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**Irrigation of Agricultural Crops**  
**Second Edition**



# Irrigation of Agricultural Crops

## Second Edition

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## FOREWORD

Irrigation has been an important part of agriculture for thousands of years. Even though humanity has had extensive experience in irrigation of crops to maximize performance, efficiency, and profitability, the science of irrigation continues to evolve. The current edition of Agronomy Monograph 30 presents the latest scientific information regarding irrigation. Authors contributing to this edition are scientists at the forefront of this important multifaceted area. The authors' diverse backgrounds in irrigation cover the broad spectrum of the science of irrigating crop plants. A variety of complex subjects are covered, which will add to the knowledge base of researchers, teachers, students, and others who desire more information on irrigation.

This edition of *Irrigation of Agricultural Crops* is a supplement to the earlier edition published in 1990. Subjects discussed in the current edition range from the latest information on monitoring technology, efficiency, to specific information tailored to individual crops. It is hoped that this Agronomy Monograph will provide the basis for improved management strategies associated with irrigation. As the worldwide human population continues to increase, applying the latest scientific principles associated with irrigating crops will be of growing importance.

We certainly appreciate the efforts of the editors, R.J. Lascano and R.E. Sojka, who have helped to develop an excellent book. The editors and the authors have developed an exceptional treatise on irrigation which will be of value for years to come. The American Society of Agronomy, Crop Science Society of America, and Soil Science Society of America are proud to present to you this book. We hope that you will find this book to be a valuable asset to your increased understanding of irrigation and that it stimulates further discussion and scientific investigations worldwide.

David A. Sleper, President of the American Society of Agronomy, 2006  
Steven L. Fales, President of the Crop Science Society of America, 2006  
Mary E. Collins, President of the Soil Science Society of American, 2006





## PREFACE

It has been postulated that irrigation was the human activity, 8000 years ago, that ultimately produced what we now recognize as civilization. Today irrigation is one of the most important human activities sustaining civilization. The rapid rise in population and longevity since the 19th century is attributed to the advancement of modern medicine and an improved food supply. The latter resulted from improved agricultural technologies, such as crop genetics, fertilizers, herbicides, etc., and—more importantly—irrigation.

On average, irrigated crop yields are double those from unirrigated land. Improved crop quality and higher value crops raise the average value of irrigated production to triple that of non-irrigated crops. The yield advantage of irrigated agriculture spares vast expanses of natural lands from agricultural development. From 1900 until the 1950s the global land area under cultivation nearly doubled. Since the 1950s, cultivated land area has remained nearly constant while crop yields have steadily risen. This same period also saw a major expansion of irrigation. Growth of irrigated area slowed in the 1980s because the most easily exploited water supplies had been developed by then. That trend began changing in the 1990s as water conservation enabled irrigation of more land. Additional increases are now occurring as underdeveloped nations (or previously underdeveloped nations) can afford to develop water resources that were not economically feasible three decades ago.

Meanwhile, the human population continues to increase. It has been estimated that to meet the needs of the 8 billion population by 2025, the irrigated area must expand more than 20% and irrigated crop yields must improve by 40% above current yields. Thus, to meet these needs, it is fitting that the issues and the newest technologies affecting irrigation are again compiled in comprehensive reviews to facilitate efficient, sustainable, economical, and environmentally responsible irrigation.

In 1999, ASA President H.H. Cheng authorized ASA then-Editor-in-Chief Jerry Hatfield to identify an editorial committee to assess technology changes and emerging issues affecting irrigation with an eye toward revising and updating the 1990 edition of Agronomy Monograph 30, *Irrigation of Agricultural Crops*. We were appointed co-editors and were privileged to draw on the expertise of Floyd Adamsen, James Hook, Grant Cardon, and John Letey, who were appointed as editorial advisors to the project. The experience of editorial teams in compiling the earlier editions and versions of the monograph suggested that the undertaking could take a number of years to complete. While every effort was made to compress this time frame, in order to keep contributions as current as possible, following the initial planning, a period of nearly four years elapsed between submission of the first and final chapters received.

