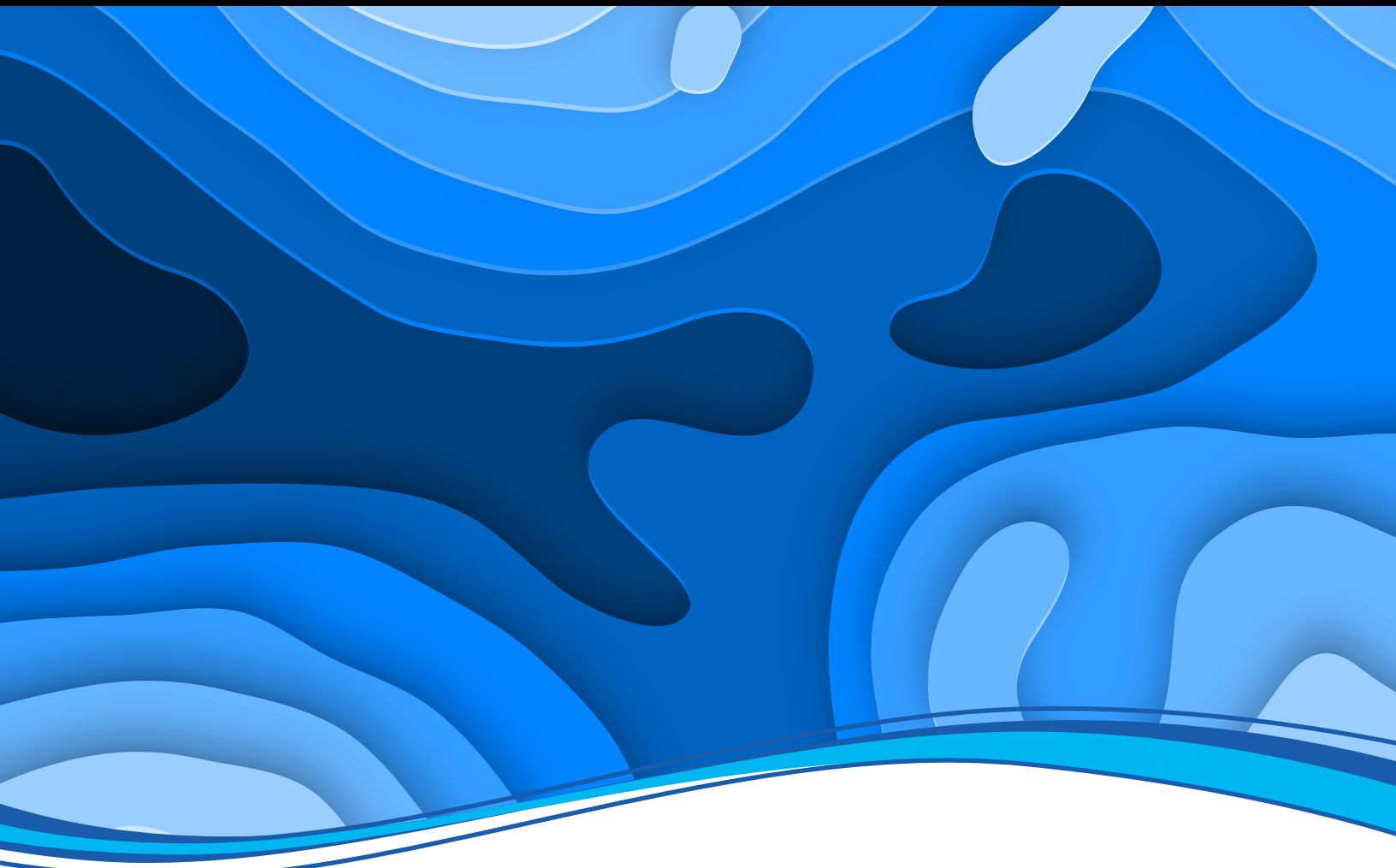


Groundwater Management



American Water Works
Association



Documents

Document Sharing Hub

Groundwater Management



**American Water Works
Association**



Documents
Document Sharing Hub

Manual of Water Supply Practices—M73, First Edition

Groundwater Management

Copyright © 2021 American Water Works Association

All rights reserved. No part of this publication may be reproduced or transmitted in any form or by any means, electronic or mechanical, including scanning, recording, or any information or retrieval system. Reproduction and commercial use of this material is prohibited, except with written permission from the publisher.

Disclaimer

The authors, contributors, editors, and publisher do not assume responsibility for the validity of the content or any consequences of its use. In no event will AWWA be liable for direct, indirect, special, incidental, or consequential damages arising out of the use of information presented in this book. In particular, AWWA will not be responsible for any costs, including, but not limited to, those incurred as a result of lost revenue. In no event shall AWWA's liability exceed the amount paid for the purchase of this book.

If you find errors in this manual, please email books@awwa.org. Possible errata will be posted at www.awwa.org/M73

Senior Managing Editor/Project Manager: Melissa Valentine

Technical Editor: Dianne Beirne

Cover Design/Technical Illustrations: Michael Labruyere

Production: Senior Specialist - Manuals: Willadee Hitchcock

Library of Congress Cataloging-in-Publication Data

Names: Bloetscher, Frederick, author. | Roberts, Susan V., author. | American Water Works Association, sponsor.

Title: M73 Groundwater Management / by Frederick Bloetscher and Susan Roberts

Other titles: Ground water management | AWWA manual; M73.

Description: First edition. | Denver : American Water Works Association, [2021] | Series: Manual of water supply practice ; M73 | Includes bibliographical references and index. | Summary: "Manual M73 Groundwater Management is the culmination of efforts by members of the Groundwater Resource Committee to identify and demonstrate the value of using computer modeling tools to help utilities better manage their groundwater resources in light of greater competition for water and dwindling supplies in many parts of the world. I" —Provided by publisher.

Identifiers: LCCN 2021016570 | ISBN 9781647170400 (paperback) | ISBN 9781613005781 (Adobe PDF)

Subjects: LCSH: Wells. | Groundwater. | Water-supply--Management.

Classification: LCC TD403 .B57 2021 | DDC 628.1/14--dc23

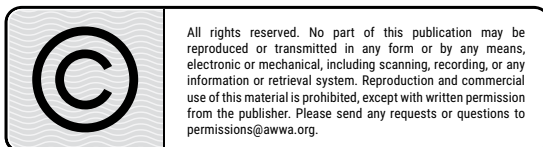
LC record available at <https://lcn.loc.gov/2021016570>

Printed in the United States of America

ISBN 978-1-64717-040-0

e-ISBN-13 978-1-61300-578-1

<https://doi.org/10.12999/AWWA.M73ed1>



**American Water Works
Association**

American Water Works Association
6666 West Quincy Avenue
Denver, CO 80235-3098
awwa.org

 **Documents**
Document Sharing Hub

Copyright © 2021 American Water Works Association. All Rights Reserved.

Full document details: [AWWA Manual M73 2021](#)

Contents

List of Figures, v

List of Tables, vii

Preface, ix

Acknowledgments, xi

Definitions, xii

Chapter 1	Introduction	1
	Coastal Carolinas – What Can Go Wrong?, 1	
	Goal of the Manual, 4	
	References, 6	
Chapter 2	The Occurrence and Behavior of Groundwater	7
	Hydrologic Cycle, 8	
	The Impact of Land Subsidence on Groundwater, 14	
	Climate Impacts on Groundwater, 14	
	Sustainability, 15	
	Development and Urbanization Impacts, 18	
	Integrating Groundwater Management, 19	
	References, 21	
Chapter 3	Motivation for Groundwater Management	23
	Water Quality, 24	
	Source Water Protection, 25	
	Example of a Wellhead Protection Zone, 28	
	Groundwater Protection Strategies, 28	
	Contaminated Groundwater Management Strategies, 29	
	References, 29	
Chapter 4	Groundwater/Aquifer Characterization Tools	31
	Groundwater Budget, 31	
	Aquifer Characterization, 32	
	Evaluation of Current Conditions, 35	
	References, 38	
Chapter 5	Monitoring to Support Management of Regional Groundwater Systems	39
	Monitoring Wells and Networks, 40	
	Data Review and Trend Analysis, 45	
	Documents and Records, 46	
	References, 48	
Chapter 6	Groundwater Models	49
	When to Use a Groundwater Model and Why, 50	
	Types of Groundwater Models, 51	
	Groundwater Model Complexity, 53	

	The Modeling Process, 59	
	Using the Results, 66	
	References, 66	
Chapter 7	Case Studies Using Groundwater Models	67
	Overview, 67	
	Summary of Case Studies, 68	
	Detailed Case Studies, 69	
	References, 99	
Chapter 8	The Future of Groundwater Management	103
	References, 105	
Appendix A	Glossary of Concepts Associated with Aquifer and Wellfield Yield	107
	Index, 113	
	List of AWWA Manuals, 119	

Figures

- 1-1 Decline in the Black Creek aquifer in rural Jones County, N.C., 2
- 1-2 Declines in the aquifer formations near Florence, S.C., 3
- 1-3 Pre- and post-development (1982) head, Black Creek aquifer, 3
- 1-4 Estimated pre- and post-development (1982) of the Middendorf Aquifer, 4
- 2-1 Hydrologic cycle, 8
- 2-2 Evapotranspiration rates, 9
- 2-3 Mean annual precipitation for the conterminous United States, 1890–2002, 10
- 2-4 Geologic configuration of aquifers and confining beds, 11
- 2-5 Development of a cone of depression, showing the central well and a series of monitoring wells that were used to define the cone of depression, 13
- 2-6 Groundwater levels typically mimic the surface topography in a given watershed, 13
- 2-7 Difference between average annual precipitation and potential ET (PET) rates, 16
- 2-8 Water deficit areas, 17
- 2-9 Water available for recharge throughout the United States (Note: Most areas are very low.), 17
- 2-10 Water-level declines, 18
- 3-1 Broward County source water protection zones, 27
- 4-1 Diagram of wells and subsurface flow, 33
- 6-1 Block-centered flow regime, 52
- 6-2 Saltwater–freshwater interface, 57
- 7-1 Saco River Valley, 70
- 7-2 Three-layer groundwater flow model developed in MODFLOW, 72
- 7-3 Aquifer formation profile, 73
- 7-4 Two- and five-year capture zones for Dunlap well field, 73
- 7-5 Upper Floridan aquifer under the Tampa, Fla., area, 75
- 7-6 Simulated area of recharge, 75
- 7-7 Nested well schematic, showing pumping-induced recharge, 78
- 7-8 Location of the Platte West wellfield (WWF), 79
- 7-9 Groundwater model domain/boundaries for Platte West wellfield (WWF) project, 81
- 7-10 Model-simulated pumping from the Platte West wellfield (WWF) at 52 mgd, 82
- 7-11 Calibration of predicted versus actual results from modeling, 83
- 7-12 California Central Valley Groundwater—Surface Water Simulation Model (C2VSim) model area, 86

- 7-13 California Central Valley Groundwater—Surface Water Simulation Model (C2VSim) model grid, 87
- 7-14 California Central Valley Groundwater—Surface Water Simulation Model (C2VSim) example model input—agricultural pumping distribution, 88
- 7-15 California Central Valley Groundwater—Surface Water Simulation Model (C2VSim) example model output, 89
- 7-16 Suffolk County, N.Y., 90
- 7-17 Suffolk County groundwater model domains, 91
- 7-18 Model-simulated contribution areas to wells and water bodies, 92
- 7-19 Model-simulated increase in water table elevation because of sea level rise, 93
- 7-20 Initial grid boundary in the Biscayne aquifer, 95
- 7-21 Groundwater table drawdown, September 2011 (wet season), 96
- 7-22 Risk contours related to rotavirus risk in raw water supply wells given injection of reclaimed wastewater, 98
- 7-23 Comparison of scenario vs. distance of risk contour from injection well, 99

Tables



- 7-1 Key features of case study models, 69
- 7-2 Results from different scenarios of viral loading rate, 98
- A-1 Selected values of porosity, 108

This page intentionally blank.

Preface

Manual M73, Groundwater Management, is the culmination of efforts by members of AWWA's Groundwater Resource Committee to identify and demonstrate the value of using computer modeling tools to help utilities better manage their groundwater resources in light of greater competition for water and dwindling supplies in many parts of the world. In North America, we see acute issues developing in the Plains states, Rocky Mountains, desert Southwest, and even along parts of the Eastern Seaboard. In many of these cases, deep and often confined aquifers are being tapped for irrigation and potable supplies, but there is little hope these aquifers can recover their supplies in our lifetime. That creates the potential for serious economic and social consequences later in the 21st century for communities whose wells may run dry and have no backup options. To this end, this manual includes a discussion on the sustainability of groundwater supplies; overdrafting; and the need for groundwater protection, planning, and evaluation efforts that have evolved in the past 10 years. While groundwater management was incorporated to a small degree in the 2014 version of M21, Groundwater, the committee felt the topic has developed considerably over the past 10 years and that a more detailed and focused manual for groundwater management was timely. M21 will now focus primarily on operations.

