SECOND EDITION

Water Resources Engineering

Larry W. Mays

Water Resources Engineering

This page intentionally left blank

Water Resources Engineering

Second Edition

Larry W. Mays
Professor
Civil, Environmental, and Sustainable Engineering Group
School of Sustainable Engineering and the Built Environment
Arizona State University
Tempe, Arizona

WILEY
John Wiley & Sons, Inc.

VP and Publisher	Don Fowley
Acquisition Editor	Jenny Welter
Editorial Assistant	Alexandra Spicehandler
Production Manager	Janis Soo
Assistant Production Editor	Elaine S. Chew
Senior Marketing Manager	Christopher Ruel
Marketing Assistant	Diana Smith
Media Editor	Lauren Sapira
Designer	RDC Publishing Group Sdn. Bhd.
Cover Image	© Larry W. Mays

This book was set in 9.5/12 Times Roman by Thomson Digital and printed and bound by Hamilton Printing Company. The cover was printed by Hamilton Printing Company.

This book is printed on acid free paper.

Copyright © 2011, 2005 John Wiley & Sons, Inc. All rights reserved. No part of this publication may be reproduced, stored in a retrieval system or transmitted in any form or by any means, electronic, mechanical, photocopying, recording, scanning or otherwise, except as permitted under Sections 107 or 108 of the 1976 United States Copyright Act, without either the prior written permission of the Publisher, or authorization through payment of the appropriate per-copy fee to the Copyright Clearance Center, Inc. 222 Rosewood Drive, Danvers, MA 01923, website www.copyright.com. Requests to the Publisher for permission should be addressed to the Permissions Department, John Wiley & Sons, Inc., 111 River Street, Hoboken, NJ 07030-5774, (201)748-6011, fax (201)748-6008, website http://www.wiley.com/go/permissions.

Evaluation copies are provided to qualified academics and professionals for review purposes only, for use in their courses during the next academic year. These copies are licensed and may not be sold or transferred to a third party. Upon completion of the review period, please return the evaluation copy to Wiley. Return instructions and a free of charge return shipping label are available at www.wiley.com/go/returnlabel. Outside of the United States, please contact your local representative.

Library of Congress Cataloging in Publication Data

Mays, Larry W.
Water resources engineering / Larry W. Mays.—2nd ed.
p. cm.
Includes index.
ISBN 978-0-470-46064-1 (cloth : alk. paper)
1. Hydraulic engineering. 2. Hydrology. I. Title.

TC145.M383 2010
627—dc22 2010005952

Printed in the United States of America

10 9 8 7 6 5 4 3 2 1

About the Author

Larry W. Mays is Professor in the Civil, Environmental, and Sustainable Engineering Group in the School of Sustainable Engineering and the Built Environment at Arizona State University (ASU), and former chair of the Department of Civil and Environmental Engineering. Prior to ASU he was Director of the Center for Research in Water Resources at the University of Texas at Austin, where he held an Engineering Foundation–endowed professorship. A registered professional engineer in several states, and a registered professional hydrologist, he has served as a consultant to many national and international organizations.

Professor Mays has published extensively in refereed journal publications and in the proceedings of national and international conferences. He was the author of the first edition of this book and *Optimal Control of Hydrosystems* (published by Marcel Dekker), and co-author of *Applied Hydrology* and *Hydrosystems Engineering and Management* (both from McGraw-Hill) and *Groundwater Hydrology* (published by John Wiley & Sons, Inc). He was editor-in-chief of *Water Resources Handbook, Water Distribution Systems Handbook, Urban Water Supply Management Tools, Stormwater Collection Systems Design Handbook, Urban Water Supply Handbook, Urban Stormwater Management Tools, Hydraulic Design Handbook, Water Supply Systems Security*, and *Water Resources Sustainability*, all published by McGraw-Hill. In addition, he was editor-in-chief of *Reliability Analysis of Water Distribution Systems* and co-editor of *Computer Methods of Free Surface and Pressurized Flow* published by Kluwer Academic Publishers.

Professor Mays developed the book, *Integrated Urban Water Management: Arid and Semi-arid Regions*, published by Taylor and Francis. This book was the result of volunteer work for the United Nations UNESCO-IHP in Paris. He recently was editor of the fourth edition of *Water Transmission and Distribution*, published by the American Water Works Association.

One of his major efforts is the study of ancient water systems and the relation that these systems could have on solving our problems of water resources sustainability using the concepts of traditional knowledge, not only for the present, but the future. His most recent book is *Ancient Water Technology*, published by Springer Science and Business Media, The Netherlands.

Among his honors is a distinguished alumnus award from the Department of Civil and Engineering at the University of Illinois at Champaign-Urbana and he is a Diplomate, Water Resources Engineering of the American Academy of Water Resources Engineering. He is also a Fellow of the American Society of Civil Engineers and the International Water Resources Association. He loves the mountains where he enjoys alpine skiing, hiking, and fly-fishing. In addition he loves photographing ancient water systems around the world and gardening. Professor Mays lives in Mesa, Arizona and Pagosa Springs, Colorado.

This page intentionally left blank

Acknowledgments

Water Resources Engineering is the result of teaching classes over the past 34 years at the University of Texas at Austin and Arizona State University. So first and foremost, I would like to thank the many students that I have taught over the years. Several of my past Ph.D. students have helped me in many ways through their review of the material and help in development of the solutions manual. These former students include Drs. Aihua Tang, Guihua Li, John Nicklow, Burcu Sakarya, Kaan Tuncok, Carlos Carriaga, Bing Zhao, El Said Ahmed, and Messele Ejeta. I would like to give special thanks to Professor Y.K. Tung of the Hong Kong University of Science and Technology. He has been a long time friend and was my very first Ph.D. student at the University of Texas at Austin. Y. K. was very gracious in providing me with some of the end of chapter problems for the hydrology chapters. I would like to acknowledge Arizona State University, especially the time afforded me to pursue this book.

I would like to thank Wayne Anderson for originally having faith in me through his willingness to first publish the book and now Jenny Welter who has worked to get this edition published.

During my academic career as a professor I have received help and encouragement from so many people that it is not possible to name them all. These people represent a wide range of universities, research institutions, government agencies, and professions. To all of you I express my deepest thanks.

Water Resources Engineering has been a part of a personal journey that began years ago when I was a young boy with a love of water. This love of water resources has continued throughout my life, even in my spare time, being an avid snow skier, fly-fisherman and hiker. Books are companions along the journey of learning and I hope that you will be able to use this book in your own exploration of the field of water resources. Have a wonderful journey.

Larry W. Mays
Mesa, Arizona
Pagosa Springs, Colorado

I would like to dedicate this book to humanity and human welfare.

Preface

AUDIENCE

Water Resources Engineering can be used for the first undergraduate courses in hydraulics, hydrology, or water resources engineering and for upper level undergraduate and graduate courses in water resources engineering design. This book is also intended as a reference for practicing hydraulic engineers, civil engineers, mechanical engineers, environmental engineers, and hydrologists.

TOPICAL COVERAGE

Water resources engineering, as defined for the purposes of this book, includes both water use and water excess management. The fundamental water resources engineering processes are the hydrologic processes and the hydraulic processes. The common threads that relate to the explanation of these processes are the fundamentals of fluid mechanics using the control volume approach. The hydraulic processes include pressurized pipe flow, open-channel flow, and groundwater flow. Each of these in turn can be subdivided into various processes and types of flow. The hydrologic processes include rainfall, evaporation, infiltration, rainfall-runoff, and routing, all of which can be further subdivided into other processes. Knowledge of the hydrologic and hydraulic processes is extended to the design and analysis aspects. This book, however, does not cover the water quality management aspects of water resources engineering.

HISTORY OF WATER RESOURCES DEVELOPMENT

Water resources development has had a long history, basically beginning when humans changed from being hunters and food gatherers to developing of agriculture and settlements. This change resulted in humans harnessing water for irrigation. As humans developed, they began to invent and develop technologies, and to transport and manage water for irrigation. The first successful efforts to control the flow of water were in Egypt and Mesopotamia. Since that time humans have continuously built on the knowledge of water resources engineering. This book builds on that knowledge to present state-of-the-art concepts and practices in water resources engineering.

NEW TO THIS EDITION

The *Second Edition* provides the most up-to-date information along with a remarkable range and depth of coverage. In addition to other changes, two new chapters have been added that explore water resources sustainability and water resources management for sustainability:

Chapter 2: Water Resources Sustainability, defines water resources sustainability, discusses challenges and specific examples of water resources systems, as well as examples of water resources unsustainability.

Chapter 19: Water Resources Management for Sustainability, introduces the idea of integrated water resources management, law related to water resources, methodologies for both arid and semi-arid regions, economics, systems analysis techniques, and uncertainty and risk-reliability analysis for sustainable design.

Principles of Flow in Hydrosystems, which was previously Chapter 2 in the *First Edition*, has now been integrated with Chapter 3 in the *Second Edition*.

Homework Problems: There are over 300 new problems in the *Second Edition*, resulting in a total of over 670 end-of-chapter problems, expanding the applications to which students are exposed.

New and updated graphics and photos: Over 50 new diagrams, maps and photographs have been integrated throughout the chapters to reinforce important concepts, and support student visualization and appreciation of water resources systems and engineering.

HALLMARK FEATURES

Breadth and Depth: The text includes a breadth and depth of topics appropriate for undergraduate courses in hydraulics, hydrology, or water resources engineering, or as a comprehensive reference for practicing engineers.

Control Volume Approach: Hydrologic and hydraulic processes are explained through their relationship to the control volume approach in fluid mechanics.

Visual program: Hundreds of diagrams, maps, and photographs illustrate concepts, and reinforce the importance and applied nature of water resources engineering.

CHAPTER ORGANIZATION

Water Resources Engineering is divided into five subject areas: Water Resources Sustainability, Hydraulics, Hydrology, Engineering Analysis and Design for Water Use, and Engineering Analysis and Design for Water Excess Management.

