

The world's groundwater resources

Contribution to Chapter 4 of WWDR-2 (Draft)

Dr Jaroslav Vrba
Jac van der Gun (coordinator)

Utrecht
December 2004

Table of contents

1 Importance of groundwater	1
2 Occurrence	3
3 Natural groundwater quality	5
4 Non-renewable groundwater	7
5 Impact of abstraction	8
6 Monitoring and management	10

Figures

Fig 4-9-1 Mean groundwater abstraction rates (mm/a) (IGRAC, 2004)	2
Fig 4-9-2 Groundwater abstraction by water use sectors (proportions) (IGRAC, 2004).....	2
Fig 4-9-3 Global groundwater regions: predominant mode of groundwater occurrence and mean rate of renewal (IGRAC, 2004)	3
Fig 4-9-4 WHYMAP – The world’s Groundwater Resources (simplified after the 1: 50 000 000 scale version of the map; source: BGR, Hannover).....	4
Fig 4-9-5 Typical groundwater flow, age and hydrochemical patterns in basin settings (adapted from British Geological Survey).....	5
Fig 4-9-6 Arsenic in shallow wells (<150 m) in Bangladesh (source: MML/BGS project “Groundwater Studies for Arsenic Contamination in Bangladesh”)	6
Fig 4-9-7 Aquifer-wide groundwater level declines in Yemen.....	8
Fig 4-9-8 Land subsidence in Shanghai arising from groundwater abstraction	8

Tables

Table 4-9-1 Natural groundwater quality hazards: contents observed in some case studies.....	6
Table 4-9-2 Selected large aquifer systems with non-renewable groundwater resources	7

Boxes

Box 4-9-1 The 10 countries with largest groundwater abstraction	1
---	---

1 Importance of groundwater

Groundwater systems are replenished by precipitation and surface water and discharge into surface waters, the ocean or by evapotranspiration back in the atmosphere. Groundwater circulation globally is less than atmospheric and surface waters but what is stored beneath the earth's surface is orders of magnitude larger. Its total volume represents 96% of all earth's unfrozen fresh water¹. Without groundwater, the face of the earth would look different. Groundwater feeds springs and streams, supports wetlands, maintains land surface stability in areas of unstable ground and overall is a critical water resource serving mankind's water needs². For example, it meets over 75% of the water needs in Estonia, Iceland, Russian Federation, Jamaica, Saudi Arabia, Georgia, Swaziland, Mongolia, Libya and Lithuania. Figure 4.9.1 reflects intensity of groundwater abstraction in different countries: particularly high (per km²) groundwater abstractions occur in Bahrain, Taiwan, Mauritius, Malta, Pakistan, Bangladesh, India and Israel. Figure 4-9-2 shows the extent groundwater is allocated to agricultural, domestic and industrial use. Box 4-9-1 lists the 10 countries in the world with largest groundwater abstraction. About 60% of groundwater withdrawn is used by agriculture; the rest is almost equally divided between the domestic and industrial sectors. The predominant use is agriculture in many countries where arid and semi-arid climates prevail³. Predominantly industrial sector use is in a few countries only. In many nations, more than half of the withdrawn groundwater is for domestic water supplies and globally it provides 25 to 40 % of the world's drinking water⁴. Today, half the world's megacities and hundreds of other major cities on all continents rely upon or make significant use of groundwater. Small towns and rural communities particularly rely on it for domestic supplies. Even where groundwater provides lower percentages of total water used, it still may serve local areas where otherwise no other accessible supply exists and it usually does so with relatively low cost and good water quality. Finally, groundwater bridges water supply gaps during long dry seasons and during droughts.

Box 4-9-1 The 10 countries with largest groundwater abstraction

Country	Groundwater abstraction (km ³ /yr) reference year		Main use (main sector)	% of main sector demands covered by groundwater
India	190	1990	Agriculture	53
USA	115	2000	Agriculture	42
China	97	1997	Agriculture	18
Pakistan	60	1991	Agriculture	34
Iran	57	1993	Agriculture	50
Mexico	25	1995	Agriculture	30
Russ. Federation	15	1996	Domestic	80
Saudi Arabia	14	1990	Agriculture	96
Italy	14	1992	Agriculture	
Japan	14	1995	Industry	35

Sources: FAO/AQUASTAT; UNEP/GEO-3; FAO, 1997; FAO, 2000; USGS, 2004 (personal communication).

¹ Shiklomanov, I.A., and J.C. Rodda, 2003. *World Water Resources at the Beginning of the 21st Century*. UNESCO/IHP Int. Hydrology Series, Cambridge University Press.

