

Groundwater

Fourth Edition



**American Water Works
Association**



Documents
Document Sharing Hub

Groundwater

Fourth Edition



**American Water Works
Association**



Documents

Document Sharing Hub

Manual of Water Supply Practices—M21, Fourth Edition

Groundwater

Copyright © 1973, 1989, 2003, 2014 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 photocopy, recording, or any information or retrieval system, except in the form of brief excerpts or quotations for review purposes, without the written permission of the publisher.

Disclaimer

The authors, contributors, editors, and publisher do not assume responsibility for the validity of the content or any consequences of their 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.

Project Manager/Senior Technical Editor: Melissa Valentine
Senior Manuals Specialist: Molly Beach
Senior Production Editor: Cheryl Armstrong

Library of Congress Cataloging-in-Publication Data

Bloetscher, Frederick.

Groundwater / Frederick Bloetscher. -- Fourth edition.

pages cm -- (AWWA manual ; M21)

Includes bibliographical references and index.

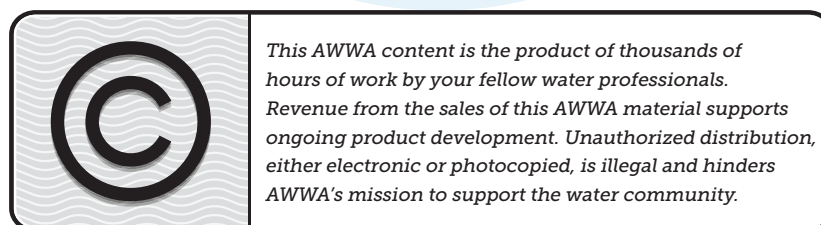
ISBN 978-1-58321-964-5 (alk. paper)

1. Groundwater. 2. Wells. I. American Water Works Association. II. Title. III. Title: Ground water.

TD403.B56 2014

628.1'14--dc23

2013031069



ISBN: 978-1-58321-964-5

eISBN: 978-1-61300-243-8

Printed in the United States of America

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


Printed on
recycled paper

 **Documents**
Document Sharing Hub

Contents

List of Figures, vii

List of Tables, xi

Foreword, xiii

Acknowledgments, xv

Chapter 1 The Occurrence and Behavior of Groundwater.....1

Hydrologic Cycle, 2

Groundwater Concepts, 6

Major Conditions That Impact Groundwater, 10

Achieving Sustainability, 12

References, 13

Chapter 2 Evaluation of Groundwater Conditions 15

Suitable Groundwater Supplies, 16

Locating Suitable Groundwater Supplies, 18

Monitoring Groundwater Quality, 27

Field Logistics and Documentation, 30

References, 33

Chapter 3 Groundwater Management and Protection 35

Introduction, 36

Regulatory Level Management, 36

Source Water Protection, 38

Management Strategies, 40

Contaminated Groundwater Management, 41

Regional Groundwater Management, 42

Groundwater Sustainability, 44

Future Groundwater Management, 49

References, 49

Chapter 4 Quantitative Evaluation of Wells 51

Aquifer Parameters, 51

Storage Coefficient, 64

Collection of Test Data, 67

Analysis, 67

References, 76

Chapter 5 Wells—Types, Construction, Design, and Use 79

Types of Wells and Their Construction, 79

Common Construction Components, 95

Well Design Procedure, 122

Sanitary Protection, 122

Well-Field Design, 123

Well Losses, 125

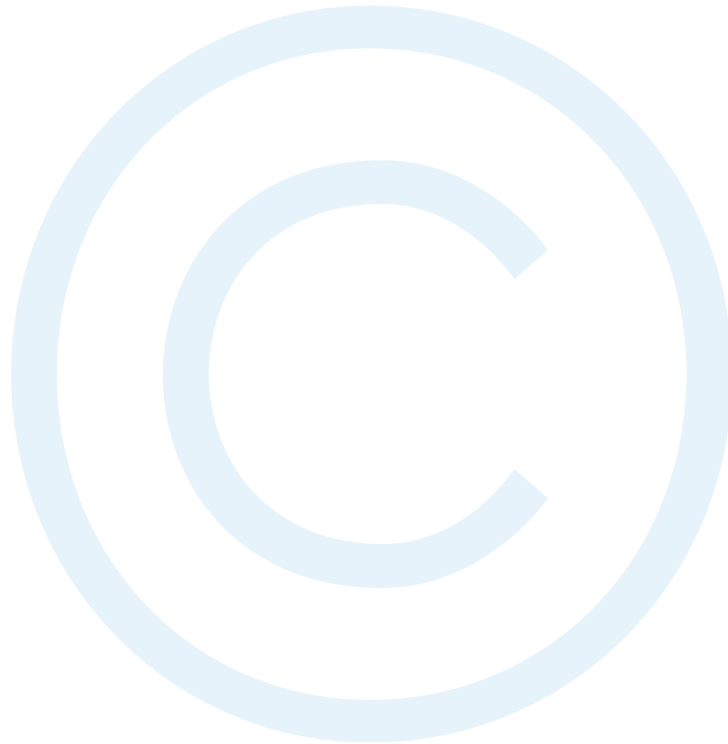
Radial-Well Yield, 127

Modeling Techniques, 127

References, 133

Chapter 6	Well Pumps and Pumping.....	135
	Pump Classifications, 137	
	Operating Conditions, 153	
	Pump Selection, 155	
	Electric Motor Selection, 158	
	Pump Installation, 158	
	References, 160	
Chapter 7	Operations Problems, Well Plugging, and Methods of Correction	161
	Evaluating Well Performance, 162	
	Poor Well Performance, 163	
	Common Pump Operating Problems, 164	
	Physical Causes of Well Deterioration, 166	
	Sand Pumping, 168	
	Microbiological Fouling, 169	
	Treatment of Fouling Problems, 172	
	Economics of Cleaning Plugged Wells, 175	
	Case Studies, 178	
	References, 188	
	Additional Reading, 189	
Chapter 8	Groundwater Quality.....	191
	Chemicals in Groundwater, 191	
	Groundwater Contamination, 195	
	Chemical Contaminants, 197	
	References, 204	
Chapter 9	Groundwater Treatment	207
	Aeration, 207	
	Oxidation, 209	
	Softening and Ion Exchange, 211	
	Filtration, 215	
	Adsorption and Absorption, 217	
	Corrosion Control, 218	
	Disinfection, 221	
	Fluoridation, 222	
	Membranes, 222	
	References, 225	
Chapter 10	Record Keeping	227
	Design and Construction Records, 227	
	Pump Data, 230	
	Well Acceptance and Pumping Test, 235	
	Monthly Pumpage , 235	
	Water Levels, 237	
	Water Temperature, 237	
	Specific Capacity, 237	
	Differential, 237	
	Well Maintenance, 238	
	Well Abandonment, 238	
	Records Filing and Maintenance, 238	

Chapter 11	Groundwater Recharge and Storage Programs.....	239
	Underground Protection Criteria and Standards, 240	
	Aquifer Storage and Recovery, 241	
	Aquifer Reclamation, 247	
	Artificial Aquifer Creation and Recharge, 252	
	References, 258	
Chapter 12	The Future of Groundwater	261
	Reference, 263	
	Glossary of Terms, 265	
	Index, 269	
	List of AWWA Manuals, 279	



This page intentionally blank.



Figures

- 1-1 Hydrologic cycle, 2
- 1-2 Evapotranspiration rates, 3
- 1-3 A comparison of ET rates and rainfall in South Florida, 4
- 1-4 One-hour rainfall (inches) to be expected once on average in 25 years, 5
- 1-5 Average annual precipitation (inches) in the United States (1961–1990), 5
- 1-6 Water movement below the earth's surface, 7
- 1-7 Geologic configuration of aquifers and confining beds, 8
- 1-8 Groundwater movement as it relates to topography, 9
- 1-9 Development of a cone of depression, 9
- 1-10 Areas where land surface subsidence is an issue, 11

- 2-1 Schlumberger and Wenner electrode arrangements for measuring earth resistivity, 20
- 2-2 Application of seismic refraction method for reconnaissance mapping, 22
- 2-3 Single-point electrode arrangement for resistance and spontaneous potential logging, 25
- 2-4 Qualitative interpretation of a suite of geophysical logs, 27
- 2-5 Schematic of a multiple-completion monitoring well, 29
- 2-6 Graphic detail of a hydrogeologic cross section, 31
- 2-7 Predevelopment groundwater contours showing potential contamination source downgradient, 32
- 2-8 Predevelopment groundwater contours showing predicted effects of ill-advised development, 32

- 3-1 Example of a surface activity that could affect groundwater through a leaky storage tank, 37
- 3-2 Broward County source water protection zones, 39
- 3-3 Groundwater management factors, 41
- 3-4 Options to address contaminated aquifers, 42
- 3-5 Difference between average annual precipitation and potential ET rates, 45
- 3-6 Water deficit areas, 46
- 3-7 Water available for recharge throughout the United States, 46
- 3-8 Water-level declines, 47

- 4-1 Theoretical cube, 52
- 4-2 Definition of porosity, 53
- 4-3 Definition of specific yield and specific retention, 53
- 4-4 Definition of heads and gradients, 55
- 4-5 Example well location to be used in determining direction of groundwater movement and hydraulic gradient, 56
- 4-6 Steps in determining direction of groundwater movement and hydraulic gradient, 56
- 4-7 Definition of hydraulic conductivity, 58
- 4-8 Hydraulic conductivity of selected rocks, 59
- 4-9 Definition of capillarity and unsaturated flow, 59
- 4-10 Determining capillary gradient from tensiometer measurements of hydraulic pressures, 61

- 4-11 Relation between degree of saturation and the ratio of saturated and unsaturated hydraulic conductivity for coarse sand, 61
- 4-12 Definition of transmissivity, 63
- 4-13 Calculation of transmissivity using stream discharge, 64
- 4-14 Definition of storage coefficient, 65
- 4-15 Hypothetical test situation—infinite aquifer, 69
- 4-16 Hydrograph for observation well No. 1, 70
- 4-17 Drawdown test data superimposed on Theis-type curve, 72
- 4-18 Straight-line approximation of drawdown data analysis, 72
- 4-19 Hypothetical test situation—aquifer bounded by impermeable barrier, 73
- 4-20 Effect of impermeable barrier shown on straight-line drawdown plot, 74
- 4-21 Hypothetical test situation—aquifer bounded by recharging stream, 74
- 4-22 Effect of recharging stream shown on straight-line drawdown plot, 75

- 5-1 Dug well, 81
- 5-2 Typical cable-tool method of drilling to remove cuttings, 84
- 5-3 Rotary method of well drilling, 85
- 5-4 Down-hole hammer, hammer drilling, 86
- 5-5 Reverse-circulation rotary method, 87
- 5-6 Dual-rotary drilling, 88
- 5-7 Two phases of gravel-wall well construction—gravel envelope method, 91
- 5-8 Details of a radial well, 92
- 5-9 Riverbank filtration using vertical wells, 94
- 5-10 Riverbank filtration using horizontal wells, 94
- 5-11 Scale of screen-opening sizes, 103
- 5-12 Cross-sectional comparison of well walls, 104
- 5-13 Details of cylindrical plummet, 113
- 5-14 Suspension of the plummet using drill rig, 113
- 5-15 Longitudinal projections of wall and constructed pump centerlines on north-south and east-west vertical planes, 115
- 5-16 Graphic representation of requirements of plumbness in Figure 5-15, 116
- 5-17 Graphic representation of requirements for alignment in Figure 5-15, 116
- 5-18 Relationship between misalignment diameter from Figure 5-15, effective diameter of the well, and inside diameter of the well, 117
- 5-19 Type 1, 118
- 5-20 Type 2, 118
- 5-21 Type 3, 118
- 5-22 Type 4, 118
- 5-23 Type 5, 119
- 5-24 Type 6, 119
- 5-25 Type 7, 119
- 5-26 Type 8, 119
- 5-27 Type 9, 119
- 5-28 Type 10, 119
- 5-29 Type 11, 120
- 5-30 Type 12, 120
- 5-31 Rossum sand sampler, 121
- 5-32 Influence for various rates of pumping in an aquifer, 124
- 5-33 Steps for model application, 129

- 6-1 Schematic illustrating total static head, 136
- 6-2 Volute-type centrifugal pump, 144
- 6-3 Diffuser-type centrifugal pump, 144
- 6-4 Plunger-type pump, 146
- 6-5 Vertical deep-well turbine pump, 148
- 6-6 Rotary-displacement pump, 150
- 6-7 Rotary-gear pump, 151
- 6-8 Airlift pump, 152
- 6-9 Jet-type deep-well pump, 153

- 7-1 Operating problems resulting from a drop in the water table, 165
- 7-2 Lakos sand separator, 169
- 7-3 Well efficiency monitoring, Catamount well field, well No. 54, 176
- 7-4 Example of well performance history, 177
- 7-5 Example of corroded column pipe, 180
- 7-6 Venice RO well construction after rehabilitation, 182

- 8-1 Flow of contamination from a ponded surface source into an aquifer, 204

- 9-1 Natural draft aeration system, 208
- 9-2 Packed-tower aeration, 209
- 9-3 Chlorine cylinders, 210
- 9-4 Advanced oxidation process—hydrogen peroxide with UV light are typical processes, 211
- 9-5 UV light system, 212
- 9-6 Typical silo for dry lime, 213
- 9-7 Slaker system, 214
- 9-8 Mixed with the raw water in some form of lime softening unit, 214
- 9-9 Ion exchange system, 215
- 9-10 Granular filtration, 216
- 9-11 Pressure filters, 216
- 9-12 Example of filter being backwashed, 217
- 9-13 Typical membrane skids, 224
- 9-14 How membranes work, 224

- 10-1 Well design, 228
- 10-2 Well drilling permit, 229
- 10-3 Well completion report, 231
- 10-4 Well summary information, 232
- 10-5 Pump data hydraulic data sheet, 233
- 10-6 Pump data, turbine 60 Hz 234
- 10-7 Monthly pumping report, 235
- 10-8 Monthly operations report, 236

- 11-1 ASR conceptual diagram for brackish water aquifers, 242
- 11-2 Collier County, Fla., ASR project graph showing recovery efficiency improvement for each succeeding cycle, 243
- 11-3 Schematic of Peace River ASR system, 244
- 11-4 Cross section of the ASR system, 244
- 11-5 Historical operation of the ASR wells, 245
- 11-6 Cumulative volume in storage, 246
- 11-7 Depletion of storage and the TDS of water, 246

GROUNDWATER

- 11-8 Results of a recent extended recovery period, 247
- 11-9 Biscayne Aquifer reclamation water movement after injection, 249
- 11-10 Biscayne Aquifer reclamation buoyancy movement after injection, 249
- 11-11 Biscayne Aquifer reclamation injection well location, 249
- 11-12 Biscayne Aquifer reclamation water movement after injection, 250
- 11-13 Schematic of treatment process, 251
- 11-14 Location of the WRP, 251
- 11-15 Aquifer recharge, 253
- 11-16 Aquifer recharge via flooding, 253
- 11-17 Aquifer reclamation to prevent upconing, 254



Tables

- 4-1 Selected values of porosity, specific yield, and specific retention, 54
- 4-2 Approximate height of capillary rise, h_c , in granular materials, 60
- 4-3 Drawdown test data for observation wells, 71

- 5-1 Summary of well types and notes, 95
- 5-2 USGS grain-size classification, 97
- 5-3 Water-well casing materials, 99
- 5-4 Standard well-casing sizes for wells, 100
- 5-5 Minimum thickness for steel well casing—single casing, 101
- 5-6 Minimum thickness for two-ply steel well casing, 102
- 5-7 Plumbness and alignment test data sheet, 114
- 5-8 Allowable interference drawdowns for various pumping rates, 125

- 6-1 Velocity-head data, 137
- 6-2 Friction loss for water in ft per 100 ft (Schedule 40 Steel Pipe), 138
- 6-3 Equivalent length of new straight pipe for valves and fittings for turbulent flow only, 142
- 6-4 Maximum practical suction lift, in feet, for single-stage centrifugal pump, 145
- 6-5 Air requirements for airlift pumps, 152
- 6-6 Summary of pump types and applications, 154

- 7-1 Well rehab versus replacement comparison, 176
- 7-2 Timeline for well capacity—well No. 1, 183
- 7-3 Timeline for well capacity—well No. 2 and well No. 3, 183

- 8-1 The principal natural chemical constituents in water, concentrations, and effects of usability, 192
- 8-2 MCLs for a variety of organic and inorganic chemicals, 198
- 8-3 Regulated pesticides detected in groundwater, 201
- 8-4 Summary of pharmaceutically active substance occurrence in wastewater effluent and associated surface waters, 203
- 8-5 Major sources of groundwater contamination, 204

- 11-1 Summary of nutrient and coliform results post RO, UV, and AOP, 255
- 11-2 Summary of BOC, COD, TOC, and organic results post RO, UV, and AOP, 255
- 11-3 Summary of pesticide and pathogen results post RO, UV, and AOP, 255
- 11-4 Summary of metals and nitrogen species results post RO, UV and AOP, 256
- 11-5 Cost comparison of AWS options for Pembroke Pines, 257

This page intentionally blank.