The contents of this revision should, perhaps more than any earlier printing, be seen as a supplement or update of the previous edition. The editorial team made a deliberate choice to avoid attempting to comprehensively cover fundamental

principals, and to focus instead on new findings and new challenges. In this vein, readers will still find significant value in the 1990 edition of the monograph as a companion volume. We trust that in the course of reading this new edition, however, the users of this new information will find a refined relevancy of its contents.

We would like to express our profound thanks to the American Society of Agronomy for entrusting us with such an important task, to our editorial advisors for their vision and perspective, and to our authors for their hard work, dedication, and formidable combined intellectual capacity. And perhaps most of all, we thank the thousands of soil, water, and crop scientists and engineers, whose work is drawn upon and cited in this monograph, and to whom we literally owe so much of our well-being as we write these thoughts in 2006.

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## **Conversion Factors for SI and non-SI Units**

## 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 Units	To convert Column 2 into Column 1, multiply by
<b>Length</b>			
0.621	kilometer, km ( $10^3$ m)	mile, mi	1.609
1.094	meter, m	yard, yd	0.914
3.28	meter, m	foot, ft	0.304
1.0	micrometer, $\mu\text{m}$ ( $10^{-6}$ m)	micron, $\mu$	1.0
$3.94 \times 10^{-2}$	millimeter, mm ( $10^{-3}$ m)	inch, in	25.4
10	nanometer, nm ( $10^{-9}$ m)	Angstrom, Å	0.1
<b>Area</b>			
2.47	hectare, ha	acre	0.405
247	square kilometer, $\text{km}^2$ ( $10^3$ m) <sup>2</sup>	acre	$4.05 \times 10^{-3}$
0.386	square kilometer, $\text{km}^2$ ( $10^3$ m) <sup>2</sup>	square mile, mi <sup>2</sup>	2.590
$2.47 \times 10^{-4}$	square meter, m <sup>2</sup>	acre	$4.05 \times 10^3$
10.76	square meter, m <sup>2</sup>	square foot, ft <sup>2</sup>	$9.29 \times 10^{-2}$
$1.55 \times 10^{-3}$	square millimeter, mm <sup>2</sup> ( $10^{-3}$ m) <sup>2</sup>	square inch, in <sup>2</sup>	645
<b>Volume</b>			
$9.73 \times 10^{-3}$	cubic meter, m <sup>3</sup>	acre-inch	102.8
35.3	cubic meter, m <sup>3</sup>	cubic foot, ft <sup>3</sup>	$2.83 \times 10^{-2}$
$6.10 \times 10^4$	cubic meter, m <sup>3</sup>	cubic inch, in <sup>3</sup>	$1.64 \times 10^{-5}$
$2.84 \times 10^{-2}$	liter, L ( $10^{-3}$ m <sup>3</sup> )	bushel, bu	35.24
1.057	liter, L ( $10^{-3}$ m <sup>3</sup> )	quart (liquid), qt	0.946
$3.53 \times 10^{-2}$	liter, L ( $10^{-3}$ m <sup>3</sup> )	cubic foot, ft <sup>3</sup>	28.3
0.265	liter, L ( $10^{-3}$ m <sup>3</sup> )	gallon	3.78
33.78	liter, L ( $10^{-3}$ m <sup>3</sup> )	ounce (fluid), oz	$2.96 \times 10^{-2}$
2.11	liter, L ( $10^{-3}$ m <sup>3</sup> )	pint (fluid), pt	0.473