² See e.g. the databases of FAO (AQUASTAT - <http://www.fao.org/ag/agl/aglw/aquastat/dbase/index.stm>), UNEP (GEO-3 Data Compendium - <http://geocompendium.grid.unep.ch/index.htm>) and IGRAC (GGIS /Global Overview - http://igrac.nitg.tno.nl/ggis_start.html) and FAO's Water Reports no's 7 (1995), 9 (1997) and 20 (2000).

³ See IGRAC's GGIS database and UNEP's GEO-3 database.

⁴ UNEP, 2003: *Groundwater and its Susceptibility to Degradation*. UNEP/DEWA, Nairobi.

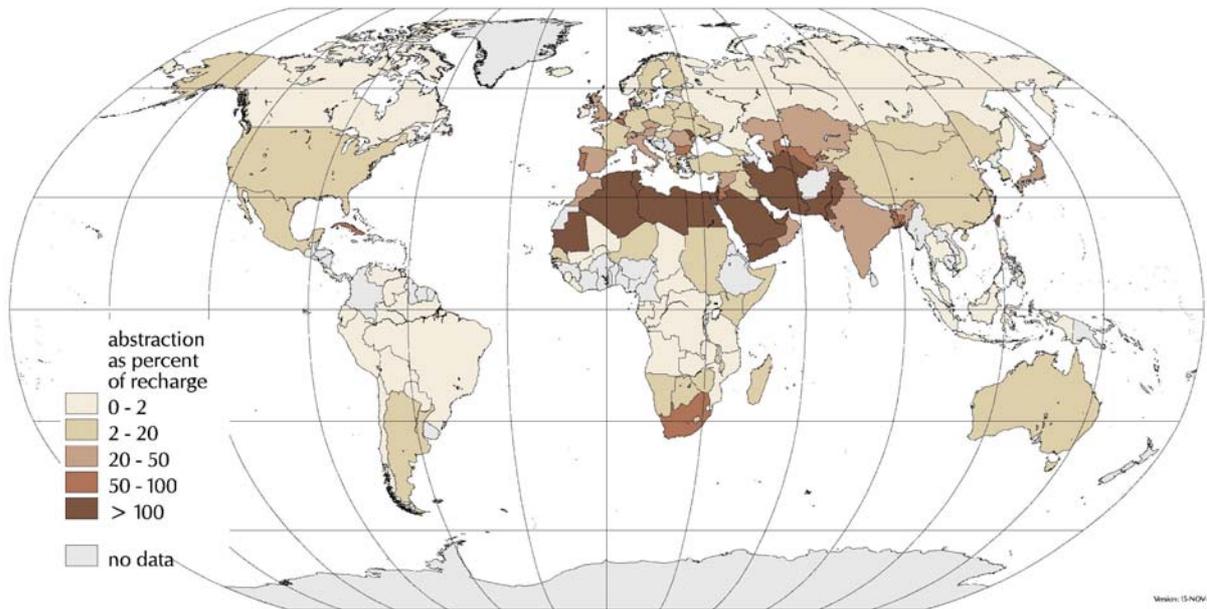


Fig 4-9-1 Mean groundwater abstraction rates (mm/a) (IGRAC, 2004)