Foreword

This AWWA revision to Manual M21 is the culmination of nearly three years of effort by members of the Groundwater Resources Committee. This edition has been written to provide the reader with a general understanding of the principles involved with ground water, its movement and character, and the subsequent impact these characteristics have on the design, construction, and maintenance of groundwater well systems for water utilities. Among the major changes included in content from prior editions are the incorporation of the well construction standards formerly attached to Standard A100 Water Wells and a discussion in chapters 1 and 3 on sustainability of groundwater supplies in light of competition, lack of regulatory limitations, overdrafting, and climate changes. In addition, groundwater protection, planning, and evaluation efforts have evolved during the past 10 years, which have been updated in chapter 3. Modeling techniques have developed as well, to the point where many consumptive-use projects include a modeling exercise. New uses of groundwater, such as aquifer storage and recovery, and new legal issues with interbasin transfers have evolved as well.

The intention of this fourth edition is to create a document that provides a general overview, without the detailed mathematical analyses that are available in many other groundwater books. This manual will provide operators and engineering staff with an understanding of groundwater principles that will help them to make decisions on design, installation, phasing, and repair needs when problems or the need to expand supplies arise.

SCOPE

Chapter 1 is an overview of the occurrence and behavior of groundwater, including the geology, hydrologic cycle, and aquifer characteristics that define groundwater flow, as well as a discussion of sustainability of groundwater supplies in light of competition and climate changes.

Chapter 2 is an overview of the process to evaluate aquifers and water quality to allow engineers, hydrogeologists, and administrators to make decisions on aquifer use. Aquifer tests to define water availability and quality are also presented.

Chapter 3 is an extension of chapter 2 that covers the areas of groundwater protection and management, similar to source water protection efforts and land use controls.

Chapter 4 demonstrates the use of the standard groundwater equations to evaluate well fields and develop computer modeling. An outline of common modeling software is included.

Chapter 5 outlines the type and construction of wells that can be used for water supplies for utilities. Horizontal wells and riverbank filtration were added to this chapter. The well construction standards (plus in the appendices) that were previously attached to the A100 standard have been incorporated into chapter 5.

Chapter 6 describes the types of pumps used in well applications, maintenance requirements, pump problems, and solutions to those problems.

If wells are constructed as discussed in chapter 5, they should be operated, as defined in **chapter 7**. The problems likely to be encountered, including plugging and fouling problems and their correction, are also discussed. Microbiological fouling is a major topic discussed in detail in this chapter, as it has been found to be a major issue throughout the world, albeit one that is not commonly understood.

Chapter 8 presents issues associated with water quality and contaminant transport resulting from organic, inorganic, and bacteriological pollution; the methods to test and monitor these problems; and treatment methods to maintain the water supply quality and reduce maintenance costs.

Chapter 9 summarizes water treatment issues arising from groundwater sources. The discussion is not meant to be exhaustive of the treatment options available but is instead intended to describe common treatment options of which the operators, engineers, and administrators of water supply agencies should be aware.

Chapter 10 discusses the record keeping used with wells and well fields systems. These records provide utility personnel with insight into the occurrence of problems and long-term trends.

Chapter 11 presents emerging groundwater technologies such as aquifer storage and recovery, artificial recharge, and salinity barriers.

Chapter 12 discusses future trends as groundwater moves away from well drilling to more of a management process.

This manual should help operators and engineers gain enough background on the subject of groundwater to improve their decision making. The manual should provide answers to many questions about complex aquifer systems and improve the operators' and engineers' response to problems. The AWWA Groundwater Resources Committee is hopeful that the new edition will meet the industry needs of the new millennium and will be as useful as the prior editions have been.

Frederick Bloetscher, PhD, PE
Chairman, AWWA Groundwater Resources Committee

Acknowledgments

This manual was developed by the AWWA Groundwater Resources Committee. The membership at the time of approval was as follows:

Frederick Bloetscher (Chair), Florida Atlantic University, Boca Raton, Fla.
D.F. Edson, Talkington Edson Environmental Management, Westborough, Mass.
Frank Getchell, Leggette, Brashears & Graham Inc., Upper Saddle River, N.J.
Jeff Henson, Black and Veatch, Kansas City, Mo.
Steve Hubbs, retired, Louisville, Ky.
H.C. Hunt III, Layne Christensen, Gahanna, Ohio
Vanessa Kelly, United States Environmental Protection Agency, Dallas, Texas
Sharon Long, University of Wisconsin, Madison, Wis.
Stewart Magenheimer, CDM Smith, Fort Lauderdale, Fla.
Margaret Medellin, AWWA staff, Denver, Colo.
Albert Muniz, Hazen & Sawyer, Boca Raton, Fla.
Susan Roberts, Abeinsa, Chesterfield, Mo.
S.A. Smith, Ground Water Science, Poland, Ohio

This page intentionally blank.



Chapter **1**

The Occurrence and Behavior of Groundwater

More than half of the people served with public water supplies in the United States and Canada obtain their water supplies from groundwater. Nearly 80 percent of all utilities, and most of the smaller systems, derive their source water from groundwater, but groundwater is not visible from the surface and the understanding of its behavior and occurrence by the public is limited. This chapter is intended to provide a general overview of the following:

- the hydrologic cycle
- general groundwater concepts
- major conditions that impact groundwater
- climate impacts on groundwater
- sustainability of groundwater

Because groundwater and surface water resources are closely related, any event that occurs aboveground can impact an underground water supply, a fact often not understood by the public and some regulatory agencies. As a result, 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, as discussed throughout this manual. In addition, the sustainability of many groundwater supplies is in question. If these groundwater supplies do not recharge, several things can occur: land subsidence in areas with friable or unconsolidated materials, potential diminishment or loss of a natural resource, and long-term negative impacts on a sustainable

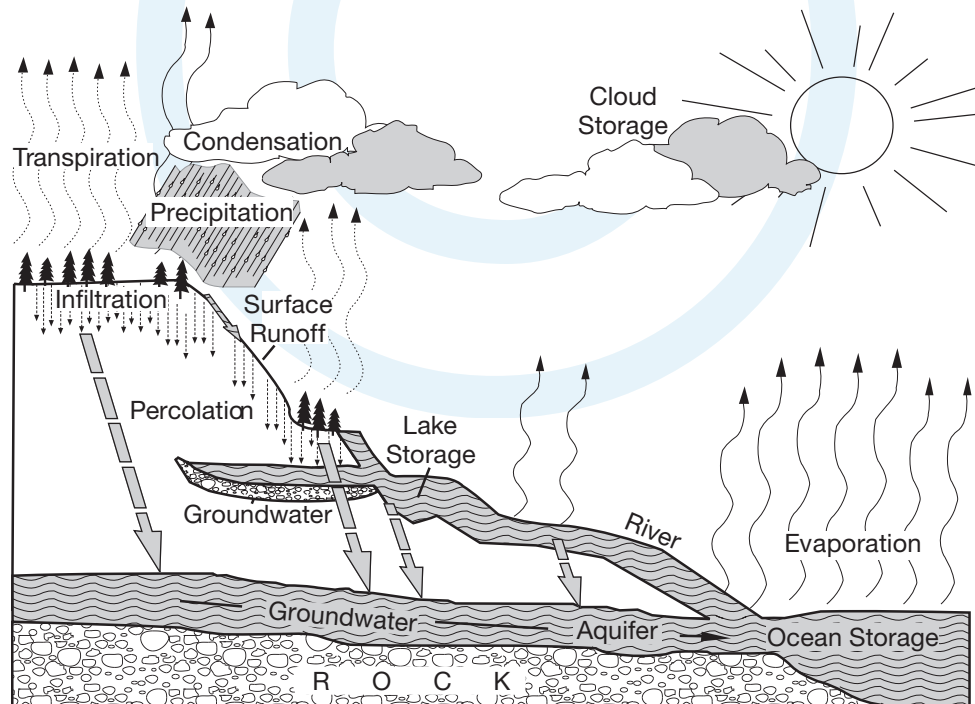
local economy. Reilly et al. (2009) have identified that the overuse of groundwater supplies may be particularly problematic in parts of the western United States and along the eastern seaboard, but this may be symptomatic of the overuse of groundwater in general. Climate impacts on groundwater are addressed in this chapter as well.

HYDROLOGIC CYCLE

Of the total water found on earth, 97.3 percent is saltwater in the oceans. Of the remaining water, over two thirds exists as ice in the polar caps. The rest, or 0.61 percent of all water, is fresh water in lakes, rivers, streams, and groundwater. Seventy-five percent is groundwater. That means that while there is a lot of water out there, getting to a sustainable supply may be of issue.

The constant movement of water above, on, and below the earth's surface is defined as the hydrologic cycle as depicted in Figure 1-1. 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)
- precipitation
- surface water and runoff
- groundwater



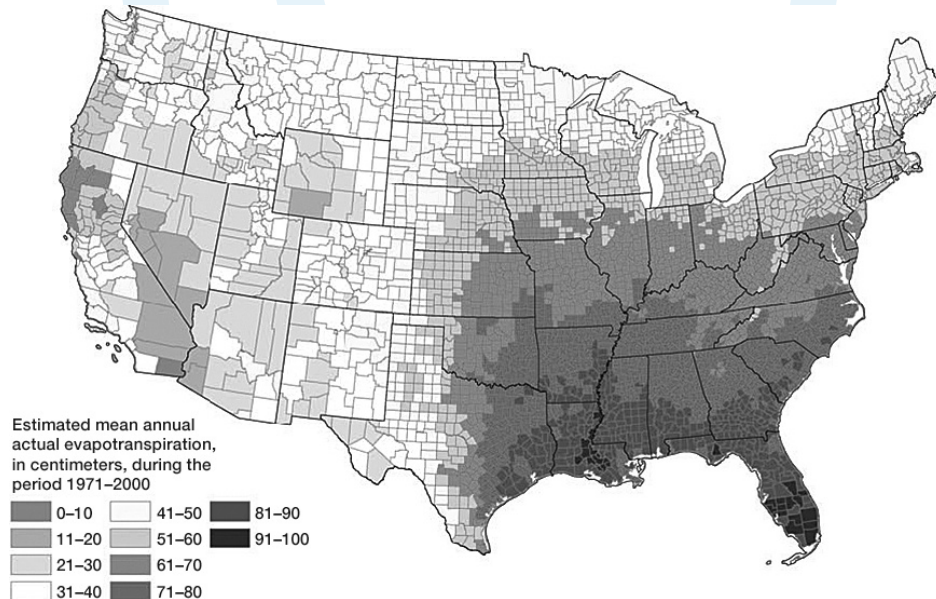
Source: US National Weather Service 1998

Figure 1-1 Hydrologic cycle

Evaporation and Transpiration

Although the hydrologic cycle is continuous and has neither a beginning nor an end, evaporation and transpiration will be discussed first in this manual. These two processes are commonly combined and referred to as *evapotranspiration* (ET). ET is the process of water vapor entering the atmosphere both through water that evaporates from open water bodies and water that transpires from vegetation or other sources. ET rates vary, depending largely on the amount of solar radiation, the latitude of the catchment area, the amount of heat, water surface area, and vegetative cover. Areas close to the equator tend to have higher ET rates. Figure 1-2 is a map of ET rates in the United States (similar mapping may be available for Canada and Mexico). In subtropical areas during the wet season or during summer months in northern latitudes, large bodies of water, including wetlands 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.

To grow, plants must continually absorb water through their roots and circulate it up through their leaves. Water vapor evaporates from the plant through transpiration during photosynthesis. For plants that grow in swampy environments, the quantity of water lost is significant. On average, ET during the summer months offsets a good portion of the rainfall. Figure 1-3 shows a comparison of ET rates and rainfall in South Florida. Figure 1-3 shows that the ET rates are normally highest in the summer, which is typical across North America. Subtropical south Florida is different in that rainfall is also highest in the summer offsetting the ET loss. In the rest of North America, the summer ET rate is not offset by extensive rainfall.



Source: NOAA 2013 <http://summitcountyvoice.com/2013/03/18/usgs-water-study-details-evapotranspiration-rates/>. Courtesy USGS.

