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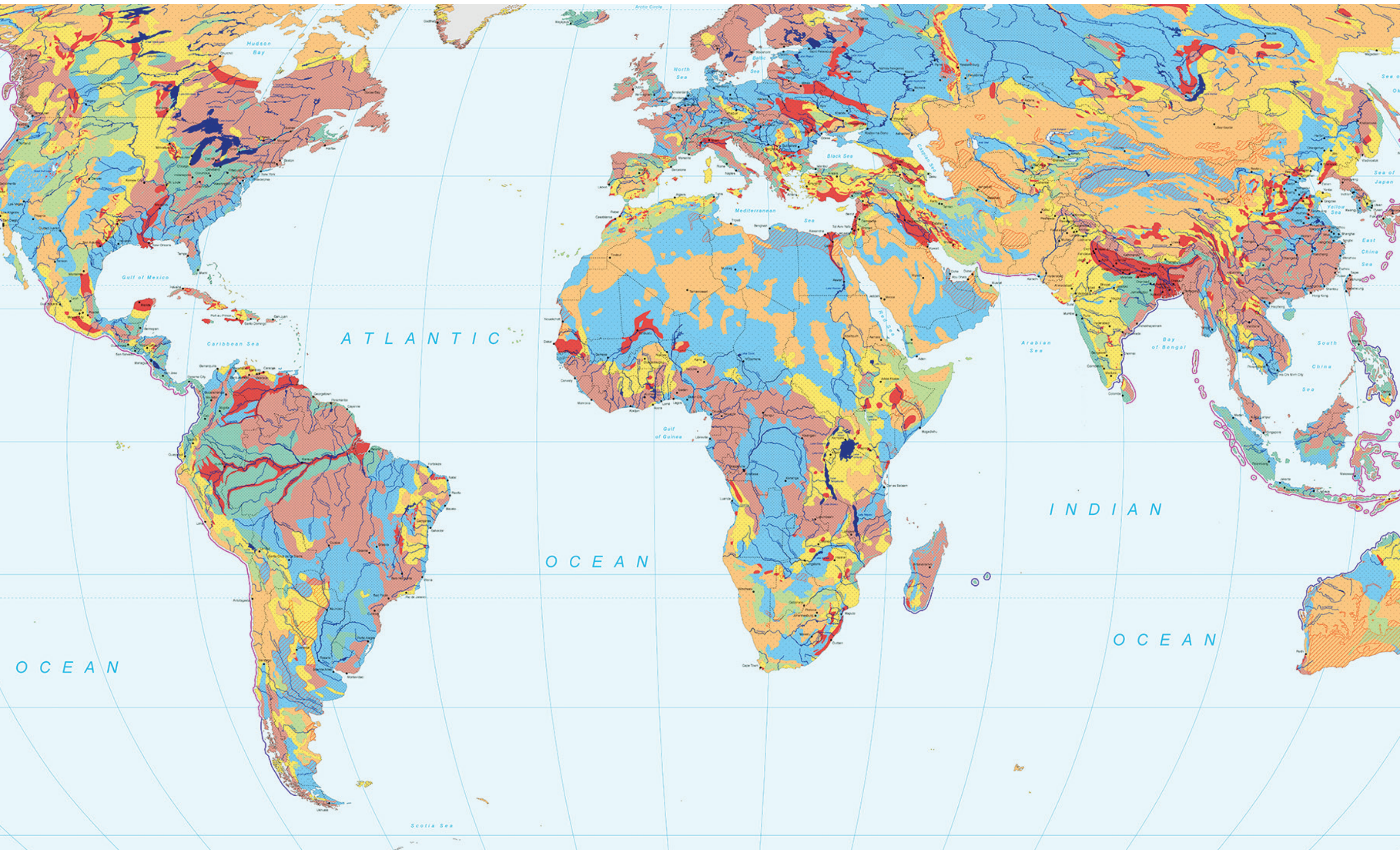
BGR

# The GLOBAL MAP of GROUNDWATER VULNERABILITY to FLOODS and DROUGHTS

## EXPLANATORY NOTES



# The GLOBAL MAP

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# 1. Introduction

*The Map of Global Groundwater Vulnerability to Floods and Droughts at the scale of 1: 25 000 000* ('Global Groundwater Vulnerability Map F.D.') is the result of a joint effort of the United Nations Educational, Scientific and Cultural Organization (UNESCO) International Hydrological Programme (IHP) project 'Groundwater for Emergency Situations' (GWES), the International Association of Hydrogeologists (IAH) and the 'World-wide Hydrogeological Mapping and Assessment Programme' (WHYMAP).

The GWES project has been implemented under the sixth (2002–2007) and seventh (2008–2013) phases of the UNESCO IHP. The aim of the GWES project is to consider extreme natural disaster events that could adversely influence human health and life, and to identify potential safe, low-vulnerability groundwater resources that can replace damaged or polluted public and domestic water supplies in emergency and post-emergency situations, and thus make drinking water rescue activities more rapid and effective.

The following activities and outcomes of the GWES project have been set out: 1) Propose an effective methodology for identifying groundwater resources of low vulnerability to extreme climatic and geological events; 2) Publish methodological guidelines for the investigation, development, management and governance of strategic groundwater bodies to be used in emergencies; 3) Present case studies relevant to the impact of different types of disasters on drinking water facilities in different countries and regions; 4) Organize international workshops oriented on the role of groundwater in emergency situations in different disaster-prone regions worldwide; and 5) Propose a methodology and develop a map depicting groundwater vulnerability to natural disasters on the global scale (Vrba and Verhagen, 2011).

The majority of the world's natural disasters is related to extreme water-related events. This global map, that covers groundwater vulnerability to floods and droughts, wishes to contribute to highlight this phenomenon and call to the attention of decision makers the areas of highest vulnerability.

WHYMAP is a programme implemented by a consortium including UNESCO, the Commission for the Geological Map of the World (CGMW), the International Association of Hydrogeologists (IAH), the International Atomic Energy Agency (IAEA) and the German Federal Institute for Geosciences and Natural Resources (BGR). Under the framework of the UNESCO IHP programme a large number of experts from different regions of the world have contributed to the WHYMAP programme. It aims at collecting, collating and visualizing hydrogeological information on a global scale. This project is intended to convey groundwater-related data in an appropriate way to support global discussion of water issues, and to raise awareness of underground water resources that are not directly visible. The products generated by the programme are compiled using data on groundwater from national, regional and global sources, and provide information on the quantity, quality and vulnerability of the Earth's groundwater resources. By visualizing the hidden resources through global maps and web map applications, WHYMAP helps to communicate groundwater-related issues to water experts as well as decision-makers and the general public. WHYMAP is recognized as making an important contribution to political discussions on global water issues.

