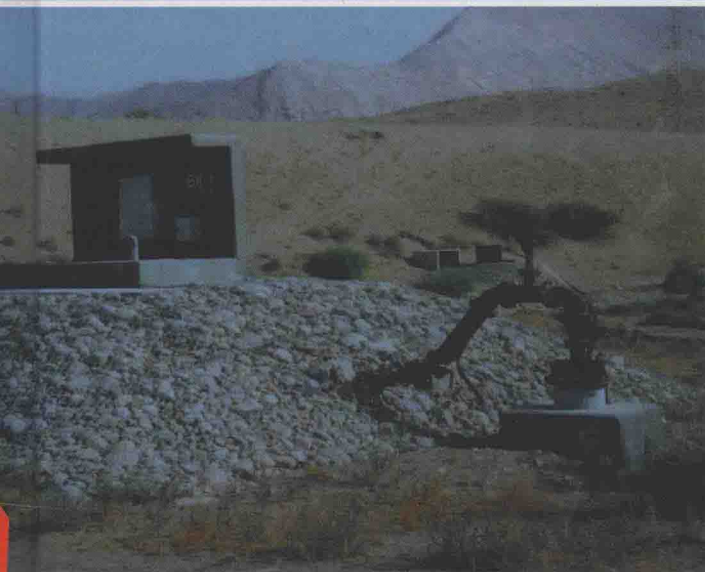




WATER WELLS AND BOREHOLES

Second Edition



Bruce Misstear | David Banks | Lewis Clark

WILEY Blackwell

Water Wells and Boreholes

Second Edition

BRUCE MISSTEAR

Trinity College Dublin, Ireland

DAVID BANKS

Holymoor Consultancy Ltd and University of Glasgow, UK

LEWIS CLARK

(Deceased) – formerly of Clark Consult Ltd, Henley on Thames, UK

WILEY Blackwell

This edition first published 2017 © 2017 by John Wiley & Sons Ltd

Registered Office

John Wiley & Sons Ltd, The Atrium, Southern Gate, Chichester, West Sussex, PO19 8SQ, UK

Editorial Offices

9600 Garsington Road, Oxford, OX4 2DQ, UK

The Atrium, Southern Gate, Chichester, West Sussex, PO19 8SQ, UK

111 River Street, Hoboken, NJ 07030-5774, USA

For details of our global editorial offices, for customer services and for information about how to apply for permission to reuse the copyright material in this book please see our website at www.wiley.com/wiley-blackwell.

The right of Bruce Misstear, David Banks and Lewis Clark to be identified as the author of the editorial material in this work has been asserted in accordance with the UK Copyright, Designs and Patents Act 1988.

All rights reserved. No part of this publication may be reproduced, stored in a retrieval system, or transmitted, in any form or by any means, electronic, mechanical, photocopying, recording or otherwise, except as permitted by the UK Copyright, Designs and Patents Act 1988, without the prior permission of the publisher.

Designations used by companies to distinguish their products are often claimed as trademarks. All brand names and product names used in this book are trade names, service marks, trademarks or registered trademarks of their respective owners. The publisher is not associated with any product or vendor mentioned in this book.

Limit of Liability/Disclaimer of Warranty: While the publisher and authors have used their best efforts in preparing this book, they make no representations or warranties with respect to the accuracy or completeness of the contents of this book and specifically disclaim any implied warranties of merchantability or fitness for a particular purpose. It is sold on the understanding that the publisher is not engaged in rendering professional services and neither the publisher nor the authors shall be liable for damages arising herefrom. If professional advice or other expert assistance is required, the services of a competent professional should be sought.

Library of Congress Cataloging-in-Publication data applied for:

9781118951705

A catalogue record for this book is available from the British Library.

Wiley also publishes its books in a variety of electronic formats. Some content that appears in print may not be available in electronic books.

