

# Groundwater around the World

## *A Geographic Synopsis*

*Jean Margat*  
*Jac van der Gun*





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# Preface

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Groundwater, water below ground surface: a fascinating subject. When rain falls, we see water disappearing into the ground and reappearing somewhere else, creating and feeding the rivers. What happens in between we cannot see, only speculate. Luckily, keen observation and scientific analysis have provided us with an insight into the world of groundwater, as this book vividly illustrates. In particular, the book highlights the kaleidoscopic variation in groundwater around the world: in its appearance and behaviour; in the role it plays in the hydrological cycle; in ecosystems and human life; in the ways it is exploited and used; and in the challenges of its proper and sustainable management. This invisible groundwater remains the most unpredictable and intriguing part of the hydrological cycle.

Lack of visibility is also reflected in the limited attention that groundwater receives in general; ‘out of sight, out of mind’, one might say. But how important is groundwater to us? About half of the world’s population drinks groundwater every day. Groundwater is of vital importance for agriculture and contributes to more than half of the world’s production of irrigated crops; it sustains wetlands and rivers, provides stability to the soil and prevents seawater intrusion. At the same time, groundwater is under increased pressure from population growth, climate change and human activities, with a widespread impact in terms of groundwater depletion and pollution. Hence, there are plenty of reasons to pay due attention to the state of groundwater resources as this wonderful book does.

Why ‘groundwater around the world’? Why a global look when groundwater is so often depicted as a local resource? There are several reasons. Firstly, groundwater systems can continuously cover thousands to millions of square kilometres, cross the borders of countries and greatly influence the socio-economic development of vast areas. Even when groundwater is relatively localized, its use and protection eventually have a global impact: in a modern world, a flow of goods is also the flow of groundwater used for their production. Secondly, comparison between the many different groundwater systems on Earth may contribute to deepening the knowledge of any particular one: it draws attention to what is most typical and most relevant in our local groundwater system and it can give suggestions on how to use and manage it optimally. Finally, a global look provides a worldwide overview of the opportunities, threats and problems related to groundwater and thus may help identify priorities for development and management action.

Assessing the groundwater resources at the global scale is a very demanding and laborious process. Data required for the assessment is often non-existent, poorly

accessible, contradictory, unreliable and difficult or even impossible to check. Current monitoring of the global state of groundwater is far from adequate and, in comparison with surface water, groundwater has only benefited to a limited extent from remote sensing. Consequently, global hydrological models employ simplistic characterisations of groundwater systems, together with numerous assumptions and poorly verifiable approximations of groundwater characteristics and behaviour. Nevertheless, both authors have not been put off by all these complicating factors. Driven by their fascination for groundwater and guided by their more than one hundred years of combined professional experience, they have patiently and meticulously collected, processed, reviewed, analysed and compared enormous quantities of information, in order to derive – by convergence of evidence – the most plausible picture of the many facets of the world's groundwater. They present this picture in such a way in their book that it is not only understandable for hydrogeologists and other groundwater specialists, but also for a much wider group of potential readers.

The subjects covered in this book are without exception relevant and essential for all themes of the Seventh Phase of UNESCO's International Hydrological Programme, entitled 'Water dependencies: Systems under stress and societal responses' (IHP-VII, 2008–2013). The information presented reflects what the International Groundwater Resources Assessment Centre (IGRAC) aims for in more detail in its Global Groundwater Information System. These were reasons for UNESCO-IHP and IGRAC to encourage the authors for preparing this book and to give them the support they needed.

The rapidly increasing worldwide attention to groundwater governance illustrates the need for a book like this. Good governance of our groundwater resources assumes the active participation of all relevant stakeholders, varying from mandated government institutions to end-users of groundwater and those who value groundwater-related ecosystems. The persons involved have different professional backgrounds and knowledge, but a basic common understanding of groundwater and the opportunities and problems it offers is a prerequisite for fruitful communication that will lead to proper decisions and action. This book, with its systematic presentation of groundwater in a broad hydrological and societal context, and with its many maps, tables and examples, provides an easily accessible introduction and a unique geographically oriented reference which we can warmly recommend to anybody interested in groundwater.

Alice Aureli,  
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Neno Kukuric,  
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After the book had been published and disseminated, UNESCO's Division of Water Sciences soon started thinking about an English version, in order to reach a much wider readership around the world. Alice Aureli and José Luis Martín invited and encouraged Jac van der Gun to prepare such a version in English. Because some years had passed before this work started, it was decided not just to translate the original book, but to seize the opportunity to update and expand the information presented and to add new elements as deemed useful. All this was subsequently carried out, in close consultation and co-operation with the senior author, and it has resulted in this present book.