# 2. Groundwater vulnerability: the general concept

The concept of groundwater vulnerability is based on the assumptions that the physical environment may provide some degree of protection to groundwater from natural and human impacts, and that some aquifers are more vulnerable to external impacts than others.

Vulnerability is an intrinsic (natural) property of a groundwater system, which depends on the sensitivity of that system to natural and/or human impacts, and the ability of the system to cope with such impacts (Vrba and Zaporozec, 1994). The 'intrinsic vulnerability' is a function of natural factors: the characteristics of an aquifer, the overlying soil and rock environment, topography and climate.

## 2.1 Methods and parameters applied for groundwater vulnerability assessment

Groundwater vulnerability is a non-directly measurable property, and is based on the assessment of several parameters that vary over regions as a function of the physical environment. The principal vulnerability parameters are associated with the hydrogeological and geological settings, hydraulic properties of the groundwater system, the climate, and topography. However, the selection and valuation of parameters vary according to the goals and scope of a vulnerability assessment. Parameter weighting and rating methods are mostly applied to express the relationship among the parameters used. Aggregating a number of parameters to create a single index of vulnerability involves the steps of selection, scaling, rating and weighting. A final groundwater vulnerability class is an aggregate of individual parameters that have different units of measurements, so the final groundwater vulnerability score is dimensionless.

Several methods have been developed and applied in the evaluation of groundwater vulnerability. The DRASTIC index (Aller at al., 1985) is based on the parameters of depth to groundwater table (D), net recharge (R) aquifer media (A), soil media (S), topography (T), impact of the unsaturated (vadose) zone (I) and hydraulic conductivity of the aquifer (C). The DRASTIC method is applied worldwide for evaluation of the potential of groundwater to become polluted. Each parameter is rated on a scale from 1–10, and is assigned a relative weight from 5 (the most significant parameter, e.g. depth to the groundwater table) to 1 (the least significant, e.g. topography). The ratings are multiplied by the weight to provide a score for each parameter, and the parameter scores are then summed. The higher the DRASTIC index, the greater the groundwater vulnerability and pollution potential.

Another well-known rating system is SINTACS (Civita,1990), which is based on the same parameters as DRASTIC, but has a more complex structure. Its discretized input stage (based on grid squares) and its output (mapping and numerical tables) are both entirely computerized (Civita,1994). The European COST Action 620 project, which is focused on vulnerability and risk assessment for the Alpine aquifer system (Cichocki and Zojer, 2007), assessed groundwater vulnerability based on parameters determined from a water balance equation (combined with hazard maps). Geographical information systems (GIS) are also widely applied to present vulnerability scenarios on vulnerability maps. Vrba and Zaporozec (1994), Witkowski at al. (2007), among others, have summarized a range of other methods and numerical models used for groundwater vulnerability assessment. Most of these methods have been applied for the assessment of the vulnerability to contamination. Often a single-purpose vulnerability assessment is carried out, focused on one contaminant or one group of contaminants with similar properties.

In the assessment of groundwater vulnerability in disaster-prone areas, isotope hydrology methods may complement the commonly used vulnerability parameters, since it helps to identify factors such as the groundwater residence time (age) and groundwater resources that are resilient to hazardous events. This is an important parameter, particularly in areas with deeper aquifers.

## 2.2 Groundwater vulnerability maps

The art of groundwater vulnerability mapping has developed historically from geological and hydrogeological maps. Groundwater vulnerability maps may be classified as problem-oriented, specialized environmental maps derived from the basic hydrogeological map (Struckmeier and Margat, 1995). They display and assist in identifying areas where groundwater is prone to natural and human impacts. These maps are not targeted on research, but have practical uses. They support planning, regulation, management and decision-making, can help in making environmentally sound decisions regarding land use and groundwater protection, and may also assist in the formulation of disaster risk assessment and risk mitigation policy. Vulnerability maps also create public awareness about environmental and groundwater protection issues, because the term 'vulnerability' is explicit and readily understood by those who are not groundwater specialists.

The maps typically show various homogenous areas, which share a certain level of vulnerability. It should be noted that the vulnerability indexes displayed on the maps strongly depend on the methods for selecting and aggregating vulnerability parameters.

# 3. The Map of Global Groundwater Vulnerability to Floods and Droughts

The extent of the impact of different natural disasters on aquifers and their groundwater resources differs depending on factors such as the origin of the disaster, its intensity and frequency, the hydrogeological conditions and geographical position of the aquifer (for instance, whether it is in a coastal area or a floodplain), and other factors that affect its vulnerability (whether it is shallow or deep, and whether the groundwater is non-renewable).

Natural disasters can be of either climatic and geological origin, or a combination of both. The following categorization is suggested: 1) hydro-climatic events (floods, droughts, storms); 2) geological events (earthquakes, volcanic activity); and 3) events caused by a combination of hydro-climatic and geological factors (tsunamis, landslides). It is not technically possible to show the vulnerability of groundwater resources to all disaster events on a single map, because the vulnerability of aquifers to climatic and geological disasters differs significantly. This map covers groundwater resources vulnerability to hydro-climatic disasters, and specifically droughts and floods.