Cover image: Courtesy of the author

Cover design: Wiley

Set in 10/12pt Times by SPi Global, Pondicherry, India

Printed in Singapore by C.O.S. Printers Pte Ltd

10 9 8 7 6 5 4 3 2 1

Preface to Second Edition

For this second edition we have retained the structure and emphasis of the original book: the text follows a life-cycle approach - from choosing a suitable well site, through the processes of designing, constructing, testing and sampling the well, to monitoring, maintenance and, if required, rehabilitating or finally abandoning the well. The target audience for this new edition continues to be students, professionals in hydrogeology and engineering and aid workers and other practitioners involved in well projects.

This second edition contains many updates on new well guidelines and standards published since the first edition. We also provide additional text on several topics, for example: the siting and construction of wells for economically-disadvantaged communities; specialist well designs for applications such as heating, cooling and aquifer recharge; drilling techniques such as sonic drilling and dual rotary that are becoming increasingly popular in the water well industry; new techniques in downhole geophysical logging; methods for analysing pumping test data under “non-ideal” conditions; and sampling wells for stable isotopes and dissolved gases.

Whilst we include some additional guidance on health and safety issues, we would again like to

stress, as we did in the first edition, that the book is not intended to be a manual. The reader should always consult the relevant regulations and guidance within their own country on these and other issues relating to water well projects.

We hope readers will enjoy this new edition and find it useful in their studies and workplace.

Bruce Misstear and David Banks
July 2016

Legal disclaimer

Although the authors and the publisher have used their best efforts to ensure the accuracy of the material contained in this book, complete accuracy cannot be guaranteed. Neither the authors nor the publisher accept any responsibility for loss or damage occasioned, or claim to have been occasioned, in part or in full, as a consequence of any person acting, or refraining from acting, as a result of matter contained within this publication. For well construction projects, the services of experienced and competent professionals should always be sought.

Preface to First Edition

The *Field Guide to Water Wells and Boreholes*, published by Lewis Clark in 1988, was a practical guide to designing and constructing wells and boreholes. It was primarily intended to be of use to field workers involved in implementing groundwater projects (it was written as one of the Geological Society of London Professional Handbook Series). This new book aims to update and expand the content of the *Field Guide*. It maintains the practical emphasis, but it has also been written with students in mind. The target readership includes:

- final-year undergraduate students in geology and civil engineering;
- graduate students in hydrogeology, groundwater engineering, civil engineering and environmental sciences;
- research students who are involved in using data from wells as part of their research;
- professionals in hydrogeology, water engineering, environmental engineering and geotechnical engineering;
- aid workers and others involved in well projects.

With its wider target audience, the new book has a broader scope than the *Field Guide*. Although it remains a practical guide, the book introduces additional theoretical detail on matters relating to the siting, design, construction, operation and maintenance of water wells and boreholes. Only a basic level of mathematical ability is assumed in the reader: the book includes a number of simple equations for the analysis of groundwater flow and well design problems which can be solved manually using a hand-calculator. Although the use of computer software is helpful for the longer and

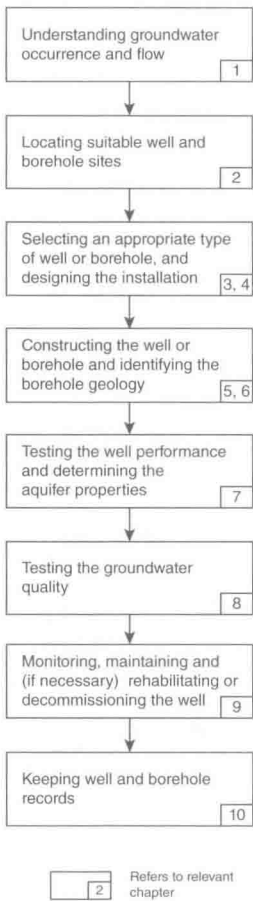
more repetitive computations, the authors are keen to promote a basic understanding of the issues, and do not support indiscriminate use of computer software without an appreciation of the basics.

