Water Wells and Boreholes

BRUCE MISSTEAR

Department of Civil, Structural and Environmental Engineering, Trinity College, Dublin, Ireland

DAVID BANKS

Holymoor Consultancy, Chesterfield, UK

LEWIS CLARK

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Library of Congress Cataloging-in-Publication Data

Misstear, B. D. R.
Water Wells and Boreholes / Bruce Misstear, David Banks, Lewis Clark
p. cm.
Includes bibliographical references and index.
ISBN-13: 978-0-470-84989-7 (cloth : alk. paper)
ISBN-10: 0-470-84989-4 (cloth : alk. paper)
1. Wells–Handbooks, manuals, etc. I. Banks, David, 1961- II. Title.

TD405.M57 2006
628.1′14–dc22 2006011280

British Library Cataloguing in Publication Data

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

ISBN-10 0-470-84989-4 (HB)
ISBN-13 978-0-470-84989-7 (HB)

Typeset in 10/12 pt Times by Thomson Digital
Printed and bound in Great Britain by Antony Rowe, Chippenham, Wiltshire
This book is printed on acid-free paper responsibly manufactured from sustainable forestry
in which at least two trees are planted for each one used for paper production.

Contents

Preface

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.

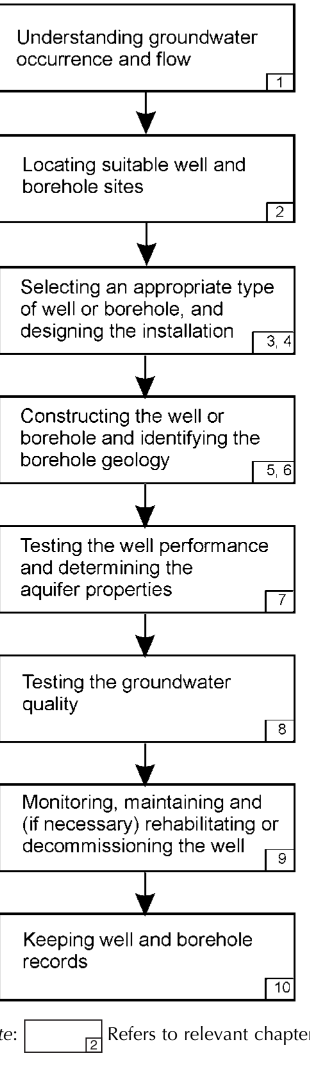
With its wider target audience, the new book has a broader scope than the *Field Guide.* Although it remains a practical guide, the book introduces additional theoretical detail on matters relating to the siting, design, construction, operation and maintenance of water wells and boreholes. Only a basic 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.



Note: Refers to relevant chapter.

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 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 book to him, and to acknowledge his contribution with 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 Surveys 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 led to 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 known 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 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 a large number 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, Peter O'Connor, David Roberts, Jan Steiner Rønning, Henrik Schiellerup and Alan Waters. Bruce Misstear would like to acknowledge his colleagues in the School of Engineering at Trinity College Dublin, his former colleagues at Mott MacDonald, and also the contribution of the University of New South Wales in Sydney where he spent a sabbatical in late 2003, and especially to say thank you to Ron Cox, Ian Acworth and their colleagues at the Water Research Centre in Many Vale. Others who helped in the preparation of the book, or provided inspiration to its authors, include: Wiktor Bakiewicz, David Ball, Sarah Beeson, Donal Daly, Eugene Daly, 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 and Jan van Wonderen.

1

Introduction

1.1 Wells and boreholes

Water wells have been a source of water for people, animals and crops since the earliest civilizations in Africa and Asia. In the Bible and Koran, for example, wells and springs feature prominently, sometimes as places for meeting and talking and often as metaphors for paradise. 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).

Wells continue to have an important role in society today. 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 last 20 years have witnessed a huge increase in the use of wells for agricultural irrigation, especially in Asia (Figure 1.3): in India 53 % of irrigation water is supplied from groundwater while this proportion rises to 98 % in Saudi Arabia (Foster *et al.*, 2000). In the USA groundwater pumping increased by 23 % between 1970 and 2000, with about 70 % of the daily withdrawal of 315 million cubic metres in 2000 being used for irrigated agriculture (McCray, 2004). There are also about 350 000 new wells constructed each year for domestic supplies in the USA.

Other uses of wells are many and diverse and include livestock watering (Figure 1.4), industrial supplies, geothermal or ground-source energy (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 used extensively for monitoring water levels and groundwater quality.