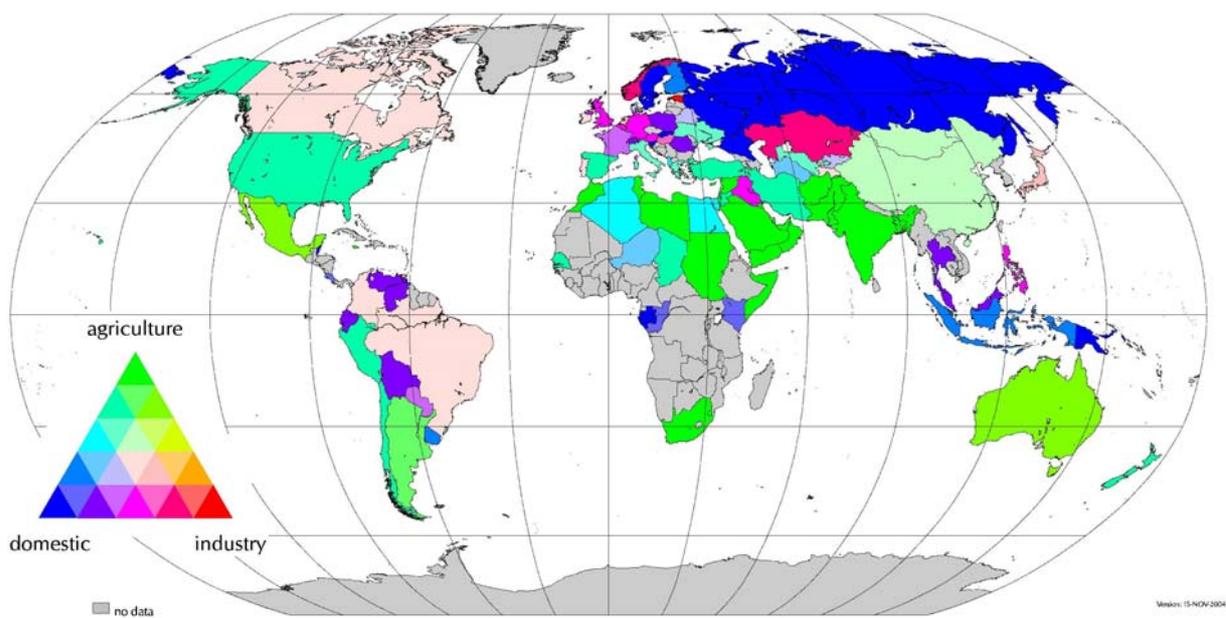


Fig 4-9-2 Groundwater abstraction by water use sectors (proportions) (IGRAC, 2004)

2 Occurrence

As recent UNESCO supported activities show⁵, large variations in groundwater exist in terms of its occurrence, rate of renewal and volume stored. Geological setting is an important factor. Shallow basement aquifers with limited storage are contrasting with large volumes of groundwater stored in thick sedimentary basins, aquifers in folded mountain zones tend to be fragmented and variable, while volcanic rock environments create special hydraulic and water quality conditions. Fig 4-9-3 shows the world divided into 36 Global Groundwater Regions and gives an idea of their predominant hydrogeological setting by classifying them into four categories: *Basement*, *Sedimentary Basin*, *High-Relief Folded Mountain* and *Volcanic regions*.. Shallow aquifer systems with near-surface water tables are present in most regions. Unlike deep groundwater, shallow groundwater is strongly linked to surface waters in a hydraulic sense. Variations of mean groundwater renewal rates between regions are reflected in the map by variation of colour intensities, with low colour intensity in regions with predominantly arid climates or with permafrost. In some arid zone areas, limited groundwater renewals contrast with large groundwater reserves created mainly during past pluvial periods of the Pleistocene (hatched zones in Fig 4-9-3).

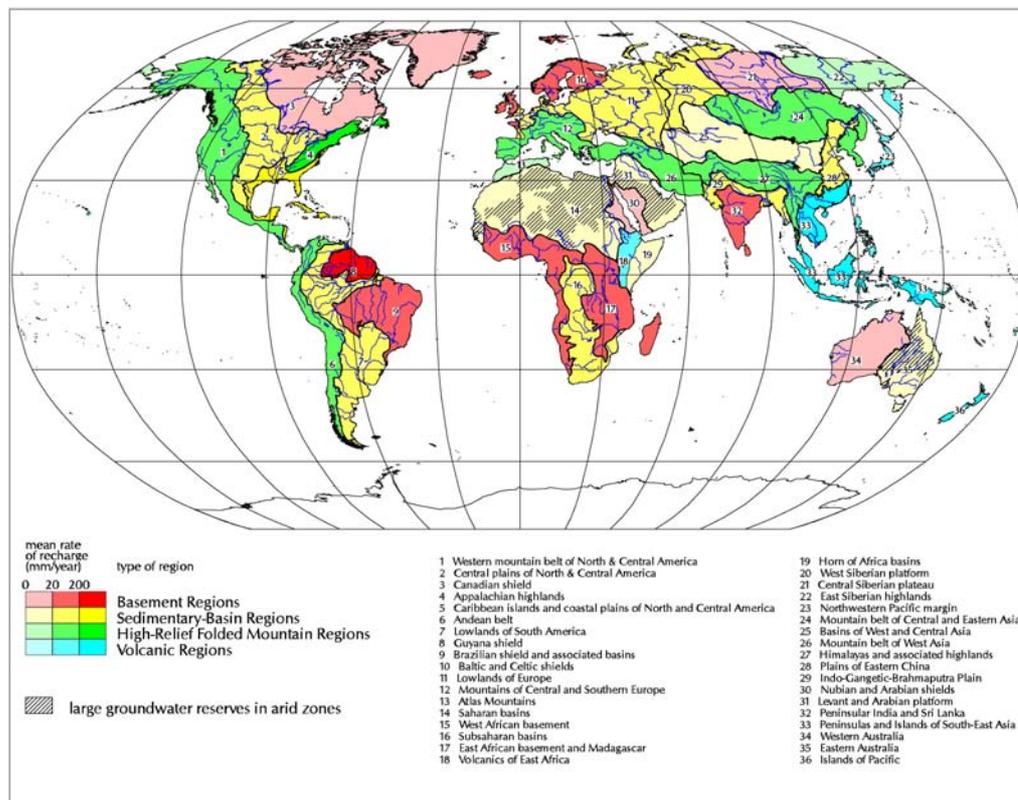


Fig 4-9-3 Global groundwater regions: predominant mode of groundwater occurrence and mean rate of renewal (IGRAC, 2004)

Small-scale world map on the basis of 36 Global Groundwater Regions depicting the predominant hydrogeological setting (Basement (red), Sedimentary Basin (yellow), High-Relief Folded Mountain (green) and Volcanic (blue)). Higher groundwater renewal rates, as averaged over each of the mentioned Global Groundwater Regions, are reflected in Fig 4-9-3 by higher colour intensities.