Water resources sustainability includes: Chapter 1 which is an introduction to water resources sustainability; Chapter 2 addresses water resources sustainability; and Chapter 19 water resources management for sustainability. Chapter 11 on water withdrawals and uses, Chapter 13 on water for hydroelectric generation, and Chapter 14 on water excess management also contain material related to water resources sustainability.

Hydraulics consists of five chapters that introduce the basic processes of hydraulics: Chapter 3 presents a basic fluid mechanics review and the control volume approach for continuity, energy, and momentum; and Chapters 4, 5, and 6 cover pressurized flow, open-channel flow, and groundwater flow, respectively. Chapter 18 covers the basics of sedimentation and erosion hydraulics.

Hydrology is covered in four chapters: Chapter 7 on hydrologic processes; Chapter 8 on rainfall-runoff analysis; Chapter 9 on routing; and Chapter 10 on probability and frequency analysis.

Engineering analysis and design for water use consists of three chapters: Chapter 11 on water withdrawals and uses; Chapter 12 on water distribution systems; and Chapter 13 on water for hydroelectric generation.

Engineering analysis and design for water excess management includes four chapters: Chapter 14 on water excess management; Chapter 15 on stormwater control using storm sewers and detention; Chapter 16 on stormwater control using street and highway drainage and culverts; and Chapter 17 on the design of hydraulic structures for flood control storage systems.

COURSE SUGGESTIONS

Several first courses could be taught from this book: a first course on hydraulics, a first course on hydrology, a first course on water resources engineering analysis and design, and a first course on hydraulic design. The flowcharts on the following pages illustrate the topics and chapters that could be covered in these courses.

This is a comprehensive book covering a large number of topics that would be impossible to cover in any single course. This was done purposely because of the wide variation in the manner in which faculty teach these courses or variations of these courses. Also, to make this book more valuable to the practicing engineer or hydrologist, the selection of these topics and the extent of coverage in each chapter were considered carefully. I have attempted to include enough example problems to make the theory more applicable, more understandable, and most of all more enjoyable to the student and engineer.

Students using this book will most likely have had an introductory fluid mechanics course based on the control volume approach. Chapter 3 should serve as a review of basic fluid concepts and the control volume approach. Control volume concepts are then used in the succeeding chapters to introduce the hydrologic and hydraulic processes. Even if the student or engineer has not had an introductory course in fluid mechanics, this book can still be used, because the concepts of fluid mechanics and the control volume approach are covered.

MOTIVATION

I sincerely hope that this book will be a contribution toward the goal of better engineering in the field of water resources. I constantly remind myself of the following quote from Baba Diodum: “In the end we will conserve only what we love, we will love only what we understand, and we will understand only what we are taught.”

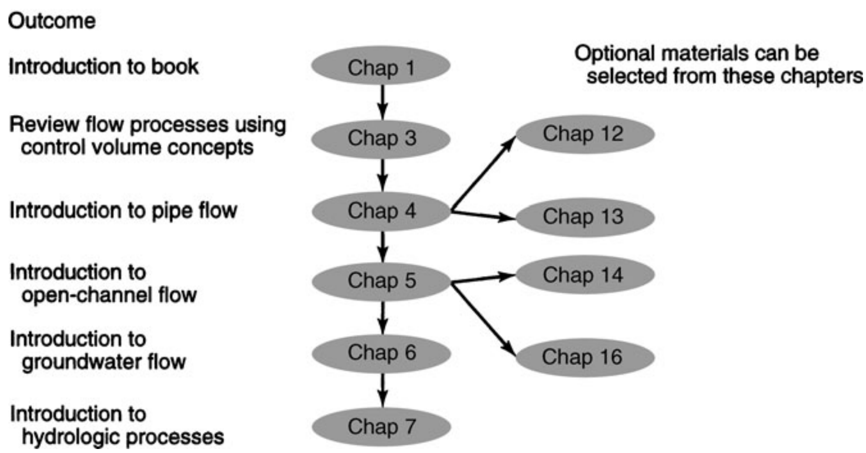
This book has been another part of a personal journey of mine that began as a young boy with an inquisitive interest and love of water, in the streams, creeks, ponds, lakes, rivers, and oceans, and water as rain and snow. Coming from a small Illinois town situated between the Mississippi and Illinois Rivers near Mark Twain’s country, I began to see and appreciate at an early age the beauty, the useful power, and the extreme destructiveness that rivers can create. I hope that this book will be of value in your journey of learning about water resources.

WEB SITE

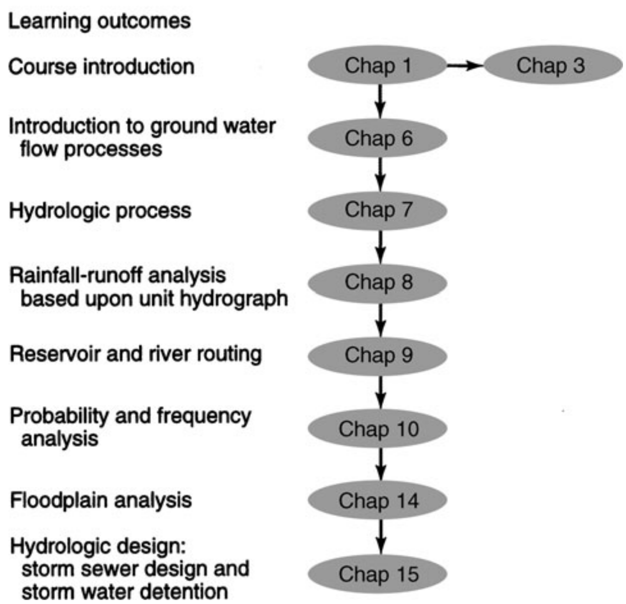
The Web site for this book is located at www.wiley.com/college/mays and includes the following resources:

- *Errata listing*: a list of any corrections that may be found in this book.
- *Figures from text*: non-copyrightable figures are available for making lecture slides or transparencies.
- *Solutions Manual for Instructors*: Includes solutions to all problems in the book. This resource is password-protected, and available only to instructors who have adopted this book for their course. Visit the Instructor Companion site portion of the Web site at www.wiley.com/college/mays to register for a password.

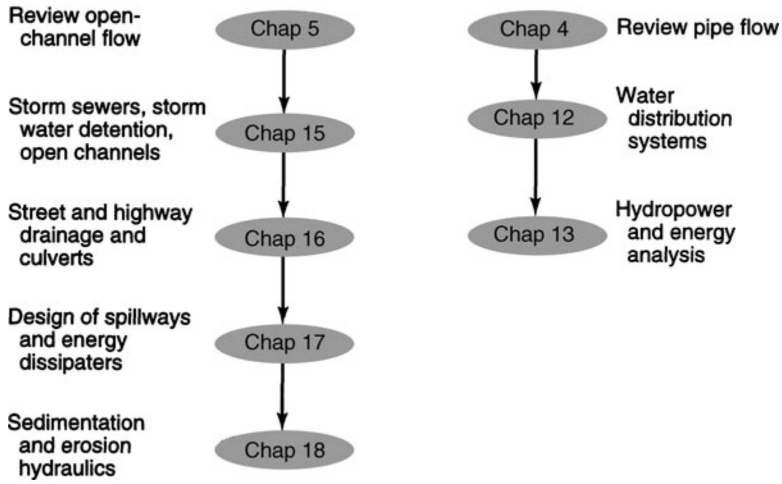
First Undergraduate Hydraulics Course



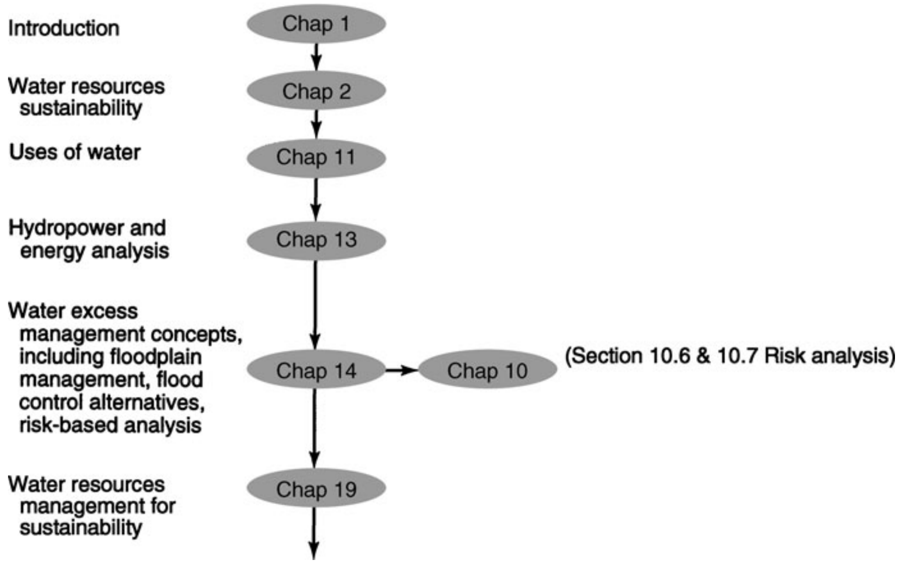
First Undergraduate Hydrology Course



Undergraduate Hydraulic Design Course



Water Resources Engineering and Sustainability



This page intentionally left blank

Brief Contents

Contents

This page intentionally left blank

Chapter 1

Introduction

1.1 BACKGROUND

Water resources engineering (and management) as defined for the purposes of this book includes engineering for both *water supply management* and *water excess management* (see Figure 1.1.1). This book does not cover the *water quality management (or environmental restoration)* aspect of water resources engineering. The two major processes that are engineered are the *hydrologic processes* and the *hydraulic processes*. The common threads that relate to the explanation of the hydrologic and hydraulic processes are the fundamentals of fluid mechanics. The hydraulic processes include three types of flow: pipe (pressurized) flow, open-channel flow, and groundwater flow.

