Irrigation Systems Management

Dean E. Eisenhauer
Derrel L. Martin
Derek M. Heeren, General Editor
Glenn J. Hoffman
This book is dedicated to our wives and children for their love and support:

Maria, Emily, and April

JoAnn, Jennifer, and Kimberly

Amber, David, Elizabeth, Nathan, and Joshua

Maria, Kimberly, Karen, and Sheryl
Foreword

Agriculture is the largest consumer of global freshwater resources, currently estimated to account for 75 percent of all water diverted for human use. The global population is anticipated to peak at approximately 10 billion in 2050, and our food systems will need to evolve to respond to the increasing population, improving diets, climate change and other political and social changes. The demand for water for food, fiber and fuel is projected to increase by another 50 percent in that time frame. Today, one third of the world’s food is produced on 21 percent of its cultivated land as a result of effective irrigation systems. This clearly highlights the import role irrigation will continue to play in intensifying agricultural production and feeding the world.

Irrigation has a long history. Around the world, water has been diverted for irrigation for thousands of years. In the United States remnants of irrigation infrastructure dating back over 3200 years can be found in the Southwest. For the last 250 years, the total area under irrigation in the U.S. has continuously increased. Despite this expansion and increasing crop productivity, the amount of water used for agriculture has remained relatively stable since the 1980s, showing an improvement in how agricultural water is managed.

With all the gains achieved through irrigation, there remain downsides to consider—and there are many if close attention is not paid to the system, its management, and the sustainability of vital soil and water resources. Over-extraction—or taking more water than can be replaced through precipitation—of both groundwater and surface water is a widespread issue around the world. This is especially true in the absence of robust water accounting to determine the resources available and ensuring overall consumptive use does not exceed system limits. Mismanagement of the water, fertilizer and other agricultural chemicals can lead to degradation of water quality and contamination of ground and surface water resources. That said, well managed irrigation presents the opportunity to minimize the level of contamination.

Farmers’ access to irrigation is a crucial component of a highly productive agricultural system—one that reduces risk and increases resilience. For it to be effective, the system must integrate into the broader farm system, provide the farmer with a solid return on their investment and sustain the vital natural resources upon which the enterprise depends.

Drawing on decades of collective experience in research, teaching, outreach and practice, the authors present the knowledge and technical insights into the development and management of the common irrigation systems adopted across the U.S. and many other parts of the world. The understanding of these systems—combined with the relevant knowledge in other contexts—are critical to addressing water and food security for the future.

Peter G. McCormick, Executive Director
Daugherty Water for Food Global Institute (DWFI)
at the University of Nebraska
Preface

Like most textbooks, this book grew out of our desire to have written material that matches the educational needs of both the students and the instructor of a college course, in this case a course entitled *Irrigation Systems Management*. The book is the culmination of course notes which have been in development and use for nearly 30 years.

The emphasis of this book is on the management of irrigation systems that are used for agricultural crop production. There are two distinct components of the book, starting with the soil-water-plant-atmosphere system and how soil water should be managed to achieve the desired crop production outcomes. This includes in-depth presentations on soil water storage and movement, plant water use, managing the soil water reservoir through irrigation scheduling, and salinity management. The book then shifts to the second component, which is the description and management of the various forms of agricultural irrigation systems along with their water supply. Whether it be a surface, sprinkler, or microirrigation system, the irrigation manager must not only know how much water to apply but also how to manage the system itself to achieve efficient application. High application efficiency can only be realized by minimizing runoff, deep percolation, evaporation, and drift onto non-target areas. Since energy costs are an integral part of the management equation, one chapter in the book deals with the hydraulics and energy requirements of pumping and distributing water. One of the key themes spread throughout the book is providing guidance to irrigation managers on how to improve irrigation water productivity (production per unit of irrigation water) and minimize water resource contamination.

