The sensitive plant, Lace fern, showed severe damage of its leaves (left) when irrigated with recycled water compared with the same species irrigated with potable water (right).

Nandina showed moderate tolerance and reduced growth (left) when irrigated with recycled water.

Hydrangea is tolerant of recycled water irrigation and had no symptoms of damage when irrigated with recycled water.

Studies of Recycled Water Irrigation and Effects of Elevated Mineral Nutrient Concentrations on Growth and Ion Uptake of Landscape Plant Species and Ornamental Grasses

Lin Wu, James A. Harding and M. A. Harivandi

Water conservation measures, in particular the use of recycled water, have forced landscapers to rethink ways to maintain landscapes and gardens. Recycled water is water that has been previously used, suffered a loss in quality and then treated to a point where it is of suitable quality for additional beneficial uses. With the increasing use of recycled water throughout the state, more knowledgeis necessary to determine which plants, if any, can be grown and how irrigation must be managed.

The use of recycled water in landscape irrigation can, however, pose problems. Water always contains measurable quantities of dissolved substances, collectively called salts. The suitability of water for irrigation purposes will depend on both the amount and the kinds of salt present in the waste water that may be quite variable from source to source and from time to time. Typically, as compared to potable water, recycled water in general will have higher total salt levels and specific ions may be present at higher concentrations, especially for sodium, chloride, magnesium, and, sometimes, calcium (Asano, Smith, and Tchobanoglous, 1981 and 1984).

There is a potential of incurring damage to both plants and the soil structure when using recycled water in the landscape. Many landscapes and ornamental plants are grown in greenhouses or other controlled environmental conditions and additional considerations must be made. One of the first places in the country to use recycled water was San Francisco’s Golden Gate Park. As early as 1912, recycled water was combined with ground water and used for irrigation, filling lakes, brooks, and spillways. A ground water and Wastewater Master Plan is currently underway in San Francisco to identify maximum uses for this untapped water source. Because limited information about the effects of elevated concentrations of different mineral elements in recycled water on performance of ornamental plant species and their possible adverse effects on soil and ground water is available, the use of recycled water irrigation has not been very successful.

A large scale screening for salinity tolerance for landscape plant species for recycled water

Plant species	Source of variation	Soil significant level	Leaves significant level	Roots significant level
Chloride	Treatment	* * *	* * *	* * *
	Species	NS	* * *	* * *
	Treat x Species	NS	NS	NS
Magnesium	Treatment	* * *	* * *	NS
	Species	NS	* * *	* * *
	Treat x Species	NS	NS	NS
Potassium	Treatment	NS	NS	NS
	Species	NS	* *	* * *
	Treat x Species	NS	NS	NS
Calcium	Treatment	NS	* * *	NS
	Species	NS	* *	* * *
	Treat x Species	NS	NS	NS

, *, NS represent significant levels at 5%, 1%, and not significantly different respectively.

Summary of analysis of variance ion uptake of the five herbaceous ornamental plant species irrigated with waste water for a period of 24 weeks. (Table 1)

irrigation has been conducted in the field and green house by Marin Municipal Water District, California. However, the mineral element compositions in the water may be quite variable over time and between seasons. Therefore, the effect of specific element and chemical compounds in recycled water needs to be identified in order to be able to manage recycled water irrigation for ornamental plants effectively. Most research concerning high concentrations of salinity effects by irrigation water on turfgrass and crop plants has emphasized N^+ concentrations (Gratten and Grieve, 1993; Harivandi, Buttler, and Wu, 1992), and sometimes boron toxicity was studied. Very limited information is available for ornamental plants. Effects of other high concentrations of mineral ions that commonly exist in recycled water, such as Cl^-, K^+, Mg^{2+}, and Ca^{2+}, on ornamental plants have rarely been studied.