This book, therefore, is a significantly revised second edition of the original book, presented in a different language. It capitalises on the original edition, but also received additional support and contributions by several persons and institutions. In particular, UNESCO-IGRAC took responsibility for preparing a completely new set of thematic world maps (which was skilfully done by Lena Heinrich), because these had to be modified as a result of updating time-dependent variables. On occasion other colleagues were also consulted to seek their advice on specific questions or subjects. These colleagues include Stefano Burchi, Jake Burke, John Chilton, Steven Foster, Todd Jarvis, Leonard Konikow, Jan Nonner, Mario Sophocleus and Raya Stephan. A number of colleagues made a special contribution by reading the draft of the book or part of it and gave useful comments and suggestions for improvement: Emilio Custodio, Lena Heinrich, Todd Jarvis, Wilhelm Struckmeier and Frank van Weert. After the book had been amended accordingly, Claire Taylor carried out the language editing and made valuable suggestions for correcting and polishing the English. Alice Aureli and José Luis Martín of UNESCO's Division of Water Sciences

have been a continuous and valuable support throughout the entire project. Finally, this book could not have been written without the efforts of the numerous individuals around the entire world – most of them unnamed – who have been involved in collecting, processing and interpreting data related to groundwater and who have shared this data and information through databases, reports or publications.

To all these persons and institutions, we extend our sincere and warm gratitude.

Jean Margat  
Jac van der Gun



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# Abbreviations and acronyms

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AAC	Association Africaine de Cartographie (African Cartographic Association)
ACSAD	Arab Center for the Studies of Arid Zones and Dry Lands
ALHSUD	Asociación Latinoamericana de Hidrología Subterránea para el Desarrollo (Latin-American Groundwater Hydrology Association for the Development)
AMOR	Aquifer management organization
AQUASTAT	FAO's Global Information System on Water and Agriculture
ASCE	American Society of Civil Engineers
BGR	Bundesanstalt für Geowissenschaften und Rohstoffe (German Federal Institute for Geosciences and Natural Resources)
BGS	British Geological Survey
BRGM	Bureau de Recherches Géologiques et Minières (French Institute for Geological and Mining Investigations)
CBLT	Commission du Bassin du Lac Tchad (Lake Chad Basin Commission)
CEDARE	Centre for Environment and Development for the Arab Region
CEE	Central and Eastern Europe
CCS	Carbon Capture and Sequestration
CGMW	Commission for the Geological Map of the World
CGWB	Central Ground Water Board (India)
CIHEAM	Centre International de Hautes Études Agronomiques Méditerranéennes (International Institute for Advanced Mediterranean Agronomic Studies)
CME	Conseil Mondial de l'Eau (= WWC)
COTAS	Comunidades de Usuarios de Aguas Subterráneas (Communities of Groundwater Users, Mexico)
DDT	Dichlorodiphenyltrichloroethane (insecticide)
DPSIR	Framework of analysis interrelating driving forces, pressures, state, impacts and responses
ECE	Economic Commission for Europe
EDC	Endocrine disruptive compound
EMWIS	Euro-Mediterranean Information System on know-how in the Water sector
EPA	Environmental Protection Agency, USA

ERWR	External Renewable Water Resources
ESCAP	Economic and Social Commission for Asia and the Pacific
ESCWA	United Nations Economic and Social Commission for Western Asia
EU	European Union
EUROSTAT	European Union Directorate responsible for detailed statistics on EU member and candidate countries (its database bears the same name)
FAO	Food and Agricultural Organization of the United Nations
GDS	Groundwater Development Stress indicator
GEF	Global Environmental Facility
GEI	Groundwater Exploitation Index
GGIS	Global Groundwater Information System (developed by IGRAC)
GRAPES	Groundwater and River Resources Action Programme on a European Scale
GRAPHIC	Groundwater Resources Assessment under the Pressures of Humanity and Climate Change (UNESCO project)
GWA	Gender and Water Alliance
GWES	Groundwater for Emergency Situations
GWP	Global Water Partnership
GW-MATE	Groundwater Management Team (World Bank)
IAEA	International Atomic Energy Agency
IAH	International Association of Hydrogeologists
IAHS	International Association of Hydrological Sciences
IAS	Iullemeden Aquifer System
IAHR	International Association of Hydro-Environment Engineering and Research
IBRD	International Bank for Reconstruction and Development
ICID	International Commission on Irrigation and Drainage
ICQHS	International Center on Qanats and Historic Hydraulic Structures (Yazd, Iran)
IFEN	Institut Français de l'Environnement (French Institute for the Environment)
IGME	Instituto Geológico y Minero de España (Geological Survey of Spain)
IGRAC	International Groundwater Resources Assessment Centre (since 2011 also called UNESCO-IGRAC)
IHD	UNESCO's International Hydrological Decade
IHP	International Hydrological Programme (UNESCO)
INBO	International Network of Basin Organizations
INSEE	Institut National de la Statistique et des Études Économiques (French National Institute for Statistics and Economic Studies)
INWEB	International Network of Water-Environment Centres for the Balkans
IPCC	Intergovernmental Panel on Climate Change
IRWR	Internal Renewable Water Resources