⁵ Zekster and Everett, 2004. *Groundwater Resources of the World and their Use*. UNESCO, IHP-VI Series in Groundwater No 6.

WHYMAP, 2004. *Groundwater Resources of the World*. Map 1: 50 M. Special Edition, August 2004, BGR Hannover/ UNESCO, Paris.

IGRAC, 2004. *Global Groundwater Information System* (http://igrac.nitg.tno.nl/ggis_start.html).



Fig 4-9-4 WHYMAP – The world’s Groundwater Resources (simplified after the 1: 50 000 000 scale version of the map; source: BGR, Hannover)

The map intends primarily to give an overall picture of the more and less favourably groundwater endowed zones on the globe.

3 Natural groundwater quality

A groundwaters' natural geochemistry reflects its host-rock or soil composition/minerals, its solubility and the rate at which water passes through it – basically its residence and surface contact time within a given geologic material. Within single groundwater systems, total dissolved solids content (TDS) and chemical composition change measurably over distance along the flow path as in-situ processes interact (Fig 4-9-5). Most renewable groundwater supplies commonly have a natural quality that is adequate for domestic, irrigation and other uses. However, examples of higher than desired levels⁶ of constituents such as iron, manganese, fluoride, arsenic (Fig 4-9-6) and other constituents can restrict its untreated suitability and some hazardous concentrations constituents which have been noted in groundwater are summarized in Table 4-9-1. Saline conditions developing in soil and groundwater occur both naturally and from man's actions in coastal aquifers as sea water intrudes when freshwater levels are lowered⁷; in arid and semi-arid regions with extensive high evapotranspiration rates⁸; as concentrated brines migrate¹⁴ or where sediments contained high salt content during their deposition⁹. A specific category forms groundwater high in minerals, gas and temperature, which is mostly connected with past and present volcanic activities.

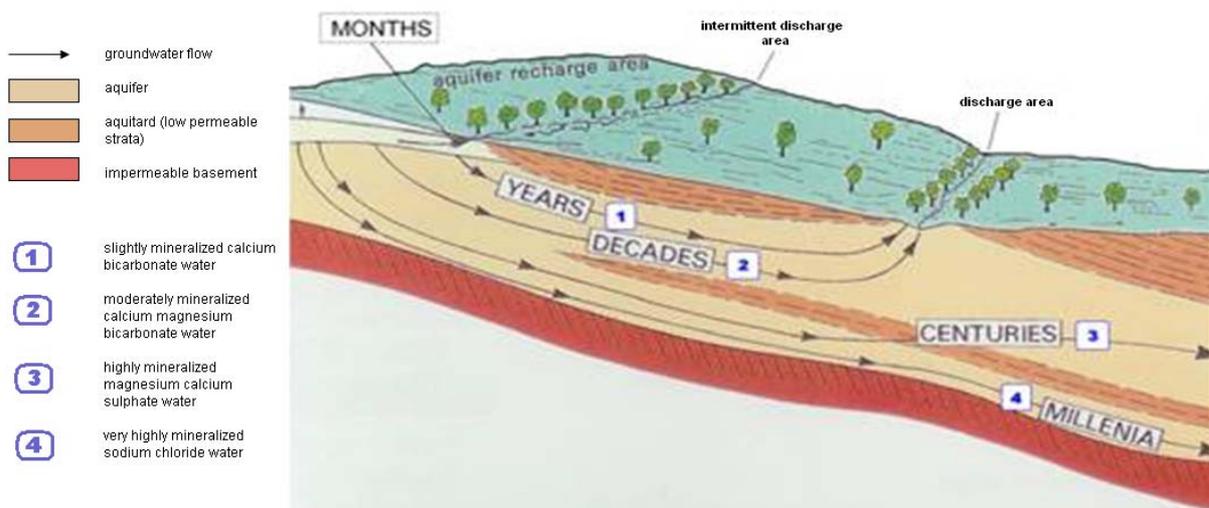


Fig 4-9-5 Typical groundwater flow, age and hydrochemical patterns in basin settings (adapted from British Geological Survey).

Groundwater in recharge areas and near-surface aquifers usually has low TDS levels (with bicarbonate the dominant anion) which reflect short contact times between water and rocks (usually tens of years). Down the flow direction, groundwater TDS increases, as gradual changes occur in the proportions of the major ions according to longer contact times and more reaction with the minerals in the rocks takes place. Commonly there is gradual transition along the flow paths from fresh bicarbonate groundwater through sulphate water to heavily mineralised chloride water. Part of this evolution is observed in most large groundwater basins, but the complete sequence is seldomly present¹⁰.