<b>Mass</b>			
gram, g ( $10^{-3}$ kg)	pound, lb	454	
gram, g ( $10^{-3}$ kg)	ounce (avdp), oz	28.4	
kilogram, kg	pound, lb	0.454	
kilogram, kg	quintal (metric), q	100	
kilogram, kg	ton (2000 lb), ton	907	
megagram, Mg (tonne)	ton (U.S.), ton	0.907	
tonne, t	ton (U.S.), ton	0.907	
<b>Yield and Rate</b>			
0.893	kilogram per hectare, kg ha <sup>-1</sup>	1.12	pound per acre, lb acre <sup>-1</sup>
$7.77 \times 10^{-2}$	kilogram per cubic meter, kg m <sup>-3</sup>	12.87	pound per bushel, lb bu <sup>-1</sup>
$1.49 \times 10^{-2}$	kilogram per hectare, kg ha <sup>-1</sup>	67.19	bushel per acre, 60 lb
$1.59 \times 10^{-2}$	kilogram per hectare, kg ha <sup>-1</sup>	62.71	bushel per acre, 56 lb
$1.86 \times 10^{-2}$	kilogram per hectare, kg ha <sup>-1</sup>	53.75	bushel per acre, 48 lb
0.107	liter per hectare, L ha <sup>-1</sup>	9.35	gallon per acre
893	tonne per hectare, t ha <sup>-1</sup>	$1.12 \times 10^{-3}$	pound per acre, lb acre <sup>-1</sup>
893	megagram per hectare, Mg ha <sup>-1</sup>	$1.12 \times 10^{-3}$	pound per acre, lb acre <sup>-1</sup>
0.446	megagram per hectare, Mg ha <sup>-1</sup>	2.24	ton (2000 lb) per acre, ton acre <sup>-1</sup>
2.24	meter per second, m s <sup>-1</sup>	0.447	mile per hour
<b>Specific Surface</b>			
10	square meter per kilogram, m <sup>2</sup> kg <sup>-1</sup>	0.1	square centimeter per gram, cm <sup>2</sup> g <sup>-1</sup>
1000	square meter per kilogram, m <sup>2</sup> kg <sup>-1</sup>	0.001	square millimeter per gram, mm <sup>2</sup> g <sup>-1</sup>
<b>Density</b>			
1.00	megagram per cubic meter, Mg m <sup>-3</sup>	1.00	gram per cubic centimeter, g cm <sup>-3</sup>
<b>Pressure</b>			
9.90	megapascal, MPa ( $10^6$ Pa)	0.101	atmosphere
10	megapascal, MPa ( $10^6$ Pa)	0.1	bar
$2.09 \times 10^{-2}$	pascal, Pa	47.9	pound per square foot, lb ft <sup>-2</sup>
$1.45 \times 10^{-4}$	pascal, Pa	$6.90 \times 10^3$	pound per square inch, lb in <sup>-2</sup>

(continued on next page)

## 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 Units	To convert Column 2 into Column 1, multiply by
<b>Temperature</b>			
	kelvin, K	Celsius, °C	1.00 (K - 273)
	Celsius, °C	Fahrenheit, °F	(9/5 °C) + 32
<b>Energy, Work, Quantity of Heat</b>			
	joule, J	British thermal unit, Btu	$1.05 \times 10^3$
	joule, J	calorie, cal	4.19
	joule, J	erg	$10^{-7}$
	joule, J	foot-pound	1.36
	joule per square meter, J m <sup>-2</sup>	calorie per square centimeter (langley)	$4.19 \times 10^4$
	newton, N	dyne	$10^{-5}$
	watt per square meter, W m <sup>-2</sup>	calorie per square centimeter minute (irradiance), cal cm <sup>-2</sup> min <sup>-1</sup>	698
<b>Transpiration and Photosynthesis</b>			
	milligram per square meter second, mg m <sup>-2</sup> s <sup>-1</sup>	gram per square decimeter hour, g dm <sup>-2</sup> h <sup>-1</sup>	27.8
	milligram (H <sub>2</sub> O) per square meter second, mg m <sup>-2</sup> s <sup>-1</sup>	micromole (H <sub>2</sub> O) per square centi- meter second, μmol cm <sup>-2</sup> s <sup>-1</sup>	180
	milligram per square meter second, mg m <sup>-2</sup> s <sup>-1</sup>	milligram per square centimeter second, mg cm <sup>-2</sup> s <sup>-1</sup>	$10^4$
	milligram per square meter second, mg m <sup>-2</sup> s <sup>-1</sup>	milligram per square decimeter hour, mg dm <sup>-2</sup> h <sup>-1</sup>	$2.78 \times 10^{-2}$
	57.3		
<b>Plane Angle</b>			
	radian, rad	degrees (angle), °	$1.75 \times 10^{-2}$