The broad topic of *water resources* includes areas of study in the biological sciences, engineering, physical sciences, and social sciences, as illustrated in Figure 1.1.1. Areas in the biological sciences range from ecology to zoology, those in the physical sciences range from chemistry to meteorology to physics, and those in the social sciences range from economics to sociology. Water resources engineering as used in this book focuses on the engineering aspects of hydrology and hydraulics for water supply management and water excess management.

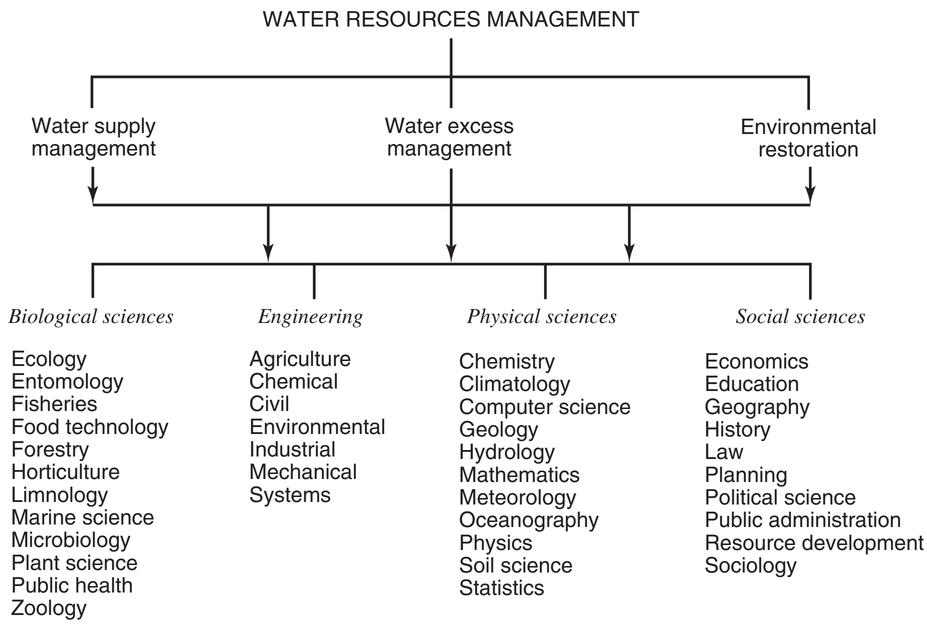


Figure 1.1.1 Ingredients of water resources management (from Mays (1996)).

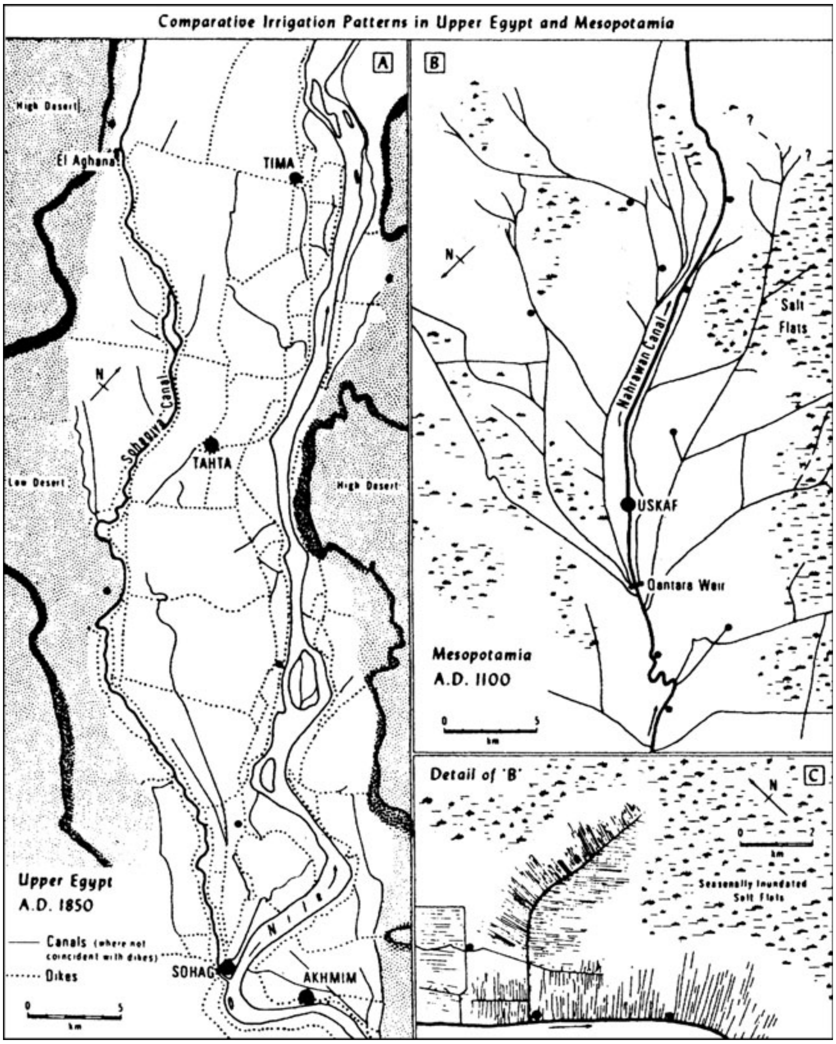


Figure 1.1.2 Comparative irrigation networks in Upper Egypt and Mesopotamia. (*a*) Example of linear, basin irrigation in Sohag province, ca. A.D. 1850; (*b*) Example of radial canalization system in the lower Nasharawan region southeast of Baghdad, Abbasid (A.D. 883–1150) (modified from R. M. Adams (1965), Fig. 9. Same scale as Egyptian counterpart); (*c*) Detail of field canal layout in (*b*) (simplified from Adams (1965), Fig. 10. Figure as presented in Butzer (1976)).

Water resources engineering not only includes the analysis and synthesis of various water problems through the use of the many analytical tools in hydrologic engineering and hydraulic engineering but also extends to the design aspects.

Water resources engineering has evolved over the past 9000 to 10,000 years as humans have developed the knowledge and techniques for building hydraulic structures to convey and store water. Early examples include irrigation networks built by the Egyptians and Mesopotamians (see Figure 1.1.2) and by the Hobokam in North America (see Figure 1.1.3). The world's oldest large dam was the Sadd-el-kafara dam built in Egypt between 2950 and 2690 B.C. The oldest known pressurized water distribution (approximately 2000 B.C.) was in the ancient city of Knossos on Crete (see Mays, 1999, 2000, for further details). There are many examples of ancient water systems throughout the world (see Mays (2007, 2008, 2010) and Mays et al. (2007)).

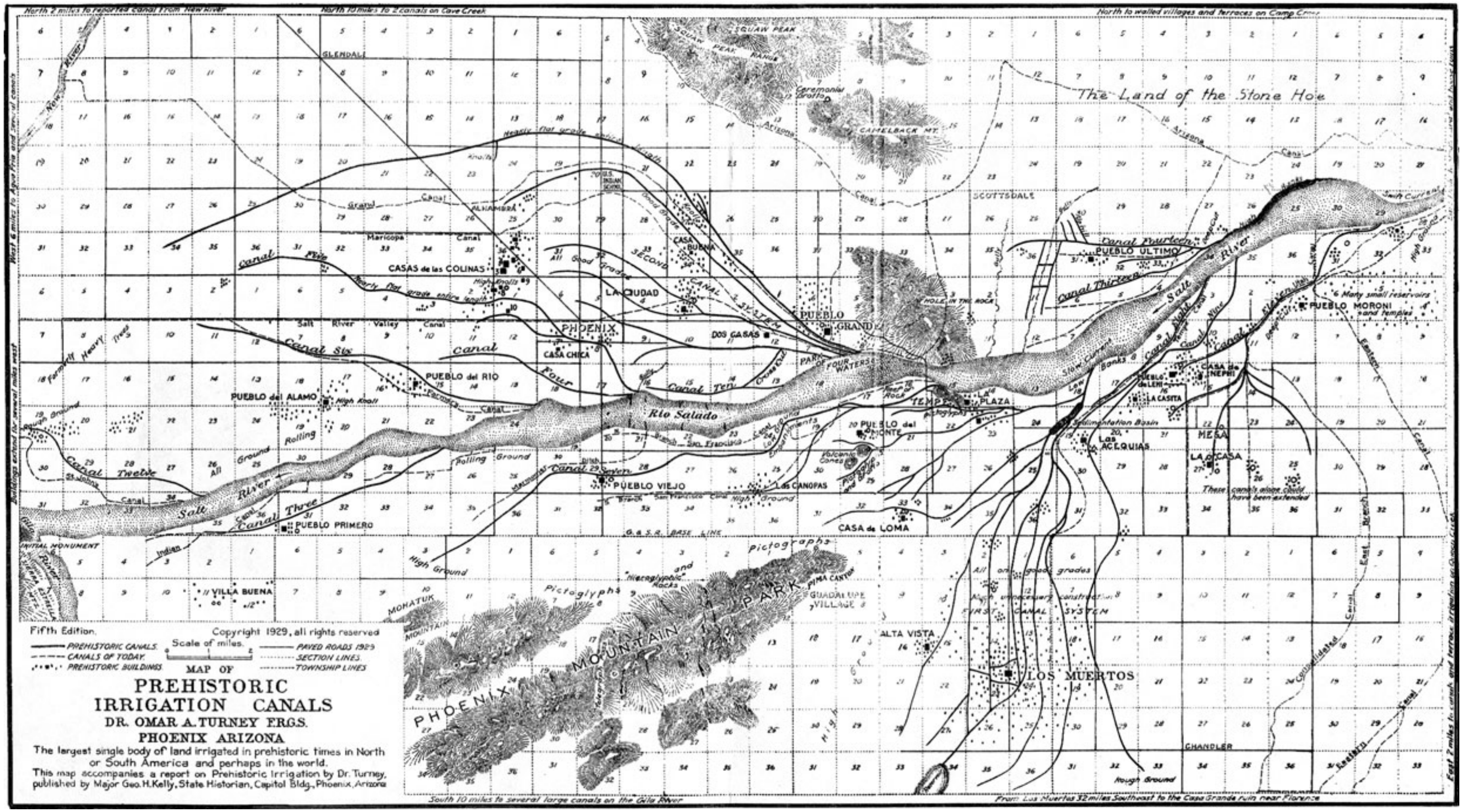


Figure 1.1.3 Canal building in the Salt River Valley with a stone hoe held in the hand without a handle. These were the original engineers, the true pioneers who built, used, and abandoned a canal system when London and Paris were clusters of wild huts (from Turney (1922)). (Courtesy of Salt River Project, Phoenix, Arizona.)