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ISARM	Internationally Shared Aquifer Resources Management
ISMAR	International Symposium on Managed Aquifer Recharge
ISO	International Organization for Standardization
ITGE	Instituto Tecnológico Geominero de España (predecessor of IGME)
IUGS	International Union of Geological Sciences
IWMI	International Water Management Institute
IWRA	International Water Resources Association
IWRM	Integrated Water Resources Management
IWRS	Indian Water Resources Society
IYPE	International Year of Planet Earth
MAP	UNEP's Mediterranean Action Plan
MAR	Managed Aquifer Recharge
MOPU	Ministerio de Obras Públicas y Urbanismo (Ministry of Public Works and Urban Affairs, Spain)
MRMWR	Ministry of Rural Municipalities and Water Resources, Oman
NAS	Nubian Aquifer System
NWSAS	North Western Sahara Aquifer System
OACT	Organisation Africaine de Cartographie et de Télédétection (African Organisation for Cartography and Remote Sensing, Algiers)
OEA	Organización de los Estados Americanos /Organisation des États Américains (=OAS)
OAS	Organization of American States
OECD	Organisation for Economic Co-operation and Development
OSS	Observatoire du Sahara et du Sahel (Sahara and Sahel Observatory, Tunis)
PAM	Plan d'Action pour la Méditerranée du PNEU (UNEP's Mediterranean Action Plan = MAP)
PAN	Pesticide Action Network Europe
PCR-GLOBWB	Global Water Balance Model (Utrecht University)
PHI	Programme Hydrologique International/ Programa Hidrológico Internacional (=IHP)
Plan Bleu	Mechanism for environmental regional co-operation between the 21 states bordering on the Mediterranean (under UNEP/MAP)
PNUD	Programme des Nations Unies pour le Développement/ Programa de las Naciones Unidas para el Desarrollo (=UNDP)
PNEU	Programme des Nations Unies pour l'Environnement (=UNEP)
PPCPs	Pharmaceuticals and personal care products
PWN	Provinciale Waterleiding Maatschappij Noord-Holland (Water Supply Company of the Province of North Holland, The Netherlands)
RIVM	Rijksinstituut voor Volksgezondheid en Milieu (Netherlands Institute for Public Health and the Environment)
RIZA	Rijksinstituut voor Integraal Zoetwaterbeheer en Afvalwaterbehandeling (Netherlands Institute for Inland Water Management and Waste water Treatment)

SADC	Southern African Development Community
SEMIDE	Système Euro-Méditerranéen d'Information sur les savoir-faire dans le Domaine de l'Eau (=EMWIS)
SOFRETEN	Société Française d'Etudes et d'Engineering
TDS	Total dissolved solids (concentration of dissolved salts in water)
TNO	Nederlandse Organisatie voor Toegepast Natuurwetenschappelijk Onderzoek (Netherlands Organisation of Applied Scientific Research)
TRWR	Total Renewable Water Resources
UN	United Nations
UNDESA	United Nations Department of Economic and Social Affairs
UNDP	United Nations Development Programme
UNDTCD	United Nations Division of Technical Cooperation for Development (also: UN-DTCD; predecessor of UNDESA)
UN-ECAFE	United Nations Economic Commission for Asia and the Far East
UN-ECE	United Nations Economic Commission for Europe (also: UNECE)
UNEP	United Nations Environmental Programme
UN-ESCAP	United Nations Economic and Social Commission for Asia and the Pacific
UNESCO	United Nations Educational, Scientific and Cultural Organization
UNESCO-IGRAC	International Groundwater Resources Assessment Centre (also know as IGRAC)
UN-ILC	United Nations International Law Commission
USGS	United States Geological Survey
USWRC	United States Water Resources Council
VLOM	Village Level Operation and Maintenance
WaterGap GHM	WaterGap Global Hydrological Model (Kassel and Frankfurt Universities)
WFD	Water Framework Directive of the European Union
WHYMAP	World-wide Hydrogeological Mapping and Assessment Programme
WHO	World Health Organization
WMO	World Meteorological Organization
WRI	Water Resources Institute, Washington
WWAP	World Water Assessment Programme
WWC	World Water Council
WWDR	World Water Development Report (prepared by WWAP)

