area. Land area over which water infiltrates and percolates downward to replenish an aquifer. For unconfined aquifers, the area is essentially the entire land surface overlying the aquifer, and for confined aquifers, the recharge area may be a part of or unrelated to the overlying area.

Reclaimed water or reclaimed wastewater. See **recycled water**.

Recycled water. Wastewater that is suitable for a beneficial use as a result of treatment. The degree of treatment provided for recycled water depends on the quality of water needed for the specific beneficial use and for public health protection and may include effluent from primary wastewater treatment, secondary wastewater treatment, tertiary wastewater treatment, or advanced treatment. Formerly known as reclaimed wastewater.

Reference crop evapotranspiration (ET_o). Rate at which water, if available, would be removed from soil and plant surfaces.

Relative humidity. Ratio of the amount of water present in the air to the amount required for saturation of the air at the same dry bulb temperature and barometric pressure, expressed as a percentage.

Replenishment. The act of replenishing an aquifer, usually through artificial recharge, to offset excess groundwater pumping.

Repurified water. As this term has been used in California, repurified water means recycled water that is used to augment water supplies by discharging advanced treated recycled water into a surface water reservoir that supplies water directly to a water treatment facility for a water supply system that serves domestic uses, including human ingestion. Typically, such waters would undergo extensive tertiary and advanced wastewater treatment, be stored in a reservoir for a specified minimum time (for example, 1 year), be blended with fresh water within the reservoir, then undergo further treatment and disinfection through a conventional surface water treatment plant before being distributed in the potable distribution system.

Reservoir (water). A pond, lake, or basin, either natural or artificial, for the storage, regulation, and control of water.

Reuse (water). The additional use of previously used water. As used in this report, it means the use of **recycled water** (wastewater that has been treated for beneficial use at a wastewater treatment plant).

Reverse osmosis (RO). A method to remove salts and other constituents from water by forcing water through membranes.

Rhizome. A prostrate, thickened stem sending out roots and capable of producing leafy shoots and flowering stems from lateral and terminal buds. May also be a food storage organ that can be used to propagate the plant (as in, for example, bearded iris).

Rib. The primary vein of a leaf.

Root-balled plant. A plant grown in the open ground and then lifted with a well-defined ball of soil around the roots, for planting elsewhere. Usually wrapped in netting for protection. (For comparison, see **bare-root plant**.)

Root zone. (1) Area of a plant that consists of the roots and related woody or nonwoody tissues that absorb water, gases, and nutrients from the soil and atmosphere. (2) Depth of soil that plant roots readily penetrate and in which the predominant root activity occurs. Sometimes spelled "rootzone."

Saline. Containing soluble salts.

Saline-sodic soil. Soil containing appreciable quantities of soluble salts and sufficient exchangeable sodium to interfere with the growth of most plants. The electrical conductivity of the saturation extract is greater than 4 dS/m (4 mmhos/cm), and the exchangeable sodium percentage is greater than 15%.

Saline soil. Nonsodic soil containing soluble salts in such quantities that they interfere with the growth of most plants. The electrical conductivity of the saturation extract is greater than 4 dS/m, and the exchangeable sodium percentage is less than 15%.

Salinity. (1) The concentration of dissolved mineral salts in water on a unit volume basis (e.g., milligrams per liter) or salts in soil on a unit mass basis (tons/acre). May be harmful or harmless for the intended use of the water. Salinity may be also expressed in terms of electrical conductivity in microsiemens per centimeter for low-salt waters and decisiemens per meter for saline waters. (2) When one is describing salinity influenced by seawater, salinity often refers to the concentration of chlorides in the water. (3) The relative concentration of salts, usually sodium chloride, in a given water sample. It is usually expressed in terms of the number of parts per thousand (‰) or parts per million (ppm) of chloride (Cl). Although the measurement takes into account all of the dissolved salts, sodium chloride (NaCl) normally constitutes the primary salt being measured. As a reference, the salinity of seawater is approximately 35‰ or 35,000 ppm. (4) Salinity can harm many plants, causing leaves to scorch and turn yellow and stunting plant growth. Also see **total dissolved solids**.

Salt tolerance. Tolerance by plants of osmotic stresses that make soil water less available.