1.2 THE WORLD'S FRESHWATER RESOURCES

Among today's most acute and complex problems are water problems related to the rational use and protection of water resources (see Gleick, 1993). Associated with water problems is the need to supply humankind with adequate, clean freshwater. Data collected on global water resources by Soviet scientists are listed in Table 1.2.1. These obviously are only approximations and should not be considered as accurate (Shiklomanov, 1993). Table 1.2.2 presents the dynamics of actual water availability in different regions of the world. Table 1.2.3 presents the dynamics of water use in the world by human activity. Table 1.2.4 presents the annual runoff and water consumption by continents and by physiographic and economic regions of the world.

Table 1.2.1 Water Reserves on the Earth

	Distribution area (10^3 km^2)	Volume (10^3 km^3)	Layer (m)	Percentage of global reserves: Of total water	Percentage of global reserves: Of fresh-water
World ocean	361,300	1,338,000	3700	96.5	—
Groundwater	134,800	23,400	174	1.7	—
Freshwater		10,530	78	0.76	30.1
Soil moisture		16.5	0.2	0.001	0.05
Glaciers and permanent snow cover	16,227	24,064	1463	1.74	68.7
Antarctic	13,980	21,600	1546	1.56	61.7
Greenland	1802	2340	1298	0.17	6.68
Arctic islands	226	83.5	369	0.006	0.24
Mountainous regions	224	40.6	181	0.003	0.12
Ground ice/permafrost	21,000	300	14	0.022	0.86
Water reserves in lakes	2058.7	176.4	85.7	0.013	—
Fresh	1236.4	91	73.6	0.007	0.26
Saline	822.3	85.4	103.8	0.006	—
Swamp water	2682.6	11.47	4.28	0.0008	0.03
River flows	148,800	2.12	0.014	0.0002	0.006
Biological water	510,000	1.12	0.002	0.0001	0.003
Atmospheric water	510,000	12.9	0.025	0.001	0.04
Total water reserves	510,000	1,385,984	2718	100	—
Total freshwater reserves	148,800	35,029	235	2.53	100

Source: Shiklomanov (1993).

Table 1.2.2 Dynamics of Actual Water Availability in Different Regions of the World

Continent and region	Area (10^6 km^2)	Actual water availability (10^3 m^3 per year per capita): 1950	1960	1970	1980	2000
Europe	10.28	5.9	5.4	4.9	4.6	4.1
North	1.32	39.2	36.5	33.9	32.7	30.9
Central	1.86	3.0	2.8	2.6	2.4	2.3
South	1.76	3.8	3.5	3.1	2.8	2.5
European USSR (North)	1.82	33.8	29.2	26.3	24.1	20.9
European USSR (South)	3.52	4.4	4.0	3.6	3.2	2.4

North America	24.16	37.2	30.2	25.2	21.3	17.5
Canada and Alaska	13.67	384	294	246	219	189
United States	7.83	10.6	8.8	7.6	6.8	5.6
Central America	2.67	22.7	17.2	12.5	9.4	7.1
Africa	30.10	20.6	16.5	12.7	9.4	5.1
North	8.78	2.3	1.6	1.1	0.69	0.21
South	5.11	12.2	10.3	7.6	5.7	3.0
East	5.17	15.0	12.0	9.2	6.9	3.7
West	6.96	20.5	16.2	12.4	9.2	4.9
Central	4.08	92.7	79.5	59.1	46.0	25.4
Asia	44.56	9.6	7.9	6.1	5.1	3.3
North China and Mongolia	9.14	3.8	3.0	2.3	1.9	1.2
South	4.49	4.1	3.4	2.5	2.1	1.1
West	6.82	6.3	4.2	3.3	2.3	1.3
South-east	7.17	13.2	11.1	8.6	7.1	4.9
Central Asia and Kazakhstan	2.43	7.5	5.5	3.3	2.0	0.7
Siberia and Far East	14.32	124	112	102	96.2	95.3
Trans-Caucasus	0.19	8.8	6.9	5.4	4.5	3.0
South America	17.85	105	80.2	61.7	48.8	28.3
North	2.55	179	128	94.8	72.9	37.4
Brazil	8.51	115	86.0	64.5	50.3	32.2
West	2.33	97.9	77.1	58.6	45.8	25.7
Central	4.46	34.0	27.0	23.9	20.5	10.4
Australia and Oceania	8.59	112	91.3	74.6	64.0	50.0
Australia	7.62	35.7	28.4	23.0	19.8	15.0
Oceania	1.34	161	132	108	92.4	73.5

Source: Shiklomanov (1993).

Table 1.2.3 Dynamics of Water Use in the World by Human Activity

Water users[a]	1900 (km^3 per year)	1940 (km^3 per year)	1950 (km^3 per year)	1960 (km^3 per year)	1970 (km^3 per year)	1975 (km^3 per year)	1980 (km^3 per year)	1980 (%)	1990[b] (km^3 per year)	1990[b] (%)	2000[b] (km^3 per year)	2000[b] (%)
Agriculture												
Withdrawal	525	893	1130	1550	1850	2050	2290	69.0	2680	64.9	3250	62.6
Consumption	409	679	859	1180	1400	1570	1730	88.7	2050	86.9	2500	86.2
Industry												
Withdrawal	37.2	124	178	330	540	612	710	21.4	973	23.6	1280	24.7
Consumption	3.5	9.7	14.5	24.9	38.0	47.2	61.9	3.2	88.5	3.8	117	4.0
Municipal supply												
Withdrawal	16.1	36.3	52.0	82.0	130	161	200	6.0	300	7.3	441	8.5
Consumption	4.0	9.0	14	20.3	29.2	34.3	41.1	2.1	52.4	2.2	64.5	2.2
Reservoirs												
Withdrawal	0.3	3.7	6.5	23.0	66.0	103	120	3.6	170	4.1	220	4.2
Consumption	0.3	3.7	6.5	23.0	66.0	103	120	6.2	170	7.2	220	7.6
Total (rounded off)												
Withdrawal	579	1060	1360	1990	2590	2930	3320	100	4130	100	5190	100
Consumption	417	701	894	1250	1540	1760	1950	100	2360	100	2900	100

[a]Total water withdrawal is shown in the first line of each category, consumptive use (irretrievable water loss) is shown in the second line.
[b]Estimated.

Source: Shiklomanov (1993).

Table 1.2.4 Annual Runoff and Water Consumption by Continents and by Physiographic and Economic Regions of the World

Continent and region	Mean annual runoff (mm)	Mean annual runoff (km^3 per year)	Aridity index (R/LP)	1980 Total	1980 Irretrievable	1990 Total	1990 Irretrievable	2000 Total	2000 Irretrievable
Europe	310	3210	—	435	127	555	178	673	222
North	480	737	0.6	9.9	1.6	12	2.0	13	2.3
Central	380	705	0.7	141	22	176	28	205	33
South	320	564	1.4	132	51	184	64	226	73
European USSR (North)	330	601	0.7	18	2.1	24	3.4	29	5.2
European USSR (South)	150	525	1.5	134	50	159	81	200	108
North America	340	8200	—	663	224	724	255	796	302
Canada and Alaska	390	5300	0.8	41	8	57	11	97	15
United States	220	1700	1.5	527	155	546	171	531	194
Central America	450	1200	1.2	95	61	120	73	168	93
Africa	150	4570	—	168	129	232	165	317	211
North	17	154	8.1	100	79	125	97	150	112
South	68	349	2.5	23	16	36	20	63	34
East	160	809	2.2	23	18	32	23	45	28
West	190	1350	2.5	19	14	33	23	51	34
Central	470	1909	0.8	2.8	1.3	4.8	2.1	8.4	3.4
Asia	330	14,410	—	1910	1380	2440	1660	3140	2020
North China and Mongolia	160	1470	2.2	395	270	527	314	677	360
South	490	2200	1.3	668	518	857	638	1200	865
West	72	490	2.7	192	147	220	165	262	190
South-east	1090	6650	0.7	461	337	609	399	741	435
Central Asia and Kazakhstan	70	170	3.1	135	87	157	109	174	128
Siberia and Far East	230	3350	0.9	34	11	40	17	49	25
Trans-Caucasus	410	77	1.2	24	14	26	18	33	21
South America	660	11,760	—	111	71	150	86	216	116
Northern area	1230	3126	0.6	15	11	23	16	33	20
Brazil	720	6148	0.7	23	10	33	14	48	21
West	740	1714	1.3	40	30	45	32	64	44
Central	170	812	2.0	33	20	48	24	70	31
Australia and Oceania	270	2390		29	15	38	17	47	22
Australia	39	301	4.0	27	13	34	16	42	20
Oceania	1560	2090	0.6	2.4	1.5	3.3	1.8	4.5	2.3
Land area (rounded off)	—	44,500	—	3320	1450	4130	2360	5190	2900

Source: Shiklomanov (1993).