Figure 1-2 Evapotranspiration rates

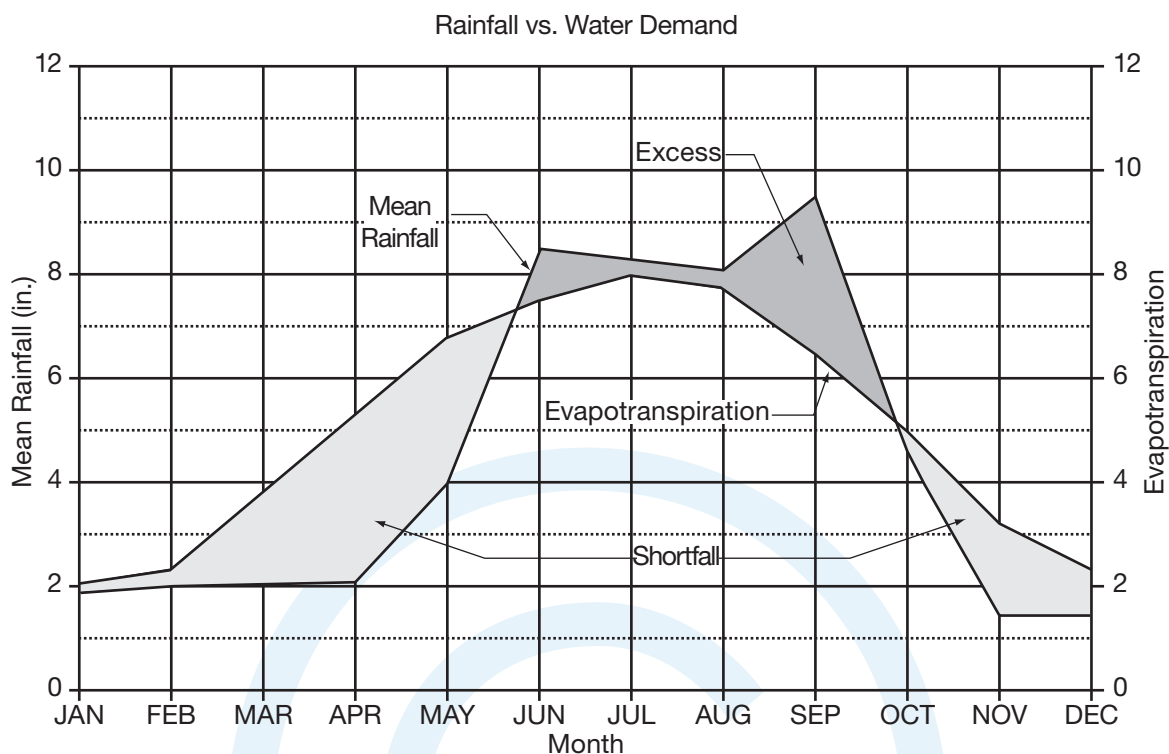


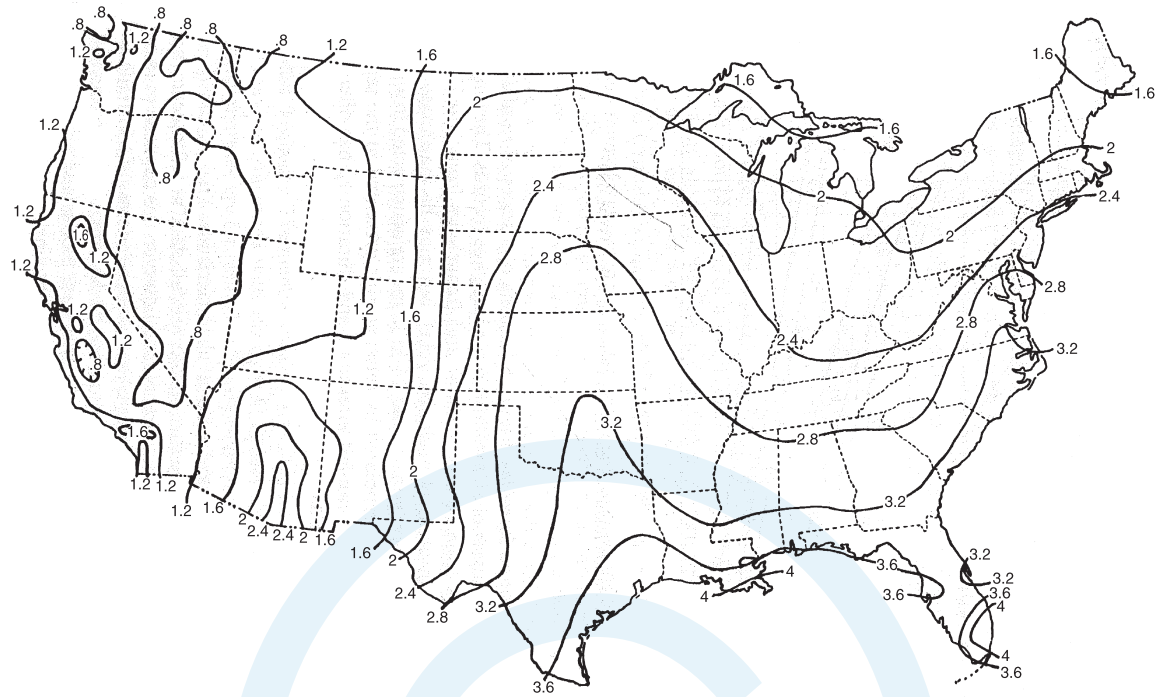
Figure 1-3 A comparison of ET rates and rainfall in South Florida

Precipitation

Precipitation occurs in several forms, including rain, snow, sleet, and hail. Water vapor from ET forms clouds. 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. per hour in subtropical areas but is commonly 2–3 in. per hour across North America. Figure 1-4 shows intensities that occur in the continental United States (similar mapping may be available for Canada and Mexico). Rainfall intensity is relevant because the rain wets vegetation and other surfaces, then infiltrates the ground. 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./hr or 25 mm/hr in mature forests on sandy soils, to almost nothing in clay soils and paved areas. If and when the rate of precipitation exceeds the rate of infiltration, overland flow or runoff occurs. Figure 1-5 shows average annual precipitation in the United States. The data can be logically extended into Canada and Mexico along the borders.

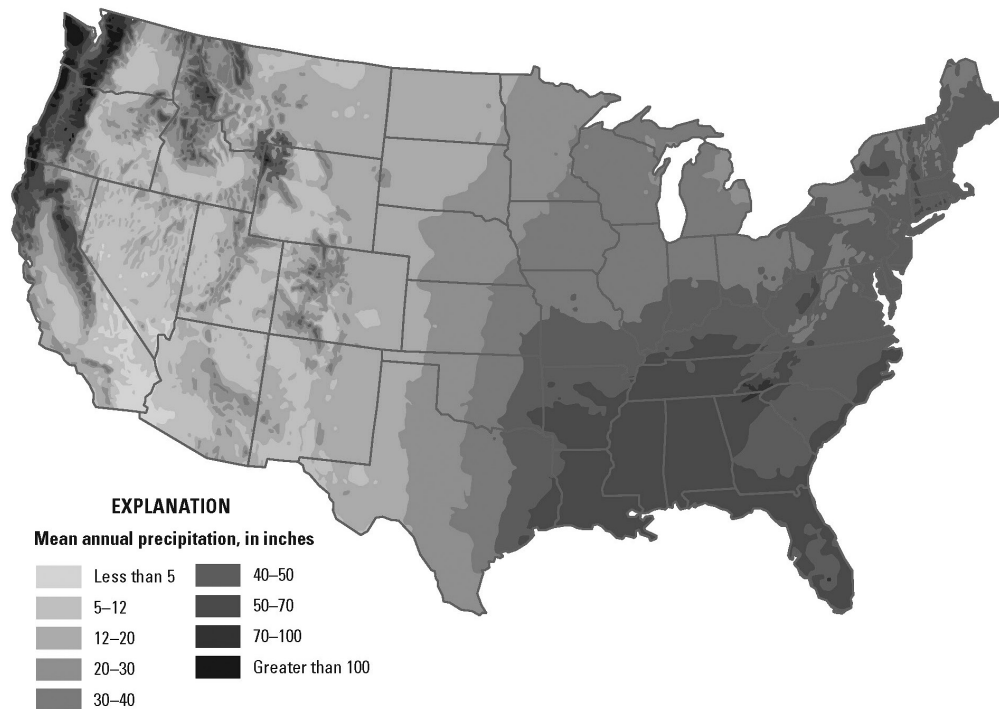
Surface Water

Precipitation that runs off the land, reaching streams, rivers, or lakes, or groundwater that discharges into these water bodies is surface water. Surface water bodies that mix with saltwater bodies along the coast are called *estuaries*; for example, where a river meets the ocean in a delta. Surface water flow is controlled by topography because water on the surface flows downward by gravity, eventually reaching the oceans.



Source: US National Weather Service 1998

Figure 1-4 One-hour rainfall (inches) to be expected once on average in 25 years



Source: NOAA 2002

Figure 1-5 Average annual precipitation (inches) in the United States (1961–1990)

GROUNDWATER CONCEPTS

The quantity and quality of groundwater depend on factors such as depth, rainfall, and geology. For example, the flow velocity and flow direction of groundwater depend on the permeability of sediment and rock layers, and the relative pressure of groundwater. A one-mile-square area 20-ft thick with a 25 percent porosity would hold one billion gallons of water. However, due to variable rates of groundwater flow and the impacts of withdrawals, such an area may not hold the one billion gallons at all times. The main concepts and factors related to groundwater include infiltration and recharge, unsaturated and saturated zones, and aquifers and confining beds. These are discussed in the following paragraphs.

Infiltration and Recharge

Precipitation that percolates downward through porous surface soils is the primary source of water for groundwater. Surface areas having this downward flow are called *recharge areas*. The characteristics of soil depend on the soil forming parent material, the climate, soil chemistry, the types of organisms in and on the soil, the topography of the land, and the amount of time these factors have acted on the material. Because vegetative types differ in their nutrient requirements and in their ability to live in water-saturated or saline areas, soil types also play a role in determining plant distribution.

Soil has the capacity to absorb some moisture initially, a factor called *initial infiltration*. Initial infiltration replaces moisture in the root or plant zones, where the roots for most vegetation exist. Because of the variable permeability and transmissivity of different soils, the rate of groundwater recharge from precipitation will vary. Recharge areas for deeper groundwater can be located far from the point of use. For an aquifer to have fresh water, there must be a source of recharge, some degree of flow (albeit slow), and a discharge area (to cause the flow). Otherwise, if there were no recharge or movement, the aquifer would become brackish through dissolution of the minerals in the rock.

Unsaturated and Saturated Zones

After precipitation has infiltrated the soil, it will travel down through two zones. The unsaturated zone occurs immediately below the land surface in most areas where pore space contains water and air. The unsaturated zone is almost invariably underlain by a zone in which all interconnected openings are full of water. This zone is referred to as the saturated zone and is illustrated in Figure 1-6.

Water in the saturated zone, technically called *groundwater*, is contained in interconnected pores located either below the water table in an unconfined aquifer or in a confined aquifer. Recharge of the saturated zone occurs by percolation of water from the land surface through the unsaturated zone. The unsaturated zone is, therefore, of great importance to groundwater hydrology. This zone may be divided usefully into three parts: the soil zone, the intermediate zone, and the upper part of the capillary fringe.

Soil zone. The soil zone typically extends from the land surface to a maximum depth of 3 to 5 ft (1 to 1.6 m). The soil zone supports plant growth, and it is crisscrossed by living roots, voids left by decayed roots of earlier vegetation, and animal and worm burrows. The porosity and permeability of the material in this zone tend to be higher than the porosity and permeability of the ground beneath it.

Intermediate zone. Below the soil zone is the intermediate zone, which differs in thickness from place to place, depending on the thickness of the soil zone and the depth to the capillary fringe. The intermediate zone is less porous than the soil zone because few roots or burrows penetrate it.

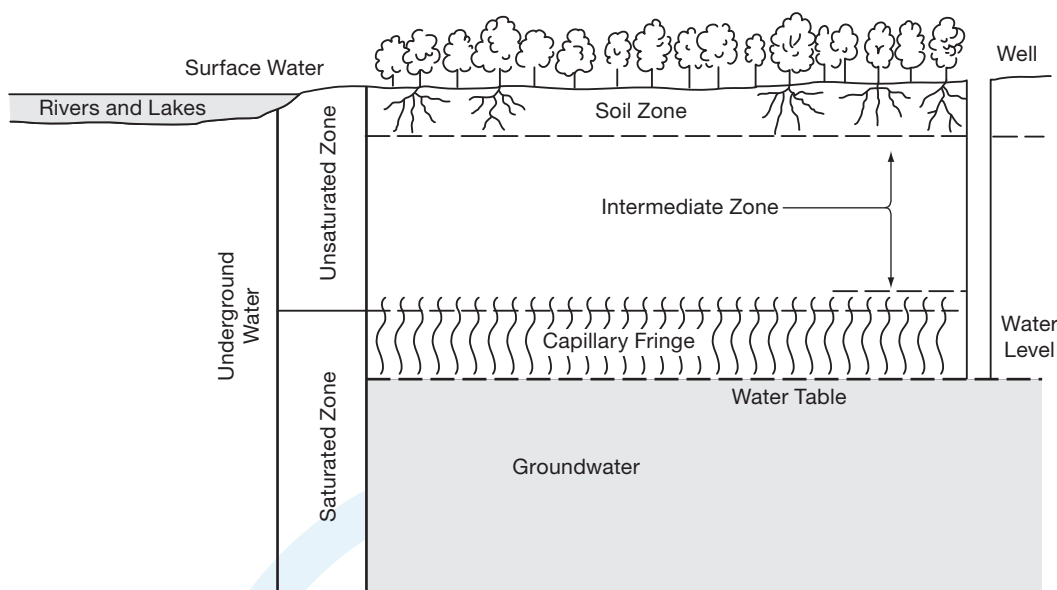


Figure 1-6 Water movement below the earth's surface

Capillary fringe. The capillary fringe is the subzone between the unsaturated and saturated zones. The capillary fringe occurs when a film of water clings to the surface of rock particles and rises in small-diameter pores against the pull of gravity. Water in the capillary fringe and in the overlying part of the unsaturated zone is under a negative hydraulic pressure, that is, less than atmospheric (barometric) pressure. The water table is the water level in the saturated zone at which the hydraulic pressure is equal to atmospheric pressure. Below the water table, the hydraulic pressure increases with increasing depth.

Aquifers and Confining Beds

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 as confining units. An aquifer is rock that will yield water in a usable quantity to a well or spring. Some of the groundwater has been stored in aquifers for hundreds or even thousands of years. The older the rock, the more constituents the water might contain because of added contact time to dissolve the formation, although flow velocity also increases dissolution. A confining unit is rock having very low hydraulic conductivity that restricts the movement of groundwater either into or out of adjacent rock formations as shown in Figure 1-7.

Groundwater occurs in aquifers under two different conditions: *unconfined* and *confined*. Near the land surface, water may only partly fill an exposed aquifer. The upper surface of the saturated zone is free to rise and decline in direct relation to recharge by precipitation. The water in this type of aquifer is *unconfined*, and the aquifer is considered to be an unconfined or water-table aquifer. Wells that pump water from 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, rainfall recharges them easily, so they are considered sustainable supplies.