M73 provides the reader with a general understanding of the principles involved with groundwater, its movement and character, and the subsequent impact these characteristics have on the development of groundwater resources systems and their long-term sustainability for water utilities. This manual should be considered a companion to M21. There are more detailed books available in the AWWA catalog on well drilling procedures, well maintenance, groundwater treatment, and injection programs that are tangential to groundwater management but are relevant to utilities that rely on groundwater for supplies. We encourage interested readers to pursue additional information, some of which is by the authors of this manual. There are also highly technical texts that deal with the mathematics of groundwater, but the math is generally beyond the scope of this manual (see Bloetscher et al. 2005, for example, for these details).

We have specifically not provided much detail on specific groundwater models since they change and anything included would be outdated before this manual was published. Most of the groundwater models are based on the US Geological Survey (USGS) model code, MODFLOW. Added packages that have been developed to complement MODFLOW include SEAWAT, MT3D, MODPATH, and others. Many commercial software providers have taken these base models and incorporated sophisticated pre- and post-processing capabilities to make the models easier to interpret for professionals and policymakers alike. Examples of the results are included in Chapter 7. Modeling has evolved to the point where many water-use projects include a modeling exercise.

Chapter 1 includes a case study of what can go wrong, an overview of groundwater for those not familiar with the topic, and what will be accomplished in this manual. Chapter 2 is an overview of the hydrologic cycle as it relates to the occurrence of groundwater, as well as a discussion of sustainability of groundwater supplies in light of regional competition for water resources and climate change. Chapter 3 starts with a discussion of issues associated with water

quality of groundwater and potential impacts from aquifer declines; water quality and contaminant transport resulting from organic, inorganic, and bacteriological pollution; and concepts for addressing source water protection and cleanup. Chapter 4 outlines regional groundwater topics on groundwater recharge, water budgets, characterizing the aquifer, aquifer yield, and some discussion on the regulatory environment. Chapter 5 outlines the monitoring to support management of regional groundwater systems. This includes identifying data and the completeness of same in anticipation of further analysis.

The discussion of using the data from Chapters 1 to 5 to construct a model of the groundwater system begins in earnest in Chapter 6. An outline of common modeling software is included as part of the discussion. The chapter is designed to offer enough detail about how the models are constructed and operate without getting into details of actual software that will inevitably change and therefore be of limited value in a few years. To show the power of these models, Chapter 7 outlines a series of applications of groundwater models. Note: Many of these are fairly complex and may be beyond the needs of small utilities, but as the cost of software drops, the ability to create dynamic system models even for small communities increases. This gets beyond the analytical calculations currently used, which have severe limitations when dealing with confined aquifers. The intent of this chapter is to provide a series of modeling case studies from places in North America, using different aquifers and modeling for different purposes. Recharge with reclaimed water (indirect potable reuse potential) along with risk is included in the last case study.

Chapter 8 summarizes the current status of groundwater management and suggests pathways to improve our understanding and policy decision-making with respect to this often-limited resource. This manual should help managers and engineers gain enough background on groundwater management to improve their decision-making, and determine when models should be used and the complexity that should be included. The manual should help these professionals answer many of their questions about complex aquifer systems and improve their ability to manage concerns. The Groundwater Resource Committee is hopeful that this manual will meet the industry needs of the new millennium.

Susan Roberts, Ph.D., P.G.
Chair, AWWA Groundwater Resource Committee

Frederick Bloetscher, Ph.D., P.E.
Manual Editor, AWWA Groundwater Resource Committee

Acknowledgments

This manual was developed by the AWWA Groundwater Resource Committee.

The membership at the time it approved this manual was as follows:

Susan Roberts (Chair), San Antonio, Tex.

Frederick Bloetscher (Past Chair, incoming Chair), Florida Atlantic University, Boca Raton, Fla.

Angela Bolton, Anchorage Water and Wastewater Utility, Alaska

Steven Colabufo, Suffolk County Water Authority, N.Y.

Leslie Dumas, RMC Water and Environment, Los Angeles, Calif.

Sandra Eberts, US Geological Survey, Columbus, Ohio

David F. Edson, Jensen Beach, Fla.

Dena Egenhoff, City of Cheyenne, Wyo.

Matthew Gamache, CDM Smith, Boston, Mass.

Alex Gerling, Lakewood, Colo.

David Jordan, Albuquerque, N.M.

Mitch Kannenberg, WSP USA Inc., Sioux Falls, S.Dak.

Sharon C. Long, retired, Madison, Wis.

Albert Muniz, Hazen & Sawyer, Boca Raton, Fla.

Willadee Hitchcock (Senior Specialist – Manuals), AWWA, Denver, Colo.

Definitions

1. *Annulus/annular space*. The space between the borehole wall and the well casing, or the space between a casing pipe and a liner pipe.
2. *Aquifer*. A rock formation that will yield water in a usable quantity to a well or spring.
3. *Aquifer mining*. The occurrence whereby the aquifer levels are drawn down with time at a rate faster than recharge.
4. *Artesian aquifer*. Confined aquifer where the water level rises above the top of the aquifer.
5. *Artificial recharge*. Occurs where a well, series of wells, or large basin is created for the purpose of putting water back into a formation. This is different from aquifer storage and recovery, where injection and withdrawal from the same well is planned as a cyclical process.
6. *Bridging*. The development of gaps or obstructions in either grout or filter pack materials during placement or development.
7. *Capillary fringe*. The subsurface layer in which groundwater seeps up from a water table because of tension saturation.
8. *Casing (well)*. The vertical pipe that is inserted after drilling, often cemented in place, to give the well structural integrity while sealing off portions of the aquifer that are not part of the production zone. There may be multiple casings in a well.
9. *Conductor casing*. Outer casing used for stability or to seal off a formation to prevent formation collapse or vertical cross-contamination within the well.
10. *Confined aquifer*. An aquifer that is not open to the surface because of some overlying formation.
11. *Confining layer*. Formations that water cannot flow through easily.
12. *Conjunctive use*. Relates to the combined use of groundwater and surface water. The idea of this management approach is to use surface water when the water table is high and change to groundwater when the water table is low, and vice versa. Other sources (reclaimed water) can be incorporated as well.
13. *Decay*. A chemical concentration decrease over time in groundwater, often because of microbial action when related to organics and nutrients.
14. *Dispersion*. The spreading of a contaminant plume from highly concentrated areas to less-concentrated areas.
15. *Filter pack*. Sand, gravel, or glass beads that are uniform, clean, and well-rounded that are placed in the annulus of the well between the borehole wall and the well intake to prevent formation material from entering through the well intake and to stabilize the formation.
16. *Finite difference models*. These computer models convert ordinary linear differential equations or nonlinear partial differential equations into a system of equations that can be solved by matrix algebra techniques, which makes finding the solution well suited to modern computers. The finite difference model is set up using a grid of rectangular grids.

17. *Finite element models*. These computer models convert partial differential equations into a system of equations that can be solved simultaneously in a nonrectangular grid (labeled “elements”).
18. *Flowing artesian well*. An artesian well in which the water level stands above the land surface.
19. *Grout*. A fluid mixture of neat cement and water, possibly with various additives or bentonite, of a consistency that can be forced through a pipe and placed in the annular space between the borehole and casing to form a seal.
20. *Head*. Pressure in a formation and/or elevation of water in the formation.
21. *Hydraulic conductivity*. The ability of water to flow through the porous media; referred to as hydraulic conductivity (K).
22. *Permeability*. A measure of the ease with which water can move through a porous rock.
23. *Pressure grouting/sealing*. A process by which grout is confined within the borehole or casings by the use of plugs or packers and by which sufficient pressure is applied to force the grout slurry into and within the annular space or aquifer zone to be grouted.
24. *Sanitary seal*. The top covering of a well, designed to keep insects, surface runoff, small animals, dirt, and debris from entering the well and contaminating the aquifer.
25. *Screen/well intake*. A screening device or length of pipe that is used to keep materials other than the aquifer fluids (groundwater) from entering the well.
26. *Slot size*. The width of the slots machined into a slotted well casing (screen) that allows aquifer fluids (groundwater) into the well.
27. *Sorption*. A physical and chemical process by which one substance becomes attached to another.
28. *Sublimation*. A chemical process where a solid turns into a gas without going through a liquid stage.
29. *Transmissivity*. The hydraulic conductivity multiplied by the aquifer thickness.
30. *Unconfined aquifer*. Shallow formations that have no overlying barrier to direct recharge from precipitation.
31. *Vadose zone*. Includes surface soils, the unsaturated material below the soil, and the capillary fringe (area where water can rise), but is not part of any aquifer system.
32. *Well liner*. Vertical pipe that is inserted inside the casing pipe, connected to the production zone.

This page intentionally blank.

Chapter **1**

Introduction

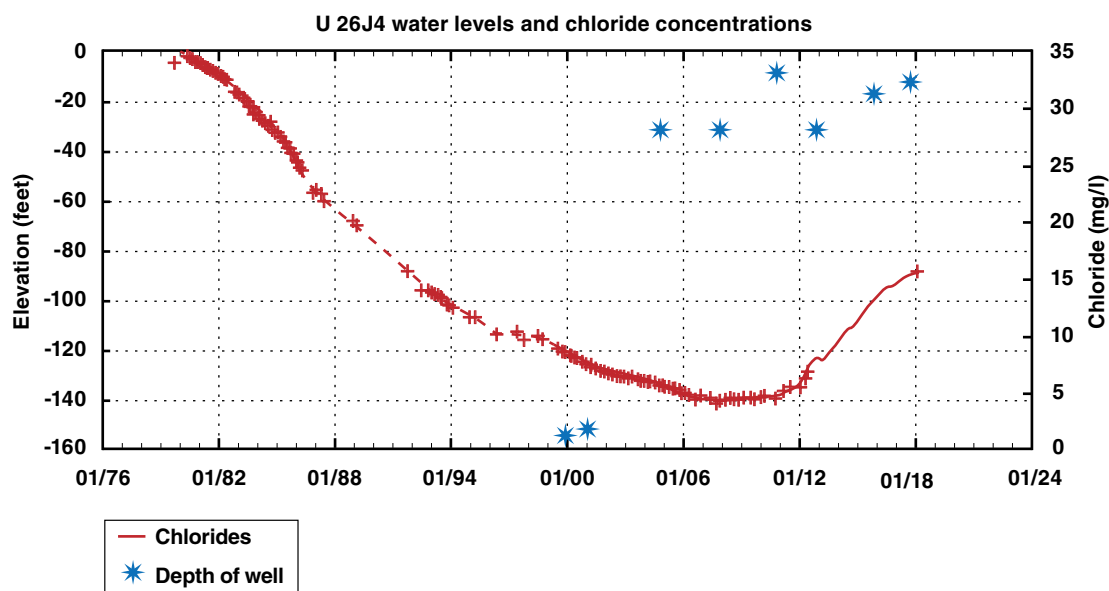
COASTAL CAROLINAS – WHAT CAN GO WRONG?

The eastern Carolinas have long used groundwater as their source water because the aquifer was deep (250–400 ft), confined, stable with respect to water quality, and required little treatment. The communities from Greenville, N.C., through Kinston and Jacksonville, N.C., Myrtle Beach, S.C., and as far south as the communities around Mount Pleasant and Charleston, S.C., withdrew water from formations labeled the Middendorf and Black Creek aquifers. The aquifers were highly productive (calibrated transmissivity values of 400–11,000 ft²/d for the Black Creek aquifer and 300–30,000 ft²/d for the Middendorf aquifer), so water was easy to withdraw. In addition, the water required no treatment so communities bragged about the quality of their water that needed no treatment. Richlands, N.C., claimed to be the “Town of Perfect Water.”

The Black Creek aquifer is composed of the Cretaceous Black Creek and Middendorf formations (Winner and Coble 1996). The Black Creek aquifer extends across most of the region. It consists of very fine to fine “salt and pepper” sands (NCDENR 2008). The thickness of Black Creek aquifer ranges up to 442 ft. In North Carolina, the Surficial, Castle Hayne, Yorktown, and Pee Dee aquifers overlie the Black Creek aquifer, and the Upper Cape Fear aquifer underlies the Black Creek (Lautier 2001). The potentiometric or hydraulic head levels of the Black Creek aquifer have been recorded since 1917 (Cooke 1936), and potentiometric maps have been published by Hockensmith (2008, 2003a, 2003b, and 1997), Stringfield and Campbell (1993), and Aucott and Speiran (1985a and 1985b). While the Black Creek aquifer is a source of high-quality drinking water, the presence of saltwater prevents the aquifer from being used for water supply immediately along the coast.