Salt water or seawater intrusion. The invasion of a body of fresh water by a body of salt water. This phenomenon is usually caused by a hydraulic gradient resulting from a higher water surface elevation or higher water pressure in the salt water zone than in the freshwater zone. It can occur either in surface or groundwater bodies. The term is applied to the flooding of freshwater marshes by seawater, the migration of seawater up rivers and navigation channels, and the movement of seawater into freshwater aquifers along coastal regions.

Salts. Commonly found cations and anions in soils contributing to soil salinity. The primary source of salts is chemical weathering of earth materials, and secondary sources include dissolved mineral salts present in waters or added such as fertilizers, amendments, and animal manures.

Sapling. A young tree; usually pertaining to self-seeded trees.

Saturated paste. A mixture of soil and water commonly used for measurements and for obtaining soil extracts. For all soils except those with high clay content, at saturation a soil paste glistens as it reflects light, flows slightly when the container is tipped, and slides freely and cleanly from a spatula.

Saturated soil extract. The solution extracted by vacuum from soil pastes wetted to its saturation percentage (about twice field capacity for most soil textures) with distilled water.

Saturated zone. Groundwater-bearing zone in groundwater basins below the vadose zone.

Savanna. Grassland with overtopping trees that are regularly present but whose canopies cover less than 30% of the ground. (See also, for comparison, **woodland** and **steppe**.)

Sclerophyllous plant. A plant with small, stiff, leathery leaves that is well adapted to hot and dry climates.

Scorch. "Burning" of leaf margins caused by infection or by unfavorable environmental conditions.

Scrub. Shrub land; any vegetation dominated by shrubs. Typical of regions where the precipitation or the water storage capacity of the soil is too low to support grassland. Desert scrub and chaparral are examples.

Secondary wastewater treatment. Treatment (following primary wastewater treatment) involving the biological process of reducing suspended, colloidal, and dissolved organic matter in effluent from primary treatment systems and which generally removes 80 to 95% of the **biochemical oxygen demand** (BOD) and suspended matter. Secondary wastewater treatment may be accomplished by biological or chemical-physical methods. Activated sludge and trickling filters are two of the most common means of secondary treatment. It is accomplished by bringing together waste, bacteria, and oxygen in trickling filters or in the activated sludge process. This treatment removes floating and settleable solids and about 90% of the oxygen-demanding substances and suspended solids. Disinfection is usually the final stage of secondary treatment. Also see **primary wastewater treatment** and **tertiary wastewater treatment**.

Senescence. The stage in the life of a plant or plant part when its rate of metabolic activity declines prior to death.

Set time (irrigation). Elapsed time between the beginning and end of water application to an irrigation set.

Sewage. The spent water of a community, now usually referred to as **wastewater**. **Sewage** has the further implication of wastewater containing domestic waste.

Shelter belt. A line or belt of trees or shrubs (or both) planted at a right angle to the direction of the prevailing wind, to provide shelter by reducing wind speed.

Shrub. A woody perennial with several stems arising from, or originating just above, the ground level. Some shrubs can live many decades if they are well adapted to their environment and if the environment remains relatively consistent.

SI units. An international metric system developed by General Conference on Weights and Measures (CGPM, Conférence Générale des Poids et Mesures). This system provides for an established single unit that applies for each physical quantity. Units for all other mechanical quantities are derived from these basic units. Also called International System of Units.

Sodic soil. A nonsaline soil containing sufficient exchangeable sodium to adversely affect crop production and soil structure. The exchangeable sodium percentage is greater than 15%, and the electrical conductivity of the saturation extract is less than 4 dS/m.

Sodium adsorption ratio (SAR). The proportion of soluble sodium ions in relation to the soluble calcium and magnesium ions in the soil water extract or water expressed as $(\text{millimoles/liter})^{0.5}$ or $(\text{milliequivalents/liter})^{0.5}$. SAR can be used to predict the exchangeable sodium percentage.

Sodium adsorption ratio, adjusted (SAR_{adj}). The sodium adsorption ratio of a water adjusted for the precipitation or dissolution of Ca^{2+} and Mg^{2+} that is expected to occur when a water reacts with alkaline earth carbonates within a soil. Numerically, it is obtained by multiplying the sodium adsorption ratio by the value $(1 + 8.4 - pHc^*)$, where pHc is the theoretical calculation of the pH of water in contact with lime and in equilibrium with soil CO_2.