1.3 WATER USE IN THE UNITED STATES

Dziegielewski et al. (1996) define *water use* from a hydrologic perspective as all water flows that are a result of human intervention in the hydrologic cycle. The National Water Use Information Program (NWUI Program), conducted by the United States Geological Survey (USGS), used this perspective on water use in establishing a national system of water-use accounting. This accounting system distinguishes the following water-use flows: (1) water withdrawals for off-stream purposes, (2) water deliveries at point of use or quantities released after use, (3) consumptive use, (4) conveyance loss, (5) reclaimed wastewater, (6) return flow, and (7) in-stream flow (Solley et al., 1993). The relationships among these human-made flows at various points of measurement are illustrated in Figure 1.3.1. Figure 1.3.2 illustrates the estimated water use by tracking the sources, uses, and disposition of freshwater using the hydrologic accounting system given in Figure 1.3.1. Table 1.3.1 defines the major purposes of water use.

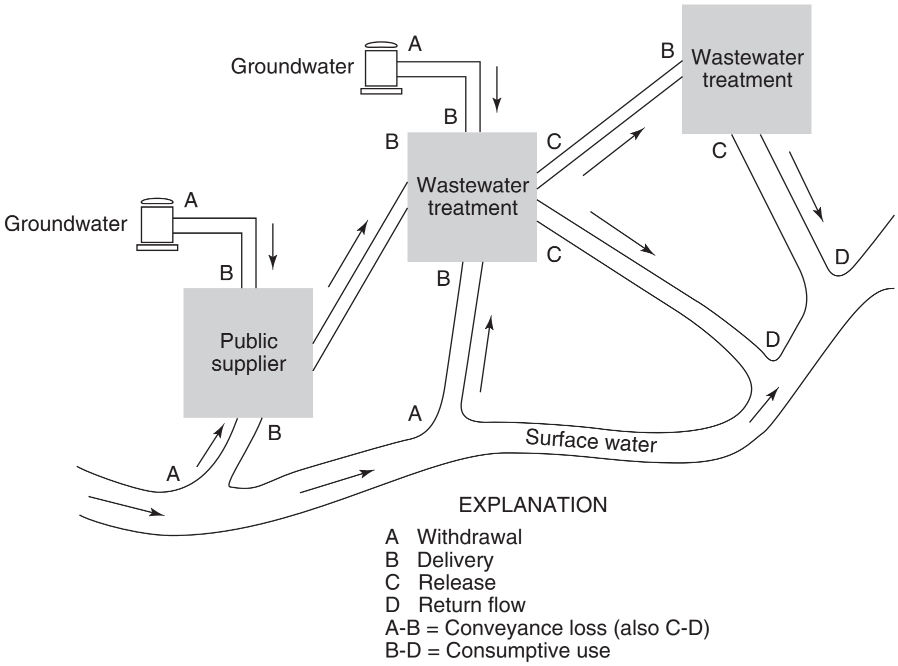


Figure 1.3.1 Definition of water-use flows and losses (from Solley et al. (1993)).

Table 1.3.1 Major Purposes of Water Use

Water-use purpose	Definition
Domestic use	Water for household needs such as drinking, food preparation, bathing, washing clothes and dishes, flushing toilets, and watering lawns and gardens (also called residential water use).
Commercial use	Water for motels, hotels, restaurants, office buildings, and other commercial facilities and institutions.
Irrigation use	Artificial application of water on lands to assist in the growing of crops and pastures or to maintain vegetative growth in recreational lands such as parks and golf courses.
Industrial use	Water for industrial purposes such as fabrication, processing, washing, and cooling.
Livestock use	Water for livestock watering, feed lots, dairy operations, fish farming, and other on-farm needs.
Mining use	Water for the extraction of minerals occurring naturally and associated with quarrying, well operations, milling, and other preparations customarily done at the mine site or as part of a mining activity.
Public use	Water supplied from a public water supply and used for such purposes as firefighting, street washing, municipal parks, and swimming pools.
Rural use	Water for suburban or farm areas for domestic and livestock needs, which is generally self-supplied.
Thermoelectric power use	Water for the process of the generation of thermoelectric power.

Source: Solley et al. (1993).

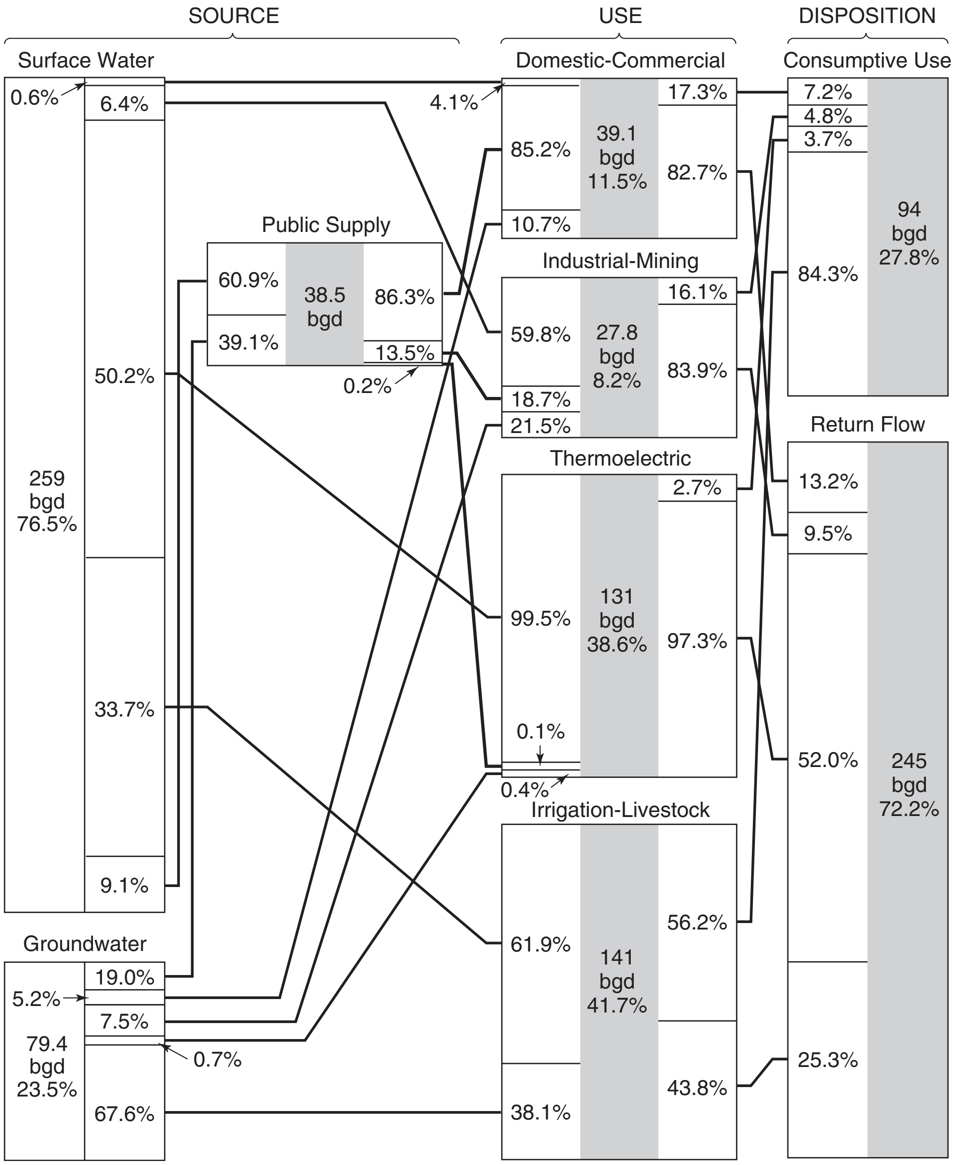


Figure 1.3.2 Estimated water use in the United States, 1990. Freshwater withdrawals and disposition of water in billion gallons per day (bgd). For each water use category, this diagram shows the relative proportion of water source and disposition and the general distribution of water from source to disposition. The lines and arrows indicate the distribution of water from source to disposition for each category; for example, surface water was 76.5 percent of total freshwater withdrawn, and, going from "Source" to "Use" columns, the line from the surface water block to the domestic and commercial block indicates that 0.6 percent of all surface water withdrawn was the source for 4.1 percent of total water (self-supplied withdrawals, public supply deliveries) for domestic and commercial purposes (from Solley et al. (1993)).

1.4 SYSTEMS OF UNITS

The analysis of pressurized (conduit) flow, open-channel flow, and groundwater flows requires an understanding of the elements of fluid mechanics (presented in Chapter 3). A review of the mechanics of materials is a prerequisite to the examination of fluid mechanics principles. Table 1.4.1

Table 1.4.1 Dimensions and SI Units for Basic Mechanical Properties

Property	SI unit	SI symbol	Dimension of unit: Derived	Dimension of unit: Basic
Mass	kilogram	kg		kg
Length	meter	m		m
Time	second	s		s
Area				m^2
Volume				m^3
Velocity				m/s
Acceleration				m/s^2
Force	newton	N		$kg \cdot m/s^2$
Weight	newton	N		$kg \cdot m/s^2$
Pressure	pascal	Pa	N/m^2	$kg/m \cdot s^2$
Work	joule	J	$N \cdot m$	$kg \cdot m^2/s^2$
Energy	joule	J	$N \cdot m$	$kg \cdot m^2/s^2$
Mass density				kg/m^2
Weight density			N/m^3	$kg/m^2 \cdot s^2$
Stress	pascal	Pa	N/m^2	$kg/m \cdot s^2$

lists the basic mechanical properties of matter with their dimensions and units in the SI system. In the United States much of the technology related to water resources engineering is still based upon the foot-pound-second (FPS) system of units, or what are referred to in this book as U.S. customary units. Table 1.4.2 provides a set of correction factors for converting U.S. customary units to SI units.