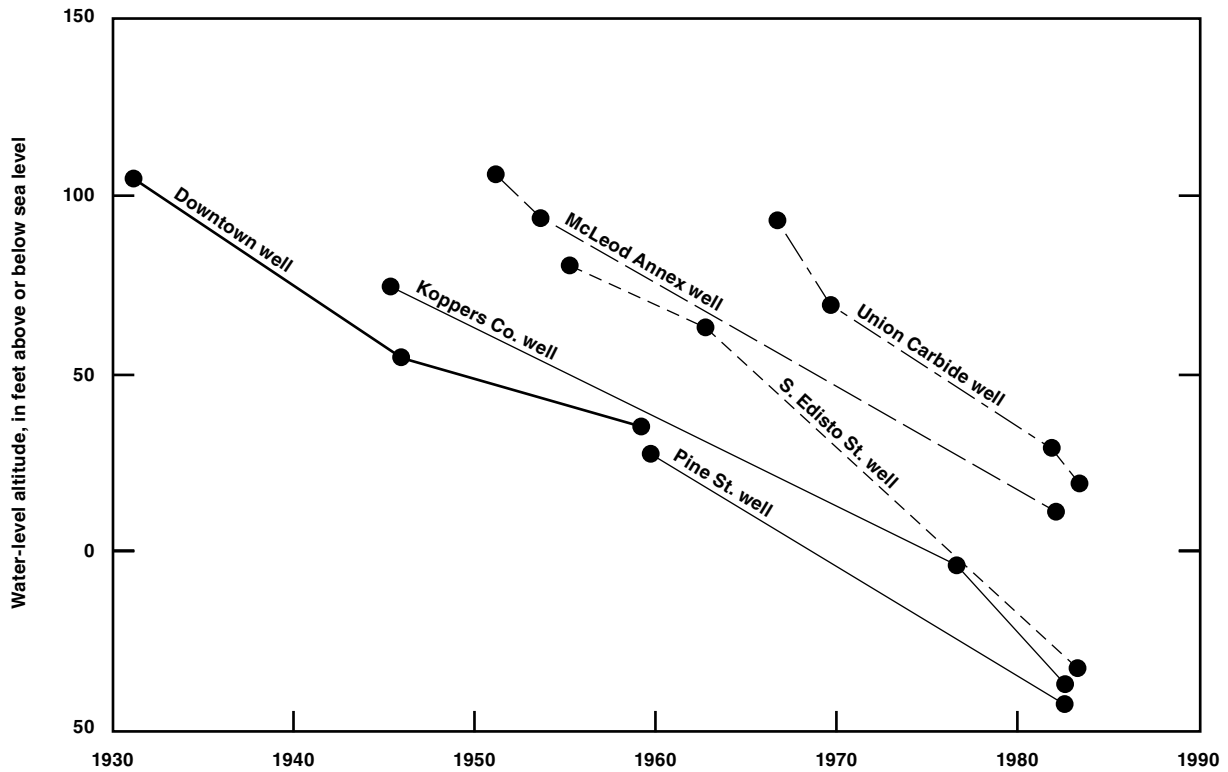
As the population of the eastern Carolinas began to grow in the 1960s, more industry and more people drilled wells into the formation, and water use began to increase rapidly. Myrtle Beach, S.C., became a tourist mecca. Growing Jacksonville, N.C., home of Camp Lejeune, and surrounding Onslow County expanded greatly in the 1980s, expanding their wellfields while deepening their wells. For example, Jacksonville lowered pumps at least 10 ft/yr over 14 years from the late 1970s through the 1980s. Kinston, N.C., was home to major textile and lumber industries that required large volumes of water that also required continual lowering of pumps more than 200 ft. The lowering of pumps began slowly, as all of these communities began to see decreases in water levels starting in the 1970s and accelerating in the 1980s. Ultimately, the aquifer has declined as much as 200 ft from overpumping and depleting storage in North Carolina (North Carolina Department of Environmental Resources 2001; see Figure 1-1).

Similar declines were noted throughout the larger communities in eastern South Carolina as well. Aucott and Speiran (1985b) compared estimates of the predevelopment surface with November 1982 water levels and determined that Black Creek aquifer water levels had declined in Horry and Georgetown counties. Stringfield and Campbell (1993) published 1989 water levels and observed that the water levels in Georgetown, Horry, northern Marion, and northeastern Williamsburg counties had declined since 1982. Data gathered in November 1995 (Hockensmith 1997) and November 2001 (Hockensmith 2003a) showed additional declines influenced by large cones of depression near Marion, Andrews, Georgetown, Pawleys Island, and Florence, S.C. (see Figure 1-2). The US Geological Survey (USGS) reported the potentiometric decline that occurred between predevelopment (1926) and 1982 near Florence, and between predevelopment (1879) and 1989 near Charleston, focused near the Mount Pleasant area, which used the Middendorf aquifer as a sole source of potable water as late as 1993. Groundwater flow for the period 1879–1989 was simulated for the Black Creek and the Middendorf aquifers and saw major declines from predevelopment times, with major cones of influence in major cities (see Figures 1-3 and 1-4).



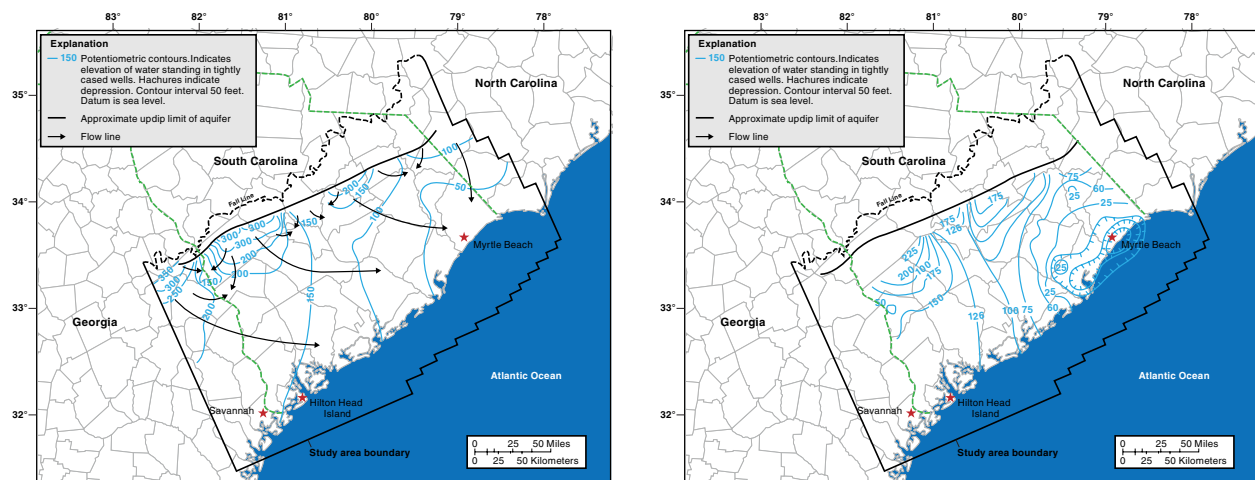
Source: NCDEQ 2018

Figure 1-1 Decline in the Black Creek aquifer in rural Jones County, N.C.



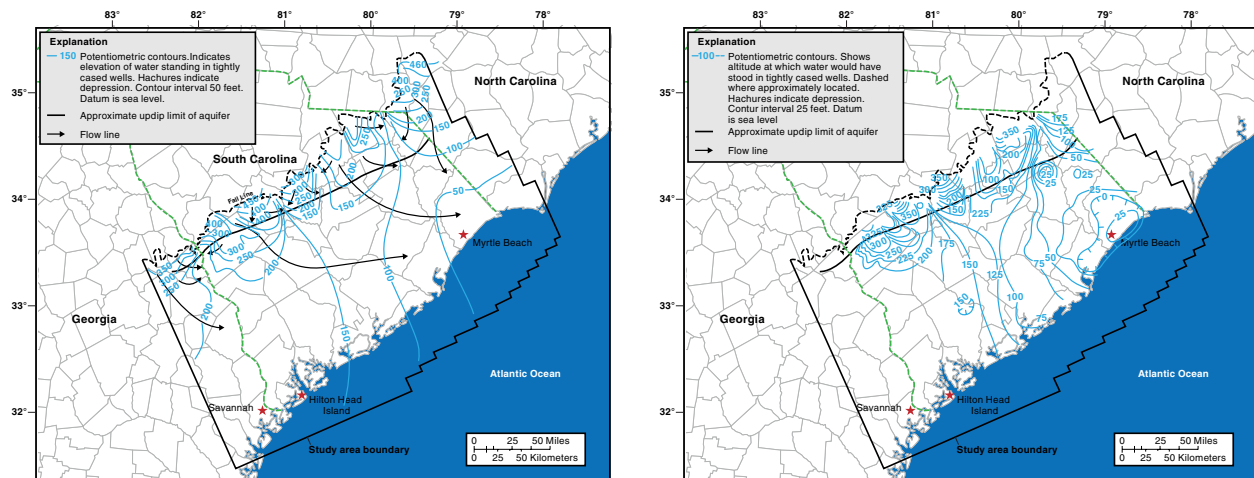
Source: Modified from Aucott and Speiran, 1985a

Figure 1-2 Declines in the aquifer formations near Florence, S.C.



Source: Aucott 1996

Figure 1-3 Pre- and post-development (1982) head, Black Creek aquifer



Source: Aucott 1996

Figure 1-4 Estimated pre- and post-development (1982) of the Middendorf Aquifer

The problem was that the declines were noted but basically ignored by the water users in the area. No user had a groundwater model in the 1980s, and no user appears to have acted to address the declining aquifer issue through changes in withdrawal patterns; they just lowered the pumps. No groundwater management plans were developed by the utilities, although the North Carolina utilities knew a shallower formation (the Castle Hayne) was available, but they had historically avoided it because its use would require lime softening treatment (as Camp LeJeune has done for more than 50 years). The decline in the aquifer levels was attributed to drought, competition, and other things, but not water use by the utilities. Regulatory action was required.

The declines became more acute in the 1990s. Because of these declines, the resulting increased potential for lateral saltwater migration along the coast and upward leakage of brackish water from deeper aquifers prompted the North Carolina Division of Water Resources (DWR) to institute the Central Coastal Plain Capacity Use Area (CCPCUA) rules for 15 counties, effective August 1, 2002 (North Carolina Department of Environmental Resources 2001). The guidelines required water users to cut back on the Black Creek aquifer and find other sources. As a result, water suppliers in North Carolina shifted to the Castle Hayne aquifer and decreased use of the Black Creek aquifer. However, the Castle Hayne is a shallower formation and is susceptible to saltwater intrusion.

South Carolina had similar issues. However, the Castle Hayne aquifer formation is lacking in South Carolina, so most of the South Carolina communities switched to surface waters as a result of aquifer declines. Fortunately, they were available to most of the larger utilities. Others, such as Myrtle Beach, monitored the decrease in its water levels until it combined its system with a consolidated Grand Strand Water and Sewer Authority that serves Horry County and others in northeastern South Carolina. Because water is a regional issue, many of the communities in the Carolinas have created countywide districts to address water supply issues. In several counties in the area, the Black Creek and Middendorf are being used or explored for aquifer storage and recovery wells. The good news: alternatives existed for the Carolinas.

GOAL OF THE MANUAL

The coastal Carolinas are not the only place in the United States that has ongoing issues with aquifer drawdowns and lacked groundwater management plans. Unlike the expectations of

many who thought that the Southwest would have the first widespread aquifer to be drained, this water sustainability crisis was in the eastern United States. Fortunately, alternative solutions existed. But what about the central and western portions of the country? Finding out where at-risk water users exist and creating a pathway to them to determine the best means to manage water supplies sustainably is the goal of this manual. As will be outlined, the issues are more acute in the central and western states. The options to move to surface waters may not be available like it was in South Carolina, creating major consequences for local economies. The issue of managing groundwater supplies is critical in light of the identification of areas of the United States that have experienced aquifer overdrafting/mining, competition for the same source, and regulatory hurdles that do not protect groundwater sources for the future. A key component is the concept that planning the utilization of water supplies requires understanding how the hydrologic cycle provides water to the groundwater service area (e.g., recharge basin), in what quantities, and with what reliability. Reliability is a risk issue; is the precipitation consistent or are there significant fluctuations that disrupt ongoing basin development? From a practical perspective, sustainable development generally means addressing the environmental, economic, and social concerns underlying the sufficient availability of water for the locale.

The AWWA's Groundwater Resources Committee emphasizes the need for utilities to understand the effects of groundwater pumpage and the long-term impacts it has on the local community, the future economic conditions, and sustainability for local consumers. This need is a major extension of AWWA's core mission to provide guidance to policymakers, the water sector and professionals on how to deal with the restrictions in water supplies, and to develop more accurate measurements of available supplies; create better tools to evaluate (and reduce) water mining; and create management, policy, and technology solutions to address the problem of water shortages. This concept is fully in line with the mission of the Water Resource Sustainability Division; meets one of the top issues facing the groundwater sector; aligns with active professionals in the field; and can attract planners, geologists, administrators, and engineers to the discussion.