**Figure 1. Simplified map of Groundwater Resources of the World**

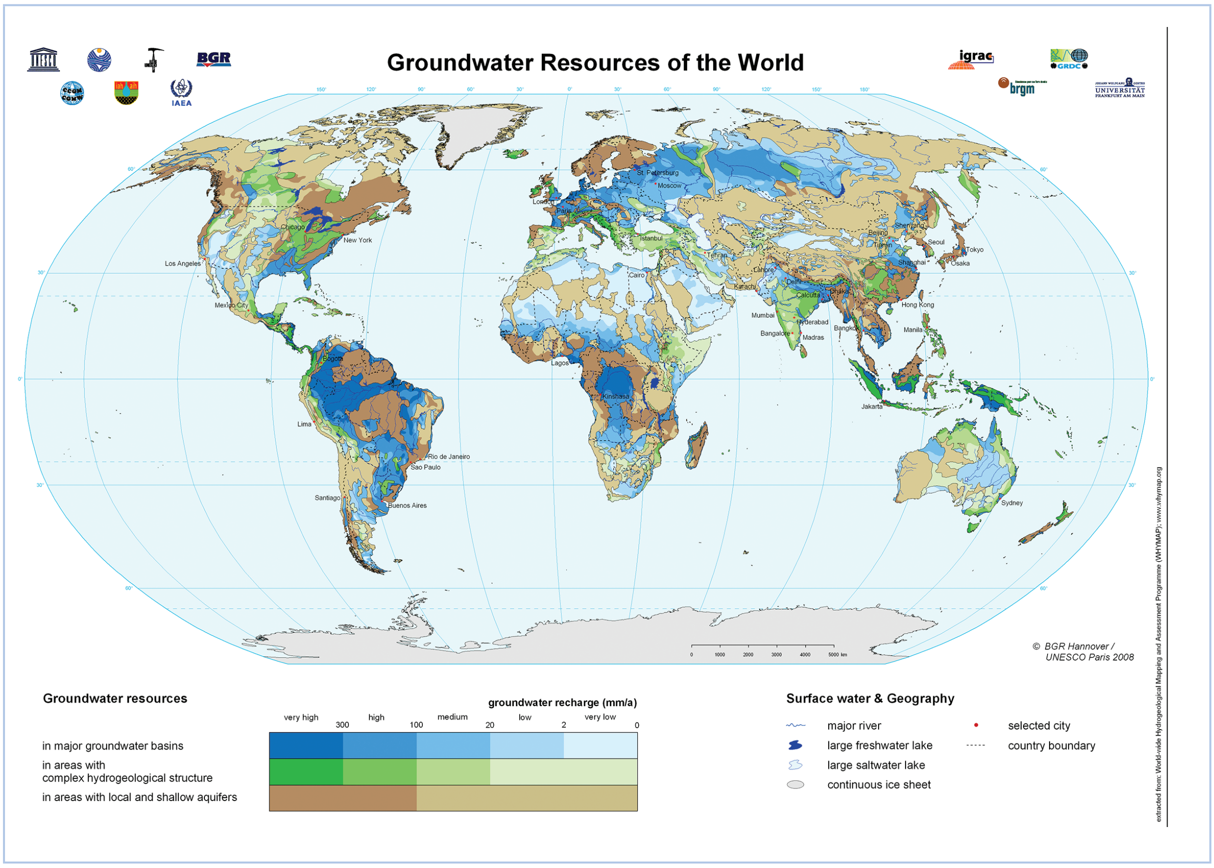
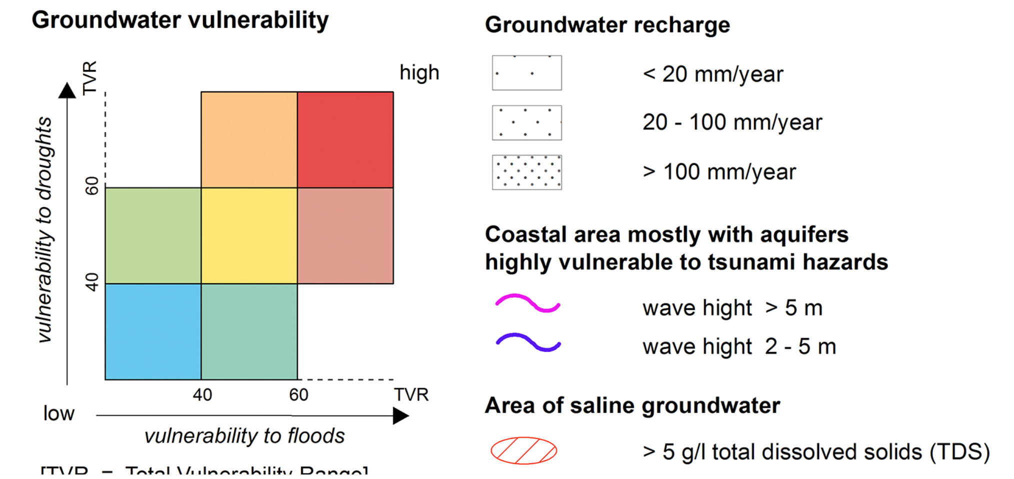


**Figure 2. Legend and classification scheme for the total vulnerability range (TVR)**




## 3.1 Data sources for the map

The Global Groundwater Vulnerability Map F.D. is largely derived from the Groundwater Resources Map of the World at the scale of 1:25 000 000, a major result of the WHYMAP programme (Richts et al., 2011). WHYMAP generally makes significant use of existing hydrogeological maps at continental, regional and national scale. Data on individual groundwater resources, and other information that is already available, are evaluated and harmonized to obtain a consistent picture of the hydrogeological situation across the world, with comparable representation of all continents.

The map of Groundwater Resources of the World shows various characteristics of groundwater environments by area (Fig. 1). It uses blue colour to indicate large and rather uniform groundwater basins (aquifers and aquifer systems, usually in large sedimentary basins, that may offer good conditions for groundwater exploitation); green colour for complex hydrogeological structures (in heterogeneous folded or faulted regions, where highly productive aquifers are found in close proximity to areas without significant aquifers); and brown colour for regions with limited groundwater resources in local and shallow aquifers (BGR/UNESCO, 2008).

In each of these three major categories, up to five different classes are defined by potential recharge rates, which range from very high (more than 300 mm per year) to very low (less than 2 mm per year). Areas with low recharge rates are potentially subject to groundwater mining. The groundwater recharge rates refer to the standard hydrologic period 1961–1990 and are derived from simulations using the global hydrological model WaterGAP, version 2.1f, by the University of Frankfurt in 2006 (Döll and Fiedler, 2008).

WHYMAP data described above were essential for defining the geometry of the major aquifer types and for drawing up the groundwater recharge categories used in the Global Groundwater Vulnerability Map F.D.. Data for delineating additional types of aquifers on the map were derived from:

- the Geological Map of the World (CGWM, 2010) for aquifers in fluvial deposits of large rivers;
- the World Map of Carbonate Rock Outcrops (Williams and Fong. 2010) for aquifers in carbonate rocks, usually karstified;
- the WHYMAP database for aquifers with non-renewable groundwater.

Some modification was necessary in order to allow for the integration of this data.

Information on areas of saline groundwater was compiled by the WHYMAP programme, making use of continental hydrogeological maps. The areas (mostly coastal) where aquifers are highly vulnerable to tsunami hazards have been highlighted according to the United Nations Global Assessment Report on Disaster Risk Reduction (UNISDR, 2013).