⁶ Matthes, 1982 and Edmunds and Smedley, 1996)

⁷ Chapman, D. (editor), 1992. *Water quality assessments*. Chapman and Hall, Cambridge.

⁸ Matthes, G., 1982. *The properties of groundwater*. A Wiley-Interscience Publication, New York.

⁹ Morgan, K. and J. Jankowski, 2003. *Origin of salts in a fractured bedrock aquifer in the Central West Region, NSW Australia*. In: Proceedings Int. Conf. on Groundwater in fractured rocks, pp 221-222, UNESCO Series on Groundwater No.7, Paris.

¹⁰ Domenico, P., 1972. *Concepts and models in Groundwater Hydrology*. McGraw-Hill, Inc.

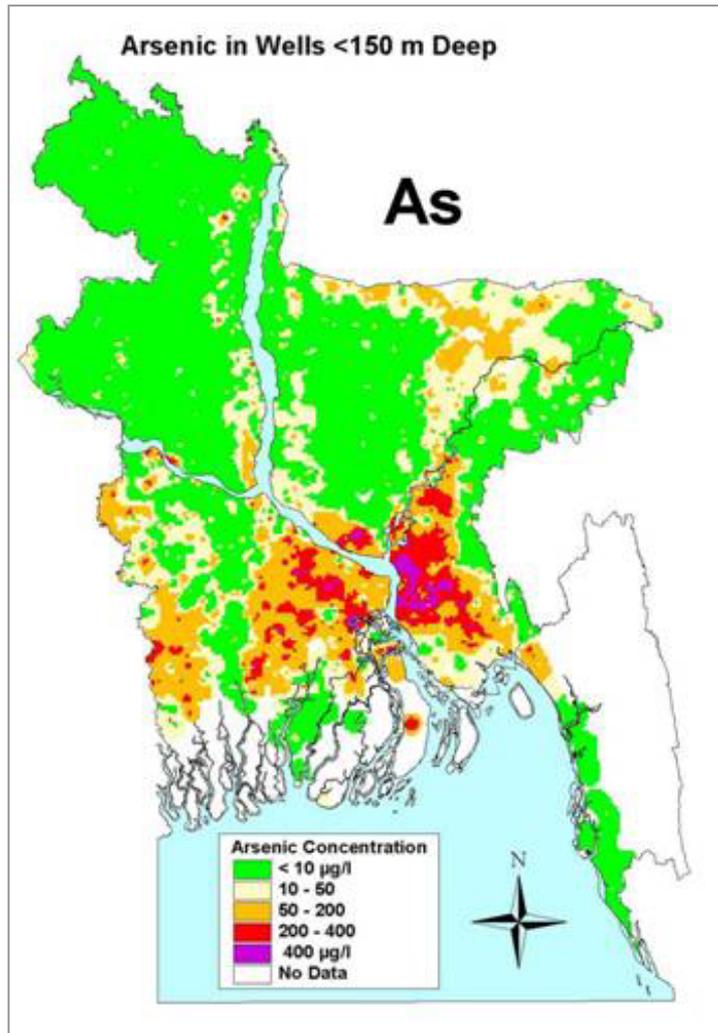


Fig 4-9-6 Arsenic in shallow wells (<150 m) in Bangladesh (source: MML/BGS project “Groundwater Studies for Arsenic Contamination in Bangladesh”)

Table 4-9-1 Natural groundwater quality hazards: contents observed in some case studies

country	chemical constituents	content (mg/l)	drinking water standards (mg/l)	origin
India, Bangladesh	arsenic	1.1 – 5.0	0.01	arsenic bearing minerals ¹
Czech Republic, India	fluorine	4.5 – 10.0	1.5	fluorine bearing minerals ^{2,3}
China	chloride	8 818	250	sea water intrusion ⁴
Australia	chloride	4 718	250	connate salts ⁵
USA	sodium	121 000	200	salt bearing strata ⁶
USA	aluminium	64.0	0.2	marine argillaceous rocks ⁷
China, India	pH	2 - 4	6.5 – 8.5	acid mine water ⁸

1 Chakraborti (2002), 2 Hercik et al. (2003), 3 Singhal and Gupta (1999), 4 Guanghui and Yuhong (2004), 5 Morgan and Jankowski (2003), 6,7 Matthes (1982), 8 Singhal and Gupta (1999).