M73 is intended to outline a platform of key requirements, discuss existing groundwater management tools, and provide an overview for utilities of the data needed to create computer models of aquifers that are or in the future may be needed as a water source. The goal is to help utilities that may be subject to overdrafting or have groundwater quality concerns identify means to avoid further damage to aquifer systems, i.e., limit the future potential for a Carolinas-type problem. Toward these goals, the following chapters address:

- Chapter 2 – The Occurrence and Behavior of Groundwater;
- Chapter 3 – Motivation for Groundwater Management;
- Chapter 4 – Groundwater/Aquifer Characterization Tools;
- Chapter 5 – Monitoring to Support Management of Regional Groundwater Systems;
- Chapter 6 – Groundwater Models;
- Chapter 7 – Case Studies Using Groundwater Models (modeling case studies around the United States that demonstrate features and issues relevant to water utilities with groundwater as source water); and
- Chapter 8 – The Future of Groundwater Management.

REFERENCES

- Aucott, W.R. 1996. *Hydrology of the Southeastern Coastal Plain Aquifer System in South Carolina and Parts of Georgia and North Carolina*. Reston, Va.: USGS.
- Aucott, W.R. and Speiran, G.K. 1985a. Ground-water Flow in the Coastal Plain Aquifers of South Carolina. *Groundwater*. 23:6:736–745.
- Aucott, W.R. and Speiran, G.K. 1985b. *Potentiometric Surfaces of November 1982 and Declines in the Potentiometric Surfaces Between the Period Prior to Development and November 1982 for the Coastal Plain Aquifers of South Carolina*. Reston, Va.: United States Geological Survey (USGS).
- Cooke, C.W. 1936. *Geology of the Coastal Plain of South Carolina*. Washington: USGS.
- Hockensmith, B.L. 1997. *Potentiometric Surface of the Black Creek Aquifer in South Carolina, November 1996*. Columbia, S.C.: South Carolina Department of Natural Resources.
- Hockensmith, B.L. 2003a. *Potentiometric Surface of the Black Creek Aquifer in South Carolina, November 2001*. Columbia, S.C.: South Carolina Department of Natural Resources.
- Hockensmith, B.L. 2003b. *Potentiometric Surface of the Middendorf Aquifer in South Carolina, November 2001*. Columbia, S.C.: South Carolina Department of Natural Resources.
- Hockensmith, B.L. 2008. *Potentiometric Surface of the Black Creek Aquifer in South Carolina, November 2004*. Columbia, S.C.: South Carolina Department of Natural Resources.
- Lautier, J.C. 2001. *Hydrogeologic Framework and Ground Water Conditions in the North Carolina Southern Coastal Plain*. Raleigh, N.C.: North Carolina Department of Environment and Natural Resources, Division of Water Resources.
- NCDENR (North Carolina Department of Environment and Natural Resources). 2008. *North Carolina Aquifers*. Raleigh, N.C.: NCDENR, Division of Water Resources.
- NCDEQ (North Carolina Department of Environmental Quality). 2018. *Central Coastal Plain Capacity Use Area Assessment Report*. Raleigh, N.C.: NCDEQ, Division of Water Resources.
- North Carolina Department of Environmental Resources. 2001. *Central Coastal Plain Capacity Use Area Rules*. Raleigh, N.C.: NCDENR, Division of Water Resources.
- Stringfield, W.J. and Campbell, B.G. 1993. *Potentiometric Surfaces of November 1989 and Declines in the Potentiometric Surfaces between November 1982 and November 1989 for the Black Creek and Middendorf Aquifers in South Carolina*. Reston, Va.: USGS.
- Winner, M.D. Jr. and Coble, R.W. 1996. *Hydrogeologic Framework of the North Carolina Coastal Plain, Regional Aquifer-System Analysis—Northern Atlantic Coastal Plain*. Reston, Va.: USGS.

Chapter **2**

The Occurrence and Behavior of Groundwater

More than a third of the people served with public water supplies in the United States and Canada obtain their water supplies from groundwater (AWWA 2014). This demand is increasing as the number of small systems has grown from less than 5,000 to more than 40,000 since 1960 (Bloetscher 2019). In part, the expansion of groundwater-supplied utilities results from the lack of suitable sites to build impoundments to capture surface waters and the water quality of existing surface waters. Also, wells can be installed in small increments with little apparent impact per well. As areas grow, those small impacts become many wells that can create significant impacts on groundwater levels, but this may be overlooked by most users except when they need to lower their pumps. Because groundwater is not visible from the surface, the understanding of its behavior and occurrence among the public is limited. This chapter is intended to provide a general overview of:

- the hydrologic cycle and general groundwater concepts;
- major conditions that impact groundwater;
- climate impacts on groundwater;
- sustainability, development, and urbanization; and
- water quality.

HYDROLOGIC CYCLE

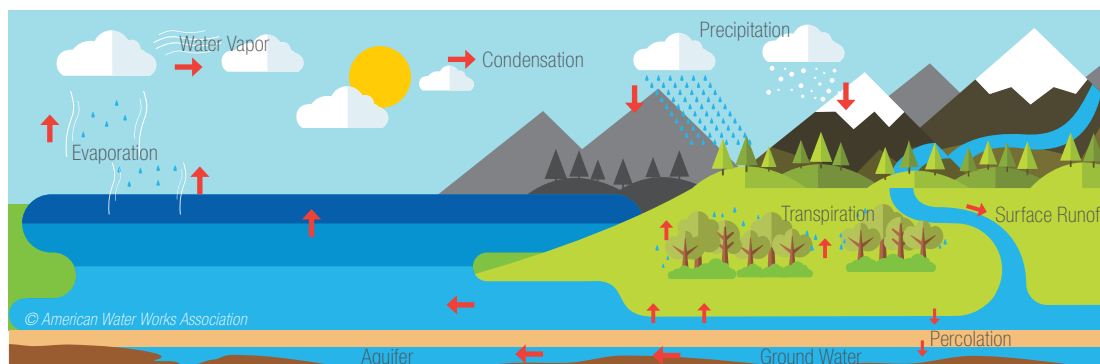
Saltwater in oceans makes up 97.3 percent of all water in the world. For most people, this water is not useful for water supply purposes because of the cost of treatment or the distance to convey desalinated seawater. Of the remaining 2.7 percent freshwater, more than two-thirds exists as ice in the polar caps while the rest (0.61 percent of all water) is freshwater in lakes, rivers, streams, and groundwater. More than half may be groundwater (AWWA 2014).

Water is not stagnant, whether in the ground or above. Water movement above, on, and below the earth's surface is defined as the hydrologic cycle (Figure 2-1). The hydrologic cycle is the main concept used in the development and management of water supplies. The components of the hydrologic cycle are:

- evapotranspiration (ET), which is the combination of evaporation from open water and transpiration from plants as an average over an area,
- precipitation,
- surface water and runoff,
- infiltration and percolation to the subsurface, and
- groundwater recharge and discharge.

Evaporation and Transpiration

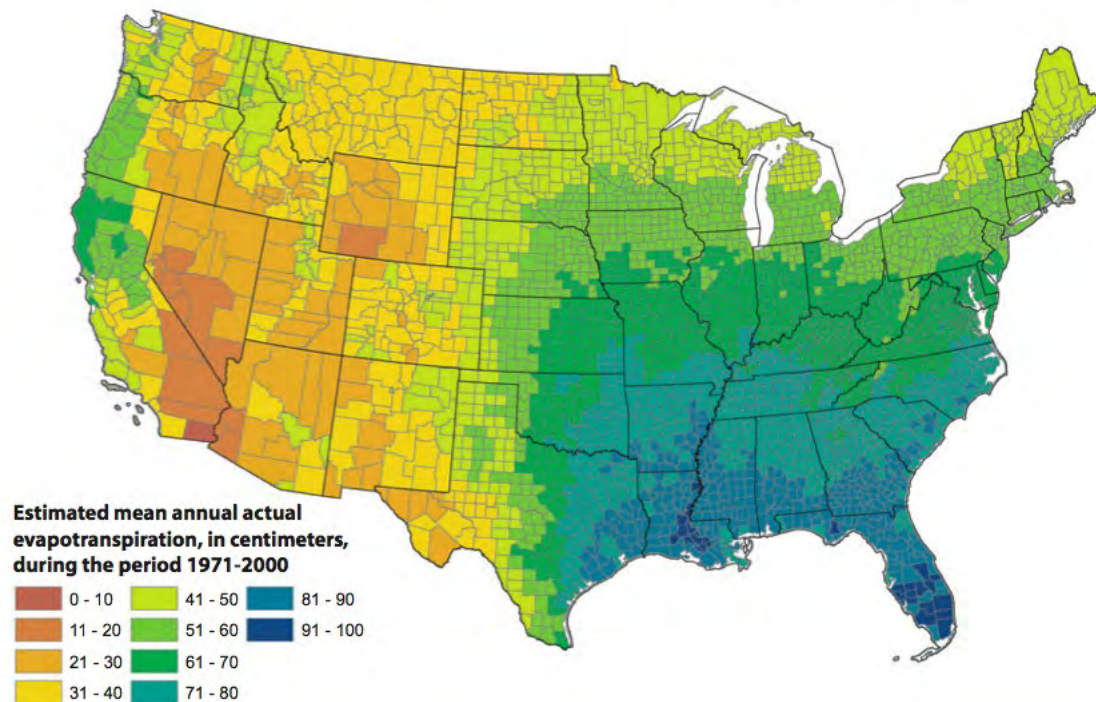
Although the hydrologic cycle is continuous, evaporation from open water and transpiration from plants are major drivers created by atmospheric conditions. Evaporation and transpiration, commonly combined and referred to as the process of ET, is water vapor entering the atmosphere. ET rates vary, depending largely on the amount of solar radiation, the elevation, the latitude of the catchment area, the amount of heat, water surface area, wind, humidity, time of year, and vegetative cover. Areas close to the equator tend to have higher ET rates. Figure 2-2 is a map of ET rates in the United States. Figure 2-2 shows that ET rates vary widely across North America and throughout the year, and whether there is open water to evaporate (hence, the desert Southwest does not have a lot of ET because there is very little surface water). In addition, visitors to the Rocky Mountains are often surprised how ET causes new snow to disappear despite the temperature being below freezing (a process called “sublimation”).



Source: DrinkTap.org by AWWA

Figure 2-1 Hydrologic cycle

ESTIMATION OF EVAPOTRANSPIRATION ACROSS THE CONTERMINOUS UNITED STATES USING A REGRESSION WITH CLIMATE AND LAND-COVER DATA



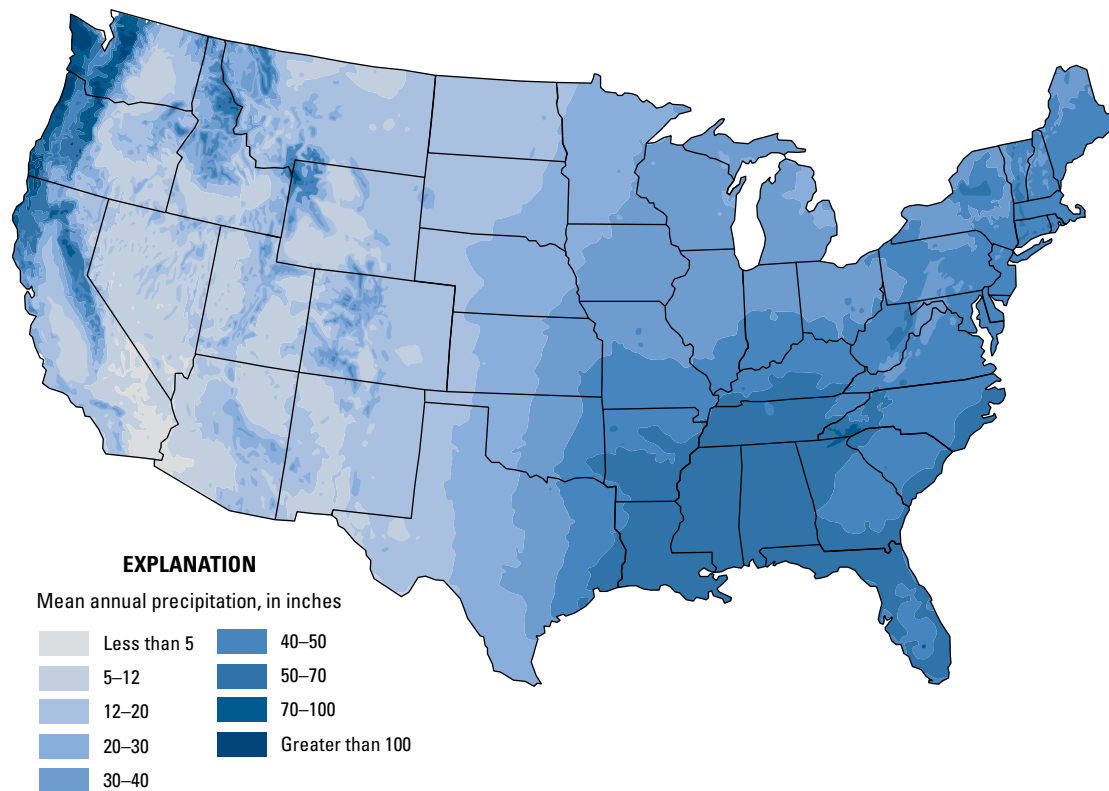
Source: National Oceanic and Atmospheric Administration 2013

Figure 2-2 Evapotranspiration rates

In subtropical areas during the wet season or during summer months in northern latitudes, large bodies of water, including wetlands, lakes, and estuarine areas, have high evaporation rates. This rising moisture forms clouds that condense and return the water to the land surface or oceans in the form of precipitation. The highest evaporation rates are associated with shallow, open water bodies. Water as much as 4 ft below the surface may be subject to evaporation to some degree.