Although clay layers (and some rock formations such as shale) have high porosity, water cannot easily flow through them. As such, they have *low hydraulic conductivity* and can be functionally impermeable. Hydraulic conductivity (K) is the ability of water to flow through a porous media. Clay or shale has very low K , which is why it is typically considered a *confining* unit as opposed to an aquifer. Water will tend to flow preferentially where

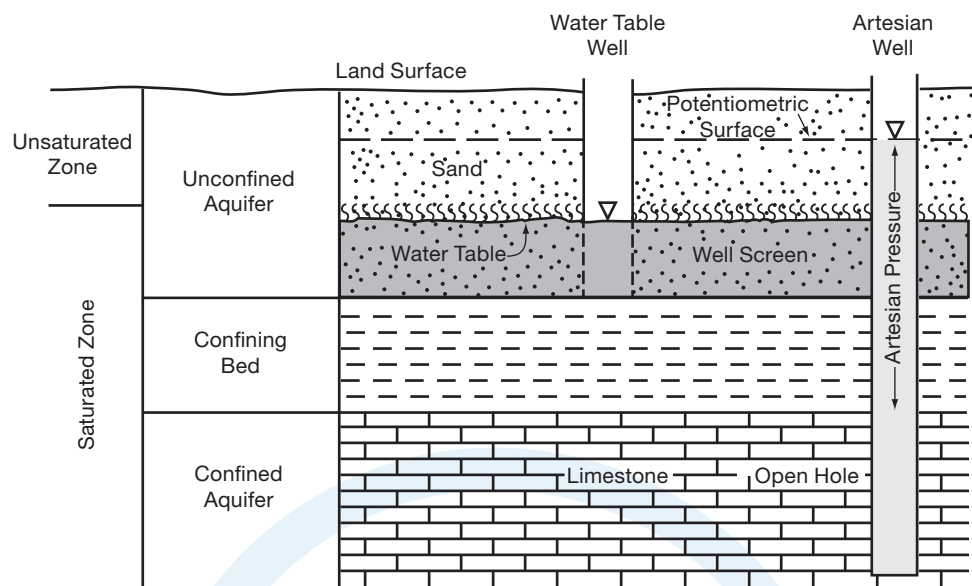


Figure 1-7 Geologic configuration of aquifers and confining beds

the resistance is lowest, and therefore clay is rarely the preferred route. Often, a clay or shale layer will intercept or overlay portions of an aquifer, making that aquifer a confined aquifer.

Where water completely fills an aquifer that is overlain by a confining bed, the water in the aquifer is said to be confined. Such aquifers are referred to as *confined aquifers*. Wells drilled into confined aquifers are referred to as *artesian wells* if the pressure of the water in the confined aquifer is above the top of the formation. If the water level in an artesian well stands above the land surface, the well is a *flowing artesian well*.

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, i.e., the oceans. 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 usually replicates the land surface as shown in Figure 1-8.

When a well (artesian or not) is pumped, the level of the aquifer falls as the water immediately surrounding the well is drawn through the pumping well. The falling level is called *drawdown*, and the three-dimensional cross-section is called the *cone of depression*. If the aquifer transmits water easily (i.e., has high transmissivity, which is a hydraulic property found by multiplying the hydraulic conductivity (K) by the thickness of the aquifer), the drawdown is slight and the cone of depression is flat and widespread as depicted in Figure 1-9. If the aquifer has low transmissivity, drawdown is significant and the cone of depression is steep. Higher flow rates result in steeper drawdown and, consequently, larger cones of depression. The cone of depression is also affected by the level of water within the aquifer. When investigating potential groundwater sources, engineers and hydrogeologists typically look for limestone, sandstone, and alluvial formations, which tend to have high transmissivity. The engineers and hydrogeologists avoid clay, shale, and similar zones, which have low transmissivity.

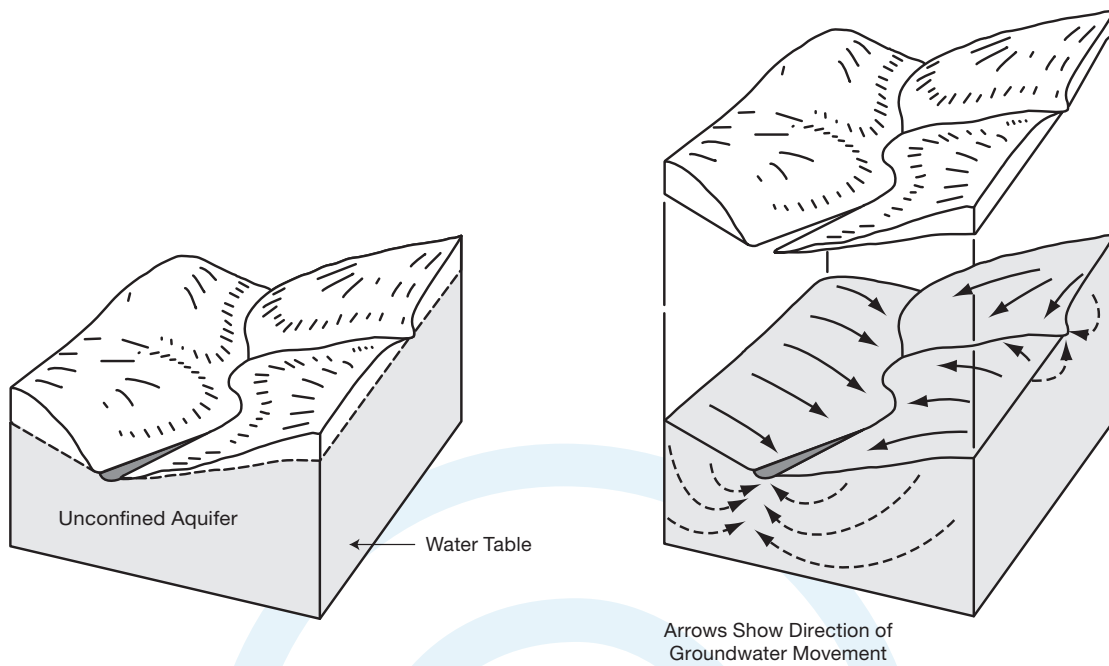


Figure 1-8 Groundwater movement as it relates to topography

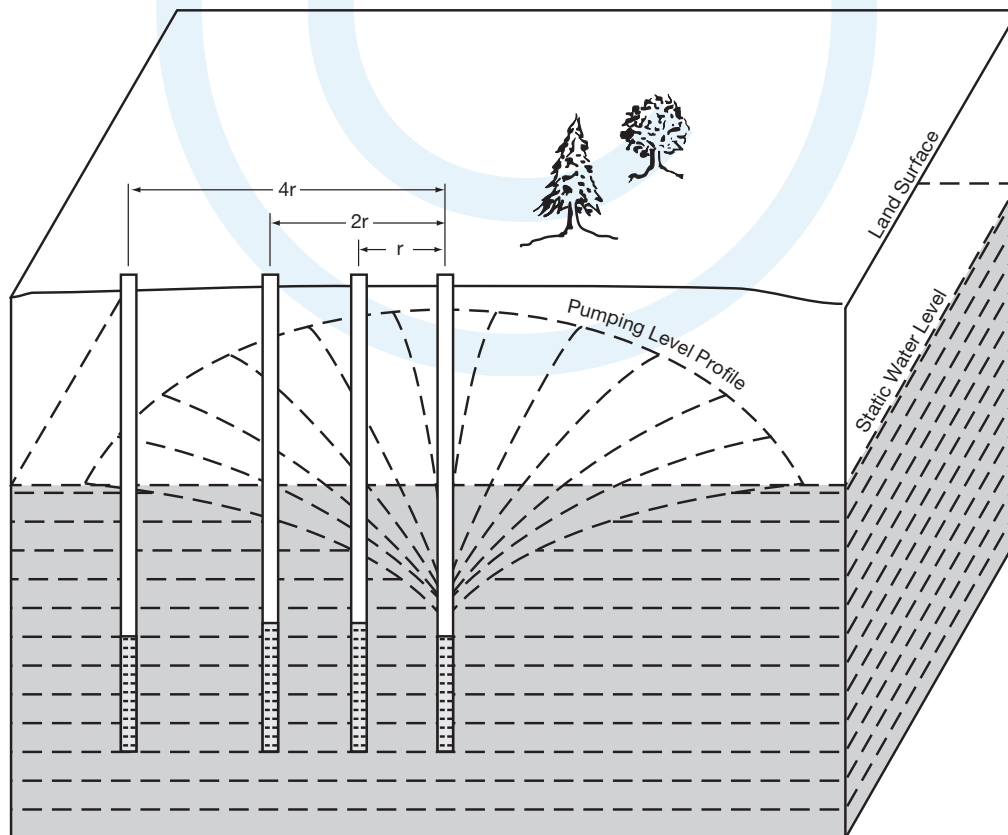


Figure 1-9 Development of a cone of depression

Formations in contact with groundwater affect water quality. Before groundwater is intercepted by a well, it is in lengthy contact with formation materials, and only moves slowly toward a well even when pumped. Groundwater also starts as recharged water that flows through a variety of formation materials before reaching an aquifer. 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.

MAJOR CONDITIONS THAT IMPACT GROUNDWATER

Along with an understanding of general groundwater concepts, it is important to recognize different conditions that impact groundwater. Two major conditions include subsidence and climate.

Land Surface Subsidence

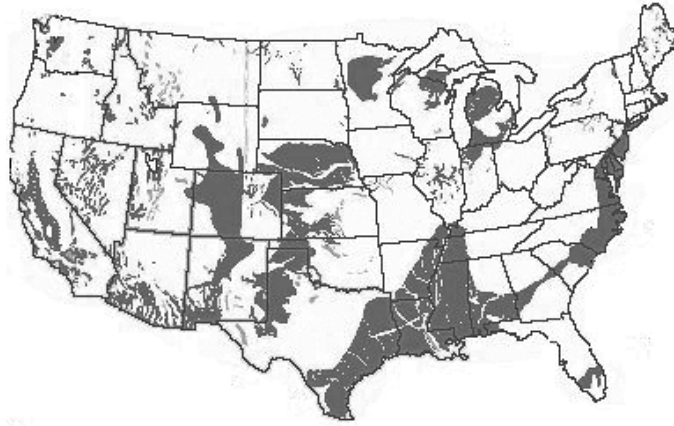
A significant consequence of groundwater development from unconsolidated or highly friable rock formations can be downward movement of the land surface, called *subsidence*. Subsidence can occur when the groundwater, which exerts pressure on the adjacent soil and rock, is removed, relieving the pressure. The formation then collapses, causing the surface topography to be altered. 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 occurred). The collapse is caused by the reorientation of aquifer grains as a result of the loss of pore pressure exerted by the water in the aquifer. Development of groundwater needs to include consideration of possible land-surface subsidence, especially from overdevelopment. Figure 1-10 shows areas that US Geological Survey has identified as having significant land subsidence issues. In some areas, clays such as montmorillonite may exist beneath the surface, causing significant problems for water purveyors. These clays can be 46 to 55 percent porous, with their structure supported by the internal pore pressure of water. As pore pressure is reduced when water levels decline, most of the compression occurs in the clay units, causing land subsidence.

Estimating Subsidence

The magnitude of subsidence in areas subject to flooding either by tidal inundation or alteration of surface drainage should be estimated, especially in aquifers with high clay or sand content, or where prior subsidence has been noted. Subsidence along faults that could lead to structural damage must be estimated.

The most readily available of the necessary data is the amount of compressible material in the subsurface. Such data may be obtained from evaluation of logs of test wells. Data on water-level changes can be used to make estimates of pressure change (stress change) at various depths for various time intervals. Where subsidence has been well documented, subsidence data may be coupled with the amount of compressible material to determine compressibility. Unfortunately, the information needed is not available in sufficient detail in most areas.

Data on the degree of compressibility of the subsurface material can be used to predict subsidence, but the data are rarely readily available. Laboratory values of compressibility determined from tests of cores have been used with limited success as a result of the expense of obtaining undisturbed cores, and the difficulty in obtaining representative cores preclude their use for regional appraisal.



Source: USGS Circular 1182

Figure 1-10 Areas where land surface subsidence is an issue

Climate Impacts on Groundwater

In a geologic timescale, the earth's climate undergoes constant changes (Bloetscher 2008). Massive continental glaciers extended as far south as the 40th parallel in North America and Eurasia. There were several advances throughout the Pleistocene era, starting more than 600,000 years before present (BP) and extending to as recently as 10,000 years BP. These glacial advances and retreats profoundly altered the landscape, covering northern Europe and the northern United States with deep till and outwash soils, and developed massive, 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, but as the climate changed, it became more arid. It should also be appreciated that much groundwater available in the western United States is fossil water from the Pleistocene period. Brief interludes of warmer and cooler periods occurred during the Dark and Middle Ages (400–1300 AD).

The conclusions of the 2007 Intergovernmental Panel on Climate Change (IPCC) report noted that water resources would be one of the areas most affected by climate change. The most relevant impact to water resources and groundwater are (IPCC 2007):

- Projected warming in the twenty-first century shows geographical patterns similar to those observed over the last few decades, which may increase ET, and reduce the potential for infiltration to replenish groundwater.
- Warming is expected to be greatest over land and at the highest northern latitudes, and least over the southern oceans and parts of the north Atlantic Ocean.
- Snow cover is projected to contract.
- Widespread increases in thaw depth are projected over most permafrost regions.
- The more optimistic globally averaged rises in sea level at the end of the twenty-first century are between 0.18–0.38 m, but an extreme scenario gives a rise up to 5 m. Sea level rise will inundate low-lying areas and increase saltwater intrusion along coastlines.
- Temperature extremes, heat waves, and heavy precipitation events will continue to become more frequent.

- Increases in the amount of precipitation are very likely at high latitudes, but not as snow pack, whereas rainfall decreases are likely in most subtropical land regions.

It should be noted that there is significant uncertainty in the models used to prepare the IPCC reports to predict the actual intensity, spatial and time variability of rainfall and temperature for a given region in part because the models can only be calibrated against a very short period of time, and that as time has proceeded, the predicted changes have moderated to some degree to comport with observed changes. In any case, the main concern raised by global warming is that climatic variations alter the hydrologic cycle, and that the current data indicated that hydrological cycle is already being impacted: more intense rainfall, less recharge, less snowpack, higher seas, all of which result in less recharge (Dragoni 1998; Buffoni et al. 2002; Labat et al. 2004; Huntington 2006; IPCC 2007; Dragoni and Sukhija 2008).

ACHIEVING SUSTAINABILITY

Climate impacts on the hydrological cycle predicate a necessary discussion of sustainable use of water supplies. The key component in planning the use of water supplies is 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 2007)? It is widely recognized that

$$\text{Withdrawals} = \text{Consumption} + \text{Returns (to hydrologic cycle)}$$

However, the concept is not that simple, and buy-in to the concept of “sustainable water” depends on the profession or perspective of the person defining it. 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 deteriorate the source or basin. While many water providers attempt to develop sustainably, others have not. Within regionally sustainable situations, unsustainable pumping can occur locally. For example, much of the groundwater in the western United States appears to be unsustainable in the long term because of limited rainfall (Reilly et al. 2009).

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

- Agriculture
- Ecosystems
- Urban demands
- Industrial demands
- Cooling water for power generation

From a practical perspective, sustainable development generally means addressing environmental, economic, and social concerns. Researchers can define a comprehensible concept of sustainability, but practitioners emphasize feasibility and limitation to sustainability of the ecosystem (Starkl and Brunner 2004). Water quantity and quality issues have significant fiscal impact on the potential users in the basin, and there are unrealized costs and benefits that are often ignored in the current water management framework (Bloetscher and Muniz 2008).

A sustainable world is not a rigid one, where population or productivity is constant; sustainability must adapt to constant change. The concept of sustainability requires rules, laws, and social constraints that are recognized and adhered to by all (Meadows

and Randers 2005). At the present time, the desire to grow and develop economically is outweighing the rule-making process. These issues will be discussed in more depth in chapter 3.