Table 1.4.2 Conversion Factors FPS (Foot-Pound-Second) System of Units to SI Units

	Multiply	By	To obtain
Length	ft	3.048×10^{-1}	m
	ft	3.048×10	cm
	ft	3.048×10^{-4}	km
	mile	1.609×10^{3}	m
	mile	1.609	km
Area	ft^2	9.290×10^{-2}	m^2
	mi^2	2.590	km^2
	acre	4.047×10^{3}	m^2
	acre	4.047×10^{-3}	km^2
Volume	ft^3	2.832×10^{-2}	m^3
	U.S. gal	3.785×10^{-3}	m^3
	U.K. gal	4.546×10^{-3}	m^3
	ft^3	2.832×10	ℓ
	U.S. gal	3.785	ℓ
	U.K. gal	4.546	ℓ
Velocity	ft/s	3.048×10^{-1}	m/s
	ft/s	3.048×10	cm/s
	mi/h	4.470×10^{-1}	m/s
	mi/h	1.609	km/h
Acceleration	ft/s^2	3.048×10^{-1}	m/s^2

(Continued)

Table 1.4.2 (*Continued*)

	Multiply	By	To obtain
Mass	lb_m	4.536×10^{-1}	kg
	slug	1.459×10	kg
	ton	1.016×10^{3}	kg
Force and weight	lb_f	4.448	N
	poundal	1.383×10^{-1}	N
Pressure and stress	psi	6.895×10^{3}	Pa or N/m^2
	lb_f/ft^2	4.788×10	Pa
	poundal/ft^2	1.488	Pa
	atm	1.013×10^{5}	Pa
	in Hg	3.386×10^{3}	Pa
	mb	1.000×10^{2}	Pa
Work and energy	ft-lbf	1.356	J
	ft-poundal	4.214×10^{-2}	J
	Btu	1.055×10^{-3}	J
	calorie	4.187	J
Mass density	lbm/ft^3	1.602×10	kg/m^3
	slug/ft^3	5.154×10^{2}	kg/m^3
Weight density	lb_f/ft^3	1.571×10^{2}	N/m^3
Discharge	ft^3/s	2.832×10^{-2}	m^3/s
	ft^3/s	2.832×10	ℓ/s
	U.S. gal/min	6.309×10^{-5}	m^3/s
	U.K. gal/min	7.576×10^{-5}	m^3/s
	U.S. gal/min	6.309×10^{-2}	ℓ/s
	U.K. gal/min	7.576×10^{-2}	ℓ/s
Hydraulic conductivity	ft/s	3.048×10^{-1}	m/s
(see also Table 2.3)	U.S. gal/day/ft^2	4.720×10^{-7}	m/s
Transmissivity	ft^2/s	9.290×10^{-2}	m^2/s
	U.S. gal/day/ft	1.438×10^{-7}	m^2/s

1.5 THE FUTURE OF WATER RESOURCES

The management of water resources can be subdivided into three broad categories: (1) *water-supply management,* (2) *water-excess management*, and (3) *environmental restoration*. All modern multipurpose water resources projects are designed and built for water-supply management and/or water-excess management. In fact, throughout human history all water resources projects have been designed and built for one or both of these categories. A *water resources system* is a system for redistribution, in space and time, of the water available to a region to meet societal needs (Plate, 1993). Water can be utilized from surface water systems, from groundwater systems, or from conjunctive/ground surface water systems.

When discussing water resources, we must consider both the quantity and the quality aspects. The hydrologic cycle must be defined in terms of both water quantity and water quality. Because of the very complex water issues and problems that we face today, many fields of study are involved in their solution. These include the biological sciences, engineering, physical sciences, and social sciences (see Figure 1.1.1), illustrating the wide diversity of disciplines involved in water resources.

In the twenty-first century we are questioning the viability of our patterns of development, industrialization, and resources usage. We are now beginning to discuss the goals of attaining an equitable and sustainable society in the international community. Looking into the future, a new set of problems face us, including the rapidly growing population in developing countries; uncertain impacts of global climate change; possible conflicts over shared freshwater resources; thinning of the ozone layer; destruction of rain forests; threats to wetland, farmland, and other renewable resources; and many others.

These problems are very different from those that humans have faced before. The fact that there are so many things undiscovered by the human race leads me to the statement by Sir Isaac Newton, shortly before his death in 1727:

> *I do not know what I may appear to the world, but to myself I seem to have been only like a boy playing on the sea shore, and diverting myself in now and then finding a smoother pebble or a prettier shell than ordinary, while the great ocean of truth lay all undiscovered before me.*

REFERENCES

Adams, R. M., *Heartland of Cities, Surveys of Ancient Settlement and Land Use in the Central Floodplain of the Euphrates*, University of Chicago Press, Chicago, 1965.

Butzer, K. W., *Early Hydraulic Civilization in Egypt*, University of Chicago Press, Chicago, 1976.

Dziegielewski, B., E. M. Opitz, and D. R. Maidment, "Water Demand Analysis," Chapter 23 in *Water Resources Handbook* edited by L. W. Mays, McGraw-Hill, New York, 1996.

Gleick, P. H., *Water in Crisis*, Oxford University Press, Oxford, 1993.

Mays, L. W., "Water Resources: An Introduction," in *Water Resources Handbook* edited by L. W. Mays McGraw-Hill, New York, 1996.

Mays, L. W., "Introduction," in *Hydraulic Design Handbook* edited by L. W. Mays, McGraw-Hill, New York, 1999.

Mays, L. W., "Introduction," in *Water Distribution Systems Handbook* edited by L. W. Mays, McGraw-Hill, New York, 2000.

Mays, L. W., D. Koutsoyiannis, and A. N. Angelakis, "A Brief History of Urban Water Supply in Antiquity," *Water and Science Technology: Water Supply*, vol. 7, no. l, pp. 1–12, IWA Publishing, 2007.

Mays, L. W., "Water Sustainability of Ancient Civilizations in Mesoamerica and the American. Southwest," *Water and Science Technology: Water Supply*, vol. 7, no. 1, pp. 229–236, IWA Publishing, 2007.

Mays, L. W., "A Very Brief History of Hydraulic Technology during Antiquity," *Environmental Fluid Mechanics*, vol. 8, no. 5, pp. 471–484, 2008.

Mays, L. W., (Editor-in-Chief), *Ancient Water Technology*, Springer, New York, 2010.

Plate, E. J., "Sustainable Development of Water Resources: A Challenge to Science and Engineering," *Water International*, vol. 18, no. 2, pp. 84–94, International Water Resources Association, 1993.

Shiklomanov, I., "World Fresh Water Resources," in *Water in Crisis* edited by P. H. Gleick, Oxford University Press, New York, 1993.

Solley, W. B., R. R. Pierce, and H. A. Perlman, *"Estimated Use of Water in the United States in 1990,"* U.S. Geological Survey Circular 1081, Washington, DC, 1993.

Turney, O. S., Map of Prehistoric Irrigation Canals, Map No. 002004, Archaeological Site Records Office, Arizona State Museum, University of Arizona, Tucson, 1922.

This page intentionally left blank

Chapter 2

Water Resources Sustainability

2.1 WHAT IS WATER RESOURCES SUSTAINABILITY?

Traditionally, sustainability explores the relationships among economics, the environment, and social equity, using the three-legged stool analogy that includes not only the technical, but also the economic and social issues.

The term "sustainable development" was defined in 1987 by the World Commission on Environment and Development as "development that can meet the needs of the present generation without compromising the ability of future generations to meet their own needs. Some of the questions related to sustainable systems and sustainable design are:

- What are the characteristics of sustainable systems?
- How does the design process encourage sustainability?
- What is sustainable water resources development?
- What are the components of sustainable development?

2.1.1 Definition of Water Resources Sustainability

We live in a world where approximately 1.1 billion people lack safe drinking water, approximately 2.6 billion people lack adequate sanitation, and between 2 and 5 million people die annually from water-related diseases (Gleick, 2004). The United Nations Children's Fund's (UNICEF) report, "The State of the World's Children 2005: Childhood under Threat," concluded that more than half the children in the developing world are severely deprived of various necessities essential to childhood. For example, 500 million children have no access to sanitation and 400 million children have no access to safe water. One might ask how sustainable is this? The key to sustainability is the attention to the survival of future generations. Also important is the global context within which we must think and solve problems. The future of water resources thinking must be within the context of water resources sustainability.

The overall goal of water resources management for the future must be water resources sustainability. Mays (2007) defined water resources sustainability as follows:

> *"Water resources sustainability is the ability to use water in sufficient quantities and quality from the local to the global scale to meet the needs of humans and ecosystems for the present and the future to sustain life, and to protect humans from the damages brought about by natural and human-caused disasters that affect sustaining life."*

The Brundtland Commissions's report, "Our Common Future" (World Commission on Environment and Development, WCED), defined sustainability as focusing on the needs of both current and future generations. A development is sustainable if "it meets the needs of the present without compromising the ability of future generations to meet their own needs."

Because water impacts so many aspects of our existence, there are many facets that must be considered in water resources sustainability including:

- Water resources sustainability includes the *availability of freshwater supplies* throughout periods of climatic change, extended droughts, population growth, and to leave the needed supplies for the future generations.
- Water resources sustainability includes having the *infrastructure*, to provide water supply for human consumption and food security, and to provide protection from water excess such as floods and other natural disasters.
- Water resources sustainability includes having the *infrastructure* for clean water and for treating water after it has been used by humans before being returned to water bodies.
- Water sustainability must have adequate *institutions* to provide the management for both the water supply management and water excess management.
- Water sustainability must be considered on a *local, regional, national, and international basis.*
- To achieve water resources sustainability, the principles of *integrated water resources management (IWRM)* must be implemented.

Sustainable water use has been defined by Gleick et al. (1995) as "the use of water that supports the ability of human society to endure and flourish into the indefinite future without undermining the integrity of the hydrological cycle or the ecological systems that depend on it." Seven sustainability requirements are presented in Section 11.1.