Our goal is for the reader to understand the complexities of irrigation systems and how they are to be managed to meet the water needs of the crop production system. This is not an irrigation engineering design book; we have purposely minimized the presentation of design steps and the supporting equations. The intended audience of the book is upper-level undergraduate students and graduate students who are pursuing degrees in Agricultural or Natural Resource Sciences. Example majors include Agricultural Systems Technology, Agronomy, Crop Science, Mechanized Systems Management (or equivalent), Natural Resources Management, Soil Science, and Water Science. We expect the reader to have a basic understanding of soils, crops, physics, and the application of algebraic equations. We have also tried to add enough advanced material to challenge graduate students when the book is used in courses that are taught simultaneously at the undergraduate and graduate level. We hope the book will match the needs of students who plan to work in irrigation and related industries, university extension and outreach, private consulting, government service, or production agriculture and that it will continue to serve as a useful reference to them following completion of their formal education.

The book is being published by the American Society of Agricultural and Biological Engineers (ASABE) as an open-access book and will be available online at no charge so that it can be used globally for a wide array of applications. Specific chapters, for example, may be useful for international workshops, industry training sessions, employee onboarding, non-governmental organizations involved in irrigation development, continuing education, etc. The book uses a mix of the U.S. Customary System of Units (USCS) and the International
System of Units (SI), although USCS is used most frequently, reflecting the context in which the book was developed. However, we have added helpful unit conversions to assist readers in countries where SI units are common.

The notes from which this book was developed have been tried and tested for many years, not just at the University of Nebraska-Lincoln (UNL), but also at other land-grant universities in the U.S. including Kansas State University, Oklahoma State University, South Dakota State University, Texas A & M University, University of Missouri, and Washington State University. For four years the book was used for continuing education of statewide field staff of the Natural Resources Conservation Service in Nebraska. In addition, selected chapters have been used regularly in our Irrigation Laboratory and Field Course, a course that we originally developed specifically for international students who were studying at the IHE Delft Institute for Water Education in Delft, The Netherlands. We appreciate the feedback for improvement from all students and instructors who have used the draft of the book.

The authors of the book have a combined and balanced experience of over 150 years in teaching, research, extension, and consulting. A very high proportion of their experience is in the Midwest, Great Plains, and Western region of the U.S. Thus, they are accustomed to larger-scale farm irrigation systems. However, the authors also have significant international experience through various assignments and projects in countries throughout the world, giving them a wider view of farm irrigation systems, including smallholder farms, which influenced the approaches taken in the book.

One final note is on the arrangement of names for the author order of the book. This can sometimes be an awkward dilemma: who contributed the most? This book was truly a team effort with all authors making significant original writing and editorial contributions. Eisenhauer, Martin, and Hoffman, now Emeriti faculty members of the Department of Biological Systems Engineering at UNL, initiated the development of the book. That said, the truth is the completion of the book would never have occurred without the final push and motivation by Derek Heeren, Associate Professor in Biological Systems Engineering and the current instructor of Irrigation Systems Management. Appropriately he is listed as General Editor because of his extra efforts in working through the publication process with our team and the publisher, ASABE.

Dean E. Eisenhauer
Derrel L. Martin
Derek M. Heeren, General Editor
Glenn J. Hoffman
May, 2021
Acknowledgements

The development of a textbook of this magnitude is only possible with the help of many people, including the support staff who prepared and formatted the manuscript and provided editorial suggestions. Biological Systems Engineering Office Associates who provided immeasurable assistance in this process include Lorna Pleasant, Teresa Ryans, and Julie Thompson. Sheila Smith, Illustrator in Biological Systems Engineering, developed most of the original artwork and drawings. Some of the concepts and questions in the book were developed during class laboratory activities; technical support for these activities was provided primarily by Alan Boldt, Research Engineer and Lab Manager in Biological Systems Engineering. We are forever grateful for the assistance of these staff members.