The waste water produced by residences has been the greatest target for water recycling. In arid and semiarid regions, the waste water produced by water softeners and residences is probably of the most concern in waste water disposal. In addition, it is a potentially useful water resource for landscape irrigation. Traditionally, sodium chloride has been used in water softeners for ion exchange. The waste water discharged from water softeners contains high concentrations of sodium, and sodium is extremely detrimental to both the plants and soil. The utilization of sodium chloride for a water softener has been prohibited by some local governments in California. The substitution of potassium chloride for sodium chloride has been proposed by both industries and local governments, and the wastewater generated by the water softeners has been considered for use in turf and landscape irrigation, and this trend is expected to increase. The ion concentrations in the waste water can be more than 30 mM for K^+, 100 mM for Ca^{2+} and Mg^{2+}, and 400 mM for Cl^-. These ion concentrations are also commonly found in so-called gray water produced by residences. This report presents the effects of high concentrations of Cl^- Mg^{2+}, Ca^{2+} and K^+ on herbaceous ornamental plant species.

Materials and Methods

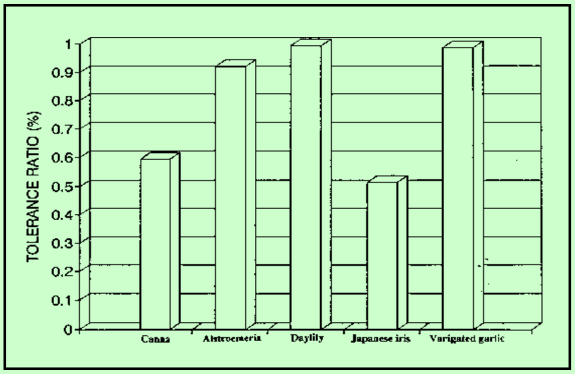
Plant Species Studies. Five herbaceous ornamental plant species including *Canna cleopatria* L. (Canna), *Alstromeria hybrid. (Alstromeria), Hemerocallis minor* Mill. (Day-lily), *Iris ensata* Thunb. (Japanese iris), and *Allium stivum* L. (Variagated garlic) that are commonly grown in California gardens and landscapes were used for this study.

Simulation of Recycled Water. The Cl^-, K^+, Mg^{2+}, and Ca^{2+} concentrations in waste waters discharged from residences may reach levels from 100 to 300 mM. The waste water was diluted with low salt-water before it was used for irrigation. A simulated full concentration waste water was prepared using a mix of KCI, $MgCl_2$ and $CaCl_2$ to attain a final ion concentration of 30 mM of K^+, 100 mM of Ca^{2+} , l00 mM Of Mg^{2+} , and 400 mM of Cl-. It was diluted with low-salinity water before it was used for the irrigation studies.

Waste Water Irrigation Treatment and Examination of Phenology of the Plants. The plant species were established in the greenhouse. For the irrigation treatment, the simulated wastewater was diluted with low-salinity city water into 1/5, 1/10, and 1/20 of its full concentrations. The plants were irrigated with the waste water twice a week, and once with regular tap water. A control treatment was irrigated with regular tap water three times every week.

Sample Collection and Chemical Analysis. The plants were grown for six months. At the end of six months, the above ground plant tissue was harvested. The dry weight was measured. The underground tissue (about 30 g fresh weight of either rhizome, crown, corm, or tuber depending on the species) was collected. In this report, these underground tissues are collectively called roots. Soil samples were collected from the center of each pot using a 2.5 cm diameter soil probe. The soil samples were air-dried at room temperature for at least four weeks. For the plant tissue analysis, 5 ml of concentrated $HN0_3$ and 2.5 ml of $HCIO_4$ were added to 50 mg of dry plant material in a volumetric digestion tube and allowed to digest overnight at room temperature. Further digestion was conducted at 150-210 C for 1 hour. The plant tissue digests were diluted with double distilled water to a final volume of 25 ml. Calcium, K, and Mg were measured with a Perkin-Elmer atomic absorption spectroscope. Chloride was measured with a Buchler Cotlove automatic titrator (Buchler Instruments, Fort Lee, NJ). For soil-exchangeable Ca, Mg, and K measurement, the ammonium acetate extraction method was used (David, 1960). Ten grams of dried soil were extracted with 40 ml ammonium acetate. Calcium, K, and Mg were measured with an atomic absorption spectroscope and chlorine was measured with a Buchler Coltove automatic titrator.