## 3.2 Contents of the map

Three major groundwater environments are depicted on the Groundwater Resources Map of the World (BGR/UNESCO, 2008): major groundwater basins, areas with complex hydrogeological structures and areas with local and shallow aquifers. These are complemented on the Global Groundwater Vulnerability Map F.D. by three additional types of aquifers: aquifers in carbonate rocks (often karstified), aquifers in fluvial deposits of large rivers, and aquifers with non-renewable groundwater resources. Groundwater recharge rates are depicted on the map in three categories: less than 20 mm/year, 20 - 100 mm/year and more than 100 mm/year.

Because of their importance for groundwater vulnerability, coastal areas with aquifers that are highly vulnerable to tsunami and areas of saline groundwater are also depicted on the map:

Coastal areas prone to tsunami hazards are highlighted according to the height of wave likely to strike the coast, in two categories: 2–5 m or more than 5 m wave height;

Areas are identified as having saline groundwater when the salinity regionally exceeds 5 g/l and the groundwater is generally not suitable for human consumption.

Topographic features (selected cities, country boundaries) and surface water features (large rivers, large freshwater and saltwater lakes, and continuous ice sheets) are also shown on the map. These both allow geographic orientation and reference, and provide some information on the availability of surface water.

The map and the legend display three categories of groundwater vulnerability (low, moderate, and high) specified as the total vulnerability range (TVR) (Fig. 2). The classification of each area is determined by combining individual parameters (using a weighting multiplied by a rating) according to a specific scheme (see Section 4 for details).

The main map is complemented by two insert maps at the scale of 1: 120 000 000, showing mean annual groundwater recharge (1961–1990) and types of aquifers. They show the individual spatial distribution of these two parameters considered in the TVR.

## 3. 3 Uses and limitations of the map

The amount and quality of groundwater data and the scale and objectives of the Global Groundwater Vulnerability Map F.D. are of critical importance to the accuracy of the map and its usability.

Availability and quality of groundwater data. The biggest constraint in the construction of global groundwater vulnerability maps is data scarcity. This affects the scale and objectives of the map and is reflected in the restricted number of groundwater vulnerability parameters that were suitable for use in the construction of this global map. Several data layers that are usually applied in assessments on the national and local scale in some countries, such as depth to groundwater table, and thickness and permeability of the unsaturated zone, are not globally available.

In order to produce a more accurate map based on reliable and compatible data, there is a need for comprehensive international cooperation in 1) determining priorities in the compilation of the data needed; 2) standardization of methods of groundwater data assessment and management; 3) standardization of digital formats of data storage; and 4) data transmission and sharing in the international level.

**The scale of the Global Groundwater Vulnerability Map F.D.**. The scale (in this case 1: 25 000 000) on which the map is constructed influences the level of data generalization, the number of vulnerability parameters that can be applied, and the accuracy of the information portrayed on the map. It must be stressed that because the Global Groundwater Vulnerability Map F.D. was drawn up on a small scale, it can only give a generalized picture of groundwater vulnerability. The map cannot be applied for site-specific purposes, such as to influence policy and decision-making in the planning, protection and management of local groundwater resources.

**The objective of the Global Groundwater Vulnerability Map F. D.**. Because of the shortage of credible and compatible groundwater data, and our current inadequate knowledge of hydrogeological settings on the worldwide scale, the Global Groundwater Vulnerability Map F.D. is presented in a simplified format. It uses just three categories: low, moderate and high. The map indicates specially areas where highly vulnerable aquifers occur. Many of those contain groundwater resources on which the drinking water supply of large number of peoples depends, and which are also important source of water for irrigation and other purposes. Such aquifers need preferential consideration and comprehensive preventive protection.

# 4. Parameters applied in the assessment and mapping of groundwater vulnerability to floods and droughts

As noted, the use of the parameters that are commonly applied in the assessment of groundwater vulnerability were restricted, because of both the scale of the vulnerability map (1: 25 000 000) and the scarcity of available, reliable and consistent data sets on the global scale. Consequently, two parameters of groundwater vulnerability to floods and droughts were employed: type of aquifers and groundwater recharge.

## 4.1 Types of aquifers

The type of an aquifer and its position in the geological environment (whether it is shallow or deep, unconfined or confined) have a decisive influence on groundwater vulnerability. On the Global Groundwater Vulnerability Map F. D. and on one of the insert maps (Fig. 3), the following types of aquifers were distinguished:

**Aquifers in carbonate rocks, often karstified** with groundwater flow in conduits, large open fissures and openings along bedding planes, typically with high groundwater flow velocities (hundreds of m/day) and secondary permeability. Springs are characteristic of a groundwater karstic regime. These aquifers are highly vulnerable to droughts and floods, particularly in areas where outcrops of karst rocks occur.

**Aquifers in fluvial deposits of large rivers.** In floodplains around large rivers, the groundwater table is close to the ground surface and therefore, the unsaturated zone has a restricted thickness. In floodplains and low terraces an interface with surface streams is often registered. These productive aquifers are generally highly vulnerable to floods, but are less vulnerable in areas covered by clayed flood deposits.

**Local and shallow** aquifers are limited to the alteration zone of the bedrock and overlying shallow layers. These minor, but locally productive, groundwater resources are highly vulnerable to floods and storms and, in arid and semi-arid regions, to droughts.

**Aquifers in complex hydrogeological structures** include groundwater flow systems in fissures or fractures. These can be found in heterogeneous folded geological structures with appreciable dual permeability, where productive aquifers may occur in close proximity to non-aquiferous strata. They are usually of moderate vulnerability to floods and droughts (depending on the thickness and permeability of the unsaturated zone).

**Aquifers in major groundwater** basins are extensive and productive, often confined, composed of thick permeable and saturated layers and overlain by thick low permeability superposed beds. They contain a large amount of groundwater, mostly of a long residence time. Their vulnerability is generally low.

**Aquifers with non-renewable** groundwater are large, thick, confined, with limited present-day replenishment and significant groundwater storage. The groundwater was recharged mostly during past pluvial periods.

There are two types of areas depicted on the map where aquifers vulnerability is not classified in this way: those with saline water (more than 5g/l) in arid and semi-arid regions (because of the low water quality, they do not provide a suitable source of drinking water) and coastal areas highly vulnerable to tsunami and to sea water intrusion. This intrusion is controlled in natural conditions, among other factors, by tidal fluctuation, the gradient and volume of groundwater flow towards the seashore and stream flow changes.

## 4.2 Groundwater recharge

Groundwater recharge is an important parameter particularly when groundwater vulnerability to floods and droughts is considered.

