Water Wells and Boreholes
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
# Contents

*Preface to Second Edition*  x

*Preface to First Edition*  xi

*Lewis Clark (1937–2004): An Appreciation*  xiii

*Acknowledgements*  xiv

1 Introduction  1
   1.1 Wells and boreholes  1
   1.2 Groundwater occurrence  5
      1.2.1 Aquifers, aquicludes and aquitards  5
      1.2.2 Porosity and aquifer storage  12
   1.3 Groundwater flow  17
      1.3.1 Darcy’s equation  17
      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
   2.1 Desk studies  31
   2.2 Field reconnaissance  35
   2.3 Well survey  36
   2.4 Geophysical surveys  41
      2.4.1 Electrical resistivity  42
      2.4.2 Electromagnetics  49
   2.5 Drilling investigations  52
   2.6 Groundwater resources assessment  59
      2.6.1 Inflow estimation: direct recharge  61
      2.6.2 Inflow estimation: indirect recharge  64
      2.6.3 Aquifer response analysis  65
      2.6.4 Outflow estimation  66
      2.6.5 Catchment water balance and modelling  66
   2.7 Groundwater quality  69
      2.7.1 Introduction  69
      2.7.2 Chemical composition of groundwater  69
      2.7.3 Groundwater for potable supply  72
      2.7.4 Groundwater for irrigation  77
   2.8 Pollution risk assessment and prevention  78
      2.8.1 Groundwater vulnerability  79
      2.8.2 Wellhead protection areas  81
      2.8.3 Estimating the pollution risk for a new well site  85
   2.9 Planning the well scheme  87

3 An Introduction to Well and Borehole Design  91
   3.1 Drilled wells  91
      3.1.1 General design principles  91
      3.1.2 Wells in crystalline aquifers  96
      3.1.3 Wells in consolidated aquifers  100
      3.1.4 Wells in unconsolidated aquifers  104
      3.1.5 Economic considerations in well design  107
   3.2 Hand-dug wells  109
      3.2.1 Design for yield  113
      3.2.2 Design for health  114
   3.3 Infiltration galleries  116
   3.4 Radial collector wells  120
   3.5 Observation boreholes  120
### Contents

3.6 Exploration boreholes 125  
3.7 Pump selection 125  
3.7.1 Vertical turbine pumps 128  
3.7.2 Electrical submersible pumps 129  
3.7.3 Motorized suction pumps 133  
3.7.4 Helical rotor pumps 134  
3.7.5 Hand pumps 135  

4 Issues in Well Design and Specialist Applications 140  
4.1 Choice of construction materials 140  
4.1.1 Strength 141  
4.1.2 Jointing system 141  
4.1.3 Durability 143  
4.1.4 Chemical inertness 143  
4.1.5 Standards 144  
4.2 Casing 145  
4.2.1 Steel casing 145  
4.2.2 Plastic and fibreglass casing 146  
4.3 Screen 147  
4.3.1 Slot design and open area 147  
4.3.2 Slot width 149  
4.4 Gravel pack design 150  
4.4.1 Natural gravel pack 150  
4.4.2 Artificial gravel pack 151  
4.5 Hydraulic design 154  
4.5.1 Partial penetration effects 156  
4.5.2 The damage zone and well bore skin 158  
4.5.3 Gravel pack loss 159  
4.5.4 Screen entrance loss 159  
4.5.5 Well upflow losses 162  
4.6 Economic optimization of well design 167  
4.6.1 General principles 167  
4.6.2 Example 168  
4.7 Groundwater and wells for heating and cooling 171  
4.7.1 Groundwater for cooling 172  
4.7.2 Heating with groundwater: geothermal fluids 173  
4.7.3 Heating with groundwater: heat pumps 174  
4.7.4 Well configurations 175  
4.8 Well doublets 177  
4.8.1 Hydraulic equations 178  

4.9 Recharge wells 180  
4.9.1 Purpose 180  
4.9.2 Construction of injection wells 182  
4.9.3 Installations 183  
4.9.4 Testing and operation 184  
4.9.5 Clogging of recharge wells 184  
4.9.6 Seismic risk from water injection 188  
4.10 Aquifer storage and recovery 188  