REFERENCES

- Beck, M.B. 2005. "Vulnerability of Water Quality in Intensively Developing Urban Watersheds," *Environmental Modeling and Software*, Vol. 20, pp. 381–400.
- Bloetscher, Frederick. 2008. "The Potential Impact of Climate Change on Groundwater Recharge," *GWPC Annual Forum Proceedings*. Groundwater Protection Council, Oklahoma City, Okla.
- Bloetscher, Frederick, and A. Muniz. 2008. Water Supply in South Florida—The New Limitations. *Sustainable Water Sources (Reno) Conference Proceedings*. Denver, Colo.: American Water Works Association.
- Buffoni, L.B. 2002. Variazioni Climate Change and Groundwater: A Short Review 7. *Italia Negli Ultimi 130 Anni. Bollettino Geofisico Anno XXIII*.
- Di Matteo, L., and W. Dragoni. 2006. Climate change and water resources in limestone and mountain areas: the case of Firenzuola Lake (Umbria, Italy). *Proceedings of the 8th Conference on Limestone Hydrogeology, Neuchâtel, Switzerland, 21–23 September 2006*. Presses Universitaires de Franche-Comté, France, 83–88.
- Dragoni, W. 1998. Some considerations on climatic changes, water resources and water needs in the Italian region south of the 438N. In A.S. Issar, *Water, Environment and Society in Times of Climatic Change*. pp. 241–271. Alphen aan den Rijn, the Netherlands: Wolters Kluwer.
- Dragoni, W.A., and B.S. Sukhija. 2008. Climate change and groundwater: a short review. *Geological Society, London, Special Publications*. 288: 1–12.
- Goudie, A. 1994. *The Human Impact on the Environment*. Cambridge, Mass.: The MIT Press.
- Hapgood, C.H. 1999. *Path of the Pole*, 2nd Ed. , Kempton, Ill.: Adventures Unlimited Press.
- Hershfield, D.M. 1963. Rainfall Frequency Atlas of the United States for Durations from 30 Minutes to 24 Hours and Return Periods from 1 to 100 Years. Technical Paper 40. Washington, D.C.: National Oceanic and Atmospheric Administration.
- Huggett, R.J. 1991. *Climate, Earth Processes and Earth History*. Berlin, Germany: Springer-Verlag.
- Huntington, T.G. 2006. Evidence for intensification of the global water cycle: Review and synthesis. *Jour. of Hydrology*. 319:83–95.
- Intergovernmental Panel on Climate Change (IPCC). 2007. *Climate Change 2007: The Physical Science Basis*. Geneva, Switzerland: IPCC.
- Issar, A.S. 2005. *Mitigating the greenhouse effect by sequestering carbon by woods planted in dry-zones, utilizing wasted water resources*. Presented at World Water Week in Stockholm, Aug. 21–27, 2005. Workshop 2 – Coping with Climate Variability, Climate Change and Water-Related Hazards.
- Labat, D.G. 2004. Evidence for global runoff increase related to climate warming. *Advances in Water Resources*. 27: 631–642.
- Lamy, F., H.W. Arz, G.C. Bond, A. Bahr, and J. Patzold. 2006. Multicentennial-scale hydrological changes in the Black Sea and northern Red Sea during the Holocene and the Arctic/North Atlantic Oscillation. *Paleo-oceanography*, 21, PA1008, 11.
- Marshall, C.H., R.A. Pielke, L.T. Steyaert, and A.W. Debra. 2004. The impact of anthropogenic land—Cover change on the Florida Peninsula sea breezes and warm season sensible weather. *Mon. Wea. Rev.* 132: 28–52.
- Meadows, D., and J. Randers. 2005. *Limits to Growth: The 30-Year Update*. White River Junction, Vt.: Chelsea Green Publishing Co.
- Molak, V. 1997. *Fundamentals of Risk Analysis and Management*. Boca Raton, Fla.: Lewis Publishers.
- National Research Council (NRC). *Assigning Economic Value to Natural Resources*. Washington, D.C.: National Academy Press.
- Pearce, D., and D. Moran. 1994. *The Economic Value of Diversity*. London, UK: IUCN, Earthscan Publications Ltd.
- Popp, J., D. Hoag, and D.E. Hyatt. 2001. Sustainability Indices with Multiple Objectives. *Ecological Indicators*, Vol. 1, pp. 37–47.

- Reilly, T.E., K.F. Dennehy, W.M. Alley, and W.L. Cunningham. 2009. Ground-Water Availability in the United States, *USGS Circular 1323*. Reston, Va.: USGS.
- Singer, F.E. (ed.). 2008. *Nature, Not Human Activity, Rules Climate Change, Summary for Policy Makers, the Nongovernmental International Panel on Climate Changes*. Chicago, Ill.: The Heartland Institute.
- Starkl, M., and N. Brunner. 2004. Feasibility versus Sustainability in Urban Water Management. *Jour. of Environmental Management*, Vol. 71, pp. 245–260.
- Strzepek, K.M. and D.N. Yates. 1997. Climate Change impacts on the hydrologic resources of Europe: a simplified continental scale analysis. *Climatic Change*, 36:79–92.
- Yang, M., T. Yao, H. Wang and X. Gou. 2006. Climatic oscillations over the past 120 k years recorded in the Guliya ice core, China. *Quaternary International*, 154–155, 11–18.



Chapter 2

Evaluation of Groundwater Conditions

Three steps are used in identifying potential groundwater sources for a public water supply. The first is identifying regions having low pollution potential, high recharge capability, and a favorable location to the utility and its customers. The second step is performing field investigations to confirm site-specific characteristics of the aquifer system to determine how much water is potentially available. Care should be taken with confined aquifers where water withdrawal capability is consistently overestimated. The third is dealing with land use and source water protection issues (which are discussed in chapter 3).

The evaluation of regional groundwater conditions and the potential for resource development should be based on the following factors:

- The quantity and quality of water required
- The availability of water resources within the vicinity of the regional demand, including the sustainable yield of the potential source aquifers
- The cost to develop the water supply for the region
- The nature and density of existing or likely future pollution sources within the recharge area of an aquifer, and the effectiveness of regulatory controls on these sources
- The amount of previous groundwater development and availability of hydrogeologic or groundwater pollution investigations
- Long-term land uses affecting quality and quantity of groundwater recharge
- Conveyance costs and treatment required for specific development projects

Additional factors include the following:

- Legal issues, such as water rights, adjudications, water transfers, and conjunctive use commitments
- Financial issues, such as taxation on pumping to pay for groundwater replenishment
- Environmental concerns, such as for endangered species and critical habitat
- Resource management issues, including potential for recycling and conservation

SUITABLE GROUNDWATER SUPPLIES

In the past, groundwater was typically assumed not to be affected by surface activities. These perceptions of purity have created expectations of consistently reliable groundwater sources. Unfortunately, groundwater sources cannot be assumed to be safe all the time. In 1969, a national study of 1,000 potable water systems found that more than a quarter of the wells associated with those systems were contaminated by pollutants ranging from minerals to solvents and other hydrocarbons, sometimes to the point of making groundwater supplies unsuitable for drinking water. These problems led directly to the passage of the Safe Drinking Water Act (SDWA).

Water Quality Considerations

Traditionally, the materials that have affected the value of a groundwater supply have included naturally occurring minerals, such as dissolved inorganic salts. High quantities of minerals results in low-quality water. A significant relationship exists between mineral quality and depth and age of groundwater: the mineral quality of groundwater generally declines with depth. Groundwater quality in many sedimentary basins, where the older and deeper sediments were deposited by oceans, can change very abruptly in mineral content. Poor-quality water can be drawn upward after production begins (*upconing*), even if a production well does not penetrate a saline zone. Similarly, operation of coastal production wells can induce saltwater intrusion into freshwater aquifers. Therefore, drilling deeper is not the solution to the problem of severe mineralization.

Today, many forms of contamination exist. Synthetic and other organic compounds, plus refined minerals, high dissolved solids content and heavy metals, must be considered when evaluating the development potential of a groundwater resource. Microbiological substances, especially in membrane treatment applications, are increasingly a concern. In many cases, construction, maintenance, and operation of facilities to remove these substances is more costly than finding a new water source.

Pollution control. The types of waste generated within local areas, methods of handling and disposing of the waste, the likelihood of accidental or unreported spills and leaks, and the hydrogeology of intervening materials are important when evaluating groundwater quality. All groundwater supplies should be analyzed for potential pollution contamination. No groundwater is free from micro-organisms.

Land Use

Agricultural use of land can affect groundwater quality because of pesticide, herbicide, fertilizer, and animal waste in the runoff. Residential land uses with septic tanks may pollute groundwater with household chemicals, microbiological contaminants, salts, and nitrates. Historical land use practices must be reviewed before any site is selected for installation of a well. Potential development and impacts of that development should also be considered so that future land use does not degrade the water that flows off the land in the vicinity of the well. The existence of private property rights laws that restrict concurrent uses of land

based on assumed or actual devaluation of the property (i.e., the well field may degrade the property to the extent that the property loses value and is in essence a taking) may frustrate utility efforts to protect water sources without significant cost for land acquisition. Testing for contaminants throughout a proposed well field is required by federal, state, and local regulations. Pollution source areas, especially capture zones and those that are currently upgradient of the proposed water supply site, are of utmost concern.

As land uses change, an aquifer with good quality at the time of development may deteriorate. Consequently, water resource professionals must obtain and maintain a good understanding of urban and industrial growth and zoning of the area associated with the groundwater supply. Today, simulation models can depict the long-term effects of a proposed water-well development and provide documentation of any land-use changes that may affect the local hydrology. Examples are industrial development displacing irrigated agriculture or paving from urbanization that reduces recharge. This modeling can take the form of analytical solutions for simple cases or numerical computer codes for more complex cases where a high degree of accuracy is needed. Medium and large utilities should all have working computer models of the groundwater in the aquifer of the well field (see chapter 5). For example, USGS's MODFLOW is currently the basis for most commercial models. MODFLOW may be sufficient for local applications, although more extensive modeling, and significantly more data, may be needed if surface interfaces and competing users are located in a given basin. The basin approach, even with groundwater, appears to be more appropriate than simple local modeling.

Because of a lack of certainty about flow patterns and possible changes in flow patterns, judgment is required for all methods of groundwater modeling. In addition, flow of discharged material in the unsaturated zone is not governed by groundwater gradients, and dense nonaqueous phase liquid and light nonaqueous phase liquid contaminants can move contrary to prevailing groundwater flow. Groundwater development should be upgradient or downgradient at an appropriate distance from potential threats to the water quality. Testing for pollutants at greater frequency may be appropriate, and establishing early-warning monitoring wells at various depths may be required to maintain groundwater quality.

Published Reports

Utility-commissioned reports from existing public suppliers, reports from local drillers, and published reports from government agencies such as the USGS are good sources to use when analyzing groundwater conditions. While drillers' logs and well-completion details can be confidential, a utility may be able to negotiate access to these records for specific projects.

Published reports on groundwater resources are available covering various geographic regions, including major aquifers, drainage and recharge basins, and state, county, and local regions. For studies within the United States, the Summary Appraisals of the Nation's *Ground-Water Resources* (USGS 1978–1982) is a good resource. An individual report covering the region of interest can be obtained separately, or a compilation of all 20 reports is offered by Todd (1984). These reports provide a summary of the quantity and quality of available groundwater. By examining the supporting references that are cited for specific localities, data can be layered to provide a more comprehensive understanding of the aquifer.

Valuable information regarding contamination sources may be obtained from state and federal programs that administer hazardous waste or effluent programs. These programs monitor groundwater quality as preliminary steps before granting operating permits for groundwater wells. A local, licensed hydrogeologist or engineer will likely have a significant amount of information on water quality parameters and drilling conditions.

Caution should be used in any investigation because even fairly site-specific reports are necessarily general in nature, and many local details may be omitted. Local conditions may differ from the regional average, and if good prospects for resource development are rare, areas that do not at first appear attractive in the general reports may have to be explored. Also, water quality can change with time (especially in the shallower groundwater zones), and site-specific variations will not appear in the published literature. Therefore, some exploratory work will have to be done to provide needed details regarding water quality.

Existing Water Rights

The development of new well fields should be shown to not infringe on existing water rights or competing water uses. The water developer should be able to demonstrate sustainable yield and also show that the side effects of pumping, such as land subsidence or saltwater intrusion, or interference with competing water or competing land users, would be negligible. Often this can be accomplished via computer modeling by using a program such as USGS's MODFLOW program. These models also can be used to demonstrate to regulatory agencies that proposed drawdowns will not be detrimental to the environment or adjacent users, or exceed the drawdowns set by regulation. Aside from the investigation of the hydrogeology, water quality should also be considered. Computer programs are also available for use in conjunction with water quality analyses.

Changes Affecting Evaluation

Changes in economics may influence local officials to develop more groundwater resources or the public to demand higher quality water. These changes may be at odds with the utility provider's aquifer protection programs or make public relations efforts difficult. Consequently, reliable measurements must be obtained when evaluating any groundwater system.

Deterioration of water quantity and quality can have grave consequences for those dependent on the water resource in the form of higher treatment costs or abandonment of the well field. However, changes other than those measured in the field can often be of great concern. Perceived changes may be caused by the availability of improved analytical methodologies (which detect levels of compounds not previously measurable or of new chemicals); regulatory priority shifts toward or away from protection of natural resources, including aquifer classifications; new toxicological data or reinterpretation of existing toxicology; or the integration of facts regarding groundwater quality into conservative measures toward the safe use of all water resources.

LOCATING SUITABLE GROUNDWATER SUPPLIES

The goal of groundwater exploration is to locate productive aquifers that yield sustainable high-quality water. The production level and quality required will guide exploration efforts, but interest will generally center on locating large deposits of the following:

- Unconsolidated sands and gravels of alluvial or glacial origin
- Sandstones and conglomerates
- Limestones and dolomites
- Porous or fractured crystalline or basalt rocks

Many other types of rock can yield small quantities of water to meet the domestic needs of a single household on its own well.

Depending on the region, the starting place of the exploration effort will vary. In undeveloped regions, reconnaissance-type interpretation of aerial photos and maps may be the first step. Light Detection and Ranging or Laser Imaging Detection and Ranging (LiDAR), high resolution photogrammetry and infrared photos of land use, foliage patterns, foliage types, and water bodies may serve as an indicator of recharge efficiency. Areas having the greatest surface-drainage capacity (i.e., paved areas) will have the least amount of groundwater recharge and may or may not overlie significant groundwater resources. Cross-sectional maps may have to be drawn from surface geologic information and existing well logs. These maps will aid in determining the location, depth, and thickness of favorable aquifers.

In many regions, general cross-sections and hydrogeologic interpretations will already exist, along with well logs and production information from existing wells. In these cases, favorable aquifers will have already been identified, and exploration efforts can fill in the details of the local hydrogeologic environment. Surface geophysical methods, borehole geophysical methods, aquifer testing, exploratory drilling, and lithologic logging are the most common methods used to accomplish these efforts. More details on these are available in Bloetscher et al. (2007) or Keys (1989).