Over the years many student hourly employees have provided assistance with proof reading, providing editorial comment, and helping prepare graphics and equation formatting. At the risk of inadvertently leaving out the names of some, we gratefully acknowledge the help of the following former students: Sonya Cooper, Clayton Blagburn, Troy Nelson, and Eric Wilkening. Eric was especially instrumental in the final push towards publication with his help in updating and refining the figures and formatting the text. The input of these students was extremely useful.

We are indebted to our publisher, ASABE. This includes staff members Donna Hull, Joseph Walker, and Peg McCann. Their guidance in navigating through the process and assistance with the book’s development was so very helpful. We appreciate the patience of this group, especially Donna who we’re sure gave up on us years ago. Also, the book’s quality was greatly enhanced by incorporating comments made by reviewers who had been selected by the publisher: Dr. Thomas Scherer, Dr. Michael Kizer, Dr. Donald Slack, Dr. Allen Thompson, and Dr. Trisha Moore.

We are especially grateful for the financial support needed to get the book into a publishable form. Support was provided by the ASABE Foundation’s Harold Pinches and Glenn Schwab Teaching Materials Fund and the Daugherty Water for Food Global Institute at the University of Nebraska.

Finally, we would like to thank the UNL administration in Biological Systems Engineering and the Institute of Agriculture and Natural Resources for allowing us to pursue and successfully complete this project.

Dean E. Eisenhauer  
Derrel L. Martin  
Derek M. Heeren, General Editor  
Glenn J. Hoffman  
May, 2021
Dr. Dean E. Eisenhauer is an Emeritus Professor of Biological Systems Engineering at the University of Nebraska-Lincoln where he specialized in hydrologic and irrigation engineering with appointments in teaching, research, and extension. He received B.S. and M.S. degrees in Agricultural Engineering from Kansas State University and a Ph.D. degree in Agricultural Engineering from Colorado State University. He was on the University of Nebraska-Lincoln faculty from 1975 until he retired in 2015. Dean taught courses in irrigation management, watershed management, engineering hydrology, hydrologic modeling, and vadose zone hydrology. His research interests include hydrologic impacts of land use and water management practices in agricultural regions, infiltration and overland flow, water flow in the vadose zone, engineering of vegetative buffers for riparian and upland ecosystems, chemigation, management of furrow irrigation, and water measurement technology for irrigation.

Dean advised or co-advised 33 graduate students and served on 73 graduate student committees during his career. He has co-authored 57 journal articles and 4 book chapters. He is a registered Professional Engineer in Nebraska. Dean is a Faculty Fellow in the Robert B. Daugherty Water for Food Global Institute (DWFI) at the University of Nebraska. At DWFI he was a co-developer of a successful partnership with IHE Delft Institute for Water Education in Delft, Netherlands (IHE). Dean’s pastimes and hobbies include spending time with family, vegetable gardening, bicycling, traveling, and reading.

Dr. Derrel L. Martin is Professor Emeritus of Irrigation and Water Resources Engineering in the Department of Biological Systems Engineering at the University Nebraska-Lincoln. He earned B.S. and M.S. Degrees in Agricultural Engineering from the University of Nebraska in 1975 and 1979. He received his PhD from Colorado State University in 1984. Derrel has also worked for a state agency and a consulting company before attending graduate school. Dr. Martin is a Professional Engineer, a Fellow of the ASABE, and served as Chair of the Soil and Water Division of the ASABE.

Dr. Martin worked in the Department of Biological Systems Engineering at the University of Nebraska-Lincoln for forty-one years. He taught courses in irrigation engineering and management, and vadose zone hydrology. His research focused on irrigation engineering and management, protection of groundwater quality by minimizing pollution from agricultural chemicals, deficit irrigation due to water limitations, evapotranspiration and crop water use, and modeling the soil-water-plant system to assess productivity. He spent over fifteen years delivering Extension programs on irrigation, water resources management and energy use in irrigated agriculture. He developed software used by state and local water management agencies. He served as an expert witness in regional litigation and United States Supreme Court actions. He grew up on an irrigated farm and ranch in western Nebraska and continues to work with family partners. Derrel’s interest include spending time with family, attending collegiate sporting events, and volunteering.