Water Wells and Boreholes, B. Misstear, D. Banks and L. Clark

Figure 1.1 *Open section of falaj (qanat) running through a village in northern Oman. Photo by Bruce Misstear*

Figure 1.2 *Hand-dug well with ornamental canopy, Prague, Czech Republic. Photo by Bruce Misstear*

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*

Figure 1.4 *Drilled well fitted with a windmill pump used for livestock watering, New South Wales, Australia. Photo by Bruce Misstear*

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*

Wells have long had a religious significance in many societies. Holy wells are 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 3.6 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 6, 19–20

They remain so today. A major point of contention in the Middle East is the control of the groundwater resources in the region.

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

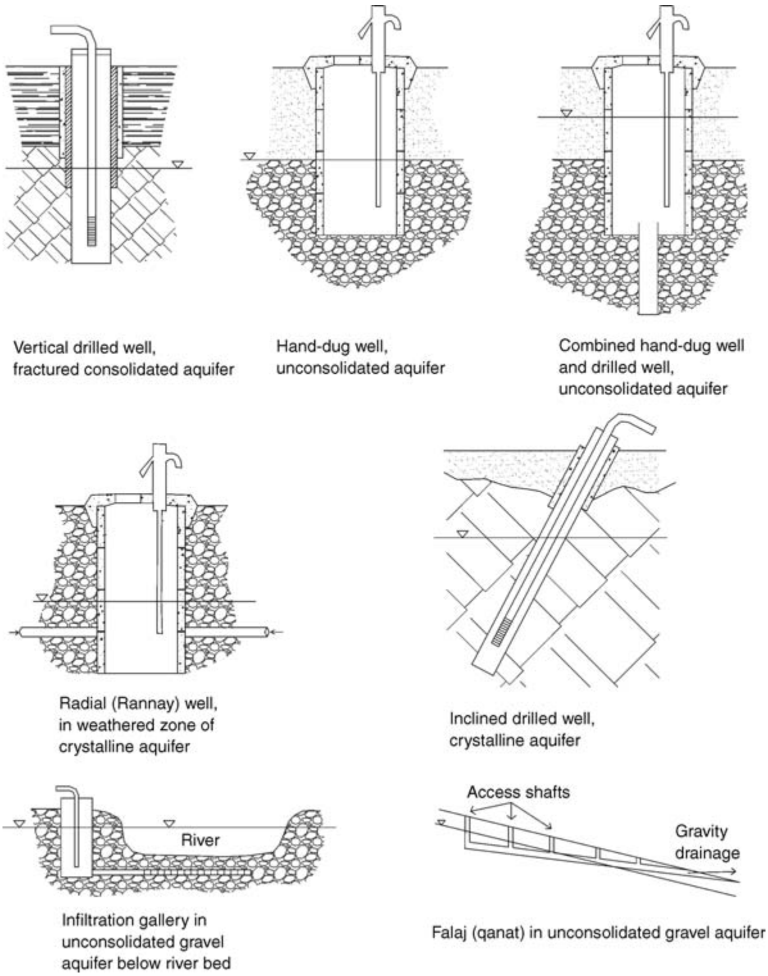


Figure 1.6 *Examples of different types of water well*

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*

with drilled wells, since readers are likely to encounter these most often, but other types of wells and boreholes 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.

Box 1.1 Well and borehole terminology

Water well	Any hole excavated in the ground that can be used to obtain a water supply
Drilled well	A water well constructed by drilling. Synonyms are tube-well, production well or production 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
Hand-dug well	A large-diameter, usually shallow, water well constructed by manual labour. Synonyms are dug well or open well
Exploratory borehole	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
Observation borehole	A borehole constructed to obtain information on variations in groundwater level or water quality. Also known as observation well
Piezometer	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
Test well	A borehole drilled to test an aquifer by means of pumping tests
Infiltration gallery	A shallow horizontal well usually constructed in the bed of a river or along a river bank in an alluvial aquifer
Radial collector well	A large diameter well with horizontal boreholes extending radially outwards into the aquifer. Also known as a Ranney well
Qanat	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 *kariz* (Azerbaijan)

1.2 Groundwater occurrence

The remainder of this chapter provides the nonspecialist 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 (Freeze and Cherry, 1979; Driscoll, 1986; Domenico and Schwartz, 1998; Fetter, 2001; Todd and Mays, 2004).