4 Non-renewable groundwater

Groundwater as a resource can be characterized by two main variables - its rate of renewal (groundwater recharge rate indicator – see Table 4-3-2) and its volume in storage. Groundwater is renewed globally at a rate about equal to 30% of the rate of renewal of surface water. However, in terms of volume stored, there is approximately one hundred times more groundwater than surface water stored on the globe¹¹. Where present-day annual groundwater renewal is negligible compared with the stored volumes, most of the groundwater stored is not related to contemporaneous recharge but to recharge events which took place in the remote past. Such groundwater is called ‘non-renewable groundwater’ or ‘groundwater reserves’. Its exploitation cannot be balanced by recharge of groundwater today, but will cause a steady reduction of the stored volume. The world’s largest non-renewable groundwater systems (Table 4-9-2) are located in arid zones of Northern Africa, the Arabian Peninsula and Australia, and under the permafrost in Western Siberia. Some of these reserves are large enough to maintain sizeable abstraction rates for many tens to hundreds of years. ‘Sustainable groundwater development’ commonly is understood as exploiting the resource in dynamic equilibrium, leaving reserves, on average, undiminished. Where renewable water resources are scarce and groundwater non-renewable reserves are large, however, it may be justified to exploit the reserves when this would not produce undesired side-effects¹².

Table 4-9-2 Selected large aquifer systems with non-renewable groundwater resources¹³
(simplified after UNESCO Working Group on Non-Renewable Groundwater Resources, 2004)

Countries	Aquifer System	Area (km ²)	Estimated total volume (km ³)	Estimated exploitable volume (km ³)	Estimated annual recharge (km ³)	Estimated annual abstraction (km ³)
Egypt, Libya, Sudan, Chad	Nubian Sandstone Aquifer System	2,200,000	150,000 to 457,000	> 6,500	13	1.6
Algeria, Libya, Tunisia	NW Sahara Aquifer System	1,000,000	60,000	1,280	14	2.5
Algeria, Libya, Niger	Murzuk Basin	450,000	> 4,800	> 60 to 80		1.75
Mali, Niger, Nigeria	Iullemeden Aquifer System	500,000	10,000 to 15,000	250 to 550	50 to 80	
Niger, Nigeria, Chad, Cameroon	Chad Basin Aquifer	600,000		>170 to 350		
S.Arabia, UAR, Bahrain, Qatar	Multilayer Aquifer Arabian Platform	250,000		500?	30	13.9
Australia	Great Artesian Basin	1,700,000	20,000	170	50	0.6
Russia	West Siberian Artesian Basin	3,200,000	1,000,000		55	

¹¹ FAO, 2004. *Aquastat* (<http://www.fao.org/ag/agl/aglw/aquastat/dbase/index.stm>)
Shiklomanov, I.A., and J.C. Rodda, 2003. *World Water Resources at the Beginning of the 21st Century*. UNESCO/IHP Int. Hydrology Series, Cambridge University Press.

¹² Abderrahman, W. A., 2003. *Should intensive use of non-renewable groundwater resources always be rejected?* In: Llamas & Custodio: *Intensive Use of Groundwater – Challenges and Opportunities*, Balkema, Lisse, The Netherlands.

¹³ Two criteria have to be satisfied by such aquifers: (a) stored volume of groundwater at least 100 times greater than current annual recharge; and (b) the exploitation of non-renewable resources should not have a significant impact on recharged water bodies.

5 Impact of abstraction

Groundwater abstraction has increased dramatically during the second half of the twentieth century, producing important benefits, as well as negative side-effects¹⁴. The benefits are beyond any doubt, as already . An impressive example is India, where the area of irrigated land approximately has doubled during the mentioned period, mainly as a consequence of groundwater development. But there are unintended negative impacts as well, because intensive exploitation of the resource causes significant changes to the local water regime: groundwater levels decline; yields of springs, contributions to baseflow and other natural groundwater outflows are reduced; the intrusion of saline water or other water of allochthonous quality may be triggered. These changes have many practical consequences: wells and qanats become less productive and eventually run dry; groundwater becomes more expensive; aquifers may become exhausted; spring and baseflow users will lose part or all of their water; groundwater quality may deteriorate; ecosystems related to groundwater may be affected; and environmental impacts produced. Examples are storage depletion in Yemen¹⁵ (Fig 4-9-7), land subsidence in Shanghai¹⁶ (Fig 4-9-8); and degradation of the Tablas de Daimiel national park in Spain¹⁷. Intensive exploitation is producing particular stress on the sustainability of groundwater systems in arid countries of the Middle East and North Africa and in Pakistan (Figure 4-9-9), and also in several parts of India, US and other countries where aridity and high population density occur. Shallow aquifers with limited storage capacity are particularly vulnerable to droughts and are more quickly exhausted by intensive abstraction than thick aquifers with large groundwater volumes in storage. Other factors play a role in the case of impacts on ecosystems or the environment, e.g. the link with surface water systems (in the case of wetlands) or the presence of compressible layers (in the case of land subsidence).

