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1.8 Fossil and young groundwater as components of the hydrological cycle

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SUMMARY: *First we define groundwater and aquifers, factors influencing groundwater quantity and quality and its relevance as a resource. Groundwater is subsurface water which can be collected by wells, tunnels, or drainage galleries, or it can flow naturally to the earth's surface via seeps or springs. It forms by infiltration of rain or surface water underground. Groundwater forms more than 30% of the global freshwater resources and is therefore a precious natural resource and of great importance for the drinking water supply. The abstraction of groundwater instead of surface water has a number of clear advantages. Groundwater is filtered naturally by physical and microbiological processes in subsurface layers during its recharge which generally results in a better water quality; nonetheless groundwater can be contaminated by geogene or anthropogenic factors. Depending on climate, morphology and geology the natural recharge varies between 2 and 50% of the annual precipitation. To guarantee sufficient freshwater supply for future generations sustainable management of groundwater resources in a quantitative and a qualitative sense is necessary. This requires monitoring strategies and research of water-rock interaction, which provide a means to control the quantity and quality of available groundwater resources in different hydrogeological contexts. Important strategies to enhance the formation of groundwater are artificial recharge via surface water bodies or wells, which are becoming more important in the future with regard to global climate changes.*

An introduction is given on the definition of groundwater and aquifers, on factors influencing groundwater quantity and quality and its relevance as a resource. Groundwater forms more than 30% of the world's freshwater and is therefore a precious natural resource and of great importance for the drinking water supply. Abstraction of groundwater instead of surface water has a number of clear advantages. Groundwater is filtered naturally by physical and microbiological processes in the subsurface during its recharge which generally results in a better water quality. Depending on climate, morphology and geology, the natural recharge varies between 2 and 50% of the annual precipitation. To guarantee sufficient freshwater supply for future generations, sustainable management of groundwater resources is necessary in both quantitative and qualitative terms. This requires monitoring strategies and research into water-rock interaction, in order to control the quantity and quality of available groundwater resources in different hydrogeological contexts. An important strategy to enhance the formation of groundwater is artificial recharge via surface water bodies or wells. In view of global climate change this technique is expected to gain importance in the future.

Fossil and young groundwater represents an important resource to meet the global demand for potable as well as irrigation and industrial water. The qualitative and quantitative evolution of this precious resource and its dependence on climate change are of great interest to humanity (UNESCO 2003).

Groundwater as part of the water cycle

Groundwater is part of the hydrological water cycle, which includes the components precipitation, evaporation, surface runoff and subsurface runoff. The hydrological water cycle can be described using the following mass balance equation (see Chapter 1.3):

$$P = E + T + D_s + D_{ss} \qquad (1) \quad \text{with :}$$

P: precipitation, D_s surface runoff, D_{ss}: subsurface runoff, E: evaporation, T: transpiration by vegetation

Origin and definition of groundwater

Groundwater originates from infiltration of surface water and precipitation into the subsurface, which can be divided into a saturated and an unsaturated zone. The unsaturated zone is not completely filled with water, i.e. the pore space is filled with water and air, and the water is attached to the pore matrix by electrostatic forces. This restricts circulation and makes the water unsuitable for extraction and drinking water supply. The following subtypes of water are distinguished in the unsaturated zone: capillary fringes, seepage water, adsorbed water, chemically bounded water, and water which is enclosed in isolated pores. The unsaturated zone is essential for the vegetation, which is able to use its water resources. Furthermore, in many cases the unsaturated zone protects the drinking water resources below owing to its sorption and microbial degradation of contaminants produced by agricultural and industrial human activities.

The real groundwater is situated in the saturated zone, where all pore spaces are filled completely with water. In pores above a critical diameter, water is no longer attached to the pore matrix and is able to flow according to gravitational forces. This water can be extracted by pumping wells and is therefore suitable for drinking water if it meets the quality standards. Therefore, an aquifer is defined as sediment with an interconnected pore space, allowing

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groundwater movement due to gravitational forces. Suitable aquifers are made of porous coarse-grained sediments (fine to coarse sands and gravel) as well as different types of hard rocks. Unsuitable for the drinking water supply are fine-grained sediments such as silts and clays which have a high porosity but very small pore spaces where water always remains attached to the sediment matrix and movement is very restricted. Only the part of infiltrating water which is not attached to the sediment or is not subject to transpiration and evaporation is able to recharge the groundwater resources of an aquifer.

