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Second Edition

Agricultural Salinity Assessment and Management



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EWRI ASCE ENVIRONMENTAL & WATER RESOURCES INSTITUTE

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Agricultural Salinity Assessment and Management, Second Edition

Prepared by the Water Quality Technical Committee of
the Irrigation and Drainage Council of
the Environmental and Water Resources Institute
of the American Society of Civil Engineers

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FOREWORD

This updated ASCE manual of practice considers salinity and trace element management in irrigated agriculture and water supplies worldwide. It is comprised of 34 chapters written by academic, agency, and consulting experts whose training ranges from the basic sciences to applied sciences and engineering. While there may appear to be some redundancy in topic coverage among the chapters, this enables each chapter to stand independently, such that if, for example, the reader needs more in-depth information on plant responses to saline/sodic soils after reading a related water-quality chapter, it is readily accessible. Wes Wallender has guided this updated manual to build and expand on the original that was assembled and published under Ken Tanji's editorship nearly 20 years ago, with the stated goal to be "a reference to help sustain irrigated agriculture." This manual goes well beyond that need and should accessed by water professionals interested in developing and managing ever-constrained water supplies worldwide.

Nature and Extent of Agricultural Salinity. This chapter presents an overview of the nature of salinity in soils and waters, its extent from global to regional scales, the reactivity of salts and salt flows, and the concerns of agriculture and other sectors of society. Note in the opening paragraphs that, in fact, saline drainage water discharge *has been challenged* and regulations *presently exist* in California and elsewhere as part of basin plans.

Chapter 2: Overview: Diagnosis of Salinity Problems and Selection of Control Practices. This critical chapter summarizes the principal adverse effects of salts on soils and plants, and describes a methodology for diagnosing the nature and cause of salinity problems, while providing guidance on assessment and selection of appropriate reclamation and management practices. This is a difficult area for many practicing engineers; ample guidance is provided here for developing evaluation and monitoring programs for impacted soils.

Chapter 3: The Chemistry of Salt-Affected Soils and Waters. When greater in-depth knowledge is needed, this chapter provides essential background information about the weathering process and geochemical

reactions in soils. Don Suarez describes the basic processes, as well as currently available chemical equilibrium-type models.

Chapter 4: Chemistry of Trace Elements in Soils and Groundwater. This is a very well written complementary chapter to the previous chapter, with the objective of providing a framework for the factors and processes to consider when evaluating trace element concentrations in soils and shallow groundwater of irrigated agricultural areas. The focus here is on the description of the U.S. Environmental Protection Agency priority trace element pollutants of concern. This information is becoming more crucial to water supplies across the globe as water managers face dilemmas associated with trace element contamination.

Chapter 5: Soil Response to Saline and Sodic Conditions. In field soils, accumulation of sodium in the soil solution and the exchange phase generally adversely affect soil physical properties critical to watershed processes affecting drainage and groundwater quality, such as structural stability, hydraulic conductivity, infiltration rate, runoff, and erosion. While extensive reviews of saline-sodic effects on soil properties in laboratory samples exist, Isaac Shainberg notes that "these conditions do not prevail in the field where slower wetting rate and ageing at different AMCs decrease the susceptibility of soils to sodic conditions." He then seeks "to demonstrate the effect of inherent soil properties and time-dependent physical conditions on the susceptibility of soils to sodic conditions." This is a critical distinction in the field as lab results to date have had little success in predicting field responses to saline-sodic conditions. At the same time, however, acquiring an understanding of these processes has guided water managers and will continue to do so as better field-applicable knowledge is developed.

Chapter 6: Plant Responses to Saline and Sodic Conditions. This is a companion chapter to Chapter 5 in providing a general overview of the principal mechanisms and crop responses to salinity and sodicity stress available in scientific literature. Because many water managers and practitioners may be less knowledgeable in the plant sciences, this is an important chapter to have available, though it may seem a little daunting. Lauchli and Grattan underscore that, since the previous edition of the manual, "our knowledge and understanding of the physiological mechanisms of salt tolerance in plants has greatly increased" with ever-more rapid progress "made in elucidating molecular and genetic aspects of salt tolerance in plants." However, as shown in the previous chapter, as crops and plants integrate a number of environmental stresses, their responses in the field have been less predictable from the laboratory results considering less than a handful of stress factors in any one set of experiments. Nonetheless, more exciting research opportunities are readily available.