2.1.2 The Dublin Principles

The following four simple, but yet powerful messages, were provided in 1992 in Dublin and were the basis for the Rio Agenda 21 and for the millennium Vision-to-Action:

1. *Freshwater is a finite and vulnerable resource, essential to sustain life, development and the environment*, i.e. one resource, to be holistically managed.
2. *Water development and management should be based on a participatory approach, involving users, planners, and policy-makers at all levels*, i.e. manage water with people—and close to people.
3. *Women play a central role in the provision, management and safeguarding of water*, i.e. involve women all the way!
4. *Water has an economic value in all its competing uses and should be recognized as an economic good*, i.e. having ensured basic human needs, allocate water to its highest value, and move towards full cost pricing, rational use, and recover costs.

Poor water management hurts the poor most! The Dublin principles aim at wise management with focus on poverty.

2.1.3 Millennium Development Goals (MDGs)

The *Millennium Development Goals* (MDGs), adopted in September 2000 during the Millennium Summit of the United Nations General Assembly, is comprised of eight goals (see Table 2.1.1). All of the goals can be translated directly or indirectly into water-related terms (Gleick, 2004). For example, Goal No. 1—"Eradicate extreme poverty and hunger"—and No. 7—"Ensure

Table 2.1.1 UN Millennium Development Goals and Targets for Goal 7

Goal 1 Eradicate Extreme Hunger and Poverty
Goal 2 Achieve Universal Primary Education
Goal 3 Promote Gender Equality and Empower Women
Goal 4 Reduce Child Mortality
Goal 5 Improve Maternal Health
Goal 6 Combat HIV/AIDS, Malaria, and Other Diseases
Goal 7 Ensure Environmental Sustainability
Target 9 Integrate the principles of sustainable development into country policies and programs and reverse the loss of environmental resources.
Target 10 Halve, by 2015, the proportion of people without sustainable access to safe drinking water and basic sanitation.
Target 11 Achieve by 2020 a significant improvement in the lives of at least 100 million slum dwellers.
Goal 8 Develop a Global Partnership for Development

Source: http://www.mdgmonitor.org/browse_goal.cfm

environmental sustainability" have direct relevance to water; whereas Goal No. 2—"Achieve universal primary education" and No. 3—"Promote gender equality and empower women" are water-related as millions of women and young girls spend many hours every day to fetch water. The health related Goals 4, 5, and 6 also have strong relevance to water, or the lack of it.

The MDG Goal 7, target 10 of halving, by the year 2015, the proportion of people without sustainable access (to reach or to afford) to safe drinking water seems unlikely to be met. The international community has made little progress to meet the similar part of target 10—to halve, also by 2015, the proportion of people without access to basic sanitation—adopted at the *World Summit on Sustainable Development* (WSSD), in Johannesburg in 2002 (United Nations,). An interesting fact is that this goal did not specifically emphasize wastewater treatment and disposal, because in many parts of the world wastewater treatment does not exist even though sanitation services exist and the sewage is used to irrigate agricultural crops. It is estimated that in Latin America 1.3 million hectares of agricultural land is irrigated with raw wastewater and has related health and disease issues. In countries with water shortages, the reuse of untreated wastewater will likely increase in the future.

2.1.4 Urbanization – A Reality of Our Changing World

Urban populations demand high quantities of energy and raw material, water supply, removal of wastes, transportation, etc. Urbanization creates many challenges for the development and management of water supply systems and the management of water excess from storms and floodwaters. Many urban areas of the world have been experiencing water shortages, which are expected to explode this century unless serious measures are taken to reduce the scale of this problem (Mortada, 2005). Most developing countries have not acknowledged the extent of their water problems, as evidenced by the absence of any long-term strategies for water management.

Changes Caused by Urbanization

Urbanization is a reality of our changing world. From a water resources perspective, urbanization causes many changes to the hydrological cycle including radiation flux, amount of precipitation, amount of evaporation, amount of infiltration, increased runoff, etc. Changes brought about by urbanization can be summarized briefly as follows (Marsalek et al., 2006):

- Transformation of undeveloped land into urban land (including transportation corridors);
- Increased energy release (i.e., greenhouse gases, waste heat, heated surface runoff); and
- Increased demand on water supply (municipal and industrial).

2.2 CHALLENGES TO WATER RESOURCES SUSTAINABILITY

Urban populations are growing rapidly around the world with the addition of many mega-cities (populations of 10 million or more inhabitants). In 1975 there were only four mega-cities in the world and by 2015 there may be over 22 mega-cities in the world (Marshall, 2005). Other cities that will not become mega-cities are also growing very rapidly around the world. By 2010, more than 50% of the world's population is expected to live in urban areas (World Water Assessment Program, 2006).

Mega-cities mean mega problems of which urban water supply management and water excess management are among the largest. Mega-cities and other large cities will be a drain on the Earth's dwindling resources, while at the same time significantly contributing to the environmental degradation. Many of the large cities around the world are prone to water supply shortages, others are prone to flooding, and many are prone to both. A large number of the cities of the world do not have adequate wastewater facilites and most of the waste is improperly disposed or used as irrigation of agricultural lands. As the Earth's population continues to grow, so will the growth of cities continue across the globe, stretching resources and the ability to cope with disasters such as floods and droughts. These factors, coupled with the consequences of global warming, create many challenges for future generations.

There are many factors that affect water resources sustainability including: urbanization, droughts, climate change, flooding, and human-induced factors. Developed areas of the world such as the United States are not exempt from the need for water resources sustainability. Figure 2.2.1 shows areas in the western United States with potential water supply crisis by 2025.

2.2.1 Urbanization

The Urban Water Cycle

The overall urban water cycle is illustrated in Figure 2.2.2 showing the main components and pathways. How does the urbanization process change the water budget from predevelopment to developed conditions of the urban water cycle in arid and semi-arid regions? This change is a very complex process and very difficult to explain.

Urban Water Systems

Urban water system implies that there is a single urban water system and the reality of this is that it is an integrated whole. The concept of a single "urban water system" is not fully accepted because of the lack of integration of the various components that make up the total urban water system. For example, in municipalities it is common to plan, manage, and operate urban water into separate entities such as by service, i.e. water supply, wastewater, flood control, and stormwater. Typically there are separate water organizations and management practices within a municipality, or local or regional government because that is the way they have been historically. Grigg (1986) points out that integration could be achieved by functional integration

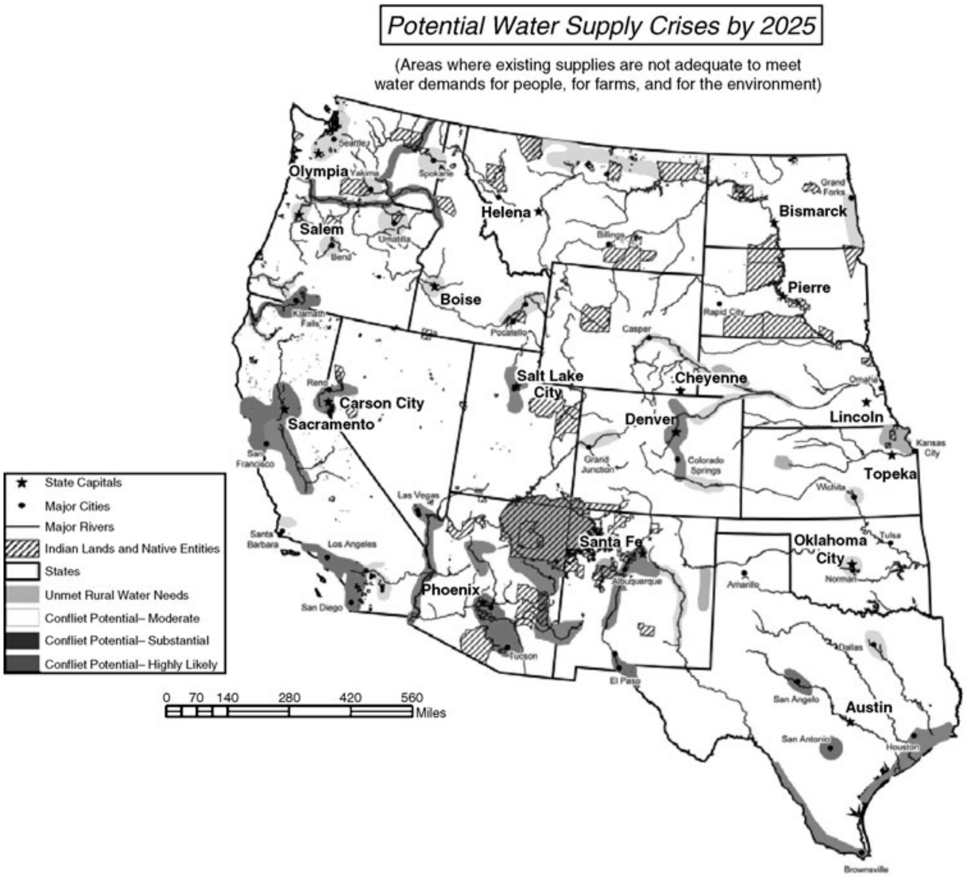


Figure 2.2.1 Areas in the western United States with potential water supply crisis by 2025.
Source: U.S. Department of the Interior (2003).