Three types of groundwater can be distinguished with regard to their involvement in the hydrological cycle. These are fossil groundwater, deep waters and meteoric waters. Fossil groundwater was enclosed in the pore spaces during sedimentation. After sedimentation the exchange of this groundwater was inhibited by impermeable geological units, and therefore the water was excluded from the hydrological cycle for long periods at geological time scales. Groundwater more than 250 m below surface is called deep water and is also characterised by very long residence times in the underground. Owing to the long contact time with the sediment matrix these waters show a high mineralisation and are only of minor suitability for the drinking water supply. Often these waters can be applied for healthy issues because of their high concentration of dissolved minerals. If groundwater is involved in the annual or perennial meteoric cycle it is defined as meteoric water. Owing to its chemical quality and hydraulic extractability this type of groundwater is the major contributor to the drinking water supply.

Aquifer types

Porous aquifers and hard rock aquifers are distinguished according to their cavities. Normally, porous aquifers are geologically young sediments whose pore spaces have not been filled by mineral precipitation and which therefore possess an interconnected pore space. Important porous aquifers can, for example, be found in the Northern German Lowlands where 2 million years of glacial sedimentation led to the formation of sediments up to several hundred metres thick (Ehlers 1994). In qualitative and quantitative terms, porous aquifers provide optimal conditions for the drinking water supply.

Hard rock aquifers are characterised by a cemented pore space inhibiting free circulation of groundwater. In these rocks groundwater movement occurs mainly within structural cavities such as faults, joints and fissures and only to a minor extent in the remaining pore space.

Important parameters characterising an aquifer are its hydraulic conductivity, thickness and storage capacity. They control the tempo-spatial characteristics of the hydraulic drawdown during groundwater extraction. Information about hydraulic conductivity can be obtained by analysing the grain size distribution of the sediment (Beyer 1964), by pumping tests (Krusemann & De Ridder 1994) and by different types of permeability tests with sediment samples in the laboratory. Information about aquifer thickness can also be obtained by borehole drilling.

Groundwater recharge

Estimations of the available supply of drinking water require information about the groundwater recharge. A number of methods to quantify groundwater recharge have been developed (Matthes & Ubell 1983), the most important of which are briefly described in the following. Direct measurements can be carried out by lysimeters, which are vessels containing local soil installed below ground (DVWK 1980). Groundwater recharge can further be derived by measuring the remaining components of the hydrological water balance (see eq. 1) and calculating the difference to the precipitation. Also numerical groundwater models provide a means of estimating groundwater recharge as a result of parameter calibration. Another method is based on measurements of river discharge starting from the assumption that the surface runoff in rivers is composed of groundwater exfiltration and surface water runoff after rainfall events. The base flow of rivers which remains after longer dry periods can be used to determine the groundwater recharge within the watershed (Natermann 1951). Furthermore, tritium and chloride concentrations are used to calculate groundwater recharge rates.

In humid moderate climates about 30% of the precipitation reaches the aquifers as groundwater recharge, whereas in semiarid and arid climates this amount is often reduced to 10–20% and 0–2% respectively. This is mainly due to the higher rates of evaporation and the physical conditions of dry soils, which inhibit infiltration and lead to very high amounts of surface runoff (Bouwer 2002).

Groundwater quality

Along with quantitative and hydraulic aspects the chemical quality of water is an important aspect for the assessment of groundwater resources. The hydrogeochemical composition is controlled by geogenic and anthropogenic factors.

Geogenic factors

Geogenic conditioning of groundwater quality is mainly due to water rock interaction via redox reactions, sorption and desorption, dissolution and precipitation of minerals. The resulting composition depends on the contact time between water as discussed above for fossil groundwater and deep groundwater. Furthermore it depends strongly on the aquifer material and its solubility. The end members with regard to solubility are silicate-bearing rocks showing a very low solubility on the one hand and highly soluble evaporates of former oceans on the other. For example, pure sandstones and granites are composed mainly of silicates and lead to low mineralised groundwater, whereas evaporate sediments are mainly composed of gypsum, halite and other salts, giving rise to highly mineralised groundwater which is normally not suitable for drinking water supply. They can even contaminate other groundwater resources. Salinisation of groundwater resources often results from seawater intrusion (Chapter 2.10) into coastal aquifers and is a global problem. Between these end members a number of different aquifer materials such as carbonates, metamorphic and igneous rocks exist which also leave a characteristic fingerprint on groundwater composition.