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## About the authors

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Jean Margat

**Jean Margat** is a hydrogeologist. After fifteen years at the *Service Géologique* of Morocco at the beginning of his career, he moved to the *Bureau de Recherches Géologiques et Minières* (BRGM) at Orléans, France, for almost another twenty-five years. There he initiated, carried out and – later on – supervised groundwater investigations. During this period he was also the Director General's personal advisor on water resources. His professional experience has taken him to many areas in France and abroad, first and foremost in arid regions, in particular in Africa and the Middle East.

In addition to his professional activities at BRGM, Jean Margat was Vice-President of the *International Association of Hydrogeologists* (IAH) and afterwards President of the French national chapter of the Association.

Until recently, he was Vice-President of the Blue Plan for the Mediterranean. He is still consulted as an expert by international organisations such as FAO, UNESCO, World Bank and UNDP.

He is the author of a large number of publications related to water resources assessment and management, mapping, water resources terminology and water economics. In 2008 he received the International Hydrology Prize of the IAHS, UNESCO and WMO.



Jac van der Gun

**Jac van der Gun** is a groundwater hydrologist. After graduating at Wageningen University he worked for one year at a water supply company in The Netherlands and then for four years in Bolivia, participating in water resources assessment activities initiated by UNDTCD. After that he joined the *Institute of Applied Geoscience* of the R&D organisation TNO (*Applied Scientific Research*) in The Netherlands, where he remained until retirement.

At TNO, Jac van der Gun participated in the Groundwater Reconnaissance of The Netherlands, and after a few years took over the overall responsibility for this programme. Soon he was also involved in the international water resources assessment and manage-

ment projects of the institute. Among others, he was the resident manager of water resources assessment projects in Yemen and Paraguay, and carried out numerous short missions in Asia, Latin America, Africa and Europe for various international and national organisations, providing scientific-technical input, supervising projects, and formulating or evaluating projects and programmes. He has also lectured at UNESCO-IHE on groundwater for more than thirty years.

Jac van der Gun was actively involved in establishing the International Groundwater Resources Assessment Centre (IGRAC) and in 2003 became its first director. He is still active in several groundwater-related projects of international organisations, mostly as a consultant to UNESCO or IGRAC.

# Introduction

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Water not only covers three quarters of the Earth's surface: it is also present almost everywhere below ground surface, down to considerable depths and in continuous motion. Groundwater – as we can refer to the vast majority of this subsurface water<sup>1</sup> – is an invisible component of the hydrosphere, representing a hidden part of the water cycle. The general public is not unaware of groundwater, but usually knows hardly anything about it.

Since time immemorial people all over the world have been able to find and exploit subsurface water to supply themselves, or they have managed to drain subsurface water to facilitate mining activities and land use. Over time, they have invented various techniques to capture groundwater and bring it to the surface, making use of different sources of energy, ranging from gravity and muscular energy of humans and animals to wind energy, fossil fuel, electricity or solar pumps. Today, the world's population abstracts two hundred times more water than oil, in terms of volume per year, from the subsurface. Groundwater is widely used in many countries. It is often the primary source of drinking water (supplying half of the world's population) and contributes significantly to irrigation, hence to food security in arid and semi-arid regions. It therefore represents an important component of the water economy. However, for a long time there has been a general misunderstanding about where groundwater comes from and where it is going to. Likewise, proper and accurate knowledge on the place and role of groundwater in the water cycle has been lacking. Groundwater has been the subject of numerous myths rather than of scientific knowledge. Even today, it is a poorly understood resource. Too many simplistic and often erroneous ideas do not do justice to the diversity and complexity of groundwater around the world. For a long time, fundamental misconceptions on groundwater have persisted, as is illustrated in Box 1.1. This suggests that other conceptual flaws in understanding groundwater may still exist, without the professional community being aware of them.

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<sup>1</sup> Strictly speaking, subsurface water is divided into groundwater and water in the unsaturated zone. The latter is present above the groundwater table and has a much smaller volume than groundwater.