**Electrical Conductivity, Electricity, and Magnetism**

10	siemen per meter, S m <sup>-1</sup>	0.1	millimho per centimeter, mmho cm <sup>-1</sup>
10 <sup>4</sup>	tesla, T	10 <sup>-4</sup>	gauss, G

**Water Measurement**

9.73 × 10 <sup>-3</sup>	cubic meter, m <sup>3</sup>	102.8	acre-inch, acre-in
9.81 × 10 <sup>-3</sup>	cubic meter per hour, m <sup>3</sup> h <sup>-1</sup>	101.9	cubic foot per second, ft <sup>3</sup> s <sup>-1</sup>
4.40	cubic meter per hour, m <sup>3</sup> h <sup>-1</sup>	0.227	U.S. gallon per minute, gal min <sup>-1</sup>
8.11	hectare meter, ha m	0.123	acre-foot, acre-ft
97.28	hectare meter, ha m	1.03 × 10 <sup>-2</sup>	acre-inch, acre-in
8.1 × 10 <sup>-2</sup>	hectare centimeter, ha cm	12.33	acre-foot, acre-ft

**Concentrations**

1	centimole per kilogram, cmol kg <sup>-1</sup>	1	milliequivalent per 100 grams, meq 100 g <sup>-1</sup>
0.1	gram per kilogram, g kg <sup>-1</sup>	10	percent, %
1	milligram per kilogram, mg kg <sup>-1</sup>	1	parts per million, ppm

**Radioactivity**

2.7 × 10 <sup>-11</sup>	becquerel, Bq	3.7 × 10 <sup>10</sup>	curie, Ci
2.7 × 10 <sup>-2</sup>	becquerel per kilogram, Bq kg <sup>-1</sup>	37	picocurie per gram, pCi g <sup>-1</sup>
100	gray, Gy (absorbed dose)	0.01	rad, rd
100	sievert, Sv (equivalent dose)	0.01	rem (roentgen equivalent man)

**Plant Nutrient Conversion**

	<i>Elemental</i>		<i>Oxide</i>
2.29	P	0.437	P <sub>2</sub> O <sub>5</sub>
1.20	K	0.830	K <sub>2</sub> O
1.39	Ca	0.715	CaO
1.66	Mg	0.602	MgO

## Conversion Factors for SI and non-SI Units

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0.621	kilometer, km ( $10^3$ m)	mile, mi	1.609
1.094	meter, m	yard, yd	0.914
3.28	meter, m	foot, ft	0.304
1.0	micrometer, $\mu\text{m}$ ( $10^{-6}$ m)	micron, $\mu$	1.0
$3.94 \times 10^{-2}$	millimeter, mm ( $10^{-3}$ m)	inch, in	25.4
10	nanometer, nm ( $10^{-9}$ m)	Angstrom, Å	0.1
		<b>Area</b>	
2.47	hectare, ha	acre	0.405
247	square kilometer, $\text{km}^2$ ( $10^3$ m) <sup>2</sup>	acre	$4.05 \times 10^{-3}$
0.386	square kilometer, $\text{km}^2$ ( $10^3$ m) <sup>2</sup>	square mile, mi <sup>2</sup>	2.590
$2.47 \times 10^{-4}$	square meter, m <sup>2</sup>	acre	$4.05 \times 10^3$
10.76	square meter, m <sup>2</sup>	square foot, ft <sup>2</sup>	$9.29 \times 10^{-2}$
$1.55 \times 10^{-3}$	square millimeter, mm <sup>2</sup> ( $10^{-3}$ m) <sup>2</sup>	square inch, in <sup>2</sup>	645
		<b>Volume</b>	
$9.73 \times 10^{-3}$	cubic meter, m <sup>3</sup>	acre-inch	102.8
35.3	cubic meter, m <sup>3</sup>	cubic foot, ft <sup>3</sup>	$2.83 \times 10^{-2}$
$6.10 \times 10^4$	cubic meter, m <sup>3</sup>	cubic inch, in <sup>3</sup>	$1.64 \times 10^{-5}$
$2.84 \times 10^{-2}$	liter, L ( $10^{-3}$ m <sup>3</sup> )	bushel, bu	35.24
1.057	liter, L ( $10^{-3}$ m <sup>3</sup> )	quart (liquid), qt	0.946
$3.53 \times 10^{-2}$	liter, L ( $10^{-3}$ m <sup>3</sup> )	cubic foot, ft <sup>3</sup>	28.3
0.265	liter, L ( $10^{-3}$ m <sup>3</sup> )	gallon	3.78
33.78	liter, L ( $10^{-3}$ m <sup>3</sup> )	ounce (fluid), oz	$2.96 \times 10^{-2}$
2.11	liter, L ( $10^{-3}$ m <sup>3</sup> )	pint (fluid), pt	0.473