Chapter 7: Deficiencies and Toxicities of Trace Elements. In this review of general trace element chemistry in soils, Chen, Chang, and Page

consider the factors affecting their availability, mobility, and accumulation by crops, as well as their fate and transport through a generalized mass balance-type model. For many trace elements there is a narrow window of concentrations in soil solutions between deficient and toxic conditions for either the plant or those that consume the plants; understanding something of this window and the processes affecting it is ever-more important. This is essential information because various recycled and treated waters are increasingly reused in irrigated agriculture, as well as from the perspective of water managers considering the quality of these waters.

Chapter 8: Transgenic Strategies toward the Development of Salt-Tolerant Plants. Understanding plant response stresses associated with salinity, sodicity, and trace elements sets the stage for developing alternative, or transgenic, plants that better tolerate some of these stresses brought on by the changing environmental conditions facing irrigated agriculture. This chapter is one of hope; it summarizes some of these opportunities and how they may play out. For example, boron phytotoxicity is a problem for citrus production in many salinity-affected areas, though the general irrigation water quality is acceptable for a wide variety of other uses (including human consumption). Development of a transgenic lemon rootstock would facilitate sustaining the citrus industry in such areas.

Chapter 9: Field Sampling of Soil, Water, and Plants. Field sampling and monitoring is critical toward evaluation and assessment of soil-water processes and plant responses to those processes. Unfortunately, this dimension of investigation is often lacking or entirely absent in diagnosing various environmental problems. Hanson and Grattan have the necessary background and provide a straightforward description of what is needed to develop a sampling strategy for different requirements. Integrated simultaneous sampling and monitoring of the soil, waters, and plants are essential to furthering research in these irrigated systems. This chapter provides a basic starting point for the practitioner to design and establish a field monitoring and sampling program.

Chapter 10: Laboratory and Field Measurements. Management of the plant rootzone is the focus of irrigated agriculture, and this chapter begins with a description of the "leaching fraction" concept (a more in-depth review of leaching fraction is provided in Chapter 12) and the processes associated with rootzone water and salt balances. The chapter proceeds to describe laboratory and field measurements of soil-water content and salinity with the goal of determining localized or field-wide salinity. The saturation extract, often used to reflect soil-solution chemistry, bears further consideration; this is covered in Chapter 11.

Chapter 11: Irrigation Water Quality Assessments. Irrigation water quality is a key component related to sustainability of the soil-water system affecting soils and plants. As available water resources are strained by

competing demands, a thorough understanding of the impacts of irrigation water quality is needed. This chapter summarizes the previous work on the effects of irrigation water quality on soils and crop production. The continued weak link in this area is the relationship between irrigation water quality and soil-solution chemistry; guidelines are developed for irrigation water presuming more-or-less parity between irrigation water quality and that of the soil solution. Don Suarez underscores the difference in reviewing the soil-water processes and older work on leaching fractions (also considered from a field perspective in Chapter 12).

Chapter 12: Leaching and Rootzone Salinity Control. In regions lacking adequate rainfall leaching of the soil profile salinity and trace elements, irrigation must be carefully managed so as to maintain favorable rootzone water quality without adversely affecting "downstream" (e.g., ground water) water resources. With considerable field experience, Jim Ayars and his colleagues outline the primary rootzone mass balance processes central to determining adequate leaching. They build on the old assumptions of steady-state balances but note that these are effectively conservative in their estimation of leaching requirements. That is, the gap between the actual leaching needed and that suggested by the estimated requirement is narrowing and, together with improved irrigation methods, enabling a closer match between crop water requirements and actual irrigation, so that irrigated agriculture may find sustainability.

Chapter 13: Plant Salt Tolerance. Determination of adequate leaching fractions or requirements is driven in part by knowledge of the salt tolerance of the desired crop. Salt and trace element tolerance thresholds of various crops have been studied for decades and are summarized by these same authors in several publications. Together with the information in Chapter 11, water managers must consider the tolerance thresholds to evaluate various water supplies and their applicability, as well as downstream impacts. Unfortunately, threshold information remains based on the saturation extract or soil-solution concentrations (see Chapter 10) from lab or greenhouse studies on generally coarser-textured soils, and their field applicability combined with assessments of irrigation water quality leave some regulators with a gray zone that is difficult to address. Some thresholds are based on research from the 1930s (e.g., citrus) for which updated information is needed related to more recently available rootstocks. Nonetheless, the information of this chapter is critical to the practitioner as a starting point in designing appropriate irrigation strategies.

Chapter 14: Statistical Models for the Prediction of Field-Scale and Spatial Salinity Patterns from Soil Conductivity Survey Data. This chapter continues and is complementary to the discussion begun in Chapter 10 about field-wide assessment of soil salinity and the appropriate statistical evaluations necessary to complete that spatial assessment using

the soil conductivity survey information. This chapter provides useful information when soil conductivity assessments are deployed.