**Box 1.1: Where does groundwater come from?**

One of the reasons why a scientific notion of the water cycle appeared so late comes from the lack of understanding of groundwater movement. Perceptions related to groundwater were often primarily based on the imagination, or even on mythology, rather than on scientific observation.

From ancient times and up until the seventeenth century, from Aristotle to Descartes, the prevailing belief was curiously enough that groundwater would move in a direction opposite to what we know now, thus from the bottom of the sea to the mountains, from where springs would emerge. This movement was supposed to take place through mysterious channels underground (on its way inexplicably losing salinity ...), as depicted by Father Kircher in 1665 (Figure 1.1).

Only a few brilliant men, in particular the Greek philosopher Anaxagoras (fifth century BC), the Roman architect Vitruvius (first century BC) and Leonardo da Vinci (sixteenth century), had the intuition to attribute the origin of groundwater to the infiltration of rain.

Our current understanding of the subsurface component of terrestrial waters has made it possible to establish the overall direction of groundwater movement in conformance with observations in the field. This corrected view is reflected in pictures designed to illustrate the concept of the hydrological cycle and to educate the general public on it (see next chapter, Figure 2.3). Knowledge of the origin and the final destination of groundwater has become one of the pillars on which the science of hydrogeology was founded. However, only in recent decades has attention been paid to the role that groundwater plays in the water cycle on global and national scales.

Groundwater is an ordinary component of the water cycle, not independent of the other components. A special approach and effort to understand it are nevertheless appropriate, because what most people know about groundwater is not in proportion to the use they make of it. Groundwater resources are often still poorly assessed and hardly managed, even excessively exploited and wasted, but elsewhere underestimated and unused; a wide diversity of conditions can be observed across the globe.

During the twentieth century, exploitation and pollution put unprecedented stress on groundwater in various regions – in both developed and developing countries. This stress was caused by numerous uncoordinated and unplanned individual activities. In other regions, however, people seemed to remain unaware of the potential benefits of this resource and to make no or very little use of it.

This is a book on the geography of the world's groundwater, with emphasis on its physical aspects, but to some extent also dealing with related economic aspects and management. It is somewhere in between a book for scientific and technical readers – such as *'Groundwater resources of the world and their use'* by Zektser



### A few words of caution

This book contains a lot of data aggregated by country or by continent, or even over the entire world. Most of this aggregated data has been taken from national and international databases or publications. Assessing the quality of this data is extremely difficult and was considered not feasible in preparing this compilation. Data quality is undoubtedly highly variable, given the large differences in data acquisition practices from country to country – even inside countries – and the varying percentage of areas for which no real data but only rough estimates are available. It is also not uncommon to find different versions of the same statistics in different databases. Reproducing alternative versions (with references to the information sources) has not been avoided in this text, as long as this data was considered plausible. The reader should be alert to the many possible flaws in the individual data and instead look at the global or regional variations or patterns defined by the entire set of data.

Maps are very effective for showing variations and patterns across the globe. Therefore, many world maps are included in the following chapters. The maps that show data by country – corresponding to the conventional political geography – are mainly designed to visualise statistical tables, based usually on national sources. However, variations between countries in size and demography affect the impression that these maps may give on the state of the world and inevitably produce a bias in the perception of the information presented. The effect of country or population size has been eliminated in some of the maps by expressing the displayed variable in units per square kilometre or per inhabitant (per capita). Some maps that are not country-oriented may also reduce the described inconvenience.

A related consequence of using mainly national data to develop a global picture is that it does not sufficiently highlight the regional variations inside countries that are either very large or rich in contrasts.

## REFERENCES

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# Groundwater in the global water cycle

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- *Quantities of fresh and saline water inside the Earth's crust*
- *Fresh groundwater fluxes and their geographic distribution*
- *Groundwater in the global water cycle: groundwater recharge and discharge*
- *Links with surface water*
- *Groundwater in arid and semi-arid regions*

## 2.1 WATER BELOW THE GROUND SURFACE

Water is beyond any doubt the most widespread liquid inside the earth's crust. Most of the permeable porous or fissured rocks – the environment in which aquifers<sup>1</sup> are located –, and even many low-permeability rocks such as clays, contain water down to considerable depths (several kilometres, occasionally more than ten). But the volumes of water and their contents of dissolved solids are highly variable: the volume of invisible water present below one hectare of land may vary from a few thousand to several million cubic metres (m<sup>3</sup>). It is therefore difficult to calculate the volume of groundwater in a region or country – and calculating the volume of groundwater stored in the entire world is even more difficult.