Sodium (Na). An alkali metal element having an atomic weight of 22.99 g. Commonly present in waters, plants, soils, and everyday chemical compounds such as table salt and salt for water softeners. Excessive sodium is undesirable for plants, soil properties, and human health.

Sodium percentage. Percentage of total cations that is sodium in water or soil solution.

Softened water. Water treated with sodium to replace calcium and magnesium salts in solution. This process typically does not reduce the water's total salinity.

Soil. The unconsolidated minerals and material on the immediate surface of the earth that serve as a natural medium for the growth of plants.

Soil horizon. A layer of soil differing from adjacent genetically related layers in physical, chemical, and biological properties or characteristics.

Soil moisture. (See **soil water**.)

Soil moisture (available). Water in the root zone that can be extracted by plants. The available soil moisture is the difference between field capacity and wilting point.

Soil moisture (unavailable). Water in the root zone that is held so firmly by various forces that it usually cannot be absorbed by plants.

Soil organic matter. Organic fraction of the soil, including plant and animal residues in various stages of decomposition, cells and tissues of soil organisms, and substances synthesized by the soil population.

Soil profile. Vertical section of the soil from the surface through all its horizons into the parent material.

Soil series. The lowest category of U.S. system of soil taxonomy. A conceptualized class of soil bodies having similar characteristics and arrangement in the soil profile.

Soil structure. The combination or arrangement of primary soil particles, into secondary particles, units, or peds that make up the soil mass. These secondary units may be, but usually are not, arranged in the profile in such a manner as to give a distinctive characteristic pattern. The principal types of soil structure are platy, prismatic, columnar, blocky, and granular.

Soil texture. Classification of soil by the relative proportions of sand, silt, and clay present in the soil.

Soil water. All water stored in the soil (see **water holding capacity**).

Soil-water characteristic curve. Soil-specific relationship between the soil-water matric potential and soil-water content.

Soil-water content. The mass or volume of water in a given volume of soil.

Soil-water deficit. Amount of water required to raise the soil-water content of the crop root zone to field capacity. It is measured in millimeters (inches) of water. Also called soil-water depletion.

Soil-water tension. A measure of the tenacity with which water is retained in the soil. It is the force per unit area that must be exerted to remove water from the soil and is usually measured in bars or atmospheres. It is a measure of the effort required by plant roots to extract water from the soil.

Solar radiation (R_s). Radiation from the sun that passes through the atmosphere and reaches the combined crop and soil surface. The energy is generally in a waveband width of 0.1 to 5 μm. Net R_s is incoming radiation minus reflected radiation from a surface.

Solute. Dissolved material, typically soluble ions and molecules.

Solvent. Substance in which other substances, or solutes, dissolve.

Species. A subdivision of a genus, consisting of plants that have the same distinctive characteristics and that have the capacity to interbreed.

Specific ion toxicity. Plant toxicity (phytotoxicity) resulting from excessive levels of specific ions (e.g., boron).

Spray irrigation. The application of water by a small spray or mist to the soil surface, where travel through the air becomes instrumental in the distribution of water.

Sprinkle irrigation. (See **sprinkler irrigation**.)

Sprinkler application rate. The rate at which water is applied to a given area by a sprinkler system, usually expressed as depth (volume per unit area) per unit time, millimeters per hour (inches per hour).

Sprinkler distribution pattern. Water depth-distance relationship measured from a single sprinkler head.

Sprinkler head. A device for distributing water under pressure.

Sprinkler irrigation. Method of irrigation in which the water is sprayed, or sprinkled, through the air to the ground surface. Rotor sprinkler heads are gear driven or impact driven; fixed sprinkler heads have no moving parts and water is directed through orifices and may have adjustable arcs and adjustable flow rates.

Sprinkler irrigation systems.