Geophysical Methods Without Drilling

Geophysical methods, principally electrical resistivity and seismic reflection and refraction, can be used without penetrating the ground to provide a more complete picture of subsurface structure, given some prior knowledge obtained from surface geology and borehole logs. A general model of the subsurface geology should be developed to provide the basis for a proper interpretation of the geophysical data. The information generated can be used to locate sites for further investigation with test drilling. In circumstances of well-defined subsurface geology and well-documented groundwater movement, contaminant plumes may be projected using geophysical methods of measurement.

Successful application of any geophysical method depends on the presence of distinct changes in the physical properties. The detectable physical properties provide only indirect estimates of the hydrogeologic properties, with the accuracy of such estimates depending on how closely these physical properties relate to each other. In addition, the structural configurations amenable to investigation must be relatively simple to separate from one another. A comprehensive reference on the use of geophysical methods for groundwater investigations is given by Zohdy et al. (1974).

Land parcels that often do not lend themselves to geophysical methods include areas consisting of large cobbles in alluvium, areas of severely distressed geology, or areas in which (in geologic time scale) high hydraulic energy was dissipated.

Electrical resistivity. Electrical resistivity is probably the most commonly used geophysical method for groundwater investigations. It is economical to apply, and it produces useful information.

In the direct-current resistivity method, electrodes placed into the ground transmit current through the earth, and voltage potential is measured between two points near the center of the generated field. Figure 2-1 schematically illustrates the most common electrode arrangements—the Schlumberger array and the Wenner array. Sets of resistivity readings can be gathered along the transect with constant electrode spacing (horizontal profiling) or at one location with expanding electrode spacing (electrical sounding). The first method will show apparent resistivities of materials at roughly the same depth along the transect, while the second method produces a depth profile of resistivity.

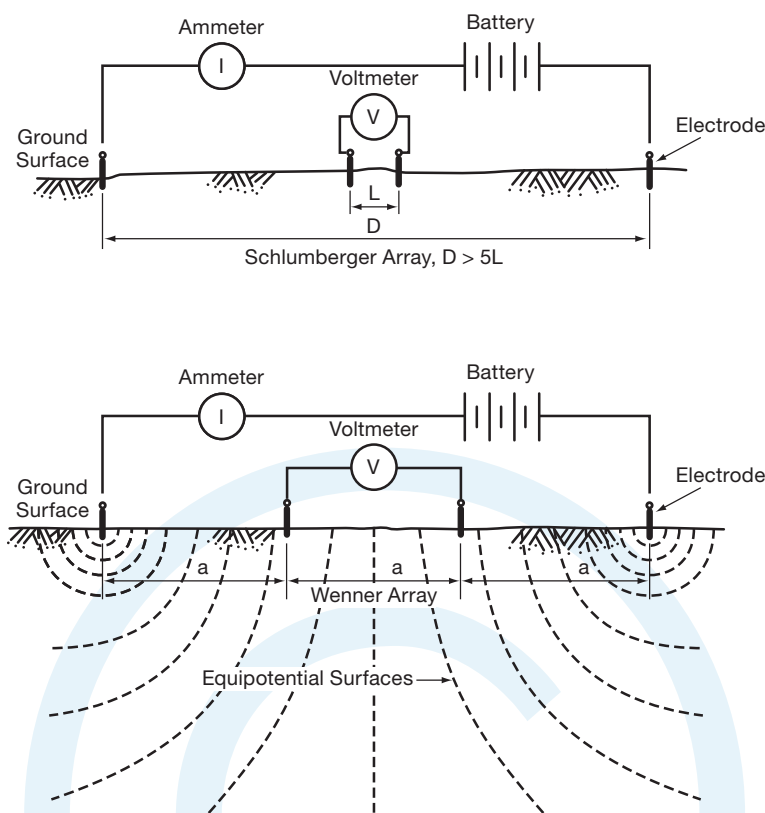


Figure 2-1 Schlumberger and Wenner electrode arrangements for measuring earth resistivity

Electrical resistivity is strongly affected by water content, thus interpretations involving the unsaturated zone are quite difficult as a result of the undefined distribution of moisture. In the saturated zone, resistivity is largely determined by the rock-matrix density and porosity, or by the saturating-fluid salinity (electrical conductivity).

Holding other factors constant, coarse sediments with low clay content will have higher resistivity than fine-grained sediments. This difference in resistivity makes it possible to map buried stream channels or perform depth profiling of shale-sandstone sequences. Such changes in mineral quality are detectable because of the relation between dissolved solids and electrical conductivity. Resistivity values for earth materials range over more than 16 orders of magnitude, and resistivity surveys can provide useful results in most environments with simple geologic structure and distinct resistivity contrasts.

Electrical resistivity may be used in existing or new well fields that require evaluation of suspect chemical migration from a polluting source. Plumes of discharged chemicals commonly have a relatively high dissolved-solids content. The boundaries of such plumes may be mapped with resistivity surveys, under the proper conditions.

The Schlumberger and Wenner arrays (see Figure 2-1) provide the simplest interpretation for measuring resistivity. The apparent resistivity R_a is given by

$$R_a = 2 \pi a V/I \quad (\text{Eq. 2-1})$$

Where:

- a = the electrode spacing
- V = voltage
- I = direct current

The apparent resistivity characterizes a volume of earth extending below the electrode array to some effective depth of penetration. The depth of penetration is related to the electrode spacing. For the Wenner array, the effective depth of penetration is commonly assumed to be equal to a . However, this assumption can lead to serious errors in calculated depths. The depths to horizontal boundaries are best determined by matching the theoretical apparent resistivity and electrode spacing curves of various model conditions to the curves obtained from field measurements. The Schlumberger array provides better resolution of subsurface features but is slightly more difficult to analyze. Interpretations should be performed by a trained analyst familiar with local conditions.

The resistivity method is generally limited to use in simple geologic environments with two or three distinct layers and where depth of penetration is limited to about 1,500 ft (460 m). Best results are obtained when the depth to groundwater is small, due to the complications of unsaturated materials. Also, the method is less effective in urban areas where the presence of buried metal pipes, wires, and similar obstructions can dominate measurements with unwanted noise.

Other geophysical methods that fall within the electrical methods category include telluric, magneto-telluric, electromagnetic, and induced polarization methods. However, their use is not generally applicable to groundwater supply investigations. Electromagnetic methods have become popular for shallow groundwater investigations, especially those involving groundwater contamination. The results are similar to those derived from the direct-current resistivity method, although resolution is poorer and exploration is generally limited to the upper 180 ft (55 m). The method has received attention because it involves no direct contact with electrodes, making it quick and easy to apply in the field. The other methods mentioned have some application in specialized research and are discussed by Zohdy et al. (1974).

Seismic refraction and reflection. Seismic methods are perhaps the most useful geophysical tools for hydrogeologic investigations, although costs are relatively high. Seismic methods use contrasts in the velocities of elastic wave propagation between different earth materials. For example, unconsolidated sands and gravels exhibit low propagation velocities, whereas crystalline rocks exhibit the highest propagation velocities. Propagation velocities are higher in saturated materials, providing for detection of the water table.

Elastic waves are commonly initiated with the use of explosive “shots” in shallow borings, although the use of truck-mounted hydraulic earth vibrators (thumpers) is fairly widespread. Lines of geophones are laid out on the ground surface to detect waves refracted or reflected from various subsurface discontinuities to measure travel time. Travel time records can then be analyzed to produce a picture of the subsurface. As with any geophysical methods, the interpretation of seismic data requires an assumed model of subsurface structure; the more preexisting information geologic data and borehole logs that are available, the more reliable the results from seismic surveying will be.

Reflection and refraction are two methods of seismic exploration. While reflection is defined as a wave that rebounds off a surface, in refraction that wave is bent as it passes through a boundary between two media. Seismic reflection is not generally used for groundwater investigations but is preferred for petroleum exploration. The cost and complexity of equipment and analyses required to apply the reflection method is greater than that required for the refraction method. For deep groundwater exploration in multilayered environments, however, the reflection method is generally superior.

Seismic refraction is the most commonly applied method in groundwater investigations. Besides cost considerations, this method can have advantages in environments where deep alluvial or glacial fill exists. Less knowledge is required to apply refraction seismology, and good results can usually be achieved in most groundwater investigations. The most severe limitation of seismic refraction is that return signals can only be obtained

as long as each successively deep layer has a higher propagation velocity than the overlying layer. In areas of scarce water, where water wells are drilled to great depths (for example, parts of the arid southwestern United States), this limitation may prove too restrictive, and the higher cost of seismic reflection may be warranted.

Figure 2-2 shows the use of the seismic refraction method for reconnaissance mapping of the depth to bedrock and the location of a buried stream channel. Seismic refraction can be used to determine the thickness of surficial fracture zones in crystalline rock and to map the depth and thickness of subsurface layers, up to at least the equivalent of three layers. As in the resistivity method, the analyses become very difficult and the results less reliable for more than three layers.

As long as the geologic structure is simple, depths of a few thousand feet (600 to 700 m) can be explored with seismic refraction, given a sufficient explosive and deep shot. Seismic reflection can be used to gather information from more than 10,000 ft (3,000 m) deep. For small area applications, where only very shallow materials need to be explored, more rudimentary methods with less seismic equipment may be employed.

Other methods. Other geophysical methods can be useful in groundwater investigations, although none have been widely used due to the low benefit-to-cost ratio associated with their use. Some relatively new methods, such as ground-penetrating radar, have proved useful in groundwater contamination studies; however, the depths of penetration may be too shallow for general use in water supply applications. Gravity methods and magnetic methods have been used for general hydrogeologic investigations, although they must be viewed as supplementary methods to be applied in situations where maximum information is desired and cost is not a limiting factor. These methods are discussed by Zohdy et al. (1974).

Borehole Geophysical Logging

Borehole geophysical logging has become a common tool in groundwater exploration. The technology of borehole logging is quite involved, and experts using special equipment are needed to perform the logging and interpretation. The discussion here introduces the capabilities and limitations of the logging tools found to be most useful in groundwater exploration. There are many texts on borehole logging, but the reader should be cautioned that most of these texts present information tailored for use in petroleum exploration. The presence of low or nonsaline water in a formation mandates the use of special analyses for interpretation. For a detailed discussion of this subject,

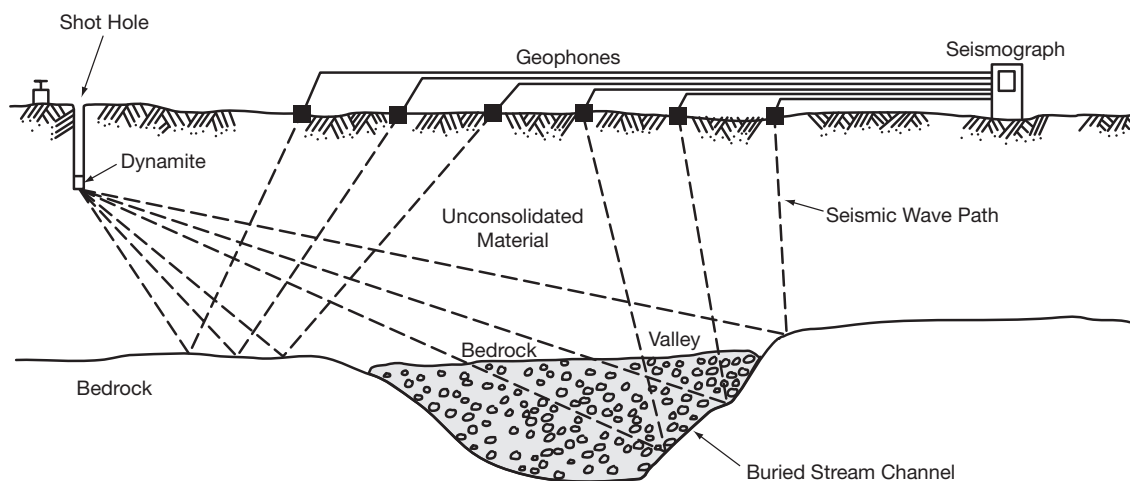


Figure 2-2 Application of seismic refraction method for reconnaissance mapping

the reader is referred to Keys and MacCary (1971) or to Keys' *Borehole Geophysics Applied to Groundwater Investigations*, as published by the National Water Well Association (1989).

There are many borehole logging techniques available, although electrical, naturally occurring gamma radiation, and caliper measurements are the most widely used. All geophysical log measurements are obtained by lowering a probe down the borehole and recording continuous measurements with depth. Logging is frequently performed during drilling operations, and quick analyses of the logs by qualified personnel provide the basis for decisions regarding well completion, including depth of casing and screened intervals. Some types of logs must be performed in an uncased well, while other logging can be done in cased wells, allowing data collection from existing wells.

Performing multiple logs in a single well will provide confidence in interpretations. Each type of log measures different physical properties, and combined analysis may resolve ambiguities that might exist from a single log. The greater the number of wells logged in an area, the greater the statistical confidence in the data and interpretations as being representative of the subsurface environment.

Determining the number of wells and the types of logs to be used in an investigation is often difficult. Most groundwater investigations obtain adequate information using caliper, resistivity, spontaneous potential, natural gamma, and lithologic logging as described in the following sections. The cost of these techniques should be evaluated in the context of the time available, accuracy needed, and the basic purpose of the survey.

Caliper logging. Caliper logging is used to measure the diameter of the borehole. A probe that usually has either three or four levered arms is brought up through the hole, while a record of the depth and degree of extension of the arms is made at the surface. Four-armed probes can be used to measure the diameter of the hole in two directions and thus permit the evaluation of the asymmetry of the borehole. Caliper logs are of importance in groundwater exploration and well construction because the interpretation of other borehole geophysical logs requires data on the borehole diameter. Caliper logs can provide indications of the presence of high-permeability, fractured, or cavernous zones, as well as the occurrence of swelling clays and well lithified layers in friable or unconsolidated rock or sediment. Caliper logs are commonly run before the cementing of well casings to determine the volume of the annular space and to locate uniform diameter areas of boreholes in which to set cement baskets and packers.

Electrical resistivity logging. Electrical resistivity logging measures the apparent resistivity of the formations in a borehole. According to Ohm's Law, resistance (ohms) is equal to potential (volts) divided by current (amperes).

$$R=V/I \quad (\text{Eq. 2-2})$$

Where:

- I = current through the conductor (amperes)
- P = potential difference measured across the conductor (volts)
- R = resistance of the conductor (ohms)

Electric resistivity logs use Ohm's Law to determine the apparent resistance of the formations in the borehole. A current is applied between a downhole electrode and an electrode at the surface. The potential (voltage) is then measured between a downhole electrode and a surface electrode or between two or more downhole electrodes. Variations in the measured resistance are related to the composition of the rocks and sediments and the salinity of pore waters. Silt, clay, and shale tend to have the lowest resistivities; sands, sandstones, and limestones with nonsaline pore waters have the highest resistivities.

The simplest and least expensive electric resistivity log is the single-point resistance log, illustrated in Figure 2-3. The single-point resistivity log measures the potential drop between a surface and downhole electrode, which are also the current electrodes. The single-point resistivity log is used primarily for geological correlation and the location of bed boundaries, changes in lithology (rock characteristics), and fracture zones. Single-point resistivity logs have a very good vertical resolution of changes in the gross physical characteristics of a rock formation, or lithologic changes, but do not provide quantitative data on formation porosity or pore water salinity.