Various researchers have nevertheless attempted to calculate the total volume of groundwater on Earth (see Table 2.1), in order to compare it with the volumes of water present in other compartments of the terrestrial hydrosphere, and even to explore how it is distributed across the continents (Figure 2.1). An estimated eight to ten million cubic kilometres (km<sup>3</sup>) of fresh groundwater represents the lion's share of all liquid freshwater on Earth, or to be more precise: about 98 to 99% of it (see Figure 2.2). In comparison, the global volume of freshwater in lakes is less than 1% of the total fresh groundwater volume. However, the volume of freshwater stored in the Earth's crust represents only one per cent of the total volume of water in the

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1 Hydraulically continuous bodies of relatively permeable porous or fissured rocks containing groundwater are called '*aquifers*', whereas groundwater-filled bodies of poorly permeable formations are called '*aquitards*' or '*aquicludes*', depending on whether or not minor groundwater seepage rates are still possible. Aquifers are the domains where the bulk of all groundwater flow takes place, because their comparatively high permeability favours flow. However, aquitards may hold large volumes of groundwater that can be exchanged with the aquifers through the large surface of contact they share.

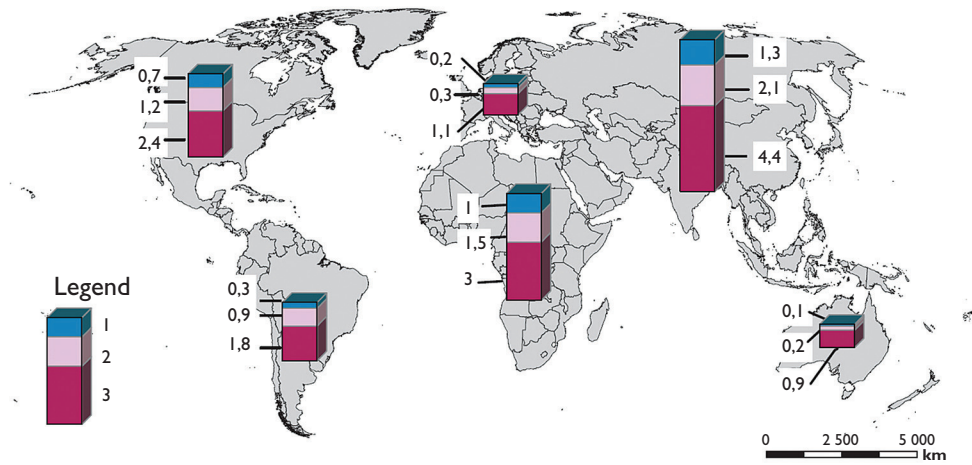
Table 2.1 Groundwater stock and flow on the continents. Some global estimates.

Source	Stock in thousands of km <sup>3</sup>			Flow
	Freshwater	Brackish or saline water	Total	Mean groundwater flux in km <sup>3</sup> /year
Nace 1964, 1968	8 336 <sup>1</sup>			
USGS/Nace 1967	8 350			
L'Vovich 1967, 1974 (English translation 1979)	4 000 <sup>2</sup>		60 000 <sup>3</sup>	12 000
Korzun 1974/USSR Com. UNESCO's IHD 1974	10 530 <sup>4</sup>	12 870	23 400 <sup>5</sup>	13 320 <sup>6</sup>
UNESCO 1978				13 200
UNESCO 1990 and Shiklomanov 1992, 2003	9 800	13 600	23 400 <sup>5</sup>	
Baumgartner & Reichel 1975	8 062 <sup>7</sup>			
Mather 1984	8 800			
Bureau des Longitudes (France) 1984	8 600 <sup>8</sup>			
National Council on Scientific Research USA 1986			15 300	
UNESCO 1988	8 500			
World Resources Institute 1991	8 200			
Döll <i>et al.</i> 2002				14 000 <sup>9</sup>
FAO 2003				11 284 <sup>10</sup>
Döll and Flörke 2005				12 882 <sup>11</sup>
Döll and Fiedler 2008				12 700 <sup>11</sup>
Wada <i>et al.</i> 2010				15 200 <sup>12</sup>
AQUASTAT 2011				11 968 <sup>13</sup>