5 Well and Borehole Construction 191  
5.1 Percussion (cable-tool) drilling 193  
5.1.1 Drilling in hard-rock formations 196  
5.1.2 Drilling in soft, unstable formations 198  
5.1.3 Light-percussion drilling 201  
5.2 Rotary drilling 202  
5.2.1 Direct circulation rotary 202  
5.2.2 Fluids used in direct circulation rotary drilling 208  
5.2.3 Reverse circulation 212  
5.2.4 Top-hole and down-the-hole hammer drilling 215  
5.2.5 Dual rotary 217  
5.2.6 Borehole testing during drilling 218  
5.2.7 Methods of casing and screen installation 220  
5.3 Sonic drilling 221  
5.4 Auger drilling 222  
5.5 Jetting 223  
5.6 Direct push and drive sampling 224  
5.7 Driving of well-points 226  
5.8 Manual construction 226  
5.9 Well development 228  
5.9.1 Well and aquifer damage 229  
5.9.2 Developing the well 229  
5.9.3 Developing the aquifer around the well 229  
5.9.4 Methods of development 231  
5.9.5 Disinfecting the well 240  
5.10 Wellhead completion 240
6 Formation Sampling and Identification 244
6.1 Observing the drilling process 244
6.1.1 Observing the drilling process in hard-rock aquifers 247
6.2 Collecting formation samples 248
6.2.1 Disturbed formation sampling 248
6.2.2 Undisturbed formation sampling 256
6.3 Description and analysis of drilling samples 260
6.3.1 Characterizing disturbed samples 261
6.3.2 Characterization of representative samples 261
6.3.3 Characterization of undisturbed samples 267
6.4 Downhole geophysical logging 269
6.4.1 The geophysical logging package 270
6.4.2 Organizing a geophysical logging mission 275
6.4.3 On arriving on site 275
6.4.4 Formation logs 276
6.4.5 Fluid logs 283
6.4.6 Well construction logs 287
6.5 Downhole geophysical imaging 287
6.6 Distributed (fibre-optic) temperature sensing (DTS) 290
6.7 Preparing a composite well log 292

7 Well and Borehole Testing 295
7.1 Objectives of test pumping 295
7.1.1 Well performance 295
7.1.2 Water quality 296
7.1.3 Sustainability 296
7.1.4 Environmental impacts 298
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
7.3 Types of pumping test 315
7.3.1 Dimension pumping 315
7.3.2 The step test 315
7.3.3 Medium to long-term (constant rate) test 316
7.3.4 Recovery test 317
7.4 Analysis of test pumping data from single wells 317
7.4.1 Fundamentals 317
7.4.2 The misuse of test pumping analysis 318
7.4.3 Well performance – the step test 320
7.4.4 Steady-state analyses 323
7.4.5 Time-variant analysis 326
7.4.6 Analysis of recovery tests 331
7.5 Multiple wells 334
7.5.1 Steady-state analysis of multiple pumping wells 334
7.5.2 Time-variant analysis of multiple wells 334
7.5.3 Application of the Cooper-Jacob approximation to multiple wells 334
7.6 The shape of the yield-drawdown curve: Deviations from the ideal response 335
7.6.1 A non-infinite aquifer: Presence of an impermeable barrier 336
7.6.2 Recharge during a pumping test 336
7.6.3 Unconfined aquifers: Delayed yield 339
7.6.4 Poroelasticity, subsidence and the ‘Noordbergum Effect’ 341
7.6.5 Large diameter wells 341
7.6.6 Diagnostic plots 342
7.7 Interpretation of pumping and recovery test data in hard-rock aquifers 344
7.7.1 High yielding hard-rock wells 345
7.7.2 Low-yielding hard-rock wells 346
7.7.3 Sustainable yield of hard-rock wells 348
7.8 Single borehole tests: slug tests 350
  7.8.1 Slug tests 350
  7.8.2 Packer testing 352
7.9 Tracer tests 353
7.10 Geophysical logging during pumping tests 355
7.11 Test pumping a major well field: the Gatehampton case study 356
7.12 Record-keeping 359