The main focus of the book is on water wells that are used for drinking, industry, agriculture or other supply purpose, although other types of wells and boreholes are also covered, including boreholes for monitoring groundwater level and groundwater quality. Just as the potential car buyer looks for a certain combination of performance, reliability, durability, cost (including running cost) and personal and environmental safety in his or her new vehicle, the potential water well owner requires that:

- the well (or group of wells) should have sufficient yield to meet the demand;
- the water quality should be fit for the particular purpose;
- the well should be reliable, requiring little maintenance (although, as with a vehicle, some regular programme of maintenance will be required);
- the well should be durable, with a design life suited to its purpose.
- the construction and operating costs should not be excessive;
- the well should not impact unacceptably on neighbouring wells or on the environment, and therefore should not violate local water resources, planning or environmental legislation.

These principles underpin the guidance given throughout this text. The book follows a 'life-cycle' approach to water wells, from identifying a suitable well site through to the successful implementation,

operation and maintenance of the well, to its eventual decommissioning. The structure of the book is illustrated in the figure below.



The book is not a driller’s manual: it does not describe drilling procedures in detail; nor does it deal in detail with issues such as drilling permits, abstraction licences, or health and safety procedures in constructing and operating wells: readers should always consult local country guidance and regulations on these issues.

Lewis Clark (1937–2004): An Appreciation

Lewis Clark died in July 2004, when the first edition of this book was at an early stage of drafting. Lewis was an inspiration to many hydrogeologists in Britain and further afield; his co-authors would like to dedicate this new edition of the book to him, and to include this short appreciation of his work.

Following a PhD from the University of Leeds in 1963 (on the subject of metamorphic geology), Lewis first became involved in hydrogeology whilst working for the Geological Survey of Uganda in the 1960s. In 1968 he joined the Hunting consultancy group where he worked on hydrogeological projects in many developing countries, including Sudan, Thailand and Saudi Arabia. He was part of the talented Hunting Technical Services and Sir M Macdonald and Partners team (which also included Wiktor Bakiewicz, Roy Stoner and the late Don Milne) that worked on a major groundwater supply project for the Saudi Arabian capital Riyadh in the early 1970s, a project which involved the design and construction of a well field with more than 50 large capacity wells tapping a deep sandstone aquifer. This and subsequent experience in the design, drilling and testing of wells

led Lewis to publish his *Field Guide to Water Wells and Boreholes* in the 1980s. He also published a significant and much-quoted paper on step draw-down tests in the *Quarterly Journal of Engineering Geology* in 1977 (Clark, 1977).

In 1976 Lewis Clark joined the Water Research Centre (now WRc plc) and he soon became involved in applied research in groundwater quality and pollution, which is perhaps the work for which he is best remembered in Britain. He studied the origins and transport of organic contaminants including chlorinated solvents and pesticides, and the resulting research publications were always insightful and useful. In 1993 he was appointed Visiting Professor in Hydrogeology at University College London. He retired from WRc and set up his own consultancy, Clark Consult, in 1997. During that year, his contribution to hydrogeology was recognized by his peers in the award of the prestigious Whitaker medal by the Geological Society of London. He continued to work as a consultant hydrogeologist up until his death, making several visits for UN agencies to groundwater projects in Africa and central Asia.

Acknowledgements

Many people contributed directly or indirectly to the completion of this book. Individual chapters in the first edition were reviewed by Paul Ashley, John Barker, Charles Jones, Atle Dagestad, Mike Jones, Nick Robins, Vin Robinson, Stuart Smith, Geoff Wright and Paul Younger. We are also indebted to Aonghus McNabola for his patience in drafting several of the original figures in the book. Many individuals and organizations were involved in making available their own illustrations, and these are acknowledged in the relevant figure captions. We would especially like to thank the following for their help in sourcing figures and photos: Asgeir Bårdsen, Kim Beesley, Aidan Briody, Rolv Dahl, Bjørn Frengstad, Jeff Meehan, Laurence Gill, Peter O'Connor, David Roberts, Jan Steiner Rønning, Henrik Schiellerup, Svein Stoveland and Alan Waters. Bruce Misstear would