Dr. Derek M. Heeren is an Associate Professor and Irrigation Engineer in the Department of Biological Systems Engineering at the University of Nebraska-Lincoln (UNL), and a Faculty Fellow of the Daugherty Water for Food Global Institute (DWFI). He graduated from
South Dakota State University in 2004 with a B.S. in Agricultural and Biosystems Engineering and an M.S. in 2008. Before graduate school, Derek spent two years working at a geotechnical engineering firm near St. Louis, Missouri. He obtained his Ph.D. in Biosystems Engineering from Oklahoma State University in 2012, before coming to UNL.

Derek has taught or co-taught eight courses, including Irrigation Systems Management, Advanced Irrigation Management, Irrigation Laboratory Field Course, and Modeling Vadose Zone Hydrology. Derek’s research has addressed irrigation management, sprinkler irrigation systems, irrigation technology, vadose zone hydrology, water quality, and surface water-groundwater interaction, with projects in the United States, India, Malawi, Zambia, and Rwanda. Derek has published 43 peer-reviewed journal articles. He has served as advisor or coadvisor for 12 graduate students from six countries and has served on graduate committees for an additional 15 graduate students. Derek is the Partnership Coordinator for the partnership between DWFI and the IHE Delft Institute for Water Education, Delft, Netherlands. Outside of work, Derek enjoys time with family, outdoor hobbies, and church activities.

Dr. Glenn J. Hoffman received combined BS and MS degrees in Agricultural Engineering in 1963 from Ohio State University followed by a PhD from North Carolina State University. He started in 1966 as a research engineer at the USDA/ARS (Agricultural Research Service) Salinity Laboratory in Riverside, California. His research led to recognition as an international authority on the management of irrigated salt-affected soils and crop salt tolerance. In 1984, Glenn led scientists at the USDA/ARS Water Management Laboratory in Fresno, California on studies of subsurface drip irrigation and the water requirement and salt tolerance of tree crops.

Glenn was selected head of the Agricultural Engineering Department at the University of Nebraska-Lincoln in 1989. He led faculty members to change the department to Biological Systems Engineering. Undergraduate enrollment increased 5-fold to 250 and graduate student numbers doubled. The department’s annual budget, including grants, increased to more than $6 million. He retired in 2003.

Glenn is the author of 170 scientific publications, including 17 book chapters and lead editor of 2 irrigation monographs. He consulted on salinity management in Israel, Australia, Spain, Pakistan, Egypt, Iran, India, Brazil, China, and Argentina. Personal interests include family activities, foreign travel, mineral collecting, and bridge.
Contents

Foreword ........................................................................................................... xiii
Preface ............................................................................................................... xv
Acknowledgements ....................................................................................... xvii
About the Authors ........................................................................................ xix
Common Unit Conversions for Irrigation ................................................... xxi

Chapter 1 Introduction to Irrigation ......................................................... 1
1.1 Introduction ............................................................................................... 1
1.2 Role of Irrigation .................................................................................... 2
1.3 Irrigation Development ........................................................................... 3
1.4 Impact of Irrigation on Water Resources and the Environment .............. 6
1.5 Irrigation Management Concepts ........................................................... 7
1.6 Summary ................................................................................................. 8
Questions ....................................................................................................... 8
References ...................................................................................................... 8