Data were subjected to analysis of variance to test for differences between waste water irrigation treatments and between plant species.

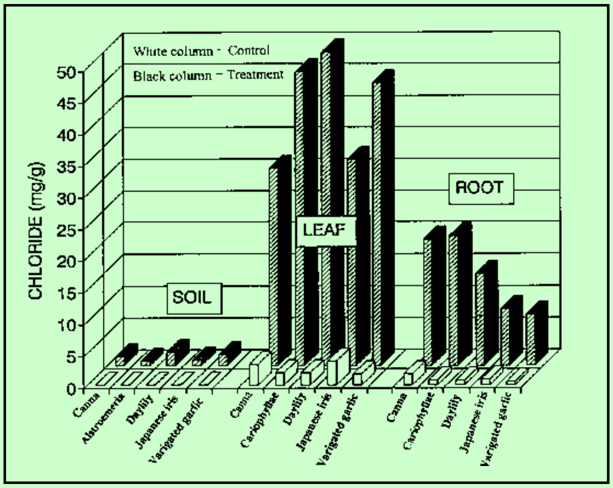


Waste water irrigation and tolerance ratio represented by percent dry weight produced under waste water irrigation to dry weight produced under regular water irrigation of five herbaceous ornamental plant species. (Fig. 1)

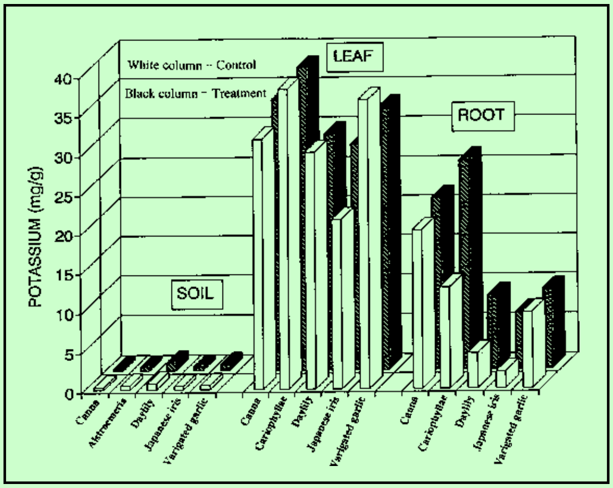
Results and Discussion

The requirement of chlorine as a mineral nutrient for plants was first demonstrated by Broyer et al, (1954). Because chloride is commonly supplied to plants from various sources such as soil reserves, rain, fertilizers, and air pollution, there is more concern about toxic levels in plants than about deficiency. Assuming a minimal requirement for optimal growth of 1 g kg^{-1} dry weight, one would expect, on average, a crop requirement of between 4 and 8 kg chloride per hectare. This is the amount of chloride supplied by rain. If the concentration of chloride in an external culture solution is more than 20 mM, it can lead to chloride toxicity in sensitive plant species (Alt et al., 1982). For tolerant species, the external chloride concentration can be four to five times higher without reduction of growth. Differences in chloride toxicity in plants are related mainly to differences in the sensitivity of leaf tissue to excessive chloride levels. Most fruit trees, beans, and cotton may show chloride toxicity under 10 mM CI^{-1}. In contrast, 20 to 30 g chloride per kg^{-1} dry leaf tissue may have no toxic effect on tolerant species such as barley, spinach, lettuce, and sugar beet. However, there is a lack of available experimental information on the effects of chloride on ornamental plants.