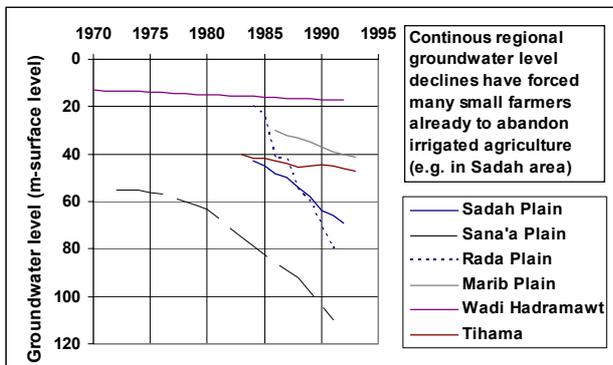


Fig 4-9-7 Aquifer-wide groundwater level declines in Yemen

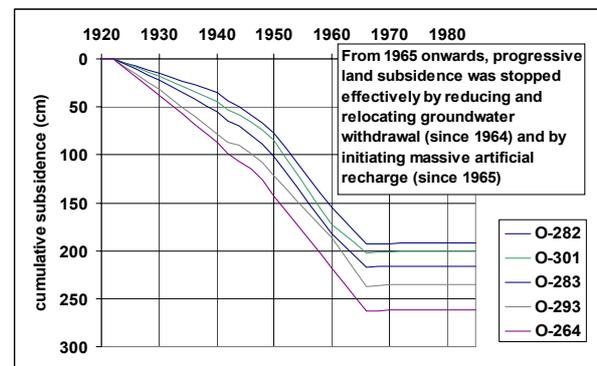


Fig 4-9-8 Land subsidence in Shanghai arising from groundwater abstraction

¹⁴ Llamas and Custodio (editors), 2003. *Intensive Use of Groundwater – Challenges and Opportunities*. Balkema, Lisse, The Netherlands.

UNEP, 2003. *Groundwater and its Susceptibility to Degradation*. UNEP/DEWA, Nairobi.

FAO, 2003. *Groundwater Management*. FAO Water Report no. 25, Rome.

Burke, J., and M. Moench, 2000. *Groundwater and Society*. United Nations publication, New York.

¹⁵ Van der Gun, J.A.M. and A.A. Ahmed, 1994. *The Water Resources of Yemen*. Report WRAY-35, TNO Delft/MOMR Sana'a.

¹⁶ Shanghai Bureau of Geology and Mineral Resources, China. *Introduction about the preventive effect of Shanghai land subsidence (China)*. Unpublished report, Shanghai Bureau of Geology and Mineral Resources.

¹⁷ Llamas, R., 1992. *Wetlands: an important issue in hydrogeology*. In: Selected Papers on Aquifer Overexploitation, IAH, Volume 3, p.p. 69-68.