Chapter 15: Spatially Distributed Solute Balance in a California Water District. This chapter illustrates the benefits of assessments of salinity and mass balance modeling at the larger spatial scales (field to district), and is complementary to Chapters 19 and 20. It combines the information presented in previous chapters into the modeling framework in an effort to determine area-wide salinity and some trace element concentrations, as well as the water quality of the drainage water "leaving" the region, using data available from the water district.

Chapter 16: On-Farm Irrigation and Drainage Practices. For the practitioner unfamiliar with commonly available irrigation and drainage systems in use, this chapter provides a brief, general overview and outlines management options that can help prevent or correct salinity problems and minimize water table build-up. Again, Ayars underscores the age-old importance of drainage for salinity management, as well as methods for management of shallow water tables, and an alternative method for disposal of saline drainage water. This and the following chapter are good background reading for those who need this information.

Chapter 17: Drip Irrigation and Salinity. Drip irrigation is one method that enables fairly high irrigation distribution uniformity and possible salinity control of the rootzone through more precise application of water and fertilizers than is otherwise possible from surface irrigation methods. This chapter provides a basic description of the factors important to drip irrigation system design for adequate irrigation and possible salinity control.

Chapter 18: Management of Dryland Saline Seeps. Saline seeps can result from dryland farming in the Plains states and are a source of downstream degradation and locations of poor, if any, crop production in the landscape. The origin of such seeps is not always readily apparent. This chapter considers the identification, control, and possible reclamation of seep areas. Because seeps occur irrespective of property or government lines and are part of the overall watershed, their identification and reclamation is an important water quality consideration.

Chapter 19: Project-Level Salinity Management Options. In order to address water and salinity management across a wide geographical area that transcends water district and various jurisdictional boundaries, both local- and regional-scale management plans must be coordinated across institutional entities—rarely a simple process. This chapter outlines an approach and provides examples of how such management may be achieved, and follows from the modeling example given in Chapter 15.

Chapter 20: San Joaquin Valley Drainage Management Options. The San Joaquin Valley Drainage Program is an exceptional example of an interagency entity established to address the contamination associated

with subsurface drainage waters as evidenced in the Kesterson Reservoir in the early 1980s. The program continues to-date and has implemented a range of strategies to address the drainage water disposal issue, including source control through land retirement, disposal via evaporation ponds and salt accumulation (solar evaporator) cells, crop rotations through reuse of progressively greater salinity drain waters, and by-product recycling.

Chapter 21: Reclamation of Saline, Sodic, and Boron-Affected Soils. If there is inadequate control of irrigation and soil-water quality such that irrigated soils become salinized and/or otherwise compromised through high boron concentrations, additional reclamation beyond regular leaching is required. In some cases mineral composition of the affected areas limits the options available for reclamation, but the understanding of the reclamation process remains important and may be essential toward development of increased production. Considering various soil processes, Rami Keren reviews the relative success of leaching and addition of amendments to reclaim salt-affected soils, as well as the chemical modeling associated with such processes. Reclamation of boron-affected soils remains problematic, especially in tourmaline-based soils.

Chapter 22: Use of Saline Drainage Waters for Irrigation. This chapter is an extension or continuation of Chapters 12 and 13. The discussion considers several practices using saline water for irrigation, including both their benefits and limitations. Trace elements, such as B, Se, and Mo, may also influence the feasibility of using saline-sodic water for irrigation. The same soil-water and plant tolerance principles apply, but special consideration must be given to potential salt or phytotoxic ion accumulations. Clearly, when using saline waters for irrigation there is an emphasis on control of soil salination and adverse effects on soil physical properties when irrigation waters are sodic as well as saline. In addition, as part of water reuse strategies, there is consideration of salt-tolerant plants and crops. Examples are provided of drainage water reuse studies from the San Joaquin Valley Drainage Program.

Chapter 23: Drainage Water Treatment and Disposal Options. As considered in the previous chapter, reuse of saline drainage waters for irrigation is one part of the drainage water disposal scheme; others involve possible treatment and alternative disposal methods. Some of these are covered in general terms as part of the San Joaquin Valley Drainage Program report considered in Chapter 20, but the focus here is on the possible technologies available or under development for drain water treatment and final disposal. They underscore the magnitude of the salt disposal problem by noting that "2 to 3 million tons of annually imported salts (in addition to significant amounts of salt mobilized from soils as a result of irrigation) needs to be disposed of to maintain salt balance in the San Joaquin Valley," and "even an optimistic estimate of the amount that could be commercially marketed would represent a only a small percent-

age of the total salts needing to be disposed. Active pursuit of commercial utilization of the salts and selenium is needed and will require a variety of options for separating the salts from productive agricultural fields" before sustainability is achievable.