> ***Boom.*** An elevated, cantilevered sprinkler(s) mounted on a central stand. The sprinkler boom rotates about a central pivot.
>
> ***Center pivot.*** An automated irrigation system consisting of a sprinkler line rotating about a pivot point and supported by a number of self-propelled towers. The water is supplied at the pivot point and flows outward through the line supplying the individual outlets.
>
> ***Corner pivot.*** An additional span or other equipment attached to the end of a center pivot irrigation system that allows the overall radius to increase or decrease in relation to the field boundaries.
>
> ***Lateral move.*** An automated irrigation machine consisting of a sprinkler line supported by a number of self-propelled towers. The entire unit moves in a generally straight path and irrigates a basically rectangular area. Sometimes called a “linear move.”
>
> ***Permanent.*** Underground piping with risers and sprinklers.
>
> ***Portable (hand move).*** Sprinkler system that is moved by uncoupling and picking up the pipes manually, requiring no special tools.
>
> ***Side-move sprinkler.*** A sprinkler system with the supply pipe supported on carriages and towing small-diameter trailing pipelines, each fitted with several sprinkler heads.
>
> ***Side-roll sprinkler.*** The supply pipe is usually mounted on wheels with the pipe as the axle and where the system is moved across the field by rotating the pipeline by engine power.
>
> ***Solid set.*** System that covers the complete field with pipes and sprinklers in such a manner that all the field can be irrigated without moving any of the system.
>
> ***Towed sprinkler.*** System where lateral lines are mounted on wheels, sleds, or skids and are pulled or towed in a direction approximately parallel to the lateral.

Steppe. Grassland interspersed with shrubs. (See also, for comparison, **woodland**, **savanna**.)

Stomata. Pores, usually in a leaf that, allow gaseous exchange with the atmosphere such as water vapor and oxygen.

Subalpine zone. A high-elevation mountain region located above the montane zone and below the alpine zone. Typically well forested, this zone differs quite a bit from the alpine zone, which is entirely above the treeline.

Subirrigation. Application of irrigation water below the ground surface by raising the water table to within or near the root zone.

Subshrub. A multibranched and genetically dwarfed shrub whose stems die back partially each growing season. Maximum height of such plants typically is 30 cm or less.

Subsoil. The soil below the topsoil layer; composed largely of mineral particles.

Subsurface drain. Subsurface conduits used primarily to remove subsurface water from soil. Classifications of subsurface drains include pipe drains, tile drains, and blind drains.

Subsurface drip irrigation. Application of water below the soil surface through emitters, with discharge rates generally in the same range as those of drip irrigation. This method of water application is different from and not to be confused with **subirrigation**, where the root zone is irrigated by water table control.

Succession. The sequence of plant communities that develops between the initial colonization of bare ground and the establishment of climax vegetation. As this sequence unfolds, the plants themselves modify the physical environment, new species invade, and the numbers of species and their proportions gradually change.

Succulent. A plant composed largely of succulent tissue, the cells of which are large and contain water-filled vacuoles. Leaves may be permanently absent or seasonally absent; when leaves are absent, the plant relies on its green stems to conduct photosynthesis.

Sunburn. Injury to bark and cambium caused by a combination of excessive light, heat, and insufficient moisture.

Surface irrigation. Broad class of irrigation methods in which water is distributed over the soil surface by gravity flow.

Surface water. Water sources located above the earth’s surface, including rivers, lakes, reservoirs, and ponds.

Suspended solids (SS). Solids that either float on the surface of, or are in suspension in, water, wastewater, or other liquid and that can be largely removed by laboratory filtering. Such suspended solids usually contribute directly to turbidity. Defined in waste management, these are small particles of solid pollutants that resist separation from the wastewater. Suspended solids (along with **biochemical oxygen demand** [BOD]) are a measurement of water quality and an indicator of treatment plant efficiency.

Tailwater. Water, in a stream or canal, immediately downstream from a structure or excess irrigation water that reaches the lower end of a field.

Temperate. Moderate, as in climate.

Tensiometer. A device to measure the tension with which water is held in the soil.

Tertiary wastewater treatment. Biological, physical, and chemical treatment processes that follow **secondary wastewater treatment**. The most common tertiary wastewater treatment process consists of flocculation basins, clarifiers, filters, and disinfection processes. The term **tertiary wastewater treatment** is also used to include **advanced wastewater treatment** beyond filters.

Tidal wetland. Coastal meadows subject to flooding by the sea. Plants in such areas must tolerate salinity, mechanical disturbance, and anaerobic conditions. Vegetation usually consists of a single, low-growing layer of perennial herbs. The soil beneath is crowded with rhizomes and roots. Flora are rather simple, with relatively few species coexisting within a given wetland.