Precipitation

Figure 2-3 shows average annual precipitation in the United States. As water vapor enters the atmosphere, conditions create the need for the atmosphere to release some of this moisture as precipitation. Precipitation occurs in several forms, including rain, snow, sleet, and hail. The intensity of the resulting rainfall is a major area of hydrologic study as it seems rainfall intensity is increasing with time. Rainfall intensity can vary up to 5 in./h in subtropical areas but is commonly 2–3 in./h across North America. Rainfall intensity is relevant because the rain wets vegetation and other surfaces, then infiltrates into the ground or travels toward shallow groundwater bodies or toward areas of lower ground elevation. Infiltration rates vary widely, depending on land use, development, the character and moisture content of the soil, and the intensity and duration of the precipitation event. Infiltration rates can vary from as much as 1 in./h in mature forests on sandy soils to almost nothing in clay soils and paved areas. If the rate of precipitation exceeds the rate of infiltration, overland flow (or runoff) occurs. This is why development and deforestation are critical concerns in watersheds as both diminish infiltration potential and increase the potential for (often faster) runoff. As development alters the land surface characteristics, stormwater systems are often overloaded and groundwater does not recharge because



Source: Reilly et al. 2008

Figure 2-3 Mean annual precipitation for the conterminous United States, 1890–2002

water stays on the ground for shorter periods of time—a major concern for water purveyors who rely on groundwater as their supply source.

Surface Water and Runoff

Precipitation that runs off the land, reaching streams, rivers, or lakes, or groundwater that discharges into these water bodies is surface water. While recharge from the surface precipitation is the norm for groundwater, there is the potential for surface water bodies to recharge groundwater. This surface water recharge of groundwater can be more important in more arid areas such as the West where the groundwater is deeper than the surface waters. The reverse is true in more humid areas; the propensity is much higher for groundwater to flow toward water bodies than for water bodies to recharge groundwater. As a result, rivers and canals can act as “sinks” to lower connected groundwater levels in lower, more humid areas. South Florida is an example of this. Surface water bodies that mix with saltwater bodies along the coast are called estuaries (e.g., where a river meets the ocean in a delta). Surface water flow is controlled by the topography because water on the surface flows downward by gravity, which means it generally and eventually flows toward the oceans.

Infiltration and Recharge

Precipitation that percolates downward through porous surface soils is the primary source of water for groundwater. Those areas on the surface that create downward flow are called “recharge areas.” The characteristics of soil material depend on the climate, soil chemistry,

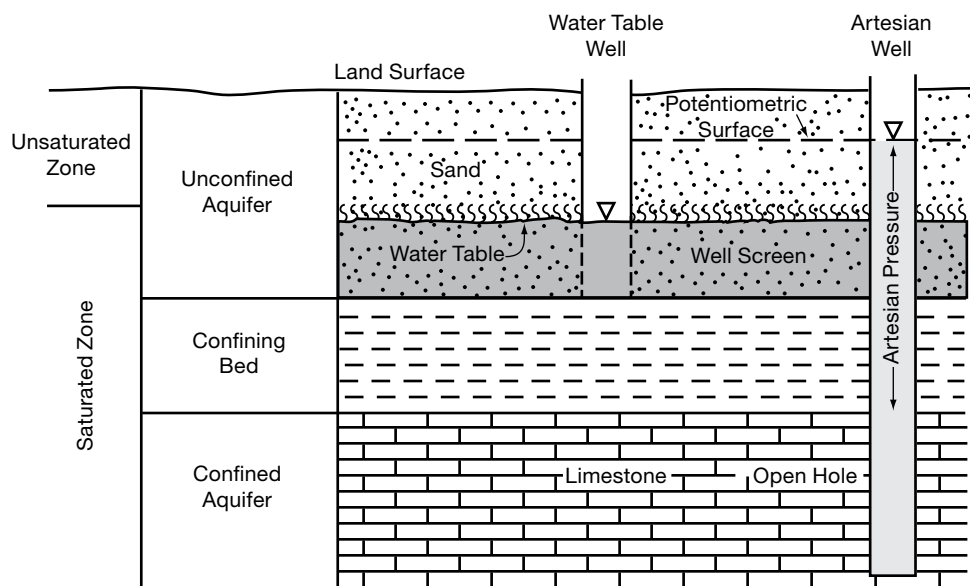
the types of organisms in and on top of the soil, the topography of the land, and the amount of time these factors have acted on the material.

Soil types also play a role in determining plant distribution (AWWA 2014). Soil has the capacity to absorb some moisture initially, a factor called “initial infiltration.” Initial infiltration fills air pockets in the root or plant zones or, in some lexicons, the *unsaturated zone*. Because of the variability of permeability and transmissivity of different soils, the rate of groundwater recharge from precipitation will vary.

Below the unsaturated soil zone, all rocks (including unconsolidated sediments) under the earth’s surface can be classified either as aquifers, semi-confining units, or confining units. An aquifer is a rock formation that will yield water in a usable quantity to a well or spring. Because groundwater moves slowly, some groundwater has been stored in aquifers for hundreds or thousands of years. The longer the water remains in contact with the rock, the more constituents the water may contain because of added contact time to dissolve the formation, although flow velocity also increases dissolution.

The ability of water to flow through the porous media is referred to as *hydraulic conductivity* (K). A confining unit is a formation having very low hydraulic conductivity that restricts the movement of groundwater either into or out of adjacent rock formations as shown in Figure 2-4. Clay layers (and some rock formations such as shale), although having high porosity, have *low hydraulic conductivity* and can be functionally impermeable. As a result, engineers and hydrogeologists typically look for limestone, sandstone, and alluvial formations, and in some areas, fractured bedrock, as these formations tend to have high hydraulic conductivity. They avoid clay, shale, and similar formations, which have low transmissivity for water supply development.

Groundwater occurs in aquifers that are defined as either “confined” or “unconfined.” If the aquifer is near the land surface and rainfall will impact the water level (filling it), such aquifers are termed *unconfined* aquifers. The upper surface of the saturated zone is free to rise and decline in direct relation to recharge by precipitation. Wells that pump water out of unconfined aquifers are water-table wells. The water level in these wells generally indicates the position of the water table in the surrounding aquifer. With unconfined aquifers, local rainfall and snow melt will recharge the formation regularly. This is not the case with confined aquifers.



Source: M21 (AWWA 2014)

Figure 2-4 Geologic configuration of aquifers and confining beds

Confining layers or confining units are formations that water cannot flow through easily. Clays are a good example. Below the confining unit is a confined aquifer (or aquifers). A *confined* aquifer is not locally open to the surface because of the confining formation. In confined aquifers, water completely fills the formation. Such aquifers may be referred to as artesian aquifers depending on whether the water level rises above the top of the aquifer formation. If the water level in an artesian well stands above the land surface, the well is a flowing artesian well. How far the water moves above the top of the formation is head or the pressure the formation is under.

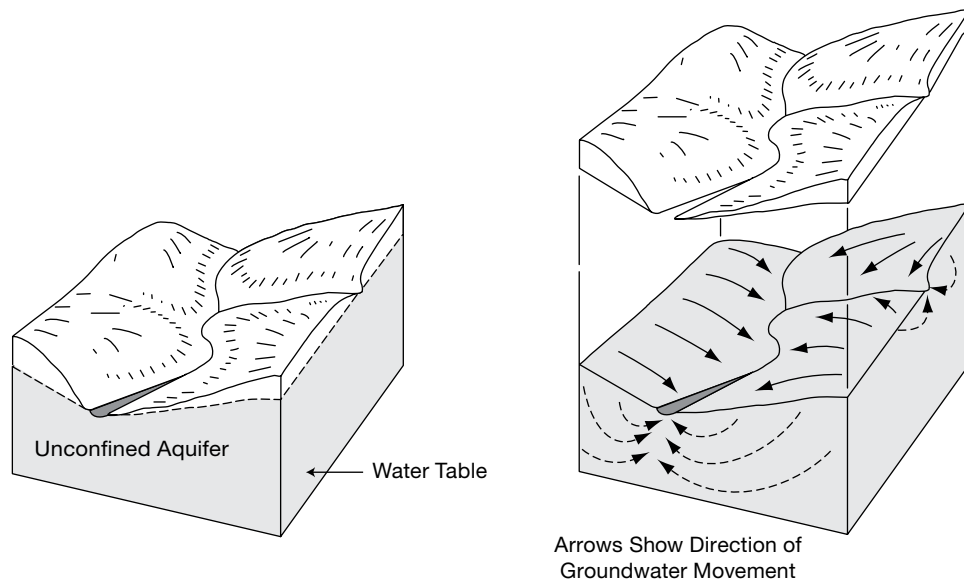
Recharge areas for confined aquifers can be located far from the point of use. Hence, snow melt and rainfall occurring some distance away—maybe hundreds of miles in some cases—is what recharges the local confined aquifer. The head within the formation may provide some guidance on recharge areas as it will indicate the approximate elevation of the recharge area. With respect to water quality, for a confined aquifer to contain fresh water, there must be a source of recharge, some degree of flow (albeit slow), and a discharge area (to cause the flow). If there is no recharge or movement, the aquifer will often become brackish through dissolution of the minerals in the rock because of contact time.

Note that the amount of water available in the surficial aquifer will vary as the water table changes. The impacts are less obvious in confined aquifers where pressure changes will need to be monitored to determine how much water is available. Too many utilities simply lower the pumps in confined aquifers, creating a long-term decrease in available water and potential for denuding (or dewatering) the aquifer in time. This aquifer degradation happened in the eastern Carolinas in the mid-1980s.

When a well is pumped, the level of the aquifer falls as the water immediately surrounding the well is drawn through the pumping well. The lower aquifer level is called “drawdown,” and the 3-D cross section is called the “cone of depression.” If the aquifer transmits water easily (i.e., has high transmissivity), the drawdown may be slight and the cone of depression flat and widespread as depicted in Figure 2-5. For the same withdrawal, if the aquifer has low hydraulic conductivity, drawdown may be significant, and the cone of depression steep. Hence, the type of rock strata that underlies the area may have significant bearing on the quantity of groundwater that can be produced (AWWA 2014). Withdrawal flows need to be adjusted to address concerns with drawdown and the extent of the cone of depression.

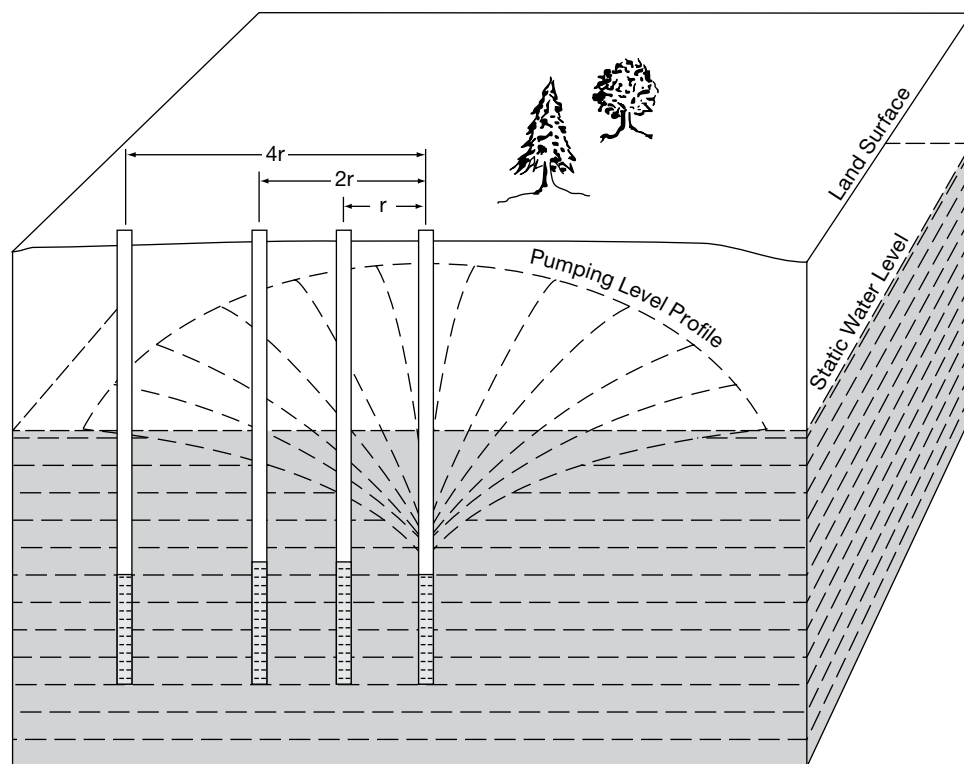
Under natural conditions, groundwater moves downgradient until it reaches the land surface at a spring or through a seep along the side or bottom of a stream channel or estuary, or, in deeper aquifers, the ocean. Groundwater in the shallowest part of the saturated zone moves from interstream areas toward streams or the coast. In many areas, the direction of groundwater movement can be derived from observations of land topography when the land slopes toward water bodies. Thus, the water table aquifer levels usually replicate the land surface as shown in Figure 2-6. Changes to upstream land use can alter confined aquifer yields, typically lessening the recharge and causing the pressure in the formation to diminish. This pressure is termed the “potentiometric” head.