The groundwater recharge rates applied on the map are defined as the amount of water that infiltrates from precipitations through the unsaturated zone to the water table and reaches the aquifer. Groundwater recharge from bank river infiltration or irrigation is not considered. Regions receiving a large quantity of rain, or occasionally extreme rainfall, have the potential for greater recharge as well as for floods. On the map groundwater recharge refers to the period 1961–1990 (Fig. 4). The rating scale of groundwater recharge uses three categories: more than 100 mm, between 100 and 20 mm, and less than 20 mm/year.

**Figure 3. Map of aquifer types used in the Global Groundwater Vulnerability Map F.D.**

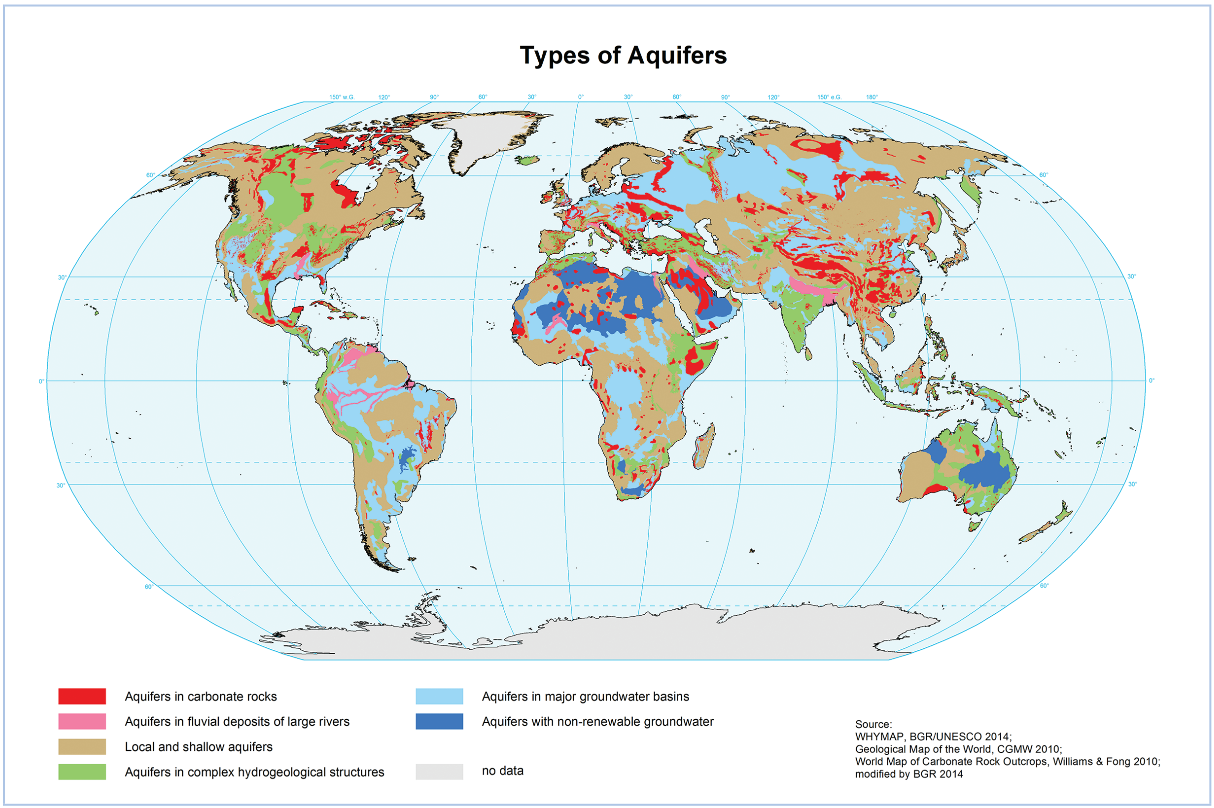
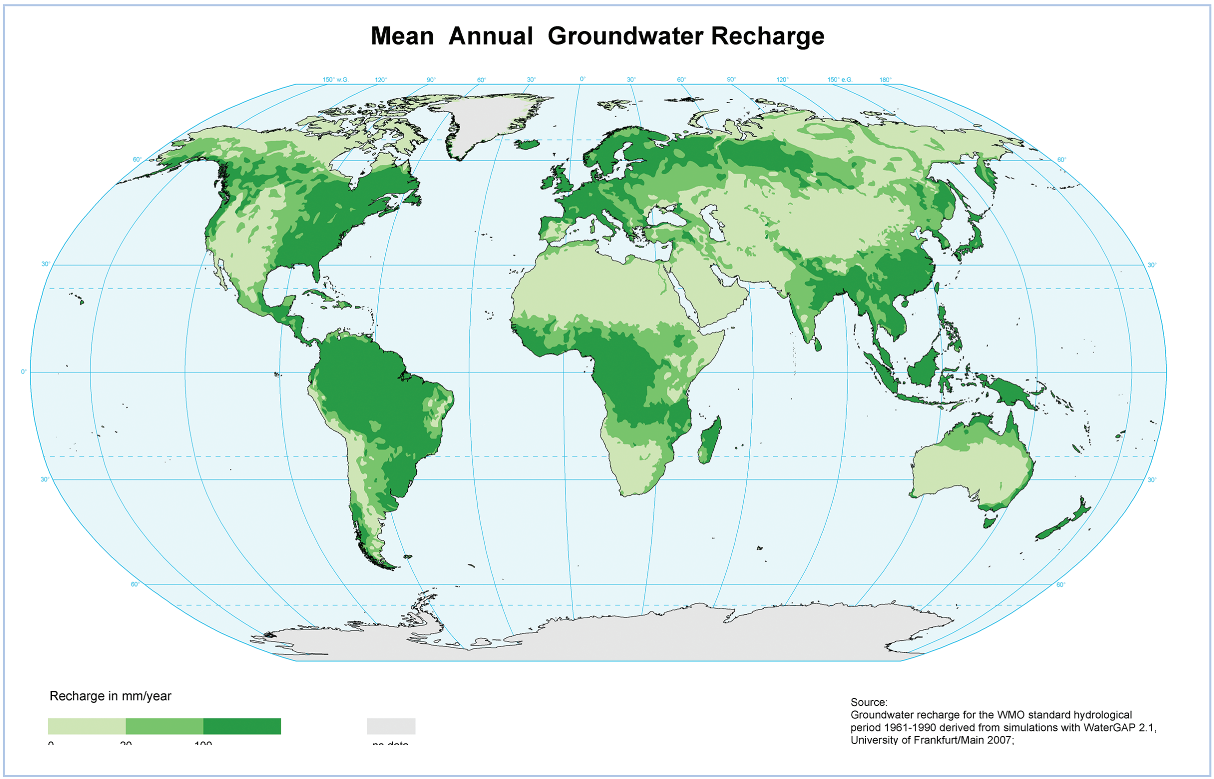



**Figure 4. Map of Annual Groundwater Recharge (1961 – 1990)**



# 5. Scheme of groundwater vulnerability classification

A parameter weighting and rating system was used to provide a relative measure of groundwater vulnerability to hydro-climatic disaster events. Weight (1–5) and rating (1–10) scales developed under the DRASTIC methodology were applied to both vulnerability parameters.