Tile drain. Drain constructed by laying drain tile with unsealed joints in the bottom of a trench that is then refilled. Tile is usually constructed of clay or concrete.

Tilth. The physical condition of the soil in relation to its ability to support plant growth.

Top dressing. Addition of a fertilizer or soil improver to the soil surface or to grass.

Topsoil. Uppermost layers of soil, containing mineral nutrients and organic matter, soil-dwelling organisms, and plant roots. Topsoil is derived from weathering of subsoil and from the decay and decomposition of plant and animal remains.

Total coliform. *Escherichia coli* and similar gram-negative bacteria that are normal inhabitants of fecal discharges and soils. The total coliform group is recognized in drinking water standards.

Total coliform bacteria. A particular group of bacteria that is used as an indicator of possible wastewater pollution. This group includes coliforms that inhabit the intestines of warm-blooded animals and those that inhabit soils. They are characterized as aerobic or facultative anaerobic, gram-negative, non-spore-forming, rod-shaped bacteria that ferment lactose with gas formation within 48 h at 35 °C. In the laboratory, these bacteria are defined as all the organisms that produce colonies with a golden-green metallic sheen within 24 h when incubated at 35 °C plus or minus 1 °C on M-Endo medium (nutrient medium for bacterial growth). Their concentrations are expressed as the number of colonies per 100 mL of sample.

Total dissolved solids (TDS). (1) The sum of all dissolved solids in a water or wastewater and an expression of water salinity in milligrams per liter (parts per million). It is empirically related to electrical conductivity (EC in decisiemens per meter) multiplied by 640 or 735. The inorganic salts are measured by filtering a water sample to remove any suspended particulate material, evaporating the water, and weighing the solids that remain. An important use of the measure involves the examination of the quality of drinking water. Water that has a high content of inorganic material frequently has taste problems and/or water hardness problems. As an example, water that contains an excessive amount of dissolved salt (sodium chloride) is not suitable for drinking. High-TDS solutions have the capability of changing the chemical nature of water. High TDS concentrations exert various degrees of osmotic pressure and often become lethal to the biological inhabitants of an aquatic environment. The common and synonymously used term for TDS is “salt.” Usually expressed in milligrams per liter.

Total organic carbon (TOC). A measure of organic matter, which contains carbon, in water. Because many organic (carbon-containing) compounds can be detrimental to human health, the measurement of TOC is a useful indicator of the quality of recycled water.

Toxicity. The capacity of a chemical compound to produce injury.

Trace elements. Mineral nutrients required in minute amounts for successful plant growth.

Translocation. Transfer of nutrients (or a virus or herbicide) through a plant.

Transpiration. The process by which water in plants is transferred as water vapor to the atmosphere.

Treated (wastewater) effluent. Water that has received primary, secondary, or advanced treatment to reduce its pollution or health hazards and is subsequently released from a wastewater facility after treatment.

Treatment. Any method, technique, or process designed to remove solids and/or pollutants from water or wastewater. Also see **primary wastewater treatment**, **secondary wastewater treatment**, and **tertiary wastewater treatment**.

Treatment plant. A structure built to treat water or wastewater before using the water, discharging wastewater into the environment, or reusing the treated wastewater (**recycled water**).

Tree. Perennial woody plant that, in its natural state, has a distinct trunk or main stem and is usually taller than a shrub.

Tree canopy. An interwoven mass of branches and leaves above the main stem of a tree.

Trickle irrigation. See **drip irrigation**.

Turbidity. (1) A measure of the reduction in transparency of water caused by suspended material. The term “turbid” is applied to waters containing suspended matter that interferes with the passage of light through the water or in which visual depth is restricted. The turbidity may be caused by a wide variety of suspended materials, such as clay, silt, finely divided organic and inorganic matter, soluble colored organic compounds, plankton, and other microscopic organisms and similar substances. Turbidity in water has public health implications due to the possibilities of pathogenic bacteria being encased in the particles and thus escaping disinfection processes. Turbidity interferes with water treatment (filtration) and affects aquatic life. Excessive amounts of turbidity also make water aesthetically objectionable. The degree of the turbidity of water is measured by a turbidimeter. (2) The collective optical properties of a water sample that cause light to be scattered and absorbed rather than transmitted in straight lines; the higher the intensity of scattered light, the higher the turbidity. Turbidity is expressed in nephelometric turbidity units (NTU) or Formazin turbidity units (FTU) depending on the method and equipment used.