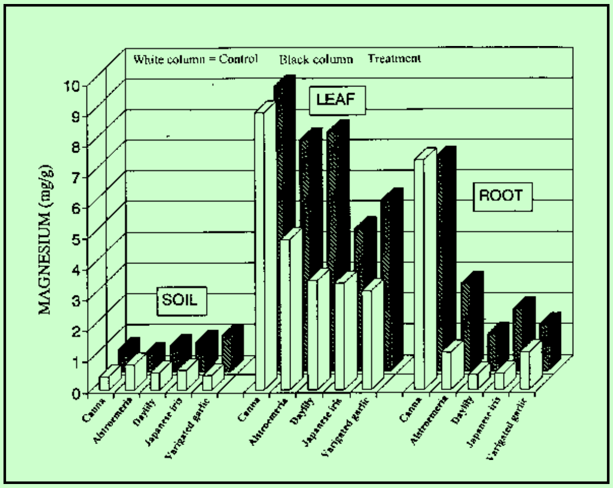
The results of this study indicate that the leaf tissues of the waste water irrigated plants had chloride



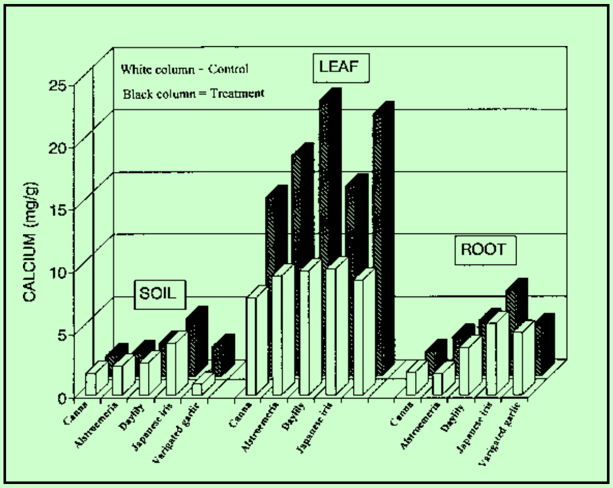
Waste water irrigation and chloride concentration detected in the soil, leaves, and roots (represented by corm, crown, rhizome or tuber) of five herbaceous ornamental plant species.



Waste water irrigation and potassium concentration detected in the soil, leaves, and roots (represented by corm, crown, rhizome or tuber) of five herbaceous ornamental plant species.



Waste water irrigation and magnesium concentration detected in the soil, leaves, and roots (represented by corm, crown, rhizome or tuber) of five herbaceous ornamental plant species.



Waste water irrigation and calcium concentration detected in the soil, leaves, and roots (represented by corm, crown, rhizome or tuber) of five herbaceous ornamental plant species.

concentrations ranged from 30 mg g^{-1} dry weight in canna and Japanese iris to about 45 mg g^{-1} in cariophyllae, daylily, and variagated garlic and was about 6 to 10 times greater than in the tissue of the control plants. Chloride concentrations in the root tissue were lower and were about 50% of the leaf tissue. Tissue chloride concentrations were significantly different between treatments and between plant species (Table 1). Chloride concentration in the soils was low and less than 10 mg g^{-1} dry weight and was not significantly different among the five plant species. This result suggests that an intrinsic difference in chloride uptake exists among the five plant species. Tolerance ratio represented by percent of dry weight (Fig. 1) shows that the three species that had greater chloride uptake also had greater tolerance ratios. These three species may be considered to be chloride tolerant plants as are barley and sugar beet.

Potassium and magnesium are required mineral elements for plant growth. In most cases, the cytoplasmic K^+ concentrations are maintained in a relatively narrow range of 100 to 120 mM. The high concentrations of K^+ in the cytoplasm and the chloroplasts are required to neutralize the soluble and insoluble macromolecular anions and to stabilize the pH between 7 and 8, the optimum for most enzyme reactions. In addition to its function in pH stabilization and osmoregulation, K^+ is required for enzyme activation and membrane transport processes. The maximum K^+ concentration that catalyzes the enzyme for starch synthesis was found to be in the range of 50 to 100 mM (Nitsos and Evans, 1969). Higher concentrations may have inhibitory effects (Preusser et a]., 1981). By increasing the K^+ supply to plant roots, it is relatively easy to increase the potassium content of various organs, except grains and seeds, which maintain a relatively constant content of 0.3% of the dry weight. When the K^+ supply is abundant, increased consumption of K^+ often occurs, and there is a possible interference with the uptake and physiological availability of Mg^{2+} and Ca^{2+}.