Chapter 2 Soil Water ................................................................................. 11
2.1 Introduction ............................................................................................... 11
2.2 Soil Composition .................................................................................... 11
2.3 Soil Water Content ............................................................................... 12
2.4 Soil Water Potential .............................................................................. 14
2.5 Available Water and the Soil Water Reservoir ...................................... 16
2.6 Determining Available Water Capacity ............................................... 18
2.7 Tabulated Values of Typical Soil Properties ....................................... 19
2.8 Infiltration ............................................................................................... 20
2.9 Storage of Infiltrated Water .................................................................. 23
2.10 Measuring Soil Water Content and Matric Potential .......................... 24
   2.10.1 Gravimetric Method .................................................................. 24
   2.10.2 Feel and Appearance ................................................................ 25
   2.10.3 Neutron Scattering .................................................................. 25
<table>
<thead>
<tr>
<th>Section</th>
<th>Pages</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.10.4 Time Domain Reflectometry</td>
<td>26</td>
</tr>
<tr>
<td>2.10.5 Capacitance Probes</td>
<td>27</td>
</tr>
<tr>
<td>2.10.6 Tensiometers</td>
<td>27</td>
</tr>
<tr>
<td>2.10.7 Electrical Resistance Blocks and Granular Matrix Sensors</td>
<td>28</td>
</tr>
<tr>
<td>2.10.8 Thermal Dissipation Blocks</td>
<td>29</td>
</tr>
<tr>
<td>2.10.9 Placement of Soil Water Sensors</td>
<td>29</td>
</tr>
<tr>
<td>2.10.10 Remote Sensing</td>
<td>29</td>
</tr>
<tr>
<td>2.11 Summary</td>
<td>30</td>
</tr>
<tr>
<td>Questions</td>
<td>30</td>
</tr>
<tr>
<td>References</td>
<td>32</td>
</tr>
<tr>
<td>Chapter 3 Measuring Water Applications</td>
<td>35</td>
</tr>
<tr>
<td>3.1 Introduction</td>
<td>35</td>
</tr>
<tr>
<td>3.1.1 Need for Water Measurement</td>
<td>35</td>
</tr>
<tr>
<td>3.1.2 Depth Volume Relationships</td>
<td>35</td>
</tr>
<tr>
<td>3.2 Basic Principles of Flow Measurement</td>
<td>37</td>
</tr>
<tr>
<td>3.2.1 Velocity-Flow-Area Relationship</td>
<td>37</td>
</tr>
<tr>
<td>3.2.2 Measurement of Mean Velocity</td>
<td>38</td>
</tr>
<tr>
<td>3.2.3 Distribution of Velocity</td>
<td>38</td>
</tr>
<tr>
<td>3.3 Flow Measurement in Pipelines</td>
<td>38</td>
</tr>
<tr>
<td>3.3.1 Mechanical Meters</td>
<td>38</td>
</tr>
<tr>
<td>3.3.2 Pressure Differential Methods</td>
<td>40</td>
</tr>
<tr>
<td>3.3.3 Ultrasonic Measurement</td>
<td>41</td>
</tr>
<tr>
<td>3.3.4 Magnetic Flowmeters</td>
<td>42</td>
</tr>
<tr>
<td>3.4 Flow Measurement in Open Channels</td>
<td>43</td>
</tr>
<tr>
<td>3.4.1 Velocity Methods</td>
<td>43</td>
</tr>
<tr>
<td>3.4.2 Pressure Differential Methods</td>
<td>44</td>
</tr>
<tr>
<td>3.5 Summary</td>
<td>46</td>
</tr>
<tr>
<td>Questions</td>
<td>46</td>
</tr>
<tr>
<td>References</td>
<td>47</td>
</tr>
<tr>
<td>Chapter 4 Plant Water Use</td>
<td>49</td>
</tr>
<tr>
<td>4.1 Introduction</td>
<td>49</td>
</tr>
<tr>
<td>4.2 Water Use Processes</td>
<td>50</td>
</tr>
<tr>
<td>4.3 Measurement of Evapotranspiration</td>
<td>52</td>
</tr>
<tr>
<td>4.3.1 Aerodynamic Methods</td>
<td>52</td>
</tr>
<tr>
<td>4.3.2 Soil Water Methods</td>
<td>53</td>
</tr>
<tr>
<td>4.3.3 Lysimetry</td>
<td>53</td>
</tr>
<tr>
<td>4.3.4 Plant Monitoring Methods</td>
<td>55</td>
</tr>
<tr>
<td>4.4 Calculating ET</td>
<td>55</td>
</tr>
</tbody>
</table>
4.5 Reference Crop ET .......................................................... 56
4.6 Crop Coefficients.......................................................... 62
  4.6.1 Basal Crop Coefficients ............................................ 64
  4.6.2 Water Stress Effects ............................................... 68
  4.6.3 Wet Soil Evaporation ............................................. 69
  4.6.4 Methods to Describe Canopy Development .......... 71
4.7 Intercropping .................................................................. 71
4.8 Accessing Climatic Information ...................................... 74
4.9 Summary ...................................................................... 75
Questions ......................................................................... 76
References ....................................................................... 77