Turf. Grass, especially short varieties upon which people may walk.

Turfgrasses. Grasses grown on playgrounds, parklands, sports fields, and golf courses.

Turfing. Establishment of grass area by laying turf onto a prepared bed.

Unavailable soil water. That portion of water in a soil held so tightly by adhesion and other soil forces that it cannot be absorbed by plants rapidly enough to sustain growth. Soil water at permanent wilting point.

Understory. A layer of vegetation growing under groups of trees or shrubs.

Uniformity coefficient. A characterization of the aerial distribution of water in a field as the result of irrigation.

Unplanned reuse. Unplanned use of treated wastewater effluent after disposal. Also called incidental reuse. Many communities already unintentionally practice such unplanned reuse by withdrawing water from rivers containing treated wastewater discharged upstream.

Upstream. From a reference point in the direction toward the source or upper part of a stream; against the current. In relation to water rights, the term refers to water uses or locations that affect water quality or quantity of downstream water uses or locations.

Vadose zone. The aerated region including the root zone above the permanent water table in groundwater basins.

Variegated. A leaf, steam, or flower of more than one color.

Vegetation type. A superset of the plant community, defined by the dominant growth form and habitat, rather than by the dominant species. Typically, a vegetation type is given a two-part name; examples include upland conifer forest, desert scrub, and tidal marsh. There are far fewer vegetation types than communities; North America has between its shores thousands of plant communities but fewer than a dozen major vegetation types.

Vein. A vascular bundle of a leaf.

Vine. A plant that has a single, weak trunk and must find additional support by twining around or otherwise climbing up and through neighboring shrubs or trees. The woody tissue in the stem of a vine typically contains many more voids than regular wood, making it light and requiring relatively little metabolic energy to build, thus allowing the plant to grow relatively rapidly and attain great length (and, with sufficient support, great height).

Virus. The smallest (10 to 300 µm in diameter) life form capable of producing infection or diseases in humans or other larger species. Complex macromolecules that are able to reproduce themselves only in living cells and are capable of producing infection and diseases.

Warm-season turfgrass. Turfgrass species adapted to favorable growth during warm portions of the growing season; may go dormant during the winter.

Wastewater. (1) A combination of liquid and water-carried pollutants from homes, businesses, industries, or farms; a mixture of water and dissolved or suspended solids. (2) That water for which, because of quality, quantity, or time of occurrence, disposal is more economical than use at the time and point of its occurrence. Wastewater to one user may be a desirable supply to the same or another user at a different location. Also referred to as domestic wastewater or sewage if it contains domestic waste.

Wastewater irrigation. Land application of treated wastewater with the primary purpose of maximizing crop production per unit of water applied; also, land treatment and disposal of wastewater where maximum crop production is a secondary objective.

Wastewater reclamation. The planned reuse of waste water for specific beneficial purposes.

Wastewater treatment. Any of the mechanical or chemical processes used to modify the quality of waste water in order to make it more compatible or acceptable to humans and the environment.

Wastewater treatment plant (WTP). A treatment plant containing a series of tanks, screens, filters, and other mechanical, biological, and chemical processes by which pollutants are removed from wastewater. Less frequently referred to as "waste treatment plant."

Water application efficiency. Ratio of the average depth of water infiltrated and stored in the root zone to the average depth of water applied.

Water holding capacity. Total amount of water held in a freely drained soil per increment of depth. It is the amount of water held between field capacity and oven dry moisture level, expressed in centimeters/centimeter, inches/inch, centimeters/meter, inches/foot, or total centimeters (inches) for a specific soil depth. Sometimes called total water holding capacity (see **available water capacity**).

Water purveyor. Anyone who sells water to the public, usually the owner of a public water supply system; a public utility, mutual water company, county water district, or municipality that delivers water to customers.

Water quality. A term used to describe the chemical, physical, and biological characteristics of water, usually in respect to its suitability for a particular purpose, such as beneficial use or discharge to the environment.

Water quality guidelines. Used to appraise suitability of water for intended purposes such as irrigation of plants.