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 unconfined aquifers are sometimes known as *water-table aquifers*. An aquifer is said

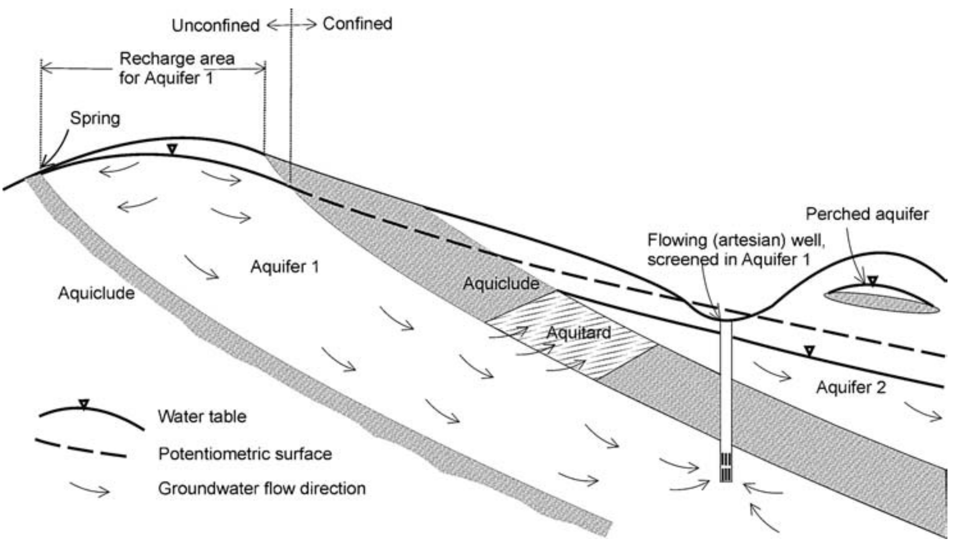


Figure 1.8 Groundwater occurrence

Box 1.2 What is groundwater head?

There is a common misconception that water always flows from high pressure to 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]), ρ is the density of the water ($[\mathrm{M}][\mathrm{L}]^{-3} = \mathrm{c}\ 1000\,\mathrm{kg\,m^{-3}}$) and g the acceleration due to gravity ($[\mathrm{L}][\mathrm{T}]^{-2} = 9.81\,\mathrm{m\,s^{-2}}$).

Thus, at point A, the water pressure is $14\,715\,\mathrm{N\,m^{-2}}$, and at point B it is $53\,955\,\mathrm{N\,m^{-2}}$. 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.

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

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:

$$h_A = \frac{14\,715}{1000 \times 9.81} + 5 = 6.5\,\mathrm{m} \qquad h_B = \frac{53\,955}{1000 \times 9.81} + 1 = 6.5\,\mathrm{m}$$

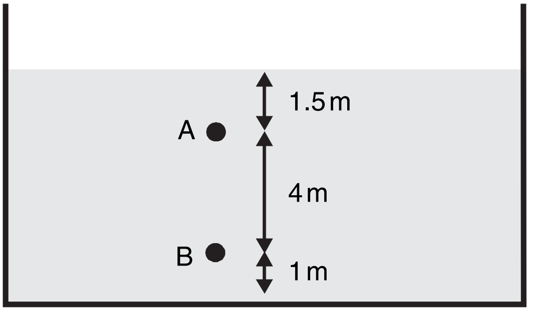


Figure B1.2(i) *Sketch of a water tank showing two points where pressure and head can be calculated*

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 *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 potentiomentric surface.

Box 1.3 Groundwater head as a three-dimensional concept

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 ($\boldsymbol{Q}$) is proportional to $-\mathrm{grad}(h)$. In vector-speak:

$$\boldsymbol{Q} \propto -\nabla h$$

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 have a static water level higher than a shallow

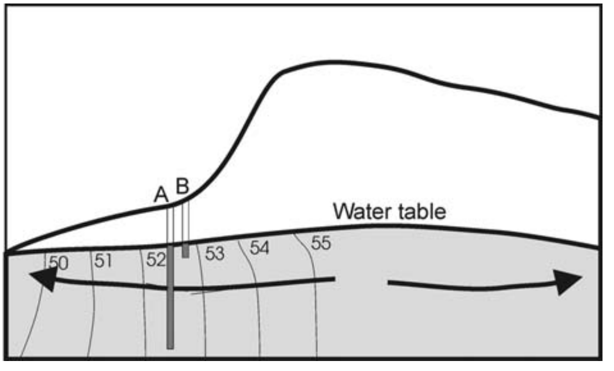


Figure B1.3(i) *Cross-section through a relatively permeable aquifer. The water table gradient is flat. Contours on piezometric head (numbered contours, in metres above sea level) are approximately vertical. Wells A and B have similar static water levels irrespective of depth*