Chapter 5 Irrigation System Performance ......................... 79
5.1 Introduction ................................................................ 79
5.2 Types of Systems ........................................................ 79
  5.2.1 Sprinkler Irrigation ................................................. 79
  5.2.2 Surface Irrigation ................................................... 80
  5.2.3 Microirrigation ........................................................ 81
5.3 Performance Measures .................................................. 82
  5.3.1 Efficiency ............................................................... 82
  5.3.2 Application Uniformity ............................................. 83
  5.3.3 Adequacy of Irrigation ............................................. 86
  5.3.4 Application Efficiency of the Low Quarter:
       Unification of Efficiency and Uniformity ................. 87
  5.3.5 The Scheduling Coefficient ...................................... 90
  5.3.6 Chemical Leaching Losses .................................... 90
  5.3.7 Conveyance Efficiency .......................................... 92
5.4 System Evaluation ....................................................... 94
5.5 Irrigation System Capacity ............................................ 95
5.6 Determining System Capacity Requirements .................... 95
5.7 Operational Factors ..................................................... 99
5.8 System Characteristics ............................................... 100
5.9 Safety with Irrigation Systems .................................... 101
5.10 Irrigation Efficiency and Water Resources
       Sustainability ............................................................ 101
5.11 Summary ................................................................ 103
Questions ....................................................................... 103
References ..................................................................... 105
Chapter 9 Water Supply Systems ................................................. 171
  9.1 Introduction ........................................................................ 171
  9.2 Water Rights and Laws ...................................................... 173
    9.2.1 Surface Water ........................................................... 173
    9.2.2 Groundwater ............................................................. 173
  9.3 Aquifers ............................................................................. 174
  9.4 Groundwater Supplies .......................................................... 176
    9.4.1 Shallow Wells ............................................................ 176
    9.4.2 Tube or Cased Wells ................................................. 178
    9.4.3 Deep Wells and Well Hydraulics ............................... 178
    9.4.4 Well Construction .................................................... 179
  9.5 Surface Water Supplies ...................................................... 180
    9.5.1 Open Canals ............................................................. 181
    9.5.2 Pressurized Delivery Systems ................................... 182
  9.6 Surface Water-Groundwater Interaction ............................ 182
  9.7 Reclaimed Water Supplies .................................................. 183
  9.8 Summary ........................................................................... 183
  Questions ................................................................................ 183
  References ............................................................................. 184

Chapter 10 Surface Irrigation ..................................................... 185
  10.1 Introduction ....................................................................... 185
  10.2 Advance, Recession, and Infiltration .................................. 187
  10.3 Water Balance ................................................................. 190
  10.4 Efficiency .......................................................................... 191
    10.4.1 Calculation of Irrigation Efficiency ............................ 191
    10.4.2 Improvement of Surface Irrigation Systems .......... 192
  10.5 Management of Sloping Furrow Irrigation Systems .......... 193
  10.6 Basin and Border Irrigation ............................................... 200
12.5.3 Operational Characteristics ........................................ 268
12.5.4 Management ............................................................ 270
12.5.5 Other Issues ............................................................ 272
12.6 Summary .................................................................. 273
Questions ....................................................................... 274
References ..................................................................... 275