Since the nature and hydrogeological characteristics of aquifers are the most important factors for groundwater vulnerability assessment to floods and droughts, the parameter 'aquifer type' was given a weighting of 5, and 'groundwater recharge' a weighting of 3.

The individual rating of different types of aquifers reflects their response to disaster impacts. For instance, shallow aquifers in the fluvial deposits of large rivers are highly vulnerable to floods, so a higher rating was given to these aquifers than to those in deep groundwater basins, which are typically well protected against external influences and impacts.

## WEIGHTING OF VULNERABILITY PARAMETERS

| | |
|---|---|
| Aquifer type | = 5 |
| Recharge | = 3 |

## RATING OF DIFFERENT AQUIFER TYPES (FOR BOTH FLOODS AND DROUGHTS)

| | |
|---|---|
| Aquifers in carbonate rocks (often karstified) | = 10 |
| Aquifers in fluvial deposits of large rivers | = 10 |
| Local and shallow aquifers | = 8 |
| Aquifers in complex hydrogeological structures | = 5 |
| Aquifers in major groundwater basins | = 2 |
| Aquifers with non-renewable groundwater | = 1 |

## RATING OF GROUNDWATER RECHARGE (FOR BOTH FLOODS AND DROUGHTS)

Three classes were used to assess the potential for groundwater recharge and their rating differentiated with regard to floods and droughts.

| Annual recharge | rating floods | rating |
|---|---|---|
| < 20 mm | 3 | 9 |
| 20–100 mm | 6 | 6 |
| > 100 mm | 9 | 3 |

For example, shallow and local aquifers in areas that are already facing, or have in the past faced, low or very low groundwater recharge are even more vulnerable to drought events (and receive a rating of 9). In contrast, aquifers with non-renewable groundwater in areas with high precipitation, where there is limited present-day replenishment and recharge, are much less vulnerable to floods or storms and were given a rating of 3.

## TOTAL VULNERABILITY RANGE (TVR)

In order to obtain a final numerical score for groundwater vulnerability, individually assigned weights and ratings for both vulnerability parameters were combined, using a scheme related to the DRASTIC methodology. Details of this scheme of multiplying and adding are illustrated in the following tables. The total vulnerability range (TVR) derived in this way has three categories:

| | |
|---|---|
| < 40 | = low vulnerability |
| 40–60 | = moderate vulnerability |
| > 60 | = high vulnerability |

## TABLES SHOWING THE CALCULATION AND CLASSIFICATION OF AQUIFERS AND GROUNDWATER VULNERABILITY TO FLOODS AND DROUGHTS

Tables 1.1–1. 6, 2.1–2.6 and 3.1 show the classification of aquifer vulnerability to floods and droughts. In all these tables, the following abbreviations are used:

| | |
|---|---|
| **W1/W2** | = weights |
| **R1/R2** | = ratings |
| **Vul1/Vul2** | = vulnerability range |
| **TVR** | = total vulnerability range |

# Tables 1.1 – 1.6 Groundwater vulnerability to floods

## Table 1.1 Aquifers in carbonate rocks (often karstified)

| AQUIFER TYPE | | | | ANNUAL RECHARGE | | | | TOTAL VULNERABILITY | |
|---|---|---|---|---|---|---|---|---|---|
| W1 | Type | R1 | Vul1 = W1 x R1 | W2 | Range | R2 | Vul2 = W2 x R2 | TVR = Vul1 + Vul2 | Category |
| 5 | Carbonate rocks, karstified | 10 | 50 | 3 | < 20 mm | 3 | 9 | 59 | moderate |
| 5 | Carbonate rocks, karstified | 10 | 50 | 3 | 20–100 mm | 6 | 18 | 68 | high |
| 5 | Carbonate rocks, karstified | 10 | 50 | 3 | > 100 mm | 9 | 27 | 77 | high |

## Table 1.2 Aquifers in fluvial deposits of large rivers

| AQUIFER TYPE | | | | ANNUAL RECHARGE | | | | TOTAL VULNERABILITY | |
|---|---|---|---|---|---|---|---|---|---|
| W1 | Type | R1 | Vul1 = W1 x R1 | W2 | Range | R2 | Vul2 = W2 x R2 | TVR = Vul1 + Vul2 | Category |
| 5 | Fluvial deposits | 10 | 50 | 3 | < 20 mm | 3 | 9 | 59 | moderate |
| 5 | Fluvial deposits | 10 | 50 | 3 | 20–100 mm | 6 | 18 | 68 | high |
| 5 | Fluvial deposits | 10 | 50 | 3 | > 100 mm | 9 | 27 | 77 | high |

## Table 1.3 Local and shallow aquifers

| AQUIFER TYPE | | | | ANNUAL RECHARGE | | | | TOTAL VULNERABILITY | |
|---|---|---|---|---|---|---|---|---|---|
| W1 | Type | R1 | Vul1 = W1 x R1 | W2 | Range | R2 | Vul2 = W2 x R2 | TVR = Vul1 + Vul2 | Category |
| 5 | Local and shallow aquifers | 8 | 40 | 3 | < 20 mm | 3 | 9 | 49 | moderate |
| 5 | Local and shallow aquifers | 8 | 40 | 3 | 20–100 mm | 6 | 18 | 58 | moderate |
| 5 | Local and shallow aquifers | 8 | 40 | 3 | > 100 mm | 9 | 27 | 67 | high |