8 Groundwater Sampling and Analysis 361
  8.1 Water quality parameters and sampling objectives 363
    8.1.1 Master variables 363
    8.1.2 Main physicochemical parameters 363
    8.1.3 Major ions 364
    8.1.4 Drinking water 365
    8.1.5 Water for agricultural and industrial purposes 367
    8.1.6 Pollution-related parameters 367
    8.1.7 Indicator parameters 369
    8.1.8 Microbiological quality and indicator parameters 370
  8.2 Field determinations 373
    8.2.1 The purpose of field determinations 373
    8.2.2 Downhole sondes and throughflow cells 374
    8.2.3 Field kits for other parameters 375
    8.2.4 Emergency water supply 377
  8.3 Collecting water samples from production wells 380
    8.3.1 The sample line 380
    8.3.2 When to sample: well testing 380
    8.3.3 When to sample: production wells 382
  8.4 Collecting water samples from observation boreholes 383
    8.4.1 Preparation for sampling 383
    8.4.2 Bailers and depth samplers 384
    8.4.3 Simple pumps 386
  8.4.4 Submersible pumps 386
  8.4.5 Other pumps 387
  8.4.6 Sampling at specific depths 389
  8.4.7 Sampling for non-aqueous phase liquids 391
  8.5 Sample filtration, preservation and packaging 392
    8.5.1 Sampling order 394
    8.5.2 Physicochemical parameters 394
    8.5.3 Microbial parameters 396
    8.5.4 Inorganic parameters: acidification and filtration 397
    8.5.5 Inorganic parameters: sampling 400
    8.5.6 Organic parameters 400
    8.5.7 Stable isotopes 403
    8.5.8 Dissolved gases 404
  8.6 Packing and labelling samples 406
  8.7 Quality control and record keeping 407
  8.8 Sample chemical analysis 408
  8.9 Hydrochemical databases 412

9 Well Monitoring and Maintenance 414
  9.1 Factors affecting well system performance 415
    9.1.1 Physical processes 415
    9.1.2 Chemical processes 416
    9.1.3 Microbiological processes 421
    9.1.4 Well design and construction 423
    9.1.5 Well system operation 423
  9.2 Monitoring well system performance 424
    9.2.1 Monitoring well performance 425
    9.2.2 Well inspection tools 433
    9.2.3 Pump performance 434
    9.2.4 Water quality monitoring 436
    9.2.5 Monitoring microbial processes 436
  9.3 Well maintenance and rehabilitation measures 437
  9.4 Well decommissioning 443
## Contents

10 Well and Borehole Records  
10.1 Well archives 446  
10.2 Operational well databases 447  
10.3 An example of a hydrogeological database - Afghanistan 454  

Appendix 1 Units and Conversion Tables 458  
Appendix 2 Hydraulic Equations for Groundwater Engineers 460  
Appendix 3 Health and Safety Plans 464  
Appendix 4 World Health Organization Drinking Water Guidelines 467  
Appendix 5 FAO Irrigation Water Quality Guidelines 473  

References 475  

Index 506
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 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 drawdown 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.
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 Bårdesen, 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.
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
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 km$^3$ 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
Introduction

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 Misstear, 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 1.2 Hand-dug well in Brittany, France. 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.
1.2 Groundwater occurrence

The remainder of this chapter provides the non-specialist reader with a brief introduction to the occurrence of groundwater and the principles of groundwater flow, including radial flow to water wells. For a more comprehensive coverage of these topics the reader is referred to standard hydrogeology texts including Freeze and Cherry (1979), Fetter (2001), Todd and Mays (2005), and Hiscock and Bense (2014).

1.2.1 Aquifers, aquicludes and aquitards

Figure 1.8 illustrates some of the basic terminology used to describe groundwater and aquifers. While some authorities define groundwater as any water occurring in the subsurface – that is, water occurring in both the unsaturated and the saturated zones – we follow the tradition of defining groundwater as that portion of water in the subsurface that occurs in the saturated zone. A geological formation that is able to store and
transmit groundwater in useful quantities is called an aquifer. Aquifer is thus a relative term, since a low permeability geological formation that would not be considered as an aquifer capable of meeting public water supply or irrigation water demands, may be able to supply ‘useful quantities’ of groundwater to a village or domestic well in regions where water is otherwise scarce. In this context, one can argue, for example, that low-permeability mudstones in parts of Africa are hugely valuable aquifers (MacDonald, 2003).