**Mass**

$2.20 \times 10^{-3}$	gram, g ( $10^{-3}$ kg)	pound, lb	454
$3.52 \times 10^{-2}$	gram, g ( $10^{-3}$ kg)	ounce (avdp), oz	28.4
2.205	kilogram, kg	pound, lb	0.454
0.01	kilogram, kg	quintal (metric), q	100
$1.10 \times 10^{-3}$	kilogram, kg	ton (2000 lb), ton	907
1.102	megagram, Mg (tonne)	ton (U.S.), ton	0.907
1.102	tonne, t	ton (U.S.), ton	0.907

**Yield and Rate**

0.893	kilogram per hectare, kg ha <sup>-1</sup>	pound per acre, lb acre <sup>-1</sup>	1.12
$7.77 \times 10^{-2}$	kilogram per cubic meter, kg m <sup>-3</sup>	pound per bushel, lb bu <sup>-1</sup>	12.87
$1.49 \times 10^{-2}$	kilogram per hectare, kg ha <sup>-1</sup>	bushel per acre, 60 lb	67.19
$1.59 \times 10^{-2}$	kilogram per hectare, kg ha <sup>-1</sup>	bushel per acre, 56 lb	62.71
$1.86 \times 10^{-2}$	kilogram per hectare, kg ha <sup>-1</sup>	bushel per acre, 48 lb	53.75
0.107	liter per hectare, L ha <sup>-1</sup>	gallon per acre	9.35
893	tonne per hectare, t ha <sup>-1</sup>	pound per acre, lb acre <sup>-1</sup>	$1.12 \times 10^{-3}$
893	megagram per hectare, Mg ha <sup>-1</sup>	pound per acre, lb acre <sup>-1</sup>	$1.12 \times 10^{-3}$
0.446	megagram per hectare, Mg ha <sup>-1</sup>	ton (2000 lb) per acre, ton acre <sup>-1</sup>	2.24
2.24	meter per second, m s <sup>-1</sup>	mile per hour	0.447

**Specific Surface**

10	square meter per kilogram, m <sup>2</sup> kg <sup>-1</sup>	square centimeter per gram, cm <sup>2</sup> g <sup>-1</sup>	0.1
1000	square meter per kilogram, m <sup>2</sup> kg <sup>-1</sup>	square millimeter per gram, mm <sup>2</sup> g <sup>-1</sup>	0.001

**Density**

1.00	megagram per cubic meter, Mg m <sup>-3</sup>	gram per cubic centimeter, g cm <sup>-3</sup>	1.00
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**Pressure**

9.90	megapascal, MPa ( $10^6$ Pa)	atmosphere	0.101
10	megapascal, MPa ( $10^6$ Pa)	bar	0.1
$2.09 \times 10^{-2}$	pascal, Pa	pound per square foot, lb ft <sup>-2</sup>	47.9
$1.45 \times 10^{-4}$	pascal, Pa	pound per square inch, lb in <sup>-2</sup>	$6.90 \times 10^3$

(continued on next page)