## Table 1.4 Aquifers in complex hydrogeological structures

| AQUIFER TYPE | | | | ANNUAL RECHARGE | | | | TOTAL VULNERABILITY | |
|---|---|---|---|---|---|---|---|---|---|
| W1 | Type | R1 | Vul1 = W1 x R1 | W2 | Range | R2 | Vul2 = W2 x R2 | TVR = Vul1 + Vul2 | Category |
| 5 | Complex structures | 5 | 25 | 3 | < 20 mm | 3 | 9 | 52 | moderate |
| 5 | Complex structures | 5 | 25 | 3 | 20–100 mm | 6 | 18 | 43 | moderate |
| 5 | Complex structures | 5 | 25 | 3 | > 100 mm | 9 | 27 | 34 | low |

## Table 1.5 Aquifers in major groundwater basins

| AQUIFER TYPE | | | | ANNUAL RECHARGE | | | | TOTAL VULNERABILITY | |
|---|---|---|---|---|---|---|---|---|---|
| W1 | Type | R1 | Vul1 = W1 x R1 | W2 | Range | R2 | Vul2 = W2 x R2 | TVR = Vul1 + Vul2 | Category |
| 5 | Major groundwater basins | 2 | 10 | 3 | < 20 mm | 3 | 9 | 19 | low |
| 5 | Major groundwater basins | 2 | 10 | 3 | 20–100 mm | 6 | 18 | 28 | low |
| 5 | Major groundwater basins | 2 | 10 | 3 | > 100 mm | 9 | 27 | 37 | low |

## Table 1.6 Aquifers with non-renewable groundwater

| AQUIFER TYPE | | | | ANNUAL RECHARGE | | | | TOTAL VULNERABILITY | |
|---|---|---|---|---|---|---|---|---|---|
| W1 | Type | R1 | Vul1 = W1 x R1 | W2 | Range | R2 | Vul2 = W2 x R2 | TVR = Vul1 + Vul2 | Category |
| 5 | Non-renewable groundwater | 1 | 5 | 3 | < 20 mm | 3 | 9 | 14 | low |
| 5 | Non-renewable groundwater | 1 | 5 | 3 | 20–100 mm | 6 | 18 | 23 | low |
| 5 | Non-renewable groundwater | 1 | 5 | 3 | > 100 mm | 9 | 27 | 32 | low |

# Tables 2.1–2.6 Groundwater vulnerability to droughts

## Table 2.1 Aquifers in carbonate rocks (often karstified)

| AQUIFER TYPE | | | | ANNUAL RECHARGE | | | | TOTAL VULNERABILITY | |
|---|---|---|---|---|---|---|---|---|---|
| W1 | Type | R1 | Vul1 = W1 x R1 | W2 | Range | R2 | Vul2 = W2 x R2 | TVR = Vul1 + Vul2 | Category |
| 5 | Carbonate rocks, karstified | 10 | 50 | 3 | < 20 mm | 9 | 27 | 77 | high |
| 5 | Carbonate rocks, karstified | 10 | 50 | 3 | 20–100 mm | 6 | 18 | 68 | high |
| 5 | Carbonate rocks, karstified | 10 | 50 | 3 | > 100 mm | 3 | 9 | 59 | moderate |

## Table 2.2 Aquifers in fluvial deposits of large rivers

| AQUIFER TYPE | | | | ANNUAL RECHARGE | | | | TOTAL VULNERABILITY | |
|---|---|---|---|---|---|---|---|---|---|
| W1 | Type | R1 | Vul1 = W1 x R1 | W2 | Range | R2 | Vul2 = W2 x R2 | TVR = Vul1 + Vul2 | Category |
| 5 | Fluvial deposits | 10 | 50 | 3 | < 20 mm | 9 | 27 | 77 | high |
| 5 | Fluvial deposits | 10 | 50 | 3 | 20–100 mm | 6 | 18 | 68 | high |
| 5 | Fluvial deposits | 10 | 50 | 3 | > 100 mm | 3 | 9 | 59 | moderate |

## Table 2.3 Local and shallow aquifers

| AQUIFER TYPE | | | | ANNUAL RECHARGE | | | | TOTAL VULNERABILITY | |
|---|---|---|---|---|---|---|---|---|---|
| W1 | Type | R1 | Vul1 = W1 x R1 | W2 | Range | R2 | Vul2 = W2 x R2 | TVR = Vul1 + Vul2 | Category |
| 5 | Local and shallow aquifers | 8 | 40 | 3 | < 20 mm | 9 | 27 | 67 | high |
| 5 | Local and shallow aquifers | 8 | 40 | 3 | 20–100 mm | 6 | 18 | 58 | moderate |
| 5 | Local and shallow aquifers | 8 | 40 | 3 | > 100 mm | 3 | 9 | 49 | moderate |

## Table 2.4 Aquifers in complex hydrogeological structures

| AQUIFER TYPE | | | | ANNUAL RECHARGE | | | | TOTAL VULNERABILITY | |
|---|---|---|---|---|---|---|---|---|---|
| W1 | Type | R1 | Vul1 = W1 x R1 | W2 | Range | R2 | Vul2 = W2 x R2 | TVR = Vul1 + Vul2 | Category |
| 5 | Complex structures | 5 | 25 | 3 | < 20 mm | 9 | 27 | 52 | moderate |
| 5 | Complex structures | 5 | 25 | 3 | 20-100 mm | 6 | 18 | 43 | moderate |
| 5 | Complex structures | 5 | 25 | 3 | > 100 mm | 3 | 9 | 34 | low |

## Table 2.5 Aquifers of mayor groundwater basins

| AQUIFER TYPE | | | | ANNUAL RECHARGE | | | | TOTAL VULNERABILITY | |
|---|---|---|---|---|---|---|---|---|---|
| W1 | Type | R1 | Vul1 = W1 x R1 | W2 | Range | R2 | Vul2 = W2 x R2 | TVR = Vul1 + Vul2 | Category |
| 5 | Major groundwater basins | 2 | 10 | 3 | < 20 mm | 9 | 27 | 37 | low |
| 5 | Major groundwater basins | 2 | 10 | 3 | 20–100 mm | 6 | 18 | 28 | low |
| 5 | Major groundwater basin | 2 | 10 | 3 | > 100 mm | 3 | 9 | 19 | low |