Aquifers are often described according to their water level or pressure head conditions (see Boxes 1.2 and 1.3 for explanations of groundwater head). An aquifer is said to be unconfined where its upper boundary consists of a free groundwater surface at which the pressure equals atmospheric. This free surface is known as the water table and 

Figure 1.5  Drilling rig being set up for constructing a well in a gravel aquifer used as a source of geothermal energy, Dublin, Ireland. Photo by Bruce Misstear
Vertical drilled well, fractured consolidated aquifer
Hand-dug well, unconsolidated aquifer
Combined hand-dug well and drilled well, unconsolidated aquifer
Radial (Ranney) well, weathered zone of crystalline aquifer
Inclined drilled well, crystalline aquifer
Infiltration gallery in unconsolidated gravel aquifer below river bed
Falaj (qanat) in unconsolidated gravel aquifer

Figure 1.6 Examples of different types of water well
Figure 1.7  Flowing artesian well, northern Myanmar. The well was drilled into a strongly confined sandstone aquifer. Children are enjoying the ‘swimming pool’ created by the discharge until such time as the well is capped. Photo by Bruce Misstear

Box 1.1  Well and borehole terminology

<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water well</td>
<td>Any hole excavated in the ground that can be used to obtain a water supply</td>
</tr>
<tr>
<td>Drilled well</td>
<td>A water well constructed by drilling. Synonyms are tubewell or, simply, borehole. As drilled wells are the main focus of this book they will be referred to as wells for simplicity. Other types of water well will be distinguished, where necessary, using the terminology below</td>
</tr>
<tr>
<td>Hand-dug well</td>
<td>A large-diameter, usually shallow, water well constructed by manual labour. Synonyms are dug well or open well</td>
</tr>
<tr>
<td>Exploratory borehole</td>
<td>A borehole drilled for the specific purpose of obtaining information about the subsurface geology or groundwater. Synonyms are investigation borehole, exploration borehole or pilot borehole</td>
</tr>
<tr>
<td>Observation borehole</td>
<td>A borehole constructed to obtain information on variations in groundwater level or water quality. Also known as observation well</td>
</tr>
<tr>
<td>Piezometer</td>
<td>A small diameter borehole or tube constructed for the measurement of hydraulic head at a specific depth in an aquifer. In a piezometer, the section of the borehole (the screened section) in contact with the aquifer is usually very short</td>
</tr>
<tr>
<td>Test well</td>
<td>A borehole drilled to test an aquifer by means of pumping tests</td>
</tr>
<tr>
<td>Infiltration gallery</td>
<td>A shallow horizontal well usually constructed in the bed of a river or along a river bank in an alluvial aquifer</td>
</tr>
<tr>
<td>Radial collector well</td>
<td>A large diameter well with horizontal boreholes extending radially outwards into the aquifer. Also known as a Ranney well</td>
</tr>
<tr>
<td>Qanat</td>
<td>An infiltration gallery in which the water flows to the point of abstraction under gravity. There are many synonyms, including falaj (Oman), karez (Afghanistan) and karız (Azerbaijan)</td>
</tr>
</tbody>
</table>
Box 1.2 What is groundwater head?

There is a common misconception that water always flows from areas of high pressure to areas of low pressure, but it does not. Consider two points, A and B, in the tank of water illustrated in Figure B1.2(i). The pressures \( P \) at points A and B are given by:

\[
P = H \rho g
\]

where \( H \) is the height of the column of water above the point (dimension \([L]\)), \( \rho \) is the density of the water \( ([M][L]^{-3} = \text{c.}1000 \text{ kg m}^{-3}) \) and \( g \) the acceleration due to gravity \( ([L][T]^{-2} = 9.81 \text{ m s}^{-2}) \).

Thus, at point A, the water pressure is \( 14,715 \text{ N m}^{-2} \), and at point B it is \( 53,955 \text{ N m}^{-2} \). But water does not flow from B to A - the water in the tank is static. Clearly we need a more sophisticated concept. In fact, we can use the concept of potential energy: groundwater always flows from areas of high potential energy to low potential energy. Groundwater head \( h \) is a measure of the potential energy of a unit mass of groundwater at any particular point. This is the sum of potential energy due to elevation and that due to pressure.