## Notes:

- 1 Converted from  $2 \times 10^6$  cubic miles, of which 50% at less than 800 m depth and 50% at greater depths.
- 2 Groundwater in active water exchange zone, including 85 as soil moisture.
- 3 After Vernadsky and Makarenko.
- 4 Includes  $16.5 \times 10^{12}$  m<sup>3</sup> of soil moisture and  $300 \times 10^{12}$  m<sup>3</sup> of subsurface permafrost ice.
- 5 Excluding Antarctica:  $\sim 2\,000 \times 10^{12}$  m<sup>3</sup> of freshwater ice.
- 6 Groundwater outflow into streams – annual naturally renewed groundwater resources: calculation by hydrograph separation, excluding an estimated 2 200 km<sup>3</sup>/year of direct outflow into the oceans.
- 7 Including  $61.3 \times 10^{12}$  m<sup>3</sup> of soil moisture;  $3\,550 \times 10^3$  km<sup>3</sup> corresponds to depths less than 800 m.
- 8 Down to 4 000 m of depth, of which  $4\,000 \times 10^3$  km<sup>3</sup> corresponds to depths less than 800 m.
- 9 Groundwater recharge calculated with the Water GAP-2 model.
- 10 Sum of country data on groundwater produced internally (national sources compiled for the FAO database, 2003).
- 11 Groundwater recharge calculated with the WGHM model and mesh width of 0.5°, 1961–1990 average.
- 12 Groundwater recharge calculated with the PCR-GLOBWB model and mesh width of 0.5°, 1961–1990 average.
- 13 Sum of country data on groundwater produced internally (compiled by AQUASTAT from national sources, latest update). Data is missing for 3.35% of the territory of the continents; hence the incomplete sum has been corrected for this percentage.





- 1 Zone of active exchange, phreatic or confined aquifers down to 100 m of depth – freshwater (global total: 3.6).  
 2 Zone of moderately active exchange, most often confined aquifers, between 100 and 200 m of depth – predominantly freshwater (global total: 6.2).  
 3 Zone of little active exchange, down to 2 000 m of depth, predominantly saline water (global total: 13.6).

Figure 2.1 Order of magnitude of the volumes of groundwater stored, by continent (in millions of cubic kilometres, or  $10^{15} \text{ m}^3$ ). [Data sources: Korzun (1974); Shiklomanov (1990); Shiklomanov and Rodda (2003).]

hydrosphere, including the oceans. Estimating volumes of groundwater stored is most appropriate at regional scales, particularly in relation to large aquifers (see Chapter 3) and is rarely done at country level. A few examples of the latter category are presented in Table 2.2.

These astronomical numbers, of which only the order of magnitude is meaningful, are mainly of academic interest and should not mislead us. In fact, unlike most mineral resources, groundwater is in most cases a renewable resource, which allows groundwater to be developed sustainably, making use of the dynamics of groundwater in the present-day water cycle. Only a minor part of the enormous groundwater volumes or ‘reserves’ is dynamic, which means: more or less regularly replenished by recharge<sup>2</sup> and sufficiently mobile to play the role of a natural regulator or buffer. Although the dynamic reserves probably account for only a few per cent of the total volume (‘stock’ or ‘storage’) of groundwater, they are still considerable. The majority of these dynamic groundwater resources is found in phreatic aquifers<sup>3</sup>. Globally aggregated, the seasonal or multiannual variation

<sup>2</sup> Groundwater recharge, renewal or replenishment is the inflow of water into a groundwater system.

<sup>3</sup> A phreatic aquifer or ‘water-table aquifer’ is an aquifer in which the upper boundary of the groundwater mass forms a surface (water table) that is in direct contact with the atmosphere through the soil pores. This condition favours the aquifer being actively involved in the water cycle. The upper limit of a confined aquifer, on the contrary, is the bottom of an overlying poorly permeable formation