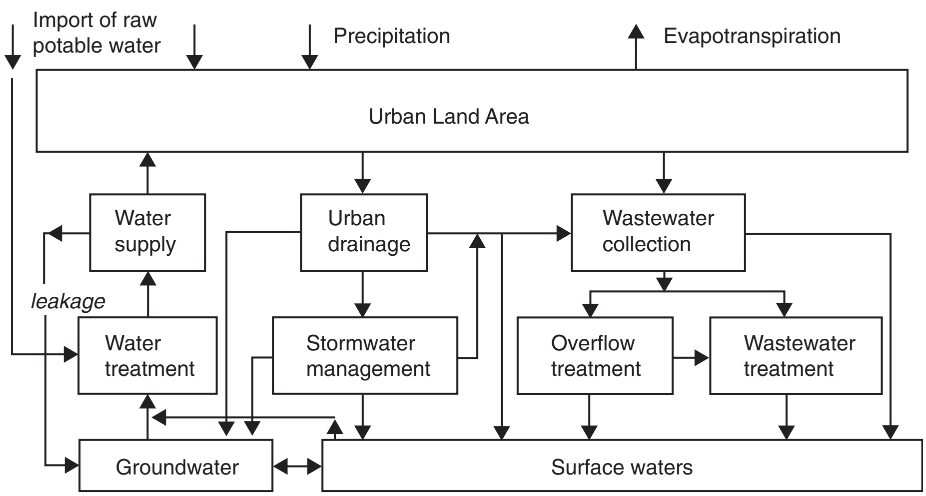


Figure 2.2.2 Urban water cycle: Main components and pathways (from Marsalek et al. (2006)).

and area-wide integration. There are many linkages of the various components of the urban water system with the hydrologic cycle being what connects the urban water system together. There are many reasons for considering the urban water system in an integrated manner. Two of the principal reasons are (a) the natural connectivity of the system through the hydrologic cycle and (b) the real benefits that are realized through integrated management rather than by independent action.

The urban water management system is considered herein as two integrated major entities, water supply management and water excess management. The various interacting components of water excess and water supply management in conventional urban water infrastructure are:

Water Supply Management

– Sources (groundwater, surface water, reuse)
– Transmission
– Water treatment (WT)
– Distribution system
– Wastewater collection
– Wastewater treatment (WWT)
– Reuse

Water Excess Management

– Collection/drainage systems
– Storage/treatment
– Flood control components (levees, dams, diversions, channels)

Sustainable Urban Water Systems

Sustainable urban water systems are being advocated because of the depletion and degradation of urban water resources coupled with the rapid increases in urban populations around the world. Marsalek et al. (2006) defined the following basic goals for sustainable urban water systems:

- Supply of safe and good-tasting drinking water to the inhabitants at all times.
- Collection and treatment of wastewater in order to protect the inhabitants from diseases and the environment from harmful impacts.
- Control, collection, transport, and quality enhancement of stormwater in order to protect the environment and urban areas from flooding and pollution.
- Reclamation, reuse, and recycling of water and nutrients for use in agriculture or households in case of water scarcity.

In North America and Europe many of the above goals have been achieved or are within reach. In many developing parts of the world these goals are far from being achieved. Climate change will be a major factor in both the developed and undeveloped parts of the world that has not been addressed for the future of water resources sustainability. The Millennium Development Goals put a strong emphasis on poverty reduction and reduced child mortality.

Urban Stormwater Runoff

Urban stormwater runoff includes all flows discharged from urban land uses into stormwater conveyance systems and receiving waters. Urban runoff includes both dry-weather, non-stormwater sources (e.g., runoff from landscape irrigation, dewatering, and water line and hydrant flushing) and wet-weather stormwater runoff. Water quality of urban stormwater runoff can be affected by the transport of sediment and other pollutants into streams, wetlands, lakes, estuarine and marine waters, or groundwater. The costs and impacts of water pollution from urban runoff are significant and can include fish kills, health concerns of human and/or terrestrial animals, degraded drinking water, diminished water-based recreation and tourism opportunities, economic losses to commercial fishing and aquaculture industries, lowered real estate values, damage to habitat of fish and other aquatic organisms, inevitable costs of clean-up and pollution reduction, reduced aesthetic values of lakes, streams, and coastal areas, and other impacts (Leeds et al., 1993).

Increased stormwater flows from urbanization have the following major impacts (FLOW, 2003):

- acceleration of stream velocities and degradation of stream channels,
- declining water quality due to washing away of accumulated pollutants from impervious surfaces to local waterways, and an increase in siltation and erosion of soils from pervious areas subject to increased runoff,
- increase in volume of runoff with higher pollutant concentrations that reduces receiving water dilution effects,
- diminished groundwater recharge, resulting in decreased dry-weather flows; poorer water quality of streams during low flows; increased stream temperatures; and greater annual pollutant load delivery,
- increased flooding,
- combined and sanitary sewer overflows due to stormwater infiltration and inflow,
- damage to stream and aquatic life resulting from suspended solids accumulation, and increased health risks to humans from trash and debris which can also endanger, and
- destroying food sources or habitats of aquatic life (FLOW, 2003).

Groundwater Changes

Urbanization often causes changes in groundwater levels as a result of decreased recharge and increased withdrawal. In rural areas, water supplies are usually obtained from shallow wells, while most of the domestic wastewater is returned to the ground through cesspools or septic tanks. Thus the quantitative balance in the hydrologic system remains. As urbanization occurs many individual wells are abandoned for deeper public wells. With the introduction of sewer systems, stormwater, and (treated or untreated) wastewater are discharged to nearby surface water bodies. Three conditions disrupt the subsurface hydrologic balance and produce declines in groundwater levels.

1. Reduced groundwater recharge due to paved surface areas and storm sewers
2. Increased groundwater discharge by pumping wells
3. Decreased groundwater recharge due to export of wastewater collected by sanitary sewers

Groundwater quality is certainly another challenge to water resources sustainability resulting in many cases from urbanization. Groundwater quality can be affected by residential and commercial development as illustrated in Figure 2.2.3. The U.S. Geological Survey's National Water Quality Assessment (NAWQA) program (http://water.usgs.gov/nawqa) seeks to determine how shallow groundwater quality is affected by development (Squillace and Price, 1996). Residential developments have taken up very large tracts of land, and as a consequence, have widespread influence on the quality of water that recharges aquifers, streams, lakes, and wetlands. Liquids discharged onto the ground surface in an uncontrolled manner can migrate downward to degrade groundwater. Septic tanks and cesspools are another source of groundwater pollution. Polluted surface water bodies that contribute to groundwater recharge are sources of groundwater pollution.

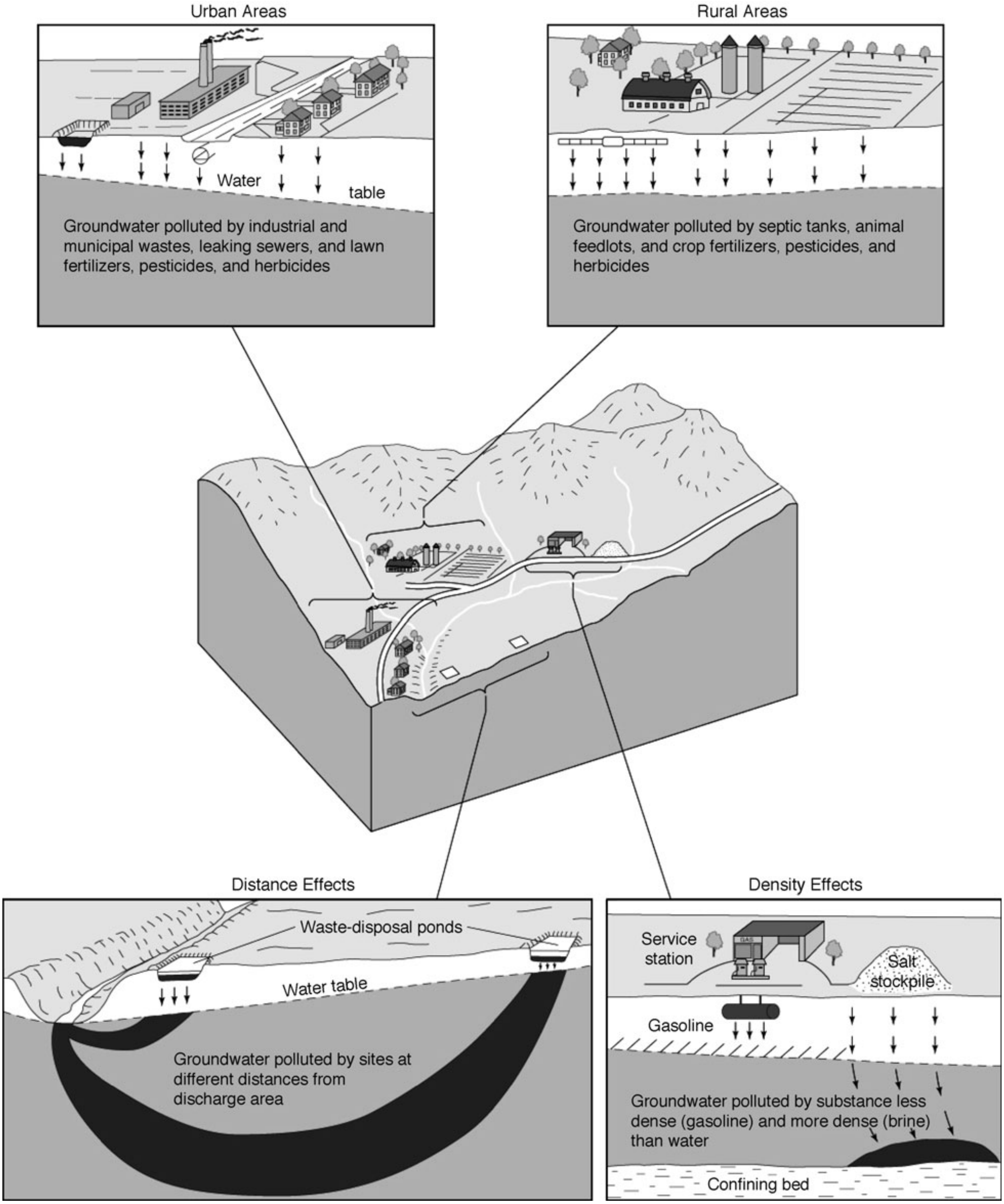


Figure 2.2.3 Groundwater pollution affected by differences in chemical composition, biological, and chemical reactions, and distance from discharge areas (from Heath, 1998).