like to acknowledge his colleagues in the School of Engineering at Trinity College Dublin, and also the contribution of the University of New South Wales in Sydney where he spent a sabbatical working on the first edition. David Banks wishes to thank the University of Glasgow and his colleagues in the School of Engineering at that venerable institution for their support. Others who helped in the preparation of the book, or provided inspiration to its authors, include: Ian Acworth, Wiktor Bakiewicz, David Ball, Sarah Beeson, Donal Daly, the late Eugene Daly, James Dodds, Jane Dottridge, Robin Farbridge, Robin Hazell, Peter Howsam, Paul Johnston, John Lloyd, the late Don Milne, David Misstear, Karen Misstear, Gillian Misstear, Steve Parsons, Alan Rendell, Peter Rippon, Roy Stoner, John Tellam, Jan van Wonderen and Paul Younger.

Contents

<i>Preface to Second Edition</i>	x	2.6.4 Outflow estimation	66
<i>Preface to First Edition</i>	xi	2.6.5 Catchment water balance and modelling	66
<i>Lewis Clark (1937–2004): An Appreciation</i>	xiii	2.7 Groundwater quality	69
<i>Acknowledgements</i>	xiv	2.7.1 Introduction	69
		2.7.2 Chemical composition of groundwater	69
1 Introduction	1	2.7.3 Groundwater for potable supply	72
1.1 Wells and boreholes	1	2.7.4 Groundwater for irrigation	77
1.2 Groundwater occurrence	5	2.8 Pollution risk assessment and prevention	78
1.2.1 Aquifers, aquicludes and aquitards	5	2.8.1 Groundwater vulnerability	79
1.2.2 Porosity and aquifer storage	12	2.8.2 Wellhead protection areas	81
1.3 Groundwater flow	17	2.8.3 Estimating the pollution risk for a new well site	85
1.3.1 Darcy's equation	17	2.9 Planning the well scheme	87
1.3.2 General equations of groundwater flow	21		
1.3.3 Radial flow to wells	25		
2 Groundwater Investigations for Locating Well Sites	28	3 An Introduction to Well and Borehole Design	91
2.1 Desk studies	31	3.1 Drilled wells	91
2.2 Field reconnaissance	35	3.1.1 General design principles	91
2.3 Well survey	36	3.1.2 Wells in crystalline aquifers	96
2.4 Geophysical surveys	41	3.1.3 Wells in consolidated aquifers	100
2.4.1 Electrical resistivity	42	3.1.4 Wells in unconsolidated aquifers	104
2.4.2 Electromagnetics	49	3.1.5 Economic considerations in well design	107
2.5 Drilling investigations	52	3.2 Hand-dug wells	109
2.6 Groundwater resources assessment	59	3.2.1 Design for yield	113
2.6.1 Inflow estimation: direct recharge	61	3.2.2 Design for health	114
2.6.2 Inflow estimation: indirect recharge	64	3.3 Infiltration galleries	116
2.6.3 Aquifer response analysis	65	3.4 Radial collector wells	120
		3.5 Observation boreholes	120