## 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 Units	To convert Column 2 into Column 1, multiply by
		<b>Temperature</b>	
	kelvin, K	Celsius, °C	1.00 (°C + 273)
	Celsius, °C	Fahrenheit, °F	5/9 (°F - 32)
		<b>Energy, Work, Quantity of Heat</b>	
	joule, J	British thermal unit, Btu	1.05 × 10 <sup>3</sup>
	joule, J	calorie, cal	4.19
	joule, J	erg	10 <sup>-7</sup>
	joule, J	foot-pound	1.36
	joule per square meter, J m <sup>-2</sup>	calorie per square centimeter (langley)	4.19 × 10 <sup>4</sup>
	newton, N	dyne	10 <sup>-5</sup>
	watt per square meter, W m <sup>-2</sup>	calorie per square centimeter minute (irradiance), cal cm <sup>-2</sup> min <sup>-1</sup>	698
		<b>Transpiration and Photosynthesis</b>	
	milligram per square meter second, mg m <sup>-2</sup> s <sup>-1</sup>	gram per square decimeter hour, g dm <sup>-2</sup> h <sup>-1</sup>	27.8
	milligram (H <sub>2</sub> O) per square meter second, mg m <sup>-2</sup> s <sup>-1</sup>	micromole (H <sub>2</sub> O) per square centi- meter second, μmol cm <sup>-2</sup> s <sup>-1</sup>	180
	milligram per square meter second, mg m <sup>-2</sup> s <sup>-1</sup>	milligram per square centimeter second, mg cm <sup>-2</sup> s <sup>-1</sup>	10 <sup>4</sup>
	milligram per square meter second, mg m <sup>-2</sup> s <sup>-1</sup>	milligram per square decimeter hour, mg dm <sup>-2</sup> h <sup>-1</sup>	2.78 × 10 <sup>-2</sup>
		<b>Plane Angle</b>	
	radian, rad	degrees (angle), °	1.75 × 10 <sup>-2</sup>
	57.3		

**Electrical Conductivity, Electricity, and Magnetism**

10	siemen per meter, S m <sup>-1</sup>	millimho per centimeter, mmho cm <sup>-1</sup>	0.1
10 <sup>4</sup>	tesla, T	gauss, G	10 <sup>-4</sup>

**Water Measurement**

9.73 × 10 <sup>-3</sup>	cubic meter, m <sup>3</sup>	acre-inch, acre-in	102.8
9.81 × 10 <sup>-3</sup>	cubic meter per hour, m <sup>3</sup> h <sup>-1</sup>	cubic foot per second, ft <sup>3</sup> s <sup>-1</sup>	101.9
4.40	cubic meter per hour, m <sup>3</sup> h <sup>-1</sup>	U.S. gallon per minute, gal min <sup>-1</sup>	0.227
8.11	hectare meter, ha m	acre-foot, acre-ft	0.123
97.28	hectare meter, ha m	acre-inch, acre-in	1.03 × 10 <sup>-2</sup>
8.1 × 10 <sup>-2</sup>	hectare centimeter, ha cm	acre-foot, acre-ft	12.33

**Concentrations**

1	centimole per kilogram, cmol kg <sup>-1</sup>	milliequivalent per 100 grams, meq 100 g <sup>-1</sup>	1
0.1	gram per kilogram, g kg <sup>-1</sup>	percent, %	10
1	milligram per kilogram, mg kg <sup>-1</sup>	parts per million, ppm	1

**Radioactivity**

2.7 × 10 <sup>-11</sup>	becquerel, Bq	curie, Ci	3.7 × 10 <sup>10</sup>
2.7 × 10 <sup>-2</sup>	becquerel per kilogram, Bq kg <sup>-1</sup>	picocurie per gram, pCi g <sup>-1</sup>	37
100	gray, Gy (absorbed dose)	rad, rd	0.01
100	sievert, Sv (equivalent dose)	rem (roentgen equivalent man)	0.01

**Plant Nutrient Conversion**

	<i>Elemental</i>	<i>Oxide</i>	
2.29	P	P <sub>2</sub> O <sub>5</sub>	0.437
1.20	K	K <sub>2</sub> O	0.830
1.39	Ca	CaO	0.715
1.66	Mg	MgO	0.602