Chapter 13 Center Pivots and Lateral Moves .......... 277
13.1 Introduction ............................................................ 277
13.2 Center Pivot Characteristics ................................. 279
  13.2.1 Sprinkler Discharge ............................................. 279
  13.2.2 Area Irrigated .................................................... 280
  13.2.3 Pressure Distribution ........................................... 281
13.3 Application Rate ....................................................... 283
  13.3.1 Center Pivots ..................................................... 283
  13.3.2 Linear or Lateral Move ......................................... 285
13.4 Sprinkler and Nozzle Selection .............................. 285
13.5 Depth of Water Applied ............................................ 286
13.6 Remote Monitoring of System Operation and Control ... 293
13.7 Variable Rate Irrigation ............................................. 293
13.8 Community Shared Center Pivot Systems ............... 294
13.9 Summary ................................................................. 295
Questions ....................................................................... 295
References ..................................................................... 296

Chapter 14 Microirrigation ............................................ 297
14.1 Introduction ............................................................ 297
14.2 History and Impact ................................................... 298
14.3 System Types .......................................................... 298
  14.3.1 Surface Drip ....................................................... 299
  14.3.2 Microspray ......................................................... 300
  14.3.3 Bubblers ............................................................ 300
  14.3.4 Subsurface Drip .................................................. 300
14.4 System Components ................................................... 301
  14.4.1 Control Station ................................................... 303
  14.4.2 Mainline and Manifolds ........................................ 304
  14.4.3 Laterals ............................................................. 305
  14.4.4 Water Applicators ............................................... 307
14.5 Preventing Clogs ...................................................... 308
  14.5.1 Filtration ............................................................ 308
# Common Unit Conversions for Irrigation

## International System of Units (SI) and U.S. Customary System of Units (USCS)

### Length Units
- 1 km (kilometer) = 0.6214 mi (miles)
- 1 mi = 1.609 km
- 1 km = 1,000 m (meters)
- 1 mi = 5,280 ft (feet)
- 1 m = 3.281 ft
- 1 ft = 0.3048 m
- 1 m = 100 cm (centimeters)
- 1 ft = 12 in (inches)
- 1 in = 2.54 cm

### Area Units
- 1 ha (hectare) = 10,000 m$^2$
- 1 ha = 2.471 ac (acres)
- 1 ac = 0.4047 ha
- 1 ac = 43,560 ft$^2$

### Volume Units
- 1 L (liter) = 0.2642 gal (gallons)
- 1 gal = 3.785 L
- 1 m$^3$ = 1,000 L
- 1 m$^3$ = 264.2 gal
- 1 ft$^3$ = 7.481 gal
- 1 m$^3$ = 35.31 ft$^3$
- 1 ft$^3$ = 0.02832 m$^3$
- 1 ac-ft (covers 1 acre with 1 foot of water) = 1,233 m$^3$
- 1 ac-ft = 325,851 gal
- 1 ac-in (acre-inch) = 27,154 gal
- 1 ha-cm (hectare-centimeter) = 100 m$^3$
- 1 ac-in = 1.028 ha-cm (1 for practical purposes)
- 1 bu (bushel) = 35.24 L
- 1 bu = 9.309 gal

### Flow Units
- 1 L/s (liter/second) = 15.85 gpm (gallons/minute)
- 1 gpm = 0.06309 L/s
- 1 cms (m$^3$/s) = 1,000 L/s
- 1 cms = 35.31 cfs (ft$^3$/s)
- 1 cfs = 448.8 gpm (450 for practical purposes)
- 1 cfs = 0.02832 cms
- 1 ac-in/hr = 1.008 cfs (1 for practical purposes)
- 1 ac-in/hr = 452.6 gpm (450 for practical purposes)