Chapter 24: Agricultural Evaporation Basins. Another disposal option for drain water from irrigated agriculture is through evaporation from open, shallow basins. These basins pose environmental hazards associated with aquatic and bird life and groundwater contamination; understanding the biogeochemical processes occurring in these basins is critical when designing agricultural irrigation systems when drain water disposal elsewhere is not a viable option. This chapter summarizes "their siting, design, operation, chemical/biological characteristics, and environmental and regulatory issues." While such basins are a temporary disposal method, they are often linked with other strategies, as outlined in Chapter 20.

Chapter 25: Salinity Assessment of Irrigation Water Using *WATSUIT*. Development and application of a rootzone water chemistry model is instrumental when evaluating the suitability of irrigation water and determining the appropriate leaching fractions needed to maintain the soil-water chemistry within an acceptable range for the crop of interest (discussed in Chapter 13). *WATSUIT* is a steady-state model due to the complexity of chemical reactions but is nonetheless useful in organizing the various processes outlined in Chapter 7 for trace elements and developing a first-approximation assessment.

Chapter 26: Leaching Requirement: Steady-State versus Transient Models. This is an interesting chapter outlining steady-state and transient modeling of the leaching process and determination of the leaching fraction of irrigated soils. This chapter is continuation of that material in Chapter 12. The verdict on the operational value of transient leaching fraction evaluation is not yet finalized, but the use of the dynamic soil-water content (unsaturated flow) together with basic chemistry models is an excellent concept depending on how one interprets the meaning of "leaching fraction."

Chapter 27: Conceptual Water Flow and Salt Transport for Flux-Limited and Ponded Infiltration. This chapter reviews another model development for rootzone water and salinity dynamics with the added component of bypass flows associated with cracking clay soils. As with the previous two chapters, it outlines the key factors that affect rootzone salinity and that guide possible management strategies.

Chapter 28: Modeling Transient Root Zone Salinity. The objective of a management model should be to represent the underlying process without undue burden on the user for collection of site specific characterization or parameter information. This chapter describes development of another rootzone salinity model (*SWS*), the processes used by the model, as well as applications to management of saline soils or waters. Together

with Chapters 25, 26, and 27, these chapters provide a comprehensive summary of rootzone modeling efforts, their advantages and disadvantages, and their overall applicability to particular problems of interest. With some effort, the average reader or practitioner can ferret through this group of chapters to extract the information needed to determine which model is best applied in the particular situation.

Chapter 29: Long-Term Regional-Scale Modeling of Soil Salinity. While each of the modeling chapters considers rootzone water content and chemistry dynamics, they differ in the scale of application or process detail. This chapter describe the development and application of a rootzone model to larger regional areas of the San Joaquin Valley. Its sister chapters are Chapters 15 and 20. In evaluating long-term salinity variations across the region and possible model simplifications that reduce computing time and data requirements, Hopmans, Schoups, and Tanji find that "a simplified modeling approach can be used with annually averaged boundary conditions and a relatively coarse spatial discretization, but that it must include cation exchange and gypsum dissolution-precipitation reactions." Perhaps more significant is the role of regional groundwater dynamics and salinity in controlling rootzone salinity.

Chapter 30: Conceptual Irrigation Project Hydrosalinity Model. This chapter considers another steady-state hydrosalinity model having similar roots to that developed in Chapter 29 but with an application toward assessing drain-water salinity as part of Total Maximum Daily Load (TMDL) establishment from an irrigated project area. The simplified model requires "only 25" input parameters and is readily available for use on PCs.

Chapter 31: Microeconomics of Salinity and Drainage Management. This chapter begins a change in focus regarding the economics of salinity management in irrigated agriculture. This is an important component of the social decisions that balance the needs of food production and environmental preservation. The framework for these salinity and drainage management models follows from economic theory. Process-based models from the physical and biological sciences are incorporated as needed. The models are "used to explore characteristics of the underlying system, develop efficient management practices, and identify shadow values and policy instruments to achieve efficient and equitable solutions to salinity and drainage problems." The economic models differ from those described in the previous chapters in that they are primarily dynamic optimization models, although some static analyses are included as appropriate. The economic-type models indicate that interseasonal variability for single-crop systems resolve quickly into steady-state conditions, suggesting that steady-state-type hydrosalinity models are adequate at the larger spatial and time scales. Mixed results with future unknown conditional costs are obtained for determinations of whether irrigation uniformity as source

control, drain water reuse, and land retirement options effectively enable sustainable irrigated agriculture.