Potential energy \( P = \frac{zg}{\rho} \) (in J kg\(^{-1}\))

To obtain head (in metres), we divide by \( g \) (a constant):

\[
h = \frac{P}{\rho g} + z
\]

where \( z \) is the elevation above an arbitrary datum \([L]\). Returning to the tank of water example, the heads at A and B, relative to the base of the tank, are:

\[
h_A = \frac{14,715}{1000 \times 9.81} + 5 = 6.5 \text{ m}
\]

\[
h_B = \frac{53,955}{1000 \times 9.81} + 1 = 6.5 \text{ m}
\]

In other words, they are identical and there is no tendency to flow between the two points. Note that we can compare heads in different locations relative to an arbitrary datum \( \text{only if} \) the density is constant (i.e., 1 m in elevation is equivalent in energy terms to the pressure exerted by a 1 m column of fluid). If we are considering groundwater systems of variable salinity (and density), it is easy to get into difficulties by applying simplistic concepts of head.

In an unconfined aquifer, the elevation of the water table represents groundwater head at that point in the aquifer. While it is often assumed that the water table represents the boundary between unsaturated and saturated aquifer material, this is not quite true, as there is a thin capillary fringe of saturated material above the water table. Strictly speaking, the water table is the surface at which the pressure is equal to atmospheric (i.e., the water pressure is zero).

For confined aquifers, we can imagine contours joining all locations of equal head. These contours then define a surface which is called the piezometric surface or potentiometric surface. The slope of this surface defines the hydraulic gradient, which in turn controls the direction of groundwater flow. Water will rise in a borehole sunk into the confined aquifer to a level corresponding to the potentiometric surface.

Figure B1.2(i) Sketch of a water tank showing two points where pressure and head can be calculated
unconfined aquifers are sometimes known as water-table aquifers. An aquifer is said to be confined when it is fully saturated and its potentiometric surface (hydraulic head) lies in an overlying, low-permeability confining layer. Very low permeability layers bounding aquifers are often known as aquicludes. However, no formation is truly impermeable and many low permeability formations can transmit quantities of groundwater that may be significant on a regional scale: thus, the term aquitard is often preferred for such formations. Where an aquitard allows some leakage of water to or from an aquifer, the aquifer is often said to be semi-confined or leaky. In a system of aquifers separated by aquitards or aquicludes, each aquifer may have a different hydraulic head, as depicted in Figure 1.8, and may contain water of a different quality. A perched aquifer may occur where a shallow water table has developed locally on a low permeability layer that lies above the regional water table.

Aquifers can be divided into three broad classes: crystalline aquifers, consolidated aquifers and unconsolidated aquifers. Crystalline aquifers are typified by the igneous and metamorphic rocks that underlie large areas of the world. They include the ancient granites and gneisses that form the ‘basement complex’ of sub-Saharan Africa and the younger volcanic rocks of the Deccan traps in southern India. Groundwater flow in crystalline aquifers takes place through discrete fractures, rather than through intergranular pore spaces.

Consolidated aquifers are composed of lithified (but not metamorphosed) sedimentary rocks such as sandstones and limestones (the term consolidated is used here in its general meaning of any sediment that has been solidified into a rock, rather than in the geotechnical engineering sense of a fine-grained cohesive soil that has been compressed). Major consolidated aquifers are found in the Chalk of England and France, the Floridan limestones in southeast United States and the Nubian sandstone in north Africa. Groundwater flow in consolidated aquifers tends to take place through a combination of fractures and intergranular pore spaces.

Figure 1.8  Groundwater occurrence
The distribution of groundwater head in an aquifer can be imagined as a three-dimensional scalar field. Each point in the scalar field has a unique value of groundwater head $h(x, y, z)$. Points of equal head can be joined by groundwater head contours. Groundwater flow has a tendency to follow the maximum gradient of head; in other words, the groundwater flow vector ($Q$) is proportional to $-\nabla h$. In vector-speak:

$$Q \propto -\nabla h$$

Thus, if we construct groundwater head contours in a porous medium aquifer, the groundwater flow lines will be perpendicular to the head contours (in fractured aquifers, groundwater flow may not be perpendicular to the regional head contours, as the groundwater is constrained to flow along fracture pathways which may not exist parallel to the head gradient).