So-called normal soil K^+ concentrations have been found to range from 80 to 300 mg K kg^{-1} dry weight. Under field conditions, soil K^+ concentrations rarely have been found to become toxic to plants. Soil may contain large amounts of potassium, but a small part, usually less than 1% of the total K^+, is in exchangeable form, and much smaller amounts are in soil solution. Therefore, most of the K^+ in the soil is present in a nonexchangable form. Much of this nonexchangeable K^+ is a component of some of the primary minerals in the soil (Bear, Prince and Malcom, 1945). Potassium in the soil minerals is released slowly by weathering, usually not rapidly enough to be of significance for immediate use by plants. However, some forms of nonexchangeable K^+ have been known to be released easily to a plant-available form. Cook and Hutchson (1960) noted that soil exchangeable K^+ was converted to a nonexchangeable form upon drying when the initial level of exchangeable K^+ was high, but when the initial level was low, nonexchangable K^+ was released by the drying process.

This study indicates that potassium uptake was significantly different between the plant species, but was not significantly different between waste water irrigation treatments. This result suggests that the potassium level in the waste water does not seem to create any mineral concentration stress to the plants.

In addition to high levels of K^+ and Cl^-, high concentrations of magnesium (Mg^{2+}) also exist in the waste water. The functions of Mg^{2+} in plants are to interact with nucleophilic ligands (phosphoric groups) through ionic bonding and to act as a bridging element and/or form complexes of different stabilities. Also, a high proportion of the total Mg^{2+} is involved in the regulation of cellular pH and the cation-anion balance (Clarkson and Hanson, 1980). Excessive soil Mg^{2+} concentrations can be toxic to plants, and the degree of toxicity is influenced by the Ca^{2+} to Mg^{2+} ratio. Although magnesium uptake was found significantly different among the plant species, but between waste water irrigation treatment was not significantly different. The magnesium concentration in the waste water did not seem to affect the growth and ion uptake of the plants.

Calcium is essential in the preservation of the structural and functional integrity of plant cell membranes (Hanson, 1984), stabilization of cell wall structure, regulate ion transport, and control of ion-exchange behavior, as well as cell wall enzyme activities (Demarty, Morvan, and Thellier, 1984). Because Ca^{2+} is readily displaced from its extracellular binding sites by other cations, plant growth may become seriously impaired by reduced Ca^{2+} availability or a high Na^+/Ca^+ ratio (Kent and Lauchli, 1985; Maas and Grieve, 1987; Solomon, et. al., 1989; Ehret et al., 1990). Lynch and Lauchli (1985) proposed that sodium may inhibit the radial movement of Ca^{2+} from the external solution to the xylem by screening cation-exchange sites in the apoplast. Cramer, Lauchli, and Polito (1985) and Cramer, et al. (1987) concluded that the primary response to NaCl stress in cotton roots is the displacement of membrane-associated Ca^{2+} by Na^+, leading to increased membrane permeability and to loss of K+/Na+ selectivity. Wang, Suhayda, and Redmann (1992) tested three ecotypes of wild barley *(Hordeum jubatum* L.) and found two of the three were more tolerant to magnesium-sulfate salinity and high Na^+ than the third, which they attributed to the two ecotypes' superior Ca^{2+} use efficiency and their ability to restrict Na^+ and Mg^{2+} translocation to the leaves. Differential susceptibility to Ca^{2+} disorders at high Na^+/K^+ levels was also reported among genotypes within crop species (Yeo and Flowers, 1985; Grieve and Maas, 1988). The waste water irrigation significantly increased calcium uptake in the leaves of the the plants, but not in the roots (the underground tissues). The increase of calcium in the leaves may be beneficial to the plants, and it seems to coincide with the chloride tolerance of the plant species. The greater ability to take up calcium may be responsible for the chloride tolerance of the plant species.

Literature Cited

Alt, D., R. Zimmer, M. Stoch, I. Peters, and J. Krupp. 1982. Erhebungsuntersuchungen zur Nahrstoffversorgung von *Picea omorika* im Zusammenhang mit dem Omorikasterben. Z. Pflanzenernaehr. Bodenkd. 145, 117-127.