3.6	Exploration boreholes	125	4.8.2	Feedback and breakthrough	178
3.7	Pump selection	125	4.8.3	Water chemistry	179
3.7.1	Vertical turbine pumps	128	4.9	Recharge wells	180
3.7.2	Electrical submersible pumps	129	4.9.1	Purpose	180
3.7.3	Motorized suction pumps	133	4.9.2	Construction of injection wells	182
3.7.4	Helical rotor pumps	134	4.9.3	Installations	183
3.7.5	Hand pumps	135	4.9.4	Testing and operation	184
4	Issues in Well Design and Specialist Applications	140	4.9.5	Clogging of recharge wells	184
4.1	Choice of construction materials	140	4.9.6	Seismic risk from water injection	188
4.1.1	Strength	141	4.10	Aquifer storage and recovery	188
4.1.2	Jointing system	141	5	Well and Borehole Construction	191
4.1.3	Durability	143	5.1	Percussion (cable-tool) drilling	193
4.1.4	Chemical inertness	143	5.1.1	Drilling in hard-rock formations	196
4.1.5	Standards	144	5.1.2	Drilling in soft, unstable formations	198
4.2	Casing	145	5.1.3	Light-percussion drilling	201
4.2.1	Steel casing	145	5.2	Rotary drilling	202
4.2.2	Plastic and fibreglass casing	146	5.2.1	Direct circulation rotary	202
4.3	Screen	147	5.2.2	Fluids used in direct circulation rotary drilling	208
4.3.1	Slot design and open area	147	5.2.3	Reverse circulation	212
4.3.2	Slot width	149	5.2.4	Top-hole and down-the-hole hammer drilling	215
4.4	Gravel pack design	150	5.2.5	Dual rotary	217
4.4.1	Natural gravel pack	150	5.2.6	Borehole testing during drilling	218
4.4.2	Artificial gravel pack	151	5.2.7	Methods of casing and screen installation	220
4.5	Hydraulic design	154	5.3	Sonic drilling	221
4.5.1	Partial penetration effects	156	5.4	Auger drilling	222
4.5.2	The damage zone and well bore skin	158	5.5	Jetting	223
4.5.3	Gravel pack loss	159	5.6	Direct push and drive sampling	224
4.5.4	Screen entrance loss	159	5.7	Driving of well-points	226
4.5.5	Well upflow losses	162	5.8	Manual construction	226
4.6	Economic optimization of well design	167	5.9	Well development	228
4.6.1	General principles	167	5.9.1	Well and aquifer damage	229
4.6.2	Example	168	5.9.2	Developing the well	229
4.7	Groundwater and wells for heating and cooling	171	5.9.3	Developing the aquifer around the well	229
4.7.1	Groundwater for cooling	172	5.9.4	Methods of development	231
4.7.2	Heating with groundwater: geothermal fluids	173	5.9.5	Disinfecting the well	240
4.7.3	Heating with groundwater: heat pumps	174	5.10	Wellhead completion	240
4.7.4	Well configurations	175			
4.8	Well doublets	177			
4.8.1	Hydraulic equations	178			

6 Formation Sampling and Identification	244	7.3 Types of pumping test	315
6.1 Observing the drilling process	244	7.3.1 Dimension pumping	315
6.1.1 Observing the drilling process in hard-rock aquifers	247	7.3.2 The step test	315
6.2 Collecting formation samples	248	7.3.3 Medium to long-term (constant rate) test	316
6.2.1 Disturbed formation sampling	248	7.3.4 Recovery test	317
6.2.2 Undisturbed formation sampling	256	7.4 Analysis of test pumping data from single wells	317
6.3 Description and analysis of drilling samples	260	7.4.1 Fundamentals	317
6.3.1 Characterizing disturbed samples	261	7.4.2 The misuse of test pumping analysis	318
6.3.2 Characterization of representative samples	261	7.4.3 Well performance – the step test	320
6.3.3 Characterization of undisturbed samples	267	7.4.4 Steady-state analyses	323
6.4 Downhole geophysical logging	269	7.4.5 Time-variant analysis	326
6.4.1 The geophysical logging package	270	7.4.6 Analysis of recovery tests	331
6.4.2 Organizing a geophysical logging mission	275	7.5 Multiple wells	334
6.4.3 On arriving on site	275	7.5.1 Steady-state analysis of multiple pumping wells	334
6.4.4 Formation logs	276	7.5.2 Time-variant analysis of multiple wells	334
6.4.5 Fluid logs	283	7.5.3 Application of the Cooper-Jacob approximation to multiple wells	334
6.4.6 Well construction logs	287	7.6 The shape of the yield-drawdown curve: Deviations from the ideal response	335
6.5 Downhole geophysical imaging	287	7.6.1 A non-infinite aquifer: Presence of an impermeable barrier	336
6.6 Distributed (fibre-optic) temperature sensing (DTS)	290	7.6.2 Recharge during a pumping test	336
6.7 Preparing a composite well log	292	7.6.3 Unconfined aquifers: Delayed yield	339
7 Well and Borehole Testing	295	7.6.4 Poroelasticity, subsidence and the 'Noordbergum Effect'	341
7.1 Objectives of test pumping	295	7.6.5 Large diameter wells	341
7.1.1 Well performance	295	7.6.6 Diagnostic plots	342
7.1.2 Water quality	296	7.7 Interpretation of pumping and recovery test data in hard-rock aquifers	344
7.1.3 Sustainability	296	7.7.1 High yielding hard-rock wells	345
7.1.4 Environmental impacts	298	7.7.2 Low-yielding hard-rock wells	346
7.1.5 Aquifer properties	298		
7.2 Planning a well pumping test	298		
7.2.1 Before starting	298		
7.2.2 When to test pump	301		
7.2.3 Consents and permissions	301		
7.2.4 Equipment	302		
7.2.5 The observation network	308		
7.2.6 Recording of data	313		