### Weight and Mass Units
- 1 t (metric ton) = 1,000 kg (kilograms)
- 1 T (U.S. ton) = 2,000 lb (pounds)
- 1 t = 1.102 T
- 1 T = 0.9072 t
- 1 kg = 2.205 lb
- 1 lb = 0.4536 kg

### Pressure Units
- 1 atm (atmosphere) = 101.3 kPa (kilopascal)
- 1 bar = 100 kPa
- 1 bar = 0.9869 atm (1 for practical purposes)
- 1 kPa = 0.1450 psi (pounds per square inch)
- 1 psi = 6.895 kPa
- 1 m (meter of water head) = 9.804 kPa
- 1 ft (foot of water head) = 0.4335 psi
- 1 kPa = 0.3346 ft = 0.1020 m (0.1 for practical purposes)
- 1 psi = 2.307 ft = 0.7032 m (0.7 for practical purposes)
Crop Yield Units

*Rice, cotton, alfalfa, and similar crops*

- 1 lb/ac (lb dry weight/ac) = 1.121 kg/ha (kg dry mass/ha)
- 1 kg/ha = 0.8922 lb/ac
- 1 T/ac (T dry weight/ac) = 2.242 t/ha (t dry mass/ha)
- 1 t/ha = 0.4461 T/ac

*Tree fruit, grapes, vegetables, and similar crops*

- 1 lb/ac (lb wet weight/ac) = 1.121 kg/ha (kg wet mass/ha)
- 1 T/ac (T wet weight/ac) = 2.242 t/ha (t wet mass/ha)

*Maize/corn*[^a]

- 1 bu/ac (bushel/ac) = 0.0530 t/ha (t dry mass/ha)
- 1 t/ha = 18.9 bu/ac

*Soybean*[^a]

- 1 bu/ac = 0.0585 t/ha (t dry mass/ha)
- 1 t/ha = 17.1 bu/ac

[^a]: The unit of bu/ac is volume per area. The volume (bu) is calculated using the wet weight of the grain, a wet bulk density of 56 lb/bu (maize) or 60 lb/bu (soybean), and an assumed grain moisture content (wet basis) of 15.5% (maize) or 13% (soybean).

---

**Temperature Conversions**

<table>
<thead>
<tr>
<th>°C</th>
<th>°F</th>
<th>°F</th>
<th>°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>32</td>
<td>30</td>
<td>−1</td>
</tr>
<tr>
<td>5</td>
<td>41</td>
<td>40</td>
<td>4</td>
</tr>
<tr>
<td>10</td>
<td>50</td>
<td>50</td>
<td>10</td>
</tr>
<tr>
<td>15</td>
<td>59</td>
<td>60</td>
<td>16</td>
</tr>
<tr>
<td>20</td>
<td>68</td>
<td>70</td>
<td>21</td>
</tr>
<tr>
<td>25</td>
<td>77</td>
<td>80</td>
<td>27</td>
</tr>
<tr>
<td>30</td>
<td>86</td>
<td>90</td>
<td>32</td>
</tr>
<tr>
<td>35</td>
<td>95</td>
<td>100</td>
<td>38</td>
</tr>
<tr>
<td>40</td>
<td>104</td>
<td>110</td>
<td>43</td>
</tr>
</tbody>
</table>

---

**U.S. Public Land Survey System**

**1 Section of Land:**
- 1 mile square
- 640 ac
- 259 ha

**1/4 Section:**
- 160 ac
- 65 ha

---

**1/4-Mile Center Pivot with End Gun:**
- 130 ac irrigated
- 53 ha irrigated

**1/4-Mile Center Pivot with Swing Boom Corner:**
- 150 ac irrigated
- 61 ha irrigated