Water reclamation. (1) The treatment of water of impaired quality, including brackish water and seawater, to produce a water of suitable quality for the intended use. (2) A term synonymous with water recycling. (3) The recovery of wastewater for useful purposes through treatment processes and subsequent return to either a surface or groundwater source. (See also **water reuse**.)

Water recycling. (1) The process of treating wastewater for beneficial use, storing and distributing recycled water, and actually using recycled water. (2) The reuse of water through the same series of processes, pipes, or vessels more than once by one user, wherein the effluent from one use is captured and redirected into the same use or directed to another use within the same facility of the user. This form of recycling, often without treatment between uses, is common in industrial facilities, such as cooling towers.

Water reuse. The preferred general term for the practice of reclaiming water from municipal and industrial wastewater effluents by applying various treatment processes.

Water softener. A pressurized water treatment device in which hard water is passed through a bed of cation exchange media for the purpose of exchanging calcium and magnesium ions for sodium or potassium ions, thus producing a softened water that is more desirable for laundering, bathing, and dishwashing.

Water table. A term used to describe the plane below which the soil or porous rock is completely saturated with water.

Water transfers. Marketing arrangements that can include the permanent sale of a water right by the water rights holder; a lease of the right to use water from the water rights holder; the sale or lease of a contractual right to water supply.

Water use. Application of a resource such as water to a particular purpose.

Beneficial use. Application of a resource to a purpose that produces economic or other benefits, tangible, or intangible, economic or otherwise, such as employment of water for domestic supply, irrigation, industrial supply, power generation, or recreation.

Conjunctive irrigation use. That portion of water applied to irrigation that is absorbed by the crop and used to build plant tissue or transpired, together with that lost from the cropped area by evaporation.

Consumptive water use. Employment of water in a manner that makes it unavailable for other application because of absorption, evaporation, transpiration, incorporation in manufactured product, or changes in quality.

Domestic use. Employment of water for the purposes of the home, including drinking, cooking, bathing, laundry, cooling, watering lawns, washing cars, and filling swimming pools.

Multiple use. Management of resources to satisfy two or more function purposes.

Nonbeneficial consumptive irrigation use. The portion of water withdrawn for irrigation that is neither used directly in crop production nor returned to the stream but rather is lost in transmission by evaporation or otherwise.

Nonconsumptive water use. Employment of water in a manner that does not reduce the amount of suitable water available for other purposes, including both on-site uses of the flow.

On-site water use. Employment of water in a manner that does not require diversion or flow of water, chiefly recreation uses and retention and temporary storage of excess water to prevent flood damage downstream.

Water use efficiency. (1) Dry matter or harvested portion of crop produced per unit of water consumed. (2) Ratio of water beneficially used to the water delivered to the area being irrigated.

Weathering. The physical, chemical, and biological processes that disintegrate the surfaces of rocks.

Wetland. An area that is periodically inundated or saturated by surface or groundwater on an annual or seasonal basis that displays hydric soils and that typically supports or is capable of supporting hydrophytic vegetation.

Weed. A plant growing where it is not wanted.

Wet feet. Roots repeatedly or continually exposed to water-saturated soil conditions.

Wilt. Loss of rigidity and drooping of plant parts, generally caused by insufficient water in the plant.

Wilting point. (Synonymous with **permanent wilting point**.)

Woodland. Grassland with overtopping trees whose canopies cover 30 to 60% of the ground. (See also, for comparison, **savanna** and **steppe**.)

Woody. Plant type that contains secondary xylem.

Woody perennials. Plants that accumulate above-ground stem tissue year after year. Depending on the size and shape of the stems, these plants may be subshrubs, shrubs, vines, or trees.

Xeric. Drought-resistant or desert-type plant.

Xeriscape. Refers to horticulture that emphasizes water conservation using specific landscape design elements and management practices.

Xerophyte. A plant able to grow in a very dry environment. Such plants often are light in color and may have small, hard leaves, an epidermis with thick cuticle, and stomata that close early during the day. They may also have succulent tissue.

Xylem. Plant tissue consisting of tracheids, vessels, parenchyma cells, and fibers; wood.

Zero discharge. The goal, in the preamble to the Clean Water Act (CWA), of zero pollutants in water discharges.

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