An example for the huge environmental impact of geogenic factors on groundwater quality is the Ganges delta in Bangladesh where drinking water was originally supplied by surface water. Since the surface water did not meet the required quality standard, the requirements of the population were met by groundwater extraction. The fact that the sediment material contains high concentrations of arsenic bearing minerals gave rise to serious health problems in a large part of the population (NICKSON et al. 1998).

Anthropogenic factors

Important anthropogenic impacts on groundwater quality result from mining activities, agriculture, industrial activities and urban agglomeration (Chapter 2.8).

Mining activities cause oxygen penetration into the subsurface, resulting in mineral oxidation, acidification and subsequent mobilisation of heavy metals. The largest environmental project world-wide that is concerned with these aspects is the remediation of several open pit lignite mines in Eastern Germany such as the former *Bitterfeld* and *Lausitz* mining areas. The groundwater discharged from the heap areals often shows pH values below 2 and extremely high charges of sulphates, arsenic and acid generating components.

The influence of agricultural activity is mainly due to the application of organic and inorganic fertilisers, leading to the input of nitrates, dissolved organic carbon (DOC), potassium and sulphate. Furthermore, the application of pesticides gave rise to an enrichment of these organic substances in the groundwater and subsequently in the food chain.

Industrialisation and the formation of urban agglomerations introduced a huge number of organic and inorganic substances and micro-organisms into the hydrological cycle and also into the groundwater. Depending on their degradability and toxicity these substances create severe problems for the human drinking water supply. Especially in less developed countries, serious problems arise from pathogenic bacteria due to groundwater contamination by faecal waste which is often deposited close to wells supplying drinking water.

Further, widespread sources of contamination are poorly soluble organic liquids, called non aqueous phase liquids (NAPL) which are divided into two groups according to their density. Light non-aqueous phase liquids (LNAPL) such as petrol, diesel or kerosene are less dense than water and normally remain on the capillary fringe of the groundwater. The second group consists of dense non-aqueous phase liquids (DNAPL), which are denser than water and often penetrate easily into greater depths of groundwater reservoirs. Widespread substances belonging to this group are halogenated hydrocarbons which are applied frequently as solvents for industrial purpose as well as in private households. In Germany, organic liquids constitute the bulk of all groundwater contaminations.

The remediation of these contaminations and the related processes of microbial degradation have been the subjects of intensive research in the last decades, and a number of remediation methods have been developed, e.g. microbial decontamination, natural attenuation, extraction and decontamination of soil air and groundwater etc. (ACKERER et al. 1991).

Groundwater as a resource

Groundwater plays a crucial role as a reservoir of freshwater for use as potable water as well as irrigation water for agriculture world-wide. Of the entire freshwater resources in the world, an estimated volume of 8 million km³ (30.8%) are present as groundwater (UNEP 2003), while the share of surface water is only about 2% (BOUWER 2002). The share groundwater has of the easily accessible freshwater resources is estimated to be even more than 90% (UNEP 2002). Roughly 30% of the continents are underlain by aquifers and about 19% contain rich groundwater reservoirs in geologically complex areas (*Fig. 1.8-1*; STRUCKMEIER et al. 2003).

The annual withdrawal of water from groundwater resources is estimated to be 600–700 km³ which is about 20% of the total water used world-wide (WMO 1997). The biggest global freshwater consumer is agriculture (75%), followed by industry (20%) and finally private households (5%) (*Abb. 1.8-2*). Only about a quarter of the world's population uses groundwater as potable water (UNEP 2002). In Germany, more than 70% of the potable water originates from groundwater; in India, the share is even more than 80% (STRUCKMEIER et al. 2003).

In most cases, groundwater has a much better quality than surface water, because it is better protected from pollution as well as being cleaned during underground passage. Hence, groundwater is an important and precious freshwater resource, and its value is expected to increase further in the future. (STRUCKMEIER et al. 2003).

Sustainable groundwater use

If groundwater withdrawal within a certain time period does not exceed natural groundwater recharge, groundwater use is sustainable with regard to the water quantity. The natural equilibrium is not disturbed, and the groundwater resources are conserved. Hence, they will not be diminished in the long term. Sustainable groundwater use may be ensured by quantifying the groundwater recharge with the methods given above.

Naturally, the preservation of the groundwater quality is also of importance for sustainable groundwater use. Hence, groundwater protection zones are