A common assumption made by engineers and hydrogeologists is that water moves through confining units to some degree. Many formations may be semi-confining units indicating water movement to some degree, but a true confining unit permits no passage. Vertical migration as vertical movement is a function of both the geometry and hydraulic properties of the semi-confining layer. However, a mistake in many modeling efforts is to assume migration. One should never assume that the connection between two aquifers is significant because groundwater moves slowly, and even more slowly through confining units. The existing tests used to measure the potential for movement are limited as well. Hence, vertical recharge to confined aquifers through a confining unit may be minimal in many formations. A modeling exercise by Gao (2010) showed that vertical recharge may be estimated to be more than 1,000 times lower than the estimates used by hydrogeologists.



Source: M21 (AWWA 2014)

Figure 2-5 Development of a cone of depression, showing the central well and a series of monitoring wells that were used to define the cone of depression.



Source: M21 (AWWA 2014)

Figure 2-6 Groundwater levels typically mimic the surface topography in a given watershed

Therefore, utilities and engineers modeling wellfields should take note that vertical recharge may be zero through a thick, continuous confining layer.

In the western part of the contiguous United States, conditions are more variable than those described above. In this area, streams flowing from mountain ranges onto alluvial plains lose water to the alluvial deposits. Thus, groundwater in the upper part of the saturated zone flows down the valleys and away from the streams.

THE IMPACT OF LAND SUBSIDENCE ON GROUNDWATER

A significant consequence of groundwater development from unconsolidated or highly friable rock formations can be the downward movement of the land surface called *subsidence*. Subsidence can occur when the groundwater, which exerts pressure on the adjacent soil and rock, is removed, relieving the interstitial pressure between grains created by the water (an incompressible liquid). With removal of the water, there is nothing to hold the grains apart, so the formation collapses, causing the surface topography to be altered. The collapse can cause the reorientation of aquifer grains, particularly unconsolidated sediments. Recharging an aquifer that has collapsed will not restore the land surface to its prior state because the collapsed formation has less void space (which is why the collapse happened in the first place). The recharge capacity may be lowered significantly, and the ability to accept recharge compromised. Development of groundwater should consider possible land-surface subsidence, especially if subsidence has been previously documented. Areas with considerable subsidence may exacerbate flooding in flood-prone areas since the land is lower. Unfortunately, the information needed is not available in sufficient detail in most areas.

CLIMATE IMPACTS ON GROUNDWATER

There has been significant discussion in popular media on the topic of climate change with much focus on the potential for greenhouse gases to be the causal agent for the accelerating warming trend on Earth. While there are several causes that may contribute to changes in the worldwide climate—including greenhouse gases (IPCC 2007), sun spot activity (Singer 2008), land use changes (Marshall et al. 2004), and even a coming change in the pole location (Hapgood 1999)—the reality is that, regardless of the cause, much of the scientific community agrees that climate change *is* occurring and that it may portend a change in water availability in the near future (Bloetscher et al. 2012, Heimlich et al. 2009, Bloetscher 2008, and references therein).

What is happening appears to be occurring at a faster rate than suggested by studying the past. The Earth's climate undergoes constant changes, but these changes have occurred at a much slower, geologic timescale. A series of continental glaciers extended as far south as the 40th parallel in North America and Eurasia in the past. The ebb and flow of glaciers has occurred throughout the *Pleistocene* geologic era, which started more than 600,000 years ago and extending to as recently as 10,000 years ago. These glacial advances and retreats profoundly altered the landscape, e.g., covering northern Europe and the northern United States with deep till and outwash soils and leaving behind large, productive, sand-and-gravel aquifers.

Less than 5,000 years ago, the Sahara Desert was a thriving, water-soaked area that supported significant human population; however, the climate changed, and the area has become a huge expanse of sand since then. Much of the groundwater available in the western United States is fossil water from the past 600,000 years. Brief interludes of warmer and cooler periods occurred during 400–1300 AD. However, in each case, the factors creating the changes in climate are unclear (AWWA 2014), and man was unable to

adapt to many of these changes. The main concern for utilities is that climatic variations alter the hydrologic cycle, and that the current data indicates that the hydrological cycle is already being impacted: more intense rainfall, less recharge, less snowpack, and higher seas (Dragoni and Sukhija 2008; IPCC 2007; Huntington 2006; Labat et al. 2004; Buffoni 2002; and Dragoni 1998), all of which may mean less freshwater recharge to existing aquifers. The uncertainty associated with temperature and precipitation yields higher uncertainty when translating rainfall and temperature to changes in ET, runoff, and aquifer recharge (Dragoni and Sukhija 2008; Di Matteo and Dragoni 2006; Strzepek and Yates 1997). That means the sustainability of supplies may be overestimated using assumptions based on historical data.

SUSTAINABILITY

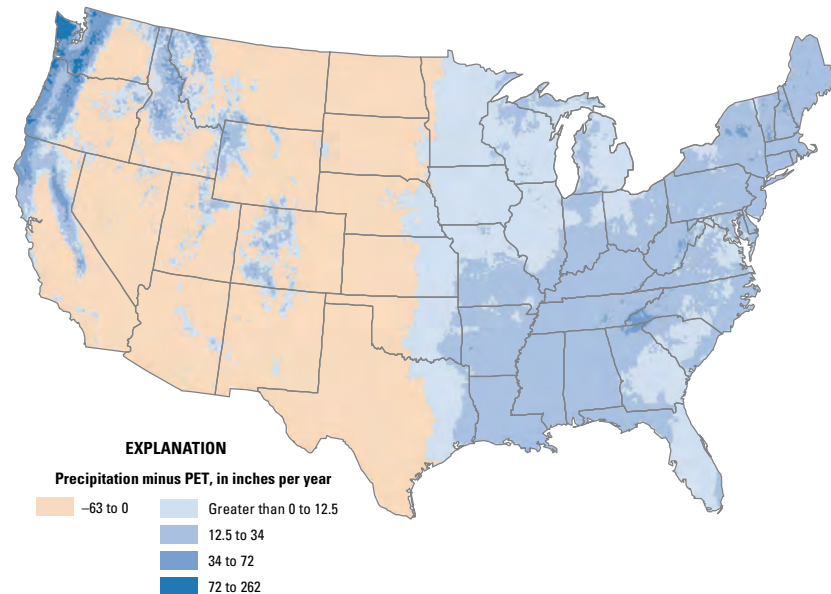
With sustainable water sources, the key component is that planning the utilization of water supplies is required to determine how the hydrologic cycle provides water to the service area (e.g., recharge basin), in what quantities, and with what reliability. The reliability is a risk issue; is the precipitation consistent or are there significant fluctuations that disrupt ongoing basin development (Molak 1997)? Additionally, because of the variability of groundwater uses and demands over time, each basin has unique characteristics (Bloetscher and Muniz 2008). From a hydrologic perspective, the term “sustainable yield” is the amount of water that can be withdrawn from a source at rates that are less than their recharge potential and that do not diminish the quantity or quality of the source or basin. While many areas attempt to develop sustainably, many others have not. The eastern Carolinas example in Chapter 1 is but one example of unsustainable groundwater development. Economics, legal ramifications and property rights, a lack of regulations, and public perception are all factors that delay action.

While no one wants to create a water supply crisis, the groundwater supply is being overdrafted where there are increasing drawdowns, indicating that doing what has been done in the past is not a sustainable usage rate. There is suspicion among many groundwater professionals and regulators that most confined aquifers are *not* sustainable supplies by the very definition of the term “confined.” Within regionally sustainable situations, unsustainable pumping can occur locally. For example, much of the western groundwater appears to be unsustainable in the long term because of limited rainfall and very low recharge rates locally (Reilly et al. 2008). One problem is competition, a situation highlighted in the AWWA compendium from 2010. Because each sector of water users is focused on their needs, no sector knows much about the others; where there are potential restrictions in water use, they see each other as competitors in a water-limited market. Hence, solutions are often litigated as opposed to resolved amicably between parties to the benefit of the public good.

Typically, there are a variety of uses competing for water resources, and each basin has unique characteristics for the following (Bloetscher and Muniz 2008):

- agriculture,
- ecosystems,
- urban demands,
- industrial demands, and
- cooling water for power generation.

From a practical perspective, sustainable development generally means addressing the environmental, economic, and social concerns over the long term, which may indicate that short-term needs are not part of long-term solutions. Researchers can define a comprehensible concept of “sustainability,” but practitioners emphasize feasibility and limitations to

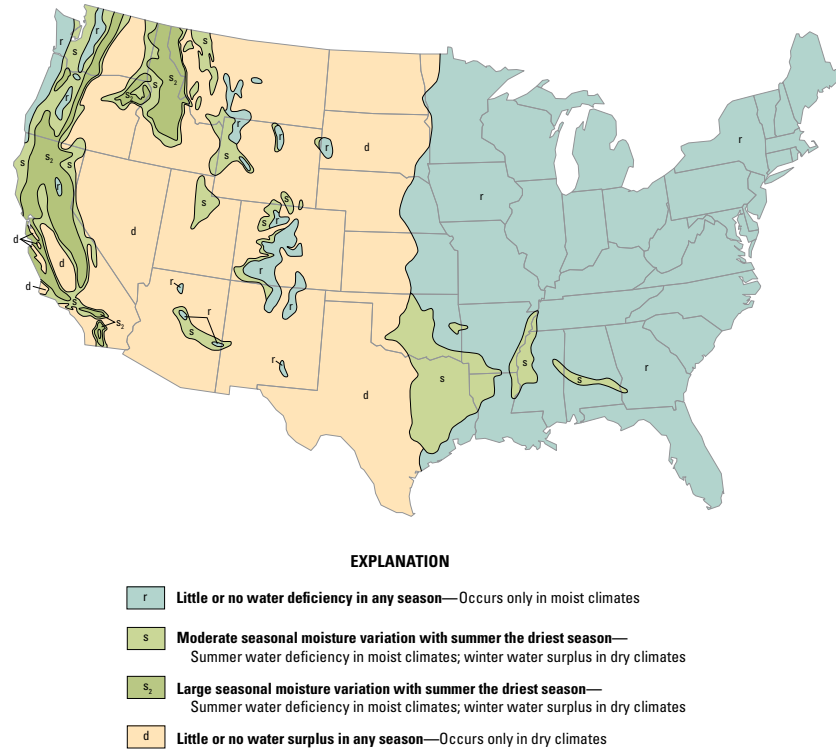


Source: Reilly et al. 2008

Figure 2-7 Difference between average annual precipitation and potential ET (PET) rates

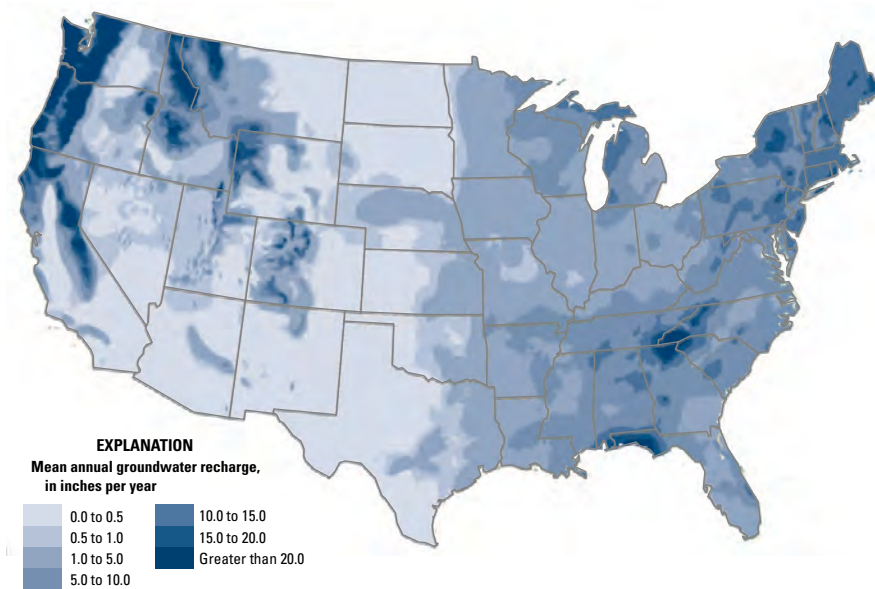
sustainability of the ecological, economic, social, and industrial community (Starkl and Brunner 2004). Scanlon et al. (2005) identified the need to fully optimize management of water resources, including those for ecosystem purposes in as many basins as possible because the ecosystem drives the economic activity (tourism, fishing, etc.). Most surficial changes decrease available recharge to groundwater.