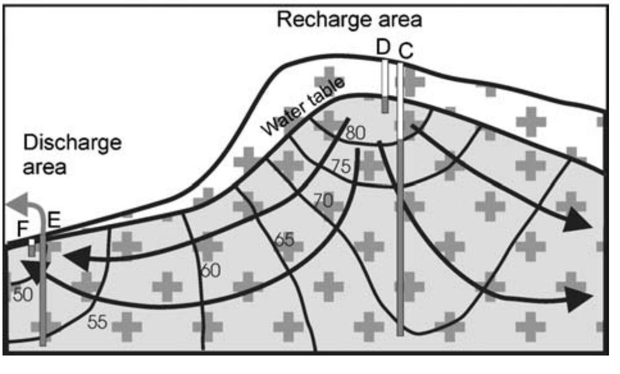


Figure B1.3(ii) *Cross-section through a relatively low permeability aquifer, such as granite. The water table gradient reflects topography. Contours on piezometric head (numbered contours, in metres above sea level) are strongly three-dimensional. Pairs of wells (C, D and E, F) have differing static water levels depending on well depth. Deep wells may even be artesian (overflowing) in discharge areas (well E)* one (well F). In extreme cases, deep wells in discharge areas in *unconfined* aquifers may even have artesian heads, and overflow at the ground surface [as shown by well E in Figure B1.3(ii)].

Aquifers with strongly three-dimensional head distributions will typically either have a strong topography or have relatively low permeability (or both). Erosionally resistant crystalline bedrock aquifers are typically of this type. Note that a two-dimensional network of observation boreholes with long well screens may be adequate to characterize the head distribution in aquifers of the type illustrated in Figure B1.3(i), but are inadequate to characterize three-dimensional head distributions of the type in Figure B1.3(ii). For the latter type, a three-dimensional network of piezometers to varying depths is required. Each piezometer will have a very short open section, and will give a reading of head (h) at a specific point (x, y, z).

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 known as *aquicludes*. However, many low permeability formations can transmit quantities of groundwater that may be significant on a regional scale, and the term *aquitard* is used 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 USA 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.

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 USA 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 threefold 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* 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 extensive cavern and conduit flow systems because of dissolution of soluble calcium carbonate minerals along the fractures (Figure 1.9). Groundwater flow rates of several hundred metres per hour can occur, comparable with surface water velocities (Drew and Daly, 1993; Banks *et al.*, 1995). Porosity values for a range of geological formations are given in Table 1.1. Figure 1.10 illustrates different types of porosity.

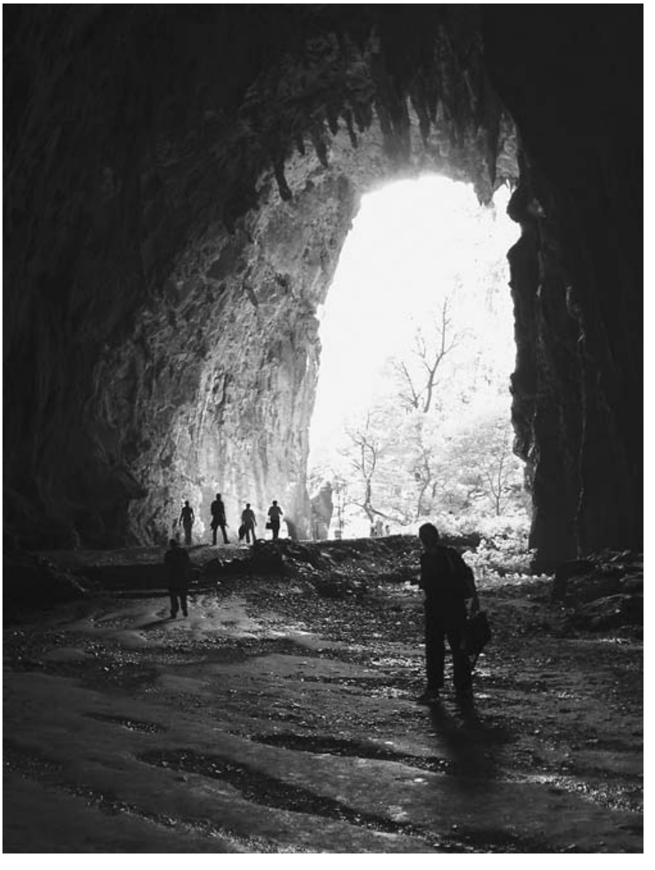


Figure 1.9 *Entrance to large limestone cave in Kras (karst) area of Slovenia. Photo by Bruce Misstear*