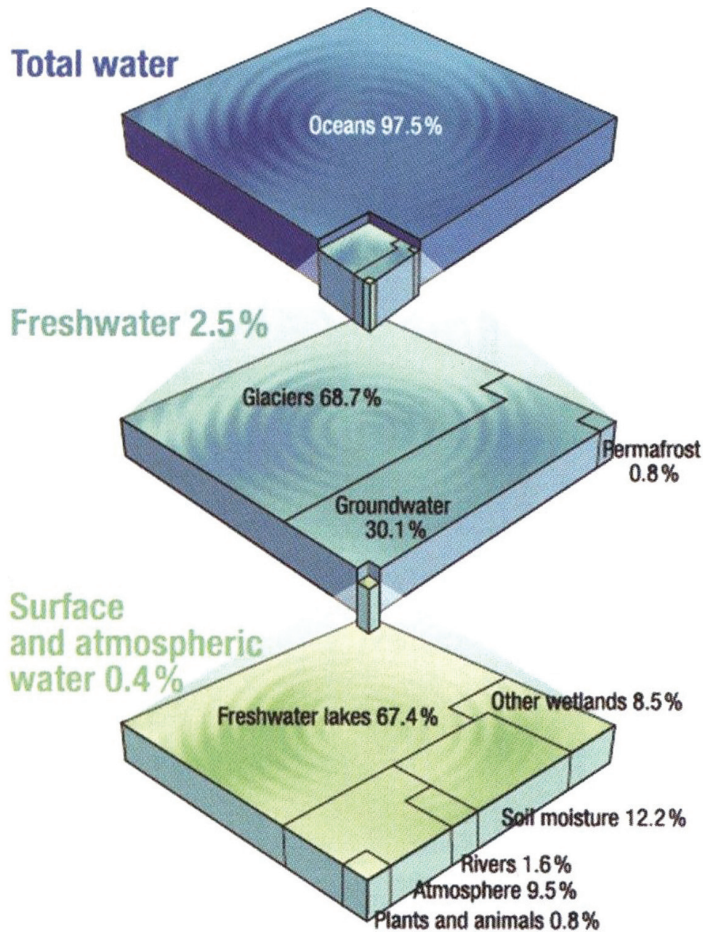


Figure 2.2 Global distribution of the world's water. [Source: WWAP (2006), based on data from Shiklomanov and Rodda (2003)]. Freshwater has a global volume of 35.2 million cubic kilometres.

in the groundwater volume stored in this category of aquifers is of the order of 10 000 billion m<sup>3</sup>.

Stocks of water in the earth's crust should therefore certainly not be used as the sole basis for assessing the quantity of the groundwater resources, despite the perhaps misleading impression given by different literature sources<sup>4</sup>. On an aggregated level,

(confining bed) that prevents the aquifer from interacting directly with the atmosphere and with surface water bodies.

<sup>4</sup> For example, Allègre (1993) writes: "La majorité des ressources en eau sont souterraines: cinq à dix mille fois supérieures aux eaux de surface" (*The majority of the water resources is underground: five to ten thousand times more than surface water*), which is reiterated by Diop and Recacewicz (2003). Similarly,



Table 2.2 Examples of total groundwater reserves calculated by country.

Country	Estimated total volume of groundwater (in km <sup>3</sup> )	Comments	References
Saudi Arabia	2 185	Down to 300 m of depth	Abdurrahman 2002
Australia	20 000	Great Artesian Basin only	Habermehl 1980, 2001
Brazil	111 661		Rebouças 1988
Egypt	150 000	Nubian Sandstone Aquifer System only	Khater 2005
France	2 000		BRGM 1986
Libya	35 000	Sirte, Kufra and Murzuk Basins only	El Gheriani 2002
USA	125 040	Of which 50% in shallow aquifers and 50% in deep aquifers	USGS 1975

the quantity of a natural resource can be characterised by two key variables: stock (quantity present, volume stored) and flow (rate of growth, rate of renewal). The latter allows sustainable exploitation to take place without depleting the resource in the longer term, while the former buffers variations in inflow over time. Compared to surface water, atmospheric water and most other components of the water cycle, groundwater tends to have a high stock/flow ratio. However, it is due to flow that groundwater participates in the planet's water cycle and that groundwater can, in most cases, be considered a renewable resource.

Table 2.1 suggests that the mean globally aggregated flow – represented by the mean groundwater recharge – is between 11 000 and 15 000 km<sup>3</sup> per year for climatic conditions prevailing during the second half of the 20th century.

For most aquifers, flow is more relevant than stock for characterising the groundwater resources quantity. So-called 'fossil groundwater'<sup>5</sup> is an exception: the corresponding water resources are expressed as a volume, like in the case of minerals, but these non-renewable resources include only the extractable fraction of the stock (see Chapter 4).

Zaporozec (2002) states: "Groundwater (...) represents some 98 per cent of the planet's freshwater resources". Shiklomanov and Rodda (2003) also refer to groundwater reserves calculated by continent as 'resources', while SEMIDE's bulletin of June 2005 repeats: "Groundwater represents around 97% of the available water resources on the planet".

<sup>5</sup> 'Fossil groundwater' or 'non-renewable groundwater' refers to groundwater bodies formed in the geological past that do not receive significant replenishment under current climatic conditions (see Chapter 4).