Chapter 32: San Joaquin Valley, California: A Case Study. Case studies provide a living history of the problems, issues, and possible solutions attempted, and the lessons learned there from, at least from the perspective of the storyteller. This chapter considers the story of the San Joaquin Valley of California from the perspective of a former water district engineer/manager, a regulator, and a federal agency engineer. As the authors note, the ultimate solution to the Valley's drain water disposal problems remains "elusive." The first effort is to "find a long-term solution to permanently dispose of the salty residue from the irrigated lands, and the second is implementation of measures to relieve the immediate drainage problems" while awaiting resolution of the first. Thus far, many of the methods "to reuse and dispose of drainage water have been driven by regulatory needs for water quality and environmental protection rather than considerations of long-term hydrologic and basin protection that must still be outlined in a long-term strategy." This shift in emphasis from salinity management has occurred as a result of the selenium contamination issues that arose at the Kesterson Reservoir. While the previous statement may appear contradictory, it reflects the ongoing story of the San Joaquin Valley agriculture and is good reading for all interested. The reader is referred to Chapter 20 for a basic background on the San Joaquin Valley Drainage Program.

Chapter 33: Institutional and Salinity Issues on the Upper Rio Grande. The Rio Grande River system is a fascinating complex of issues involving multiple states, Native American communities, and reservoirs, and two countries. With the oldest gaging station in the United States, it also has the longest record of information. This chapter is a case study of the Rio Grande basin from the perspective of hydrologic and institutional management issues, sources and impacts of salinity, and potential management alternatives. In nearly all semiarid region rivers, water salinity increases from the headwaters to the discharge point, with irrigated agriculture exacerbating this effect. An interesting outcome of the Rio Grande studies is that earlier agriculture and waterlogging undoubtedly account for some of the increasing salinity downstream, but that the lower-basin geology is such that salts are leached directly into the river and concentrated in major reservoirs. This is a good history and story that well complements that of the San Joaquin Valley.

Chapter 34: Viability of Irrigated Agriculture with Expanding Space and Time Scales. This final chapter is an effort to wrap up all of the discussions in the text, and considers the range of spatial and time scales at play in irrigated agriculture and how they may affect its future viability. This chapter sets a context for the manual and in some ways complements the opening chapter as a conceptual discussion of what is discussed

throughout the manual. As noted, this is good reading for the generalist interested in irrigated agriculture and its future in semiarid and arid regions affected by salinity.

Overall, this updated and revised manual continues the Tanji legacy of eliciting worldwide cooperation and integration of scientists and engineers to address the problems of salinity and trace element management in irrigated agriculture. It is never a small feat to bring together such a range of talents and characters.

Mark E. Grismer, Chair, Peer Review Committee

PREFACE

Under the editorship of Kenneth K. Tanji, ASCE Manuals and Reports on Engineering Practice No. 71, *Agricultural Salinity Assessment and Management*, was first published in 1990. In the years following, Ken recognized the significant gains in the knowledge base and advances in technology and initiated the process of revising the manual. In their July 2002 meeting, the Water Quality and Drainage Technical Committee agreed to the recommendation of Editor Tanji to revise the manual. A formal proposal for a Task Committee to revise the manual was first submitted on or about August 2002 to the Irrigation and Drainage Council of ASCE/EWRI (Environmental and Water Research Institute), and at that time the effort was to start on October 1, 2002 and end on September 30, 2005. After approval in 2004, the Task Committee was launched in January 2005 and, by October 2006, it had determined the revisions desired, the authors of existing chapters to be revised, and the authors for new chapters. Drafts of chapters were requested to be completed on or about March 2007, with the goal of completing a complete draft by December 2007. By September 2007, about one-third of the 34 chapters had been submitted.

Sadly, Ken passed away suddenly on Friday, September 7, 2007, and this left an enormous void in leadership and vision—not only regarding the completion of Manual 71 but also in expertise in agricultural salinity and management. Wes Wallender volunteered and was approved by the Irrigation and Drainage Council as the editor to complete one of Ken's many great works. By the fall of 2008, all the chapters had been submitted. They were technically reviewed by the Task Committee (each chapter was reviewed by a member of the Committee) and revised by the authors. The draft document, finalized by the Committee, was given to ASCE for review. The Irrigation and Drainage Council appointed a Review Committee of three members of ASCE, comprising a balance of interests, with expertise in the subject matter. They were independent from the Task Committee and were not authors. Their written reviews were completed by September 2009 and submitted to the Task Committee. By October 2, 2009, the Committee found no differences between reviews to resolve and agreed to make all the suggested changes.

All of the reviewers' suggested changes were made.

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