Separate current electrode and potential electrode(s) are located on the downhole probe in normal resistivity logs. Normal resistivity logs measure the apparent resistivity of a volume of the formation perpendicular to the borehole electrodes. The size of the volume of investigation is proportional to the electrode spacing. The probes are commonly configured so that short normal (16-in. electrode spacing) and long normal (64-in. spacing) resistivities are measured simultaneously. Normal resistivity logs are commonly used in groundwater investigations as a source of qualitative information on water quality. True formation resistivity and salinity can be calculated from the measured apparent resistivities, but the calculations require the application of a number of correction factors, whose values are estimates. Other types of resistivity logs that are less commonly used in groundwater investigations are discussed by Keys (1989).

Spontaneous potential logging. Spontaneous potential (SP) logging was the first type of downhole, geophysical log. Spontaneous potentials are the naturally occurring electrical potentials that develop at the contacts between beds of different types of geological materials, such as between shale and sandstone beds. The SP logging apparatus consists of a surface and downhole electrode connected to a voltmeter. The SP logging equipment is usually incorporated in the electric resistivity log apparatus. SP logs provide information regarding geologic correlation, bed-thickness determination, and changes in lithology. Log definition depends on the contrast in fluid conductivity between the borehole and the geologic formation penetrated.

Gamma logs. Gamma logs record naturally occurring gamma radiation emitted by earth materials. The most significant natural resource of gamma radiation is the decay of the potassium-40 isotope and the daughter products of the uranium and thorium decay series. Rocks and sediments with relatively high concentrations of potassium, uranium, and thorium give high gamma ray counts. Clay-rich rocks, such as shales and phosphatic rocks in particular, give high gamma ray counts, whereas nonphosphatic limestones and dolostones and clean quartz sandstones tend to give low gamma ray counts. The gamma log is by far the most commonly used nuclear log and is very valuable for geological correlation and lithologic determination (note: it contains no nuclear material but measures background gamma radiation in the formation). The gamma log is useful because it can be run in cased walls.

Gamma-gamma logs. Gamma-gamma logs (also called *radioactive tracer logs* or *surveys*) are obtained by introducing a gamma radiation-emitting material into the borehole (usually cesium-137 or cobalt-60) and measuring the intensity of the back-scattered radiation. The back-scattered radiation detected by the probe is proportional to the density of electrons in the formation, which is in turn correlated with the bulk density of the rock. Gamma-gamma logs provide information on lithology and porosity. This log can also be used to locate cavities in the cement outside of a well casing. Gamma-gamma logs are widely used in the oil industry, but are rarely used in groundwater investigations because of their high costs and the liabilities associated with the potential loss or rupturing of the radioactive source within the aquifer.

Neutron logging. Neutron logs are obtained by introducing a radioactive source that emits neutrons into the borehole. The emitted neutrons interact with hydrogen atoms

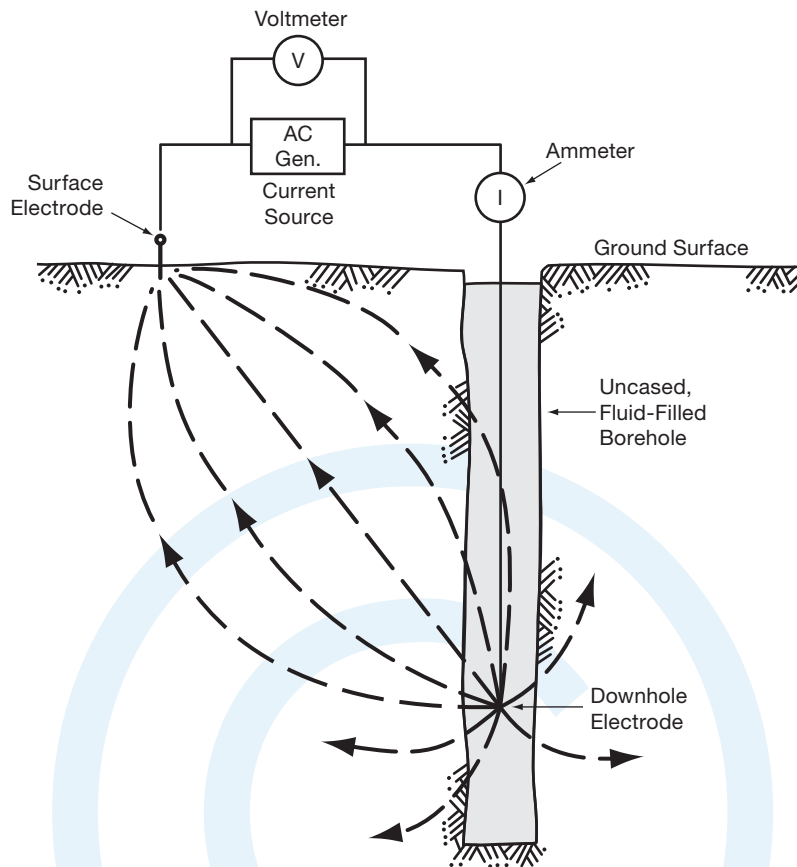


Figure 2-3 Single-point electrode arrangement for resistance and spontaneous potential logging

and release gamma radiation, which is measured by a detector on a logging probe. The intensity of the measured gamma radiation is proportional to the hydrogen atom concentration and thus water content and porosity of saturated rocks. Neutron logs are widely used in the oil industry to determine the porosity and water content of formations and lithology. As is the case with gamma-gamma logs, neutron logs are not often used in groundwater investigations because of their high costs and the liabilities associated with the potential loss or rupturing of the radioactive source within the aquifer.

Acoustic logging. Acoustic or sonic logging involves the recording of transit time of acoustic pulses radiated from a probe in a borehole to one or more receivers also located on the probe. Transit times are related to matrix mineralogy and the porosity of the rock. Transit times decrease and acoustic velocities increase in sedimentary rocks with increasing hardness and cementation. Most rock types have a limited range of travel times, which allows for acoustic logs to be used to determine lithology. Porosity and fracturing can also be approximately determined from acoustic logs. The cement bond log is a type of acoustic log that is used to determine how well a well casing has been cemented to the formation.

Fluid logs. Fluid logs include temperature, fluid resistance, and flowmeter logs. The probe used for temperature logs usually contains a glass bead thermistor. Temperature logs can be used to identify the boundaries of aquifer zones in boreholes because as water flows through permeable zones, the normal geothermal gradient will vary. Temperature logs can also be used to detect inter-aquifer flow either up the borehole or down the borehole, depending on the differential head pressure that is present. The presence of cement grout in the annular space of a well can be determined by running a temperature

log within 24 hr of grouting because the heat of hydration of the cement raises the fluid temperature in the casing in cemented areas.

The fluid resistivity (or conductivity) probe contains two internal electrodes that measure the capacity of the borehole fluid to conduct electricity. The conductivity of a fluid increases with increasing salinity and temperature. A salinity versus depth profile can be constructed for an open borehole using the results of a temperature and fluid resistivity log. The calculated salinity versus depth profile is subject to considerable error because of the flow within the well.

Flowmeter logs are used to measure flow velocity within the wells. The most common construction is the impeller-type where the rate of rotation of the impeller is proportional to the relative flow velocity of the probe. The relative flow velocity includes the actual flow velocity of water in the well and the rate at which the probe is being raised or lowered into the well. Caliper logs must be run with the flowmeter log because the flow velocity is a function of the cross-sectional area of the borehole. The relative contribution of individual aquifer zones to the total flow from a well can be calculated using data from flowmeter and caliper logs.

Hydrophysical logging. Hydrophysical logging is a new form of borehole logging where demineralized water is introduced into the borehole and the dispersion of the demineralized water is continuously logged with respect to time. This allows a more accurate measure of calculating variations in the formation's hydraulic conductivity.

Log suites. In most instances, individual borehole geophysical logs do not provide unequivocal lithological information. By running a suite of logs, more accurate qualitative and quantitative information on formation porosity, hydraulic conductivity, bulk grain density, and fluid conductivity could be extracted. Figure 2-4 depicts a qualitative interpretation of a suite of geophysical logs. A high gamma ray count, for example, could be produced by a shale bed or phosphatic limestone layer, and shale layers are identifiable by a low-resistivity and high-gamma log response.

Aquifer Testing

In the simplest form, recording flow rates of the water produced at different depths while drilling with air is a form of aquifer testing, yielding valuable information. Aquifer testing is very useful during exploration of test holes, and many effective methods are now available for performing such testing. Methods of aquifer testing will be discussed in detail in chapter 4.

Exploratory Drilling

In some instances, existing wells may not be located in a potential water supply aquifer, and drilling one or more exploratory wells into the aquifer is necessary. Exploratory drilling is performed to determine an aquifer's characteristics, including hydraulic conductivity, water quality, thickness, and areal extent. The newly drilled wells can also be used for borehole geophysical logging and aquifer testing as previously described. The number and spacing of the wells drilled will depend on the size of the aquifer and the amount of water supply development planned.

Lithologic Logging

Lithologic logs are developed by drillers to describe the type of rocks and their characteristics. Lithologic logs and drillers' logs, including the drilling rate, are used with geophysical logs to obtain the most information about the groundwater. Geophysical logs can more accurately place the depth of discontinuities than can a lithologic log.

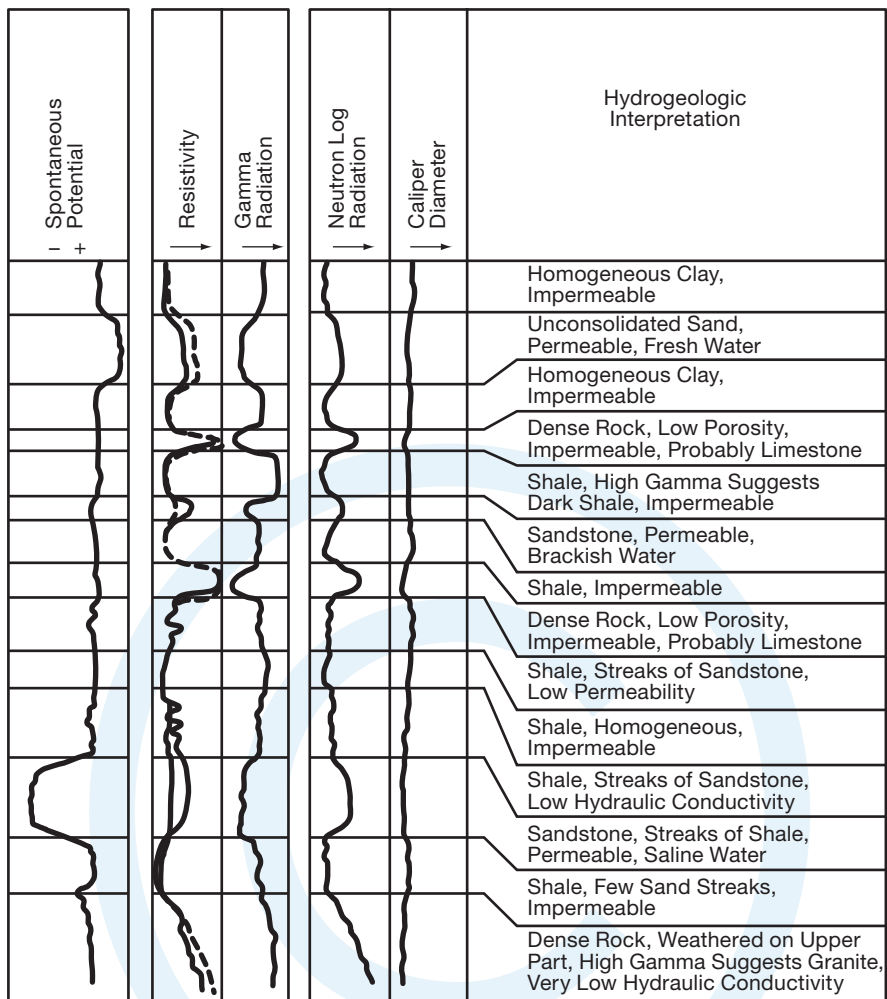


Figure 2-4 Qualitative interpretation of a suite of geophysical logs

Accurate lithologic logging during drilling is crucial, and a hydrogeologist experienced in well logging should be employed.

Application

There is no established order in which exploration methods should be applied; a balanced program of appropriate combinations will produce the most information. However, the knowledge gained through a geophysical investigation only extends the factual information gained from test drilling and adequate sampling.

MONITORING GROUNDWATER QUALITY

Before developing a groundwater supply, the water quality must be currently acceptable and expected to remain so in the foreseeable future. The SDWA and its amendments outline a series of water quality parameters that raise health and aesthetic concerns. Defining water quality will permit the appropriate treatment to be designed. This initial assessment can provide a basis for legal action against anyone who contaminates the water

supply after development. After the initial water quality assessment is performed and groundwater development is assured, a system for monitoring water quality should be maintained, and a reassessment of upgradient contamination risks should be performed periodically.

Monitoring Wells

In areas where contamination risks are high, sentinel monitoring wells should be installed. These wells, located at various depths, will provide definition for the initial groundwater assessment. Sentinel wells also serve as an early-warning system to detect changes in water quality and water elevations before they affect the water supply wells. In recent years, equipment for sampling from monitoring wells has become widely available. Small submersible or portable pumps can be installed into well casings as small as 1 in. (25 mm) in diameter, although it is common for monitoring wells to be at least 4 in. (100 mm) in diameter and made with polyvinyl chloride casings.

The number of wells needed and their locations, depths of completion, and construction details must be specified as part of an integrated plan. The plan must account for likely sources of contamination, local hydrogeology, and the hydraulic effects of the proposed groundwater development. For example, what was previously considered downgradient from the well can become upgradient either after pumping begins or as influenced by nearby surface water. These changes should be simulated with computer modeling to aid in designing a monitoring-well network.

The initial assessment may indicate that one monitoring well is sufficient to begin with, but an increased contamination threat in future years (for example, due to local growth and development) could indicate a need for additional monitoring wells. This potential for development demonstrates the importance of continual evaluation of changes that might affect the groundwater supply. One suggestion is to reverse the potential pollution site monitoring requirement of one well upgradient and three downgradient for a permitted hazardous waste site. Therefore, the water supply agency would be responsible for three wells upgradient and one downgradient.

Sampling

Multilevel sampling capability that ensures against the possibility of a monitoring well acting as a conduit for vertical migration of contaminants should be used. Several techniques are available, including locating several wells of differing depths in close proximity to one another (cluster wells) and using multiple-completion monitoring wells that consist of a nest of piezometers installed in a single borehole, as shown in Figure 2-5.

Proper construction of multiple-completion wells is not an easy task, but it can offer cost savings. Materials must be properly placed into the well bore. For example, the perforated portion of each piezometer must be isolated from the others in the nest so that fluid pressures and water quality can be monitored correctly at that isolated level. Three-dimensional data collected using a network of multilevel monitoring wells should provide a useful definition of contaminant distribution, although the cost of such information may be high.

Analysis. Samples taken from monitoring wells should be analyzed for suspected contaminants, including severe mineralization. The mineral quality of water will limit the range of possible water uses. For example, hard water (high concentrations of calcium and magnesium) will be unsuitable for boiler feed water. Water containing high concentrations of sodium or boron will be unsuitable for irrigation. Although the biological quality of deeper groundwater is usually good, testing for fecal bacteria and other microbiological indicators should be performed periodically.

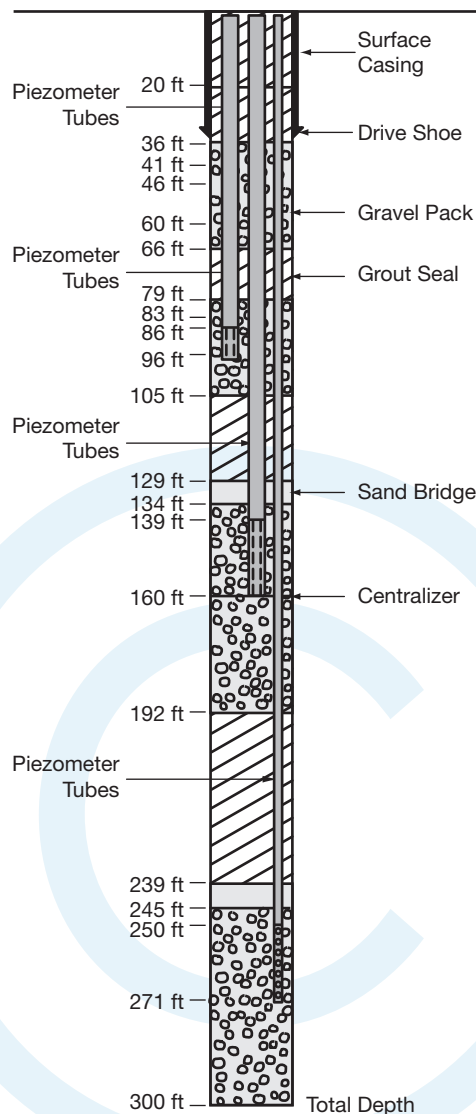


Figure 2-5 Schematic of a multiple-completion monitoring well

In recent years, a wide variety of constituents that can be harmful even in extremely low concentrations have become a concern. Unfortunately, analyses to detect all of these chemicals can be expensive, so analytical methods used should be directed toward detection of suspected compounds. Knowledge of probable sources of contaminant chemicals used in the area and selection of any key indicator constituents should be used in the design of the sampling and analysis program to reduce cost without loss of study credibility. Guidance for selecting chemicals to be tested may be obtained from state and federal regulatory officials responsible for facility permits. Indicator parameters, referred to as *priority pollutants*, often can be used to determine the likely presence or absence of chemicals that are a concern to groundwater development.

Fortunately, groundwater quality in many locations does not change because of shallow gradients, i.e., movement of groundwater is very slow, especially compared with surface water quality. Therefore, once water quality has been established, the frequency of groundwater sampling normally need not exceed quarterly or even semiannual checks, except for potable water sources or areas of suspected contamination.

FIELD LOGISTICS AND DOCUMENTATION

Land costs, permits, professional services, and documentation are very important to the evaluation of potential water supply sites.

Land Costs

Legal access to property for preliminary groundwater investigation will commonly be granted by the landowners on request. However, as soon as a property has been identified as attractive for detailed exploration, purchase or lease options should be obtained. The cost of land may be more reasonable before good water supplies are confirmed. Drilling site preparation and restoration should not be overlooked as added costs to the groundwater development.

Permits

Exploratory drilling permits must be secured and fees paid, often at the state or county level. Obtaining permits is usually the responsibility of the well driller or the engineer in charge. In addition to the driller, a qualified hydrogeologist often supervises the drilling and well-construction activities. The hydrogeologist's responsibilities will usually include procuring well construction materials, well logging, conducting or overseeing geophysical logging, interpreting logs, well designing, and certifying as-built drawings.

Part of the drilling permit will include proper abandonment once the well has served its purpose. Public agencies are concerned about well construction and post-use of a well because of the possibility of cross contamination between shallow zones and deeper high-quality aquifers. The documentation of all field work can be valuable in later phases of groundwater development or protection. Proper land survey location, global positioning system (GPS) locations, description of the wells, and complete as-built drawings of construction are desirable.

Professional Services

Firms specializing in hydrogeology are valuable to the groundwater developer for their knowledge and experience in carrying out fieldwork and preparing the necessary reports. Some firms offer total services in groundwater development, as well as highly specialized equipment or services. Budget constraints, the complexity of the project, and the adequacy of the groundwater developer's staff can determine the most appropriate team. Some states require registered engineers, certified geologists, and other professionals to verify the accuracy and completeness of fieldwork.

Documentation

Documentation of initial investigations and water supply development must be detailed and complete. Because of the complex nature of the information, the use of graphics is helpful. Cross sections (Figure 2-6) showing the hydrogeologic interpretation, with lithologic logs, geophysical logs, and as-builts for wells, present a good summary of information. Maps showing predevelopment groundwater contours versus the contours as affected by the new pumping, including surrounding land uses and any potential sources of groundwater contamination, should be available. Figures 2-7 and 2-8 illustrate such maps.

Legal documents. Multiple copies of reports pertaining to groundwater development may be required by different levels of government for differing purposes. If the required reports are not to be submitted on issued forms, a reporting system that meets the needs of all federal, state, and local organizations should be designed.

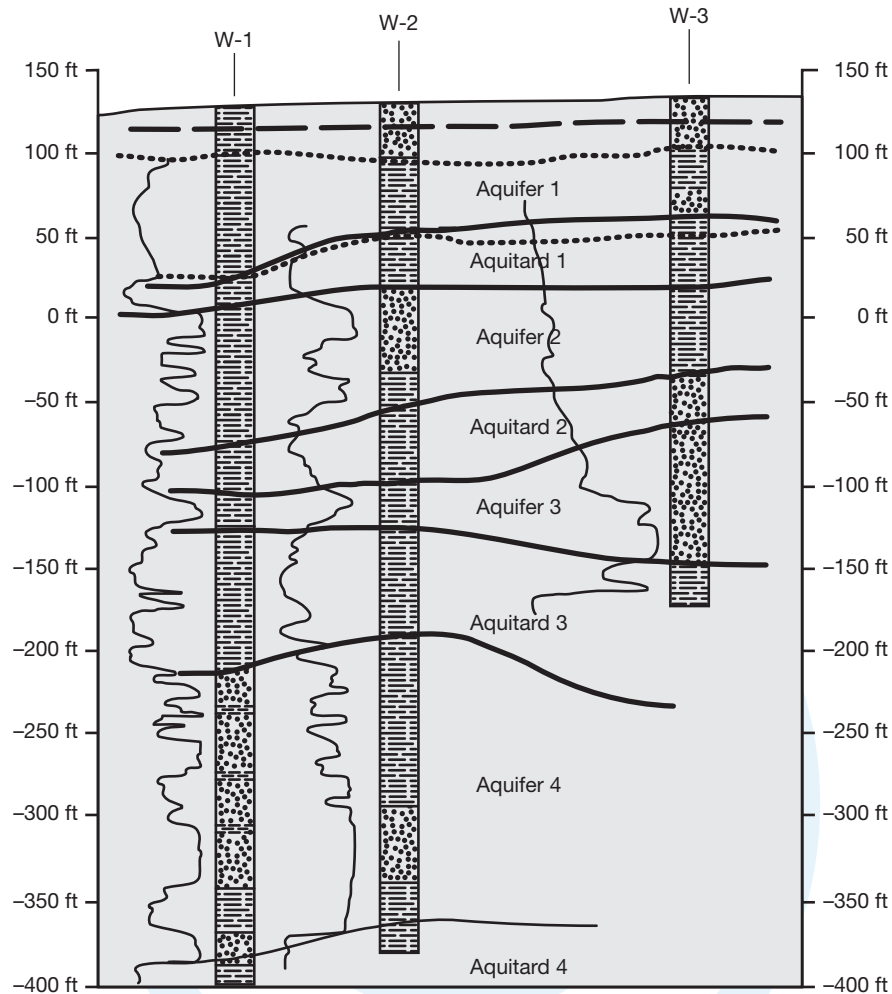


Figure 2-6 Graphic detail of a hydrogeologic cross section

Because federal, state, and local laws are requiring more information to be filed on a periodic basis, permits must be filed, fees must be paid, and monitoring must be conducted. These activities should be part of the planned groundwater development program. It may be desirable to consult an attorney knowledgeable in all aspects of the law, including groundwater, land use, and permit procedures, before finalizing reporting procedures. Reports can be of great value in litigation and, therefore, should be prepared with care and be subjected to appropriate legal, technical, and managerial review.

Application. In addition to the traditional groundwater quantity reporting (along with the few inorganic analytical tests), more extensive testing for organic contaminants is being required. Water conservation interest groups are using the pumping data to predict available groundwater supply and look for indications of groundwater mining. Information is also being filed with various government agencies involved in groundwater monitoring of facilities that produce, handle, store, treat, or dispose of chemicals determined to be hazardous to health or the environment. This information, when combined with information provided by the groundwater developer, can increase understanding of the regional groundwater system under study and its potential and reliability as a water supply.

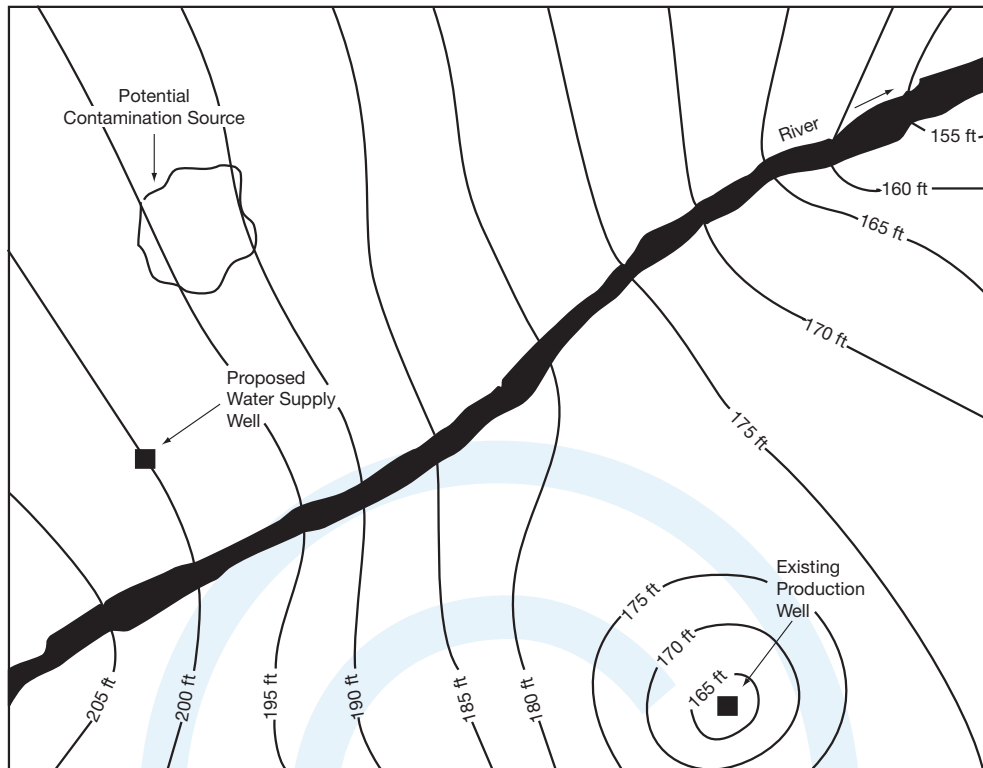


Figure 2-7 Predevelopment groundwater contours showing potential contamination source downgradient

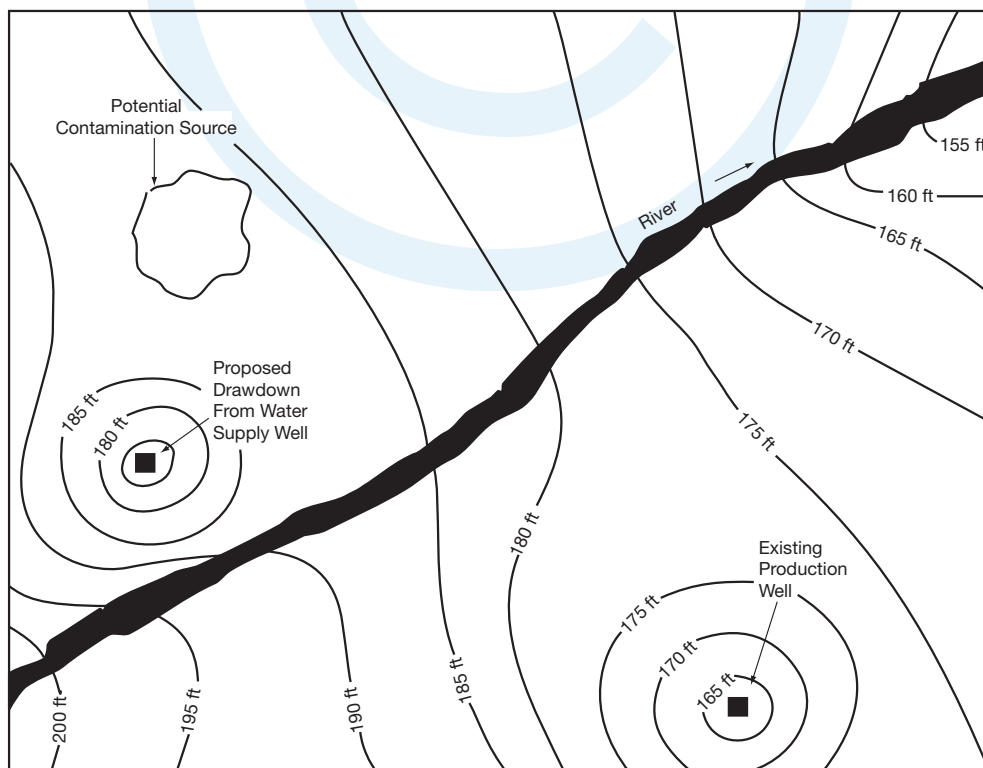


Figure 2-8 Predevelopment groundwater contours showing predicted effects of ill-advised development

REFERENCES

- Bloetscher, F., A. Muniz, and J. Largey. 2007. *Siting, Drilling, and Constructing Wells*. Denver, Colo.: American Water Works Association.
- Keys, W.S. 1989. *Borehole Geophysics Applied to Groundwater Investigations*. Westerville, Ohio: National Water Well Association.
- Keys, W.S. and L.M. MacCary. 1971. Application of Borehole Geophysics to Water-Resources Investigations. *Techniques of Water-Resources Investigations*, Book 2, Chap. E1. Denver, Colo.: US Geological Survey.
- Todd, D.K. 1984. *Ground-Water Resources of the United States*. Berkeley, Calif.: Premier Press.
- US Geological Survey. 1978–1982. *Appraisals of the Nation's Ground-Water Resources*. Prof. Paper No. 813, Chap. A-U. Denver, Colo.: USGS.
- Zohdy, A.R., G.P. Eaton, and D.R. Mabey. 1974. Application of Surface Geophysics to Ground-Water Investigations. *Techniques of Water-Resources Investigations*, Book 2, Chap. D1. Denver, Colo.: US Geological Survey.