7.7.3	Sustainable yield of hard-rock wells	348	8.4.4	Submersible pumps	386
7.8	Single borehole tests: slug tests	350	8.4.5	Other pumps	387
7.8.1	Slug tests	350	8.4.6	Sampling at specific depths	389
7.8.2	Packer testing	352	8.4.7	Sampling for non-aqueous phase liquids	391
7.9	Tracer tests	353	8.5	Sample filtration, preservation and packaging	392
7.10	Geophysical logging during pumping tests	355	8.5.1	Sampling order	394
7.11	Test pumping a major well field: the Gatehampton case study	356	8.5.2	Physicochemical parameters	394
7.12	Record-keeping	359	8.5.3	Microbial parameters	396
8	Groundwater Sampling and Analysis	361	8.5.4	Inorganic parameters: acidification and filtration	397
8.1	Water quality parameters and sampling objectives	363	8.5.5	Inorganic parameters: sampling	400
8.1.1	Master variables	363	8.5.6	Organic parameters	400
8.1.2	Main physicochemical parameters	363	8.5.7	Stable isotopes	403
8.1.3	Major ions	364	8.5.8	Dissolved gases	404
8.1.4	Drinking water	365	8.6	Packing and labelling samples	406
8.1.5	Water for agricultural and industrial purposes	367	8.7	Quality control and record keeping	407
8.1.6	Pollution-related parameters	367	8.8	Sample chemical analysis	408
8.1.7	Indicator parameters	369	8.9	Hydrochemical databases	412
8.1.8	Microbiological quality and indicator parameters	370	9	Well Monitoring and Maintenance	414
8.2	Field determinations	373	9.1	Factors affecting well system performance	415
8.2.1	The purpose of field determinations	373	9.1.1	Physical processes	415
8.2.2	Downhole sondes and throughflow cells	374	9.1.2	Chemical processes	416
8.2.3	Field kits for other parameters	375	9.1.3	Microbiological processes	421
8.2.4	Emergency water supply	377	9.1.4	Well design and construction	423
8.3	Collecting water samples from production wells	380	9.1.5	Well system operation	423
8.3.1	The sample line	380	9.2	Monitoring well system performance	424
8.3.2	When to sample: well testing	380	9.2.1	Monitoring well performance	425
8.3.3	When to sample: production wells	382	9.2.2	Well inspection tools	433
8.4	Collecting water samples from observation boreholes	383	9.2.3	Pump performance	434
8.4.1	Preparation for sampling	383	9.2.4	Water quality monitoring	436
8.4.2	Bailers and depth samplers	384	9.2.5	Monitoring microbial processes	436
8.4.3	Simple pumps	386	9.3	Well maintenance and rehabilitation measures	437
			9.4	Well decommissioning	443

10 Well and Borehole Records	446	Appendix 3 Health and Safety Plans	464
10.1 Well archives	446	Appendix 4 World Health Organization Drinking Water Guidelines	467
10.2 Operational well databases	447	Appendix 5 FAO Irrigation Water Quality Guidelines	473
10.3 An example of a hydrogeological database - Afghanistan	454	References	475
Appendix 1 Units and Conversion Tables	458	Index	506
Appendix 2 Hydraulic Equations for Groundwater Engineers	460		