Asano, T. 1981. Evaluation of agricultural irrigation projects using reclaimed water. Agreement 8-179-215-2. Office of Water Recycling. California State Water Resources Control Board, Sacramento, CA.

Asano, T., R.G. Smith and G. Tchobanglous. 1984. In Pettygrove, G.S. andT. Asano (Eds.). 1984. Irrigation with reclaimed municipal wastewater-a guidance manual Report No. 84-1 wr. Calif. State Water Resource Control Board, Sacramento, CA.

Bear, F.E., A.L. Prince, and J.L. Malcolm. 1945. Potassium needs of New jersey soils. New Jersey Agr. Exp. Sta. Bull. 721.

Clarkson, D.T. and J.B. Hanson. 1980. The mineral nutrition of higher plants. Annu. Rev. Plant Physiol. 31:239-298.

Cook, M.G. and T.B. Hutcheson, Jr. 1960. Soil potassium reactions as related to clay mineralogy in selected kentucky soil. Soil Sci. Amer. Proc. 24, 252-256.

Cramer, G.R., Lauchli, A., and Poliyto, V.S. 1985. Displacement of Ca^{2+} by Na^+ from the plasmalemma of root cells: A primary response to salt stress, *Plant Physiology* 79**,** 207-211.

Cramer, G.R., Lunch, J., Lauchli, A. and Epstein, E. 1987. Influx of Na^+, K^+, and Ca^{2+} into roots of salt-stressed cotton seedlings. Effects of supplemented Ca^{2+}, *Plant Physiology*, 83, 510-516.

David, D.S. 1960. The determinations of exchangeable sodium, potassium, calcium, and magnesium in soils by atomic absorption spectrophotometry. *Analyst*, 85:495-503.

Demarty, M., Morvan, C., and Thellier, M. 1984. Calcium and cell wall, *Plant Cell Environment*, 7, 441-448.

Ehret, D.L., Redmann, R.E., Harvey, B.L., and Cipywnky A. 1990. Salinity-induced calcium deficiencies in wheat and barley, *Plant and Soil*, 128, 143-151.

Grieve, C.M. and Maas, E.V. 1988. Differential effects of sodium/calcium ratio on sorghum genotypes, *Crop Science*, 28, 659-665.

Harivandi, M.A., J.D. Butler, and L. Wu. 1992. Salinity and turfgrass culture. turfgrass (D.V. Wadington, R.N. Carrow, and R.C. Shearman, eds.), *Agronomy*, 32:207-229.

Kent, L.M. and Lauchli, A. Germination and seedling growth of cotton: Salinity-calcium internations, *Plant Cell Environment,* 8, 155-159.

Lynch, J. and Lauchli, A. 1985. Salt stressed disturbs the calcium nutrition of barley (*Hordeum vlugare* L.), *New Phytologist*, 99, 345-354.

Maas, E.V. and Grieve, C.M. 1987. Sodium-induced calcium deficiency in salt-stressed corn, *Plant Cell Environment*, 10, 559-564.

Nitsos, R.E. and H.J. Evans. 1969. Effects of univalent cations on the activity of particulate starch synthetase. *Plant Physiol.* 44, 1260-1266.

Preusser, E., F.A. Khalil, and H. Goring. 1981. Regulation of activity of the granule-bound starch synthetase by monovalent cations. *Biochem. Physiol. Pflanz.* 176, 744-752.

Solomon, M. Ariel, R., Mayer, A.M. and Poljakoff, A. 1989. Reversal by calcium of salinity-induced growth inhibition in excised pea roots, *Israeli Journal of Botan*y, 38, 65-69.

Yeo, A.R. and Flowers, T.J. 1985. the absence of an effect of the Na/Ca ratio on sodium chloride uptake by rice (*Oryza sativa* L.), *New Phytologist*, 99, 81-90.

Lin Wu and James A. Harding, Professors, are with the Department of Environmental Horticulture, UC Davis. M. A. Harivandi is Area Advisor, UC Cooperative Extension, Alameda, Contra Costa and Santa Clara Counties.