Figure 1.8 implies that artesian boreholes can occur in confined aquifers where the potentiometric surface is higher than ground level. However, artesian boreholes can also occur in unconfined aquifers. Consider the two aquifer sections below. Figure B1.3(i) shows a relatively high permeability aquifer. The water-table gradient is shallow and groundwater flow is predominantly horizontal. Thus, the head contours are approximately vertical and the head at any depth in the aquifer at a given horizontal ($x, y$) coordinate is approximately equal to the elevation of the water table. Hence wells exhibit similar static water levels, irrespective of depth [wells A and B in Figure B1.3(i)]. Groundwater flow thus approximately follows the gradient of the water table.

Consider, then, the second drawing [Figure B1.3(ii)], of groundwater flow in a low permeability aquifer in an area of high topography. Here, head is truly three-dimensional, varying with elevation ($z$) as well as horizontally ($x, y$). Head contours are complex and not necessarily vertical. Groundwater flow has upwards and downwards components. Typically, in recharge areas, head decreases with increasing depth, and groundwater flow has a downward component. A deep-drilled well here (well C) will have a lower static water level than a shallow one (well D). In discharge areas, head increases with increasing depth and groundwater flow has an upward component. A deep-drilled well here (well E) will

---

**Figure B1.3(i)** Cross section through a relatively permeable aquifer. The water table gradient is flat. Contours on piezometric head (numbered contours, in m above sea level) are approximately vertical. Wells A and B have similar static water levels irrespective of depth.
Unconsolidated aquifers are typically formed of relatively young sediments laid down by water, wind or glaciers. Notable examples include the High Plains alluvial aquifer of the mid-west United States and the Indus valley alluvial aquifer system in Pakistan. Flow through such sediments is typically via intergranular pore spaces.

The main hydraulic properties of the three aquifer classes are described in the following sections. The three-fold aquifer classification also forms the basis of the general introduction to drilled well design given in Chapter 3.

1.2.2 Porosity and aquifer storage

Porosity. The ability of a geological formation to store water is governed by its porosity \( n \), which is the ratio between the volume of voids and the total volume of geological material. Primary porosity is a characteristic of unconsolidated aquifers and some consolidated aquifers where the voids were formed at the same time as the geological material. In crystalline aquifers and in consolidated aquifers where the original pores have been infilled with cement, porosity results from openings formed at a later time due to fracturing and weathering. This is known as secondary porosity.
Porosity and typically comprises tectonic fractures and dissolution fissures. Secondary porosity is usually much smaller than primary porosity. In karst limestone aquifers, secondary porosity can develop into conduit-like or even extensive cavern flow systems because of dissolution of soluble calcium carbonate minerals along the fractures [Figure 1.9(a)]. Groundwater flow rates of several hundred metres per hour can occur, comparable to surface water velocities (Banks et al. 1995; Coxon and Drew, 2000), and springs issuing from karstic aquifers can provide substantial water supplies [Figure 1.9(b)].

Porosity values for a range of geological formations are given in Table 1.1. Figure 1.10 illustrates different types of porosity. Sometimes, active groundwater flow only occurs through a portion of an aquifer’s total porosity (some of the pores may be “blind” or too small to permit efficient flow). This porosity is often referred to as the effective porosity ($n_e$).

Aquifer storativity or coefficient of storage. While porosity gives an indication of the amount of water that can be held by a geological formation it does

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{cave.png}
\caption{(a) Entrance to large limestone cave in Kras (karst) area of Slovenia; (b) major karst limestone spring near the city of Dubrovnik, Croatia. Photos by Bruce Misstear}
\end{figure}
not indicate how much it will release. The amount of water that an aquifer will readily take up or release is determined by its *storativity* or *coefficient of storage*. Aquifer storativity is defined as the volume of water that an aquifer will absorb or release per unit surface area, for a unit change in head. It is a dimensionless quantity. Aquifer storativity has two facets (Figure 1.11): unconfined storage (*specific yield, $S_Y$*) and confined storage (*specific storage $S_z$* or *elastic storage*).

The *specific yield* of an unconfined aquifer is the volume of water that will drain from it by gravity alone, per unit area, when the water table falls by one unit. The quantity is dimensionless. The water that is unable to drain and which is retained in the pores is termed the *specific retention ($S_r$)*. Specific yield and specific retention together equal the porosity. Fine-grained materials such as clays and silts have a high specific retention. Because of this, and because of their low permeability, they do