1

Introduction

1.1 Wells and boreholes

Water wells in some form or other have existed for almost as long a time as people have occupied this planet. The earliest wells were probably simple constructions around springs and seeps, or shallow excavations in dry river beds, but such wells have not left any traces for archaeologists. One of the oldest well discoveries is in Cyprus, dating from 7000 to 9000 BC (Fagan, 2011), whilst the earliest well remains in China have been dated at around 3700 BC (Zhou *et al.*, 2011). Since the first millennium BC, horizontal wells or *qanats* have been widely used for water supply and irrigation in the Middle East and western Asia, notably Iran, and continue to be used today (Figure 1.1). In Europe, the development of many towns and cities in the middle ages and on through the industrial period was aided considerably by the abstraction of relatively pure water supplies from wells and springs (Figure 1.2). In the nineteenth century, new drilling technology was used to construct deep wells to exploit artesian (flowing) aquifers (see Section 1.2 for explanations of aquifer terminology), including the Grenelle well in the Paris basin, which was drilled between 1833 and

1841, and reached a depth of 548 m (Margat *et al.*, 2013). The first mechanically-drilled well in the United States dates from 1823, whereas the first drilled well in the Great Artesian Basin of Australia was constructed in 1878 (Margat and van der Gun, 2013).

Wells continue to have an important role in society today. Some 2 billion people obtain their drinking water supplies directly from drilled or hand-dug wells (UNICEF and WHO, 2012). A further 4 billion people have access to piped water or public taps, a proportion of which will be sourced from groundwater, so it is likely that more than 3 billion people worldwide rely on water wells for their drinking water. Over half the public water supplies in European Union countries come from groundwater, ranging from between 20% and 30% of drinking water supplied in Spain and the United Kingdom, to nearly 100% in Austria, Lithuania and Denmark (Hiscock *et al.*, 2002).

The largest use of groundwater worldwide is for irrigation (70%), with India, China and the United States the leading countries in terms of total groundwater withdrawals (Margat and van der Gun, 2013). The last 30 years have witnessed a huge increase in the use of wells for agricultural