Although determining the amount of groundwater available may seem straightforward, it is quite complex as noted by Reilly et al. (2008). Reilly et al. (2008) outlined the condition of groundwater in the United States and found that the loss of groundwater supplies is because of overpumping in many areas. In part, this was because, while eastern rainfall is much higher than the west as noted in Figure 2-3, much of the Great Plains, Rocky Mountain, and Western states have ET rates that exceed precipitation. The result is Figure 2-7, which shows the difference between rainfall and potential ET rates. The red areas are areas where the ET rate is higher than the rainfall, meaning net rainfall (Rainfall – ET) for crops and other purposes is not available and extensive surficial water use is not a sustainable practice. This is confirmed by the fact that in many of these areas, streamflows are variable and limited, so groundwater is used to ensure water supplies for crops and people. Aerial views that show extensive irrigation “crop circles” in many areas of high agricultural production and low rainfall; this is generally an example of unsustainable water use. Figure 2-8 shows that many of these areas are water deficit areas, meaning that there is a deficit of available water in the area as determined by US Geological Survey (USGS) data. Figure 2-9 shows the amount of water available for recharge throughout the United States. Most areas have less than 1 in. per year available for recharge, yet aquifers are falling in feet per year. Figure 2-10 combines regional water-level declines and local water-level declines for changes on a national scale. The red regions indicate areas in excess of 500 mi² that have water-level decline in excess of 40 ft in at least one *confined* aquifer since predevelopment, or in excess of 25 ft of decline in unconfined aquifers since predevelopment. The confined aquifers recharge at very low rates, meaning that in most cases, these aquifers are being mined (overdrafted). The blue dots on Figure 2-10 are wells in the USGS National Water Information System database where the measured water-level decline over time is equal to or greater than 40 ft.



Source: Thornthwaite 1948

Figure 2-8 Water deficit areas



Source: Reilly et al. 2008; Wolock 2007

Figure 2-9 Water available for recharge throughout the United States (Note: Most areas are very low.)

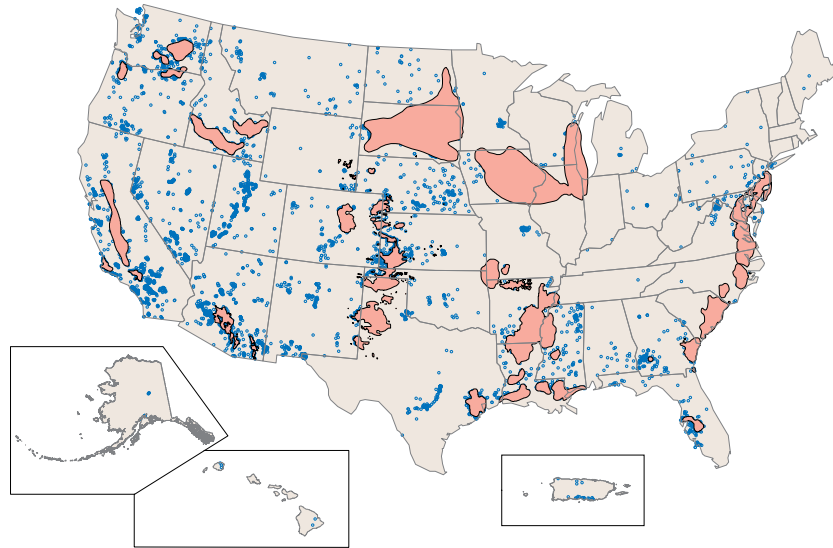


Figure 12. Water-level declines. Red regions indicate areas in excess of 500 square miles that have water-level decline in excess of 40 feet in at least one confined aquifer since predevelopment, or in excess of 25 feet of decline in unconfined aquifers since predevelopment. Blue dots are wells in the USGS National Water Information System database where the measured water-level difference over time is equal to or greater than 40 feet.

Source: Reilly et al. 2008

Figure 2-10 Water-level declines

USGS reports the need for a nationwide effort to organize available information on changes in groundwater storage, similar to what was done for the High Plains aquifer (Reilly et al. 2008). Confounding the problem is that many aquifer systems cross political boundaries, so careful regulation in one jurisdiction may not be supported by others.

Regulations to ensure groundwater supplies are sustainable are recent. Since 1974, Florida has had a groundwater permitting program in place for large agricultural and utility entities. Over time, this program has become more sophisticated given increasing demands in the state so that today, utilities must demonstrate via modeling that their withdrawals will not affect other users. California passed the Sustainable Groundwater Management Act in September 2014 with a goal to ensure better local and regional management of groundwater use; it seeks to have a sustainable groundwater management in California by 2042. The basic tenets were to ensure that any use of the groundwater be both reasonable and beneficial, while authorizing local agencies to implement a groundwater plan, and authorizing the California Department of Water Resources (DWR) to offer support to “entities that extract or use groundwater to promote water conservation and protect groundwater resources” (DANR 2018, CDWR 2017, California Senate 2014). Texas has begun efforts to legislate means to manage groundwater as much of the state depends on it.

DEVELOPMENT AND URBANIZATION IMPACTS

Groundwater recharge is affected by precipitation, actual ET, topography, land use, soil type, land cover, aquifer transmissivity, vegetation characteristics, and contributions to recharge along active stream channels (Herrera-Pantoja and Hiscock 2008). In most cases, there is limited historical information about the quantity of water that was initially

available, so while one can recognize that historical water availability in a basin changed as a result of water use practices, the magnitude of the changes is uncertain.

The change in land use from forests to agriculture or urban uses can have significant impacts on runoff characteristics. Hydrologists point out that areas with higher surface imperviousness will accelerate runoff and decrease infiltration. Urban land use increases runoff because of imperviousness from buildings, parking lots, roads, and other improvements that replace forest or grassland cover (Bloetscher and Muniz 2008). Examples of activities that may affect raw water supplies include delivery times of the water through piping installed to reduce flooding as opposed to natural channels and/or development that replaces irrigated agriculture with paving. Urbanization reduces recharge to groundwater but increases flows to surface reservoirs and streams with potential added nutrients and contaminants. As a result, determining the changes to groundwater availability involves more than calculating the volume of groundwater within an aquifer: it requires a consideration of recharge, water quality, the economics of recovery or the treatment for poor quality water, interconnectedness with the hydrologic system, and ecosystem/user demands. Groundwater management thus involves understanding adjacent users, future demands, limitations of the aquifer and formations and the impacts these have to water supply, and water quality. Water quality, the subject of Chapter 3, is another reason groundwater management is needed.

INTEGRATING GROUNDWATER MANAGEMENT

As this discussion has shown, groundwater has been and continues to be managed under distinctly different approaches by region, by state vs. federal rules, and by tradition. A more integrated management approach in the future is key to having groundwater as a water supply, as base flow to rivers, and as a fundamental basis for healthy systems. Integrated management is required as a part of utility management plans for the future as utilities grow and develop their raw water sources, as well as bring in alternative water sources. Those utilities that invest in their future now will be best placed to weather the uncertainties of future water supply and demands.

Of the two major concerns of groundwater management—quantity and quality—the former has traditionally been the reason that brought entities with an interest in water together. Three methods employed to stretch supplies further by expanding locally available supplies are artificial recharge, conjunctive use, and water wheeling. In arid regions such as the southwestern United States, artificial recharge has been practiced for decades, with conjunctive-use agreements initiated in the 1960s and water-wheeling arrangements starting in the 1990s.

Artificial Recharge

Artificial recharge augments groundwater supplies by supplementing natural recharge. Surface aquifers percolate stormwater captured from precipitation, imported water, and sometimes, recycled water. This concept is discussed more fully in the 4th edition of M21. It is applied in many parts of the country where there are large catchment areas that will percolate water easily. One example is Southeast Florida's water conservation areas.

Conjunctive Use

Groundwater management programs can improve the long-term reliability of water supplies by integrating the use of surface water and groundwater together or "conjunctively." Conjunctive use may be accomplished through either direct or replacement operations.

Direct conjunctive use places imported water into the aquifer, and the water is then pumped as needed. Replacement (or *in-lieu*) conjunctive use is when a water supplier uses imported water instead of pumping its groundwater, leaving the groundwater available in the aquifer for use at a later time. *Seasonal storage* operations recharge an aquifer with imported water during wet times of the year, when surface and imported waters are plentiful, and pump the water out during high-demand months, generally within that same water year. This management strategy results in a seasonal shift, with water typically stored in winter months and pumped during summer months. In some cases, it can be stored underground, the subject of AWWA Manual M63, Aquifer Storage and Recovery. *Carryover storage* occurs when the recharged water is held for use beyond the next water year, such as for a drought.

Wheeling

Water wheeling uses a water supplier's transportation system for delivery of water not owned or controlled by that agency. Wheeling is a common practice in the energy and communications industries. Wheeling permits water suppliers to move water supplies (groundwater or surface water) from areas of plenty to areas of need. Central Florida has a water wheeling program that withdraws water from wellfields that are unstressed to areas where stressed wells may have limited withdrawal allocations. Surface water, aquifer storage, and other concepts supplement the wheeling issue.

Some states have enacted legislation regulating wheeling. For example, the California Water Code requires that water wheeling must not harm any other legal user of water. Other states only require agreements among the parties and agencies that might permit supplies. The cost of wheeling typically recovers costs such as transportation, including capital and operating costs associated with pipelines, reservoirs, and other facilities required to distribute water.

Water Marketing and Water Transfers

Water marketing is the general term encompassing the transfer, lease, or sale of water or water rights. A water transfer is the shift or sale of water from a seller to a buyer. Water transfers can take many forms, each with its own benefits and risks. A *spot transfer* denotes purchase of supplies when needed, such as to offset the effects of a prolonged drought. Under an *option transfer*, the buyer takes a certain amount of water at any time during the life of the agreement, making option payments on an annual basis and making an additional payment in those years in which the water is needed. Buyers in a *core transfer* (or take-and-pay) take a specified amount of water each year and must pay the cost of that water, year in and year out, whether or not the water is needed. This concept is currently applicable only in the 18 western continental states where water rights can be bought and sold. In the remaining states, the waters are owned by the state. Water marketing is increasing in the general public's awareness because of concerns with transferring water from one basin to another, and potential issues that can develop because of decreased surface water and groundwater that is available to residents, natural habitats, and riparian corridors.

REFERENCES

- AWWA. 2014 (4th ed.). M21, Groundwater. Denver, Colo.: AWWA.
- AWWA. 2015. M63, Aquifer Storage and Recovery. Denver, Colo.: AWWA.
- Bloetscher, F. 2019. *Infrastructure Management*. Plantation, Fla.: J. Ross Publishing.
- Bloetscher, F.; Romah, T.; Berry, L.; Hernandez Hammer, N.; and Cahill, M.A. 2012. Identification of Physical Transportation Infrastructure Vulnerable to Sea Level Rise. *Journal of Sustainable Development*. 5:12:40.
- Bloetscher, F. (ed.). 2010. *Sustainability Compendium*. Denver, Colo.: AWWA.
- Bloetscher, F. 2008. The Potential Impact of Climate Change on Groundwater Recharge. Proc. GWPC Annual Forum Proceedings, Oklahoma City, Okla.
- Bloetscher, F. and Muniz, A. 2008. Water Supply in South Florida—The New Limitations. Proc. AWWA 2008 Sustainable Water Sources Conf., Reno, Nev.
- Buffoni, L.B. 2002. Variazioni Climate Change and Groundwater: A Short Review 7. *Italia Negli Ultimi 130 Anni. Bollettino Geofisico Anno XXIII*.
- California Senate. 2014. SB-1319, *Groundwater*.
- CDWR (California Division of Water Resources). 2017. *Sustainable Groundwater Management Act*. Sacramento, Calif.: CDWR.
- DANR (University of California Division of Agriculture and Natural Resources). 2018. *Groundwater: Sustainable Groundwater Management Act*. Davis, Calif.: University of California DANR.
- Di Matteo, L. and Dragoni, W. 2006. Climate Change and Water Resources in Limestone and Mountain Areas: The Case of Firenzuola Lake (Umbria, Italy). Proc. 8th Conf. on Limestone Hydrogeology, Neuchatel, Switzerland.
- Dragoni, W. 1998. Some Considerations on Climatic Changes, Water Resources and Water Needs in the Italian Region South of the 43°N. *Water, Environment and Society in Times of Climatic Change* (Issar, A.S. and Brown, N., eds.). Dordrecht, the Netherlands: Kluwer. pp. 241–271.
- Dragoni, W. and Sukhija, B.S. 2008. Climate Change and Groundwater: A Short Review. *Geological Society, London, Special Publications*. 288:1–12.
- Gao, J. 2010. Collection and Analyses of Physical Data for Deep Injection Wells in Florida. A Thesis Submitted to the Faculty of The College of Computer Science and Engineering in Partial Fulfillment of the Requirements for the Degree of Master of Science, Florida Atlantic University, Boca Raton, Fla.
- Hapgood, C.H. 1999. *Path of the Pole* (2nd ed.). Kempton, Ill.: Adventures Unlimited Press.
- Heimlich, B.N.; Bloetscher, F.; Meeroff, D.M.; and Murley, J. 2009. *Southeast Florida's Resilient Water Resources: Adaptation to Sea Level Rise and Other Impacts of Climate Change*. Jupiter, Fla.: Center for Environmental Studies at Florida Atlantic University.
- Herrera-Pantoja, M. and Hiscock, K.M. 2008. The Effects of Climate Change on Potential Groundwater Recharge in Great Britain. *Hydrological Processes*. 22:73–86.
- Huntington, T.G. 2006. Evidence for Intensification of the Global Water Cycle: Review and Synthesis. *Journal of Hydrology*. 319:83–95.
- IPCC (Intergovernmental Panel on Climate Change). 2007. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Solomon, S.D.; Qin, M.; Manning, Z.; Chen, M.; Marquis, K.B.; Avery, M.T.; and H.L. Miller, H.L. (eds.). Cambridge, United Kingdom, and New York: Cambridge University Press.