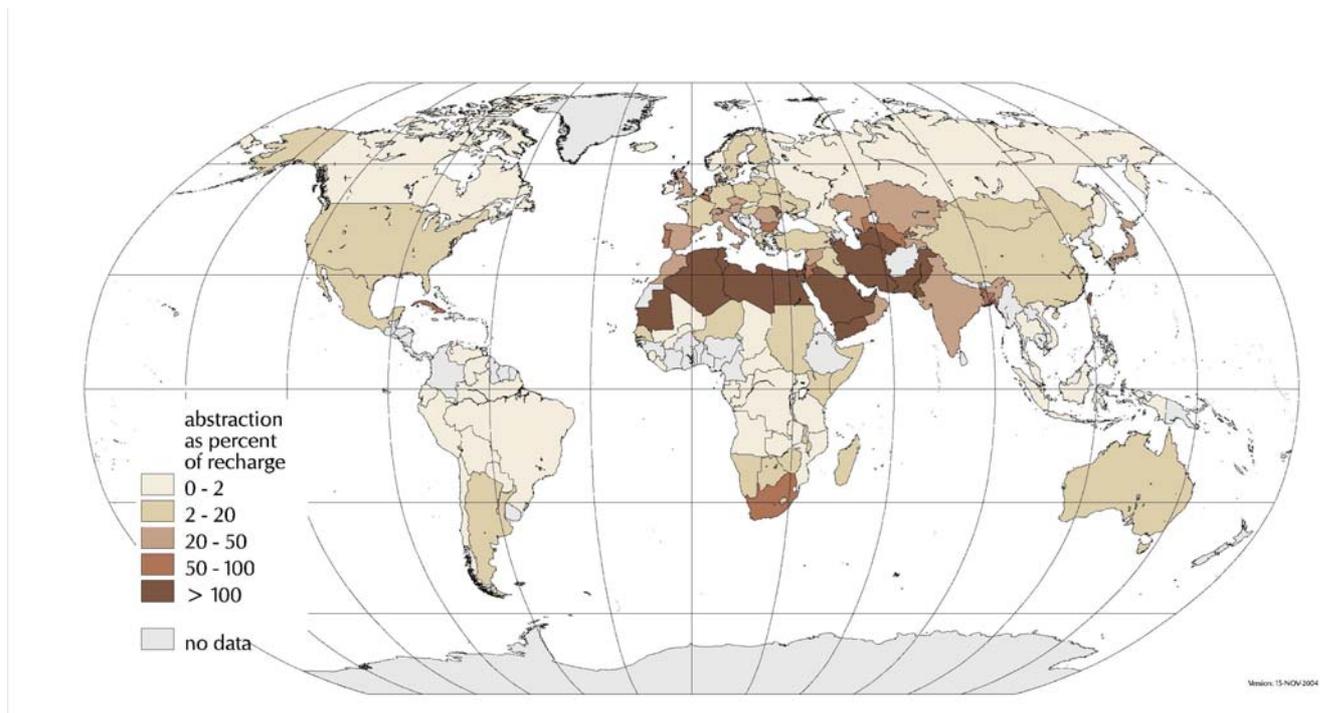


Fig 4-9-8 Groundwater development indicator: abstraction rate as a percentage of mean recharge rate (IGRAC, 2004).

Low percentages indicate underdeveloped groundwater resources, high percentages point to development stress or eventually overexploitation.

6 Monitoring and management

Groundwater resources management requires strategic planning and makes use of a wide range of instruments and measures, such as technical measures, incentives, legally enforced measures and sanctions, public awareness raising, etc¹⁸. Adequate legal and institutional frameworks are crucial for implementing effective management measures, preferably done as part of integrated water resources management. Assessment and monitoring are indispensable for the development of a management plan, valuing the water appropriately may strengthen the plan, stakeholder participation may be crucial for its acceptance.

While groundwater is less vulnerable to human impacts than surface water, once groundwater is polluted, remediation can be relatively long term (years), technically demanding and costly¹⁹. Vulnerability assessments have been developed as part of management strategies for groundwater resources²⁰. The results are typically portrayed on maps now being used to plan, regulate, manage and take decisions when combined with land use, hydrogeological and other environmental maps. Large scale maps have been compiled in e.g. France, Germany, Spain, Italy, The Czech Republic, Poland, Russia, Australia where they serve as guidelines for land use zoning on the national or regional level, to identify areas susceptible to human impacts and to support policy and strategy for groundwater resources protection and water quality conservation.

Groundwater monitoring programmes operate variably at national, regional or local levels. Water levels are the most observed parameter, with widespread and continuous water quality and natural groundwater discharge and abstraction networks operational in only a few countries²¹. Several large-scale efforts are underway to upgrade networks, e.g. in Europe (initiated by the EU Water Framework Directive²²) and in India (Hydrology Project²³). Countries concerned and financed adequately to carry out these programs understand how crucial credible, reliable and readily accessible groundwater monitoring data are to best plan and use their water resources. However, groundwater assessment, monitoring and data management activities are minimal or ineffective in many developing countries and are being downsized and reduced in comprehensiveness in several developed countries. The resulting lack of data will certainly make adequate groundwater management more difficult.

Groundwater does not respect administrative boundaries. Most of the large groundwater reserves listed in Table 4-9-1 are shared between countries, but there are numerous smaller transboundary aquifers as well scattered all over the world. Attention for internationally shared groundwater resources management is increasing, with strong support of several international organizations (GEF, UNESCO, IAH/ISARM, OAS, OSS, etc.)²⁴.

¹⁸ Foster, S., and K. Kemper, 2003: *Sustainable Groundwater Management: Concepts and Tools*. World Bank GW-Mate. UNEP, 2003. *Groundwater and its Susceptibility to Degradation*. UNEP/DEWA, Nairobi.

FAO, 2003. *Groundwater Management*. FAO Water Report no. 25, Rome.

Burke, J., and M. Moench, 2000. *Groundwater and Society*. United Nations publication, New York.

¹⁹ Vrba, J., 1985. *Impact of domestic and industrial wastes and agricultural activities on groundwater quality*. In: Hydrogeology in the service of man, Vol. XVIII, Part I, pp.91 – 117, IAH Memoires of the 18th Congress, Cambridge

²⁰ J. Vrba and A. Zaporozec, editors, (1994). *Guidebook on mapping groundwater vulnerability*. Vol. 16, IHP-IAH International contribution to hydrogeology, Verlag H. Heise, Germany.

²¹ See http://igrac.nitg.tno.nl/gpm_start.html

²² See <http://europa.eu.int/comm/environment/water/>

²³ <http://web.worldbank.org/WBSITE/EXTERNAL/NEWS/0,,contentMDK:20246117~menuPK:34468~pagePK:40651~piPK:40653~theSitePK:4607,00.html>

²⁴ See e.g. <http://www.iah.org.isarm/index.html>