## Table 2.6 Aquifers with non-renewable groundwater

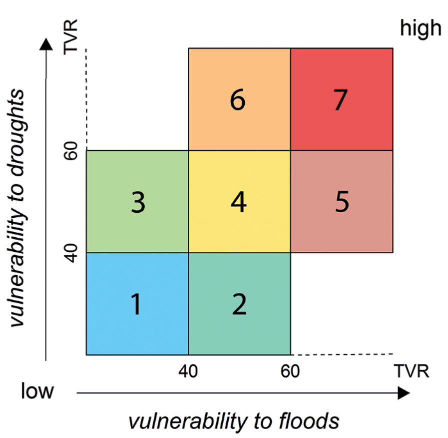
| AQUIFER TYPE | | | | ANNUAL RECHARGE | | | | TOTAL VULNERABILITY | |
|---|---|---|---|---|---|---|---|---|---|
| W1 | Type | R1 | Vul1 = W1 x R1 | W2 | Range | R2 | Vul2 = W2 x R2 | TVR = Vul1 + Vul2 | Category |
| 5 | Non-renewable groundwater | 1 | 5 | 3 | < 20 mm | 9 | 27 | 32 | low |
| 5 | Non-renewable groundwater | 1 | 5 | 3 | 20-100 mm | 6 | 18 | 23 | low |
| 5 | Non-renewable groundwater | 1 | 5 | 3 | > 100 mm | 3 | 9 | 14 | low |

Finally the TVRs for floods and droughts were combined (Table 3), resulting in seven different groundwater vulnerability categories. These are distinguished in different colours on the Global Groundwater Vulnerability Map F. D.

**Table 3 Combined categories of groundwater vulnerability to floods and droughts depicted on the map**

| AQUIFER TYPE | ANNUAL GROUNDWATER RECHARGE | CATEGORY FOR FLOODS (CF) | CATEGORY FOR DROUGHTS (CD) | COMBINED CATEGORY (CF + CD); SEE SCHEME BELOW |
|---|---|---|---|---|
| Aquifers in carbonate rocks (often karstified) | < 20 mm | moderate | high | 6 |
| | 20–100 mm | high | high | 7 |
| | > 100 mm | high | moderate | 5 |
| Aquifers in fluvial deposits of large rivers | < 20 mm | moderate | high | 6* |
| | 20–100 mm | high | high | 7 |
| | > 100 mm | high | moderate | 5* |
| Local and shallow aquifers | < 20 mm | moderate | high | 6 |
| | 20–100 mm | moderate | moderate | 4 |
| | > 100 mm | high | moderate | 5 |
| Aquifers in complex hydrogeological structures | < 20 mm | low | moderate | 3 |
| | 20–100 mm | moderate | moderate | 4 |
| | > 100 mm | moderate | low | 2 |
| Aquifers in major groundwater basins | < 20 mm | low | low | 1 |
| | 20–100 mm | low | low | 1 |
| | > 100 mm | low | low | 1 |
| Aquifers with non-renewable groundwater | < 20 mm | low | low | 1 |
| | 20–100 mm | low | low | 1 |
| | > 100 mm | low | low | 1 |

**Groundwater vulnerability**




[TVR = Total Vulnerability Range]

* Due to their location in floodplain areas these aquifers are generally highly vulnerable to floods and potentially to droughts (particularly in arid and semi-arid areas) and were therefore included in the category '7' on the map, overriding the results of TVR calculation scheme.

# 6. Key messages

Vulnerability should be a primary consideration when groundwater is considered as a source of drinking water in emergency situations such as floods and droughts.. Although the scarcity of reliable data meant that a restricted number of groundwater vulnerability parameters had to be used, a number of conclusions can be drawn from the Global Groundwater Vulnerability Map F.D..

- Groundwater is a vital resource for human life and dependent ecosystems, and for economic and social development. It is a significant source of drinking water in emergency situations, such as flood and drought events. Groundwater bodies are naturally less vulnerable and more resilient to external influences than highly vulnerable surface waters, and in many cases they provide a reliable and sustainable solution to water challenges. When extreme hydro-climatic events occur, surface water sources often fail to supply people with drinking water of good quality, while groundwater is protected from those impacts and serves as a safe emergency source of water.

- The Global Groundwater Vulnerability Map F. D. is intended for use as a global overview. Because of its small scale and the impact of that scale on the content, the map is not suitable to be used for site specific and local purposes. It is not a substitute for vulnerability maps on national and local levels, which do provide useful tools for planning, regulatory, managerial and decision-making purposes, and help environmentally sound decisions to be made regarding land use and groundwater protection.

- The biggest constraint and limitation in the construction and use of the Global Groundwater Vulnerability Map F.D. is the scarcity of reliable data on groundwater. The type of credible, compatible and spatially distributed data and information that is routinely applied in creating groundwater vulnerability maps on a larger scale is simply not available on a worldwide basis. For global groundwater vulnerability assessment and mapping to be carried out effectively in the future, it is essential to improve the availability of data. This will need regular groundwater monitoring programmes, which will provide readily accessible and compatible data for assessing the current state of groundwater quality and quantity. That will mitigate the uncertainties associated with the construction of groundwater vulnerability maps, and make it possible to predict the potential threat of disasters that affect groundwater systems and to apply relevant protective measures for highly vulnerable aquifers.

- When prospecting for groundwater resources in flood and drought-prone areas and regions, the map focuses the attention mainly on low-vulnerability deeper aquifers in sedimentary basins and deep aquifers with limited replenishment and non-renewable (fossil) groundwater, which was recharged during past pluvial periods. Both types of aquifers provide storage for large quantities of groundwater with a long residence time, and serve in many parts of the world as a safe source of drinking water in emergency situations. They need however comprehensive protection and management.

- Aquifers in carbonate rocks (often karstified) or in fluvial deposits of large rivers and shallow and local aquifers are all highly vulnerable to natural disasters, particularly floods, storms and tsunamis. They are also greatly vulnerable to droughts in arid and semi-arid regions. Groundwater resources in such aquifers may not be considered as a suitable source of drinking water in emergency situations. However, if they are to be used for regular drinking water supplies, it is essential to take adequate and sound protective measures.

- If more detailed and accurate global vulnerability maps are to be produced in the future, comprehensive international cooperation will be desirable. This will need establishment and operation of groundwater monitoring and early warning networks at the national and transboundary level (above all in disaster-prone areas), and determination of priorities in the selection and compilation of the data needed for global and regional groundwater vulnerability assessment. It is also important to standardize methods of data measurement, assessment and management, and to agree standard digital formats for data storing and data sharing at an international level.

- Priority in future global and regional groundwater vulnerability assessment and mapping should be given to areas with highly vulnerable productive aquifers that could be required to provide drinking water for a large number of people and which are also important sources of water for irrigation, industry and other purposes. Such aquifers need preferential consideration and comprehensive management, and a preventive protection policy should be developed and applied to them.

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