- Labat, D.G.; Godd  ris, Y.; Probst, J.L.; and Guyot, J.L. 2004. Evidence for Global Runoff Increase Related to Climate Warming. *Advances in Water Resources*. 27:6:631–642.
- Marshall, C.H.; Pielke, R.A.; Steyaert, L.T.; Willard, D.A. 2004. The Impact of Anthropogenic Land-Cover Change on the Florida Peninsula Sea Breezes and Warm Season Sensible Weather. *Monthly Weather Review*. 132:1:28–52.
- Molak, V. 1997. *Fundamentals of Risk Analysis and Management*. Boca Raton, Fla.: Lewis Publishers.
- Reilly, T.E.; Dennehy, K.F.; Alley, W.M.; and Cunningham, W.L. 2008. *Ground-Water Availability in the United States*. Reston, Va.: USGS (United States Geological Survey).
- Scanlon, B.R.; Reedy, R.C.; Stonestrom, D.A.; Prudic, D.E.; and Dennehy, K.F. 2005. Impact of Land Use and Land Cover Change on Groundwater Recharge and Quality in the Southwestern US. *Global Change Biology*. 11:10:1577–1593.
- Singer, S.F. (ed.). 2008. *Nature, Not Human Activity, Rules Climate Change: Summary for Policy Makers by the Nongovernmental International Panel on Climate Change*. Chicago, Ill.: The Heartland Institute.
- Starkl, M. and Brunner, N. 2004. Feasibility Versus Sustainability in Urban Water Management. *Journal of Environmental Management*. 71:3:245–260.
- Strzepek, K.M. and Yates, D.N. 1997. Climate Change Impacts on the Hydrologic Resources of Europe: A Simplified Continental Scale Analysis. *Climatic Change*. 36:79–92.
- Thornthwaite, C.W. 1948. An Approach Toward a Rational Classification of Climate. *Geographical Review*. 38:1:55–94.
- Wolock, D.M. 2007. *Estimated Mean Annual Natural Ground-water Recharge in the Conterminous United States*. Reston, Va.: USGS.

Chapter **3**

Motivation for Groundwater Management

There are several reasons for utilities to assess and manage their water supplies. This manual opened with a discussion of the issue that caused the eastern Carolinas to change to a different water source. Fortunately, they had options. Having options is not always the case as noted in Chapter 2. The US Geological Survey (USGS) reports concerns with the Ogallala aquifer in the Great Plains; the Edwards aquifer in San Antonio, Tex.; the aquifers beneath South Dakota; groundwaters in eastern Wisconsin; and challenges throughout the desert Southwest to name a few. The concern is that many of these aquifers are overtaxed and their supplies unsustainable. Southwestern Utah (St. George / Cedar City) went through a similar exercise in the mid-2000s. The aquifer was dropping and the state geologist got involved. It was determined that groundwater was not available to supply the region. The region moved to a new impoundment meant to trap snowmelt for water supplies. The region will not be the last to seek alternative water supplies because of the lack of sustainable groundwater.

This chapter will focus on the quality issues associated with groundwater management. Keep in mind that upstream users can significantly impact the water quality that downstream users receive. The federal Superfund program is primarily about upstream contamination of groundwater and soils that can migrate and impact off-site users. The result is that groundwater contamination can take an apparent supply and make it unusable.

WATER QUALITY

The use of groundwater by utilities, agriculture, and industry is easy to understand. Small withdrawals are less likely to have major impacts on adjacent users of the aquifer; also, because costs are always a concern, groundwater is often perceived to be “better” than surface waters—or even “pristine,” since contamination pathways into groundwaters are not as obvious as they are for surface waters. The perception is that less treatment will be required and well operations are straightforward. But this viewpoint is incorrect, as groundwater systems are as susceptible to contamination as surface waters and may be subject to contamination for more significant periods of time because of the slow movement of the water. Naturally occurring constituents, such as arsenic and barium, can impair groundwater quality.

Contamination includes metals, salt, arsenic, organics, and bacteria. Other contaminants are transported through the soils above the groundwater source from contaminant sources such as landfills and other hazardous waste sites and leaking underground storage tanks for chemicals and petroleum products. Pesticides and herbicides are transported off agricultural fields, along with phosphorous and ammonia fertilizers. Nitrates result from the breakdown of ammonia in fertilizer and septic tanks from bacteria. Unlined wastewater holding ponds and improper sludge or manure application sites are major contributors to nitrate contamination. Examples include *Escherichia coli* in a study conducted in Walkerton, Ont. (Schuster et al. 2005). Most users want to avoid these contaminants to the degree practical.

Groundwater-related disease outbreaks have risen as a result of contamination from biological contaminants, and other health conditions have increased as a result of contamination from chemical and biological agents. Of the 673 waterborne illness outbreaks that occurred in the United States between 1946 and 1980 (affecting 150,000 people), 44 percent were attributable to groundwater sources (Asano 1985). Furthermore, Keswick et al. (1982) estimated that 50 percent of the waterborne illnesses in the United States in a given year originate from groundwater, and 65 percent of those are enteric viruses (Yates et al. 1985). More recently, between 1997 and 2006, 137 waterborne disease outbreaks were reported to the Centers for Disease Control and Prevention, with 8,498 illnesses and 17 deaths (Yoder et al. 2008; Liang et al. 2006; Blackburn et al. 2004; Lee et al. 2002; Barwick et al. 2000). Of the 101 groundwater outbreaks with a known cause, 17 were attributed to chemical or toxin poisoning and 84 to pathogens. Bacteria were the most commonly implicated pathogen (Bloetscher et al. 2010).

In addition, many layers of rock that were previously thought to be highly confining may contain fractures or intrusions, such as wells that create pathways for contaminants to move into underlying aquifers. As a result, groundwater may also be “self-contaminating.” Groundwater aquifers may be physically connected, which allows movement of lower-quality water into the production zone. Normally, this is caused by improper well design or construction, which allows poorer-quality water to migrate from one formation to another through potential protective or confining layers. Self-contamination can also occur if the water table lowers, causing saltwater to intrude from below or laterally from saltwater bodies. Saltwater intrusion is an example of the production zone being contaminated by adjacent saltwater bodies via upconing (pumping the wells too much, thereby pulling contaminants, typically salt, upward to the well), lowering regional groundwater levels (such as the case in South Florida) or overpumping along the coast.

The issue also manifests when wells are drilled deeper because the groundwater level drops. Drilling deeper may solve immediate issues with water quantity, but this decision may cause more problems, especially if the drilling occurs in the same exhausted aquifer. Deeper waters generally tend to have poorer water quality as a result of having often been in contact with the rock formation longer and dissolving the minerals in the rock into the

water. Therefore, the types of rock strata that underlie the area have significant bearing on the quality and quantity of groundwater available and the ability of the rocks to store water.

While some deep aquifers may be prolific, the quality of water obtained from a well may not be desirable or even usable for drinking water without substantial amounts of treatment. Older water, and typically deeper water, poses greater challenges for treatment. The result is the potential for poorer water quality in the wells, along with greater aquifer drawdowns, accompanied by aquifer mining and land subsidence. Ideally, source water should be free of microbial contamination from human and animal activities and free of toxic natural and synthetic chemical contaminants; it should also be of adequate quantity to meet the needs of the population served. Having fewer contaminants means lower treatment costs as each increment of treatment to address constituents in the water increases the cost of the finished water. The real and unrealized costs to other users are often ignored in the current water management framework (Bloetscher and Muniz 2008). Since groundwater is rarely pristine and the potential for contamination is significant, water purveyors that derive their water sources from groundwater need to monitor surface events, such as rainfall, spills, development, and drought, to determine the potential impact on their water systems. That is where source water protection comes in.

SOURCE WATER PROTECTION

The 1996 amendments to the Safe Drinking Water Act require the states to assess areas serving as sources of drinking water to identify potential threats and initiate protection efforts. Most states delegated this requirement to local entities. Watershed protection can be broadly defined as a program to reduce the threat to water supplies from contaminants; for groundwater, this is called a wellhead protection program. Local communities protect their groundwater resources by incorporating wellhead protection activities into land use management as a means to reduce contamination. The protection of public water supply wells through wellhead protection programs is considered an important component of a comprehensive state groundwater protection program, as established by the US Environmental Protection Agency (USEPA 1991).

When a site has been selected for installation of a well or well field, the water supply entity must protect it from contamination through a wellhead protection regulation. A wellhead protection program reduces the potential for contaminants to leach into the groundwater by identifying and managing recharge areas specific to the wellfield. Wellhead protection programs range from simple regulations concerning the location of facilities in the vicinity of the wells to extensive land purchases and comprehensive land use restrictions. Typical action involving wellhead protection efforts include:

- new requirements for installation and testing of underground storage tanks;
- increased regulation for handling, using, and transporting toxic chemicals to reduce the possibility of spills;
- greatly increased regulation of landfills and other waste disposal sites;
- closer control of the use of pesticides and agricultural chemicals;
- sampling and monitoring of identified groundwater contamination locations; and
- action plans to remove the contamination.

Most states have groundwater programs. For example, California has established a process for developing groundwater management plans for individual aquifers. Connecticut ranks aquifers according to levels of protection. Texas has begun to develop regulations for aquifer management. The regulations are constantly in flux, so engineers

and hydrogeologists need to contact the state's or province's division of water resources (or similar entity) to inquire about specific regulations for a given locale. AWWA's standard for source water protection ANSI/AWWA G300 provides a framework to protect source water.

Developing a Source Water Protection Program

Source protection is the first step in safeguarding public water supplies, reducing the need to use expensive alternative treatment techniques. Source water management options or tools can be broadly classified between regulatory and nonregulatory options. At the local level, the regulatory practices are usually in the form of zoning ordinances, subdivision ordinances, or regulations assigned directly to the protection of groundwater. The USEPA *Handbook for Ground Water and Wellhead Protection* (1994) indicates several options for implementation of a source water protection program including land use practices, regulations or legal measures, and administrative considerations. Other regulations, such as the Class V rule of 1999 to ban motor vehicle waste disposal wells and large-capacity cesspools, help protect aquifers.

The management of a source water protection area to prevent contamination involves the following:

- Identify protection options appropriate to the potential contaminants.
- Select the options that are technically and politically feasible.
- Implement the management practices.
- Develop contingency plans to address possible threats.
- Monitor the effectiveness of management practices.

To accomplish these goals, AWWA's G300, Source Water Protection, recommends the following steps:

- creating a vision,
- stakeholder engagement,
- characterization,
- goal setting,
- development of an action plan,
- implementation of action plan, and
- evaluation and revision as needed.

A groundwater-monitoring program is necessary to monitor the success of any source water protection program.

Delineation of a source water protection area is typically done through the use of computer modeling of travel time and pollutant transport. These models can be complex and can create large areas where many land uses are prohibited. Such source water protection efforts can conflict with private property rights objectives. These laws indicate that if the property is damaged significantly (often defined as a devaluation of 10 percent), the regulating agency must compensate the affected property owner. As a result, the concept of source water protection conflicts with this legal concept, which could be a significant impediment for utilities attempting to implement source water protection programs.