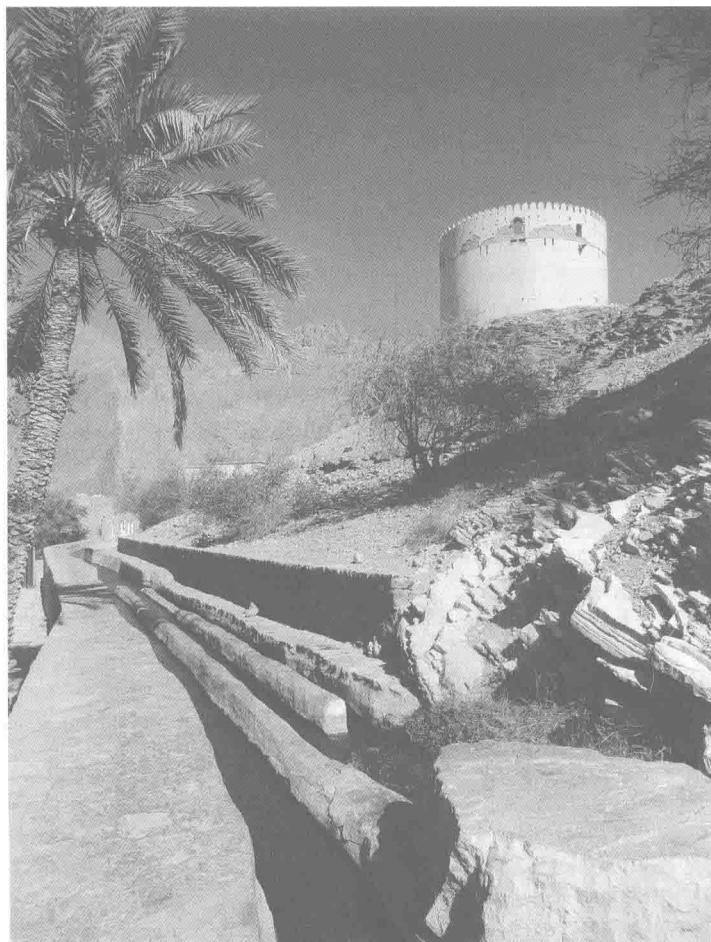


Figure 1.1 Open section of falaj (qanat) running through a town in northern Oman. Here, the channel is divided into three, with two of the channels then rejoining (at the bottom of the picture), in order to produce a two-thirds: one third split in the flow downstream. This Falaj al Khatmeen is included on the UNESCO list of World Heritage Sites. Photo by Bruce Misstear

irrigation, especially in Asia (Figure 1.3): in China 54% of irrigation water is supplied from groundwater while this proportion rises to 89% in India and 94% in Pakistan. In the United States, groundwater pumping increased by 144% between 1950 and 1980, with 71% of the annual withdrawal of 111.7 km³ in 2010 being used for irrigated agriculture (Margat and van der Gun, 2013). According to the National Ground Water Association, 44% of the population of the United States depends on

groundwater for its drinking water and there are about 500 000 new private wells constructed each year for domestic supplies.

Other uses of wells are many and diverse and include livestock watering (Figure 1.4), industrial supplies, geothermal energy or ground-source heating/cooling (Figure 1.5), construction dewatering, brine mining, water injection to oil reservoirs, aquifer clean up, river support and artificial recharge of aquifers. Wells and boreholes are also



Figure 1.2 Hand-dug well in Brittany, France. Photo by Bruce Missteart

used extensively for monitoring water levels and groundwater quality.

Wells have long had a religious significance in many societies. In India, the Holy Vedic Scriptures dating back to 8000 BC contain references to wells (Limaye, 2013). In the Bible and Koran, wells and springs feature prominently, sometimes as places for meeting and talking and often as metaphors for paradise. Holy wells remain an important feature of local culture throughout the Celtic lands in western Europe, for example, where there may be as many as 3000 holy wells in Ireland alone

(Logan, 1980; Robins and Missteart, 2000). Many of these wells are still visited regularly and votive offerings such as rags, statues and coins are common (see Box 3.7 in Chapter 3).

Water wells have also been a source of conflict since Biblical times:

But when Isaac's servants dug in the valley and found there a well of springing water, the herdsmen of Gerar quarrelled with Isaac's herdsmen, saying "This water is ours".

Genesis 26:19-20



Figure 1.3 A dual purpose irrigation and drainage well in the Indus valley, Pakistan. In this 'scavenger well' the outlet pipe in the foreground of the picture is discharging fresh groundwater from the upper part of the well, whereas the pipe to the right is discharging saline water from the lower section of the well, thus preventing the saline water from moving upwards and contaminating the good quality water. The good quality water is used for irrigation whilst the saline water is diverted to the drainage system. Photo by Bruce Misstear

They remain so today. A major point of contention in the Middle East is the control of the groundwater resources in the region (Shuval and Dweik, 2007; Younger, 2012).

Water wells come in many forms, orientations and sizes. Traditionally most water wells were excavated by hand as shallow, large diameter, shafts; nowadays, the majority are constructed from relatively small diameter boreholes drilled by machine, sometimes to great depths. Water wells are typically vertical but can be horizontal (infiltration gallery), a combination of vertical and horizontal well (radial collector well), or occasionally inclined (Figure 1.6). The water may be abstracted

by hand-operated or motorized pumps, or it may flow to the surface naturally under positive upward pressure (artesian well; Figure 1.7) or by gravity drainage (*qanat* or *falaj*). This book deals mainly with drilled wells (often called boreholes), since readers are likely to encounter these most often, but other types of wells are also covered.

Water well terminology is not standard throughout the world, and different names are commonly applied to identical constructions. The terms used in this book are explained in Box 1.1. Further details of the different types of wells and boreholes, and their component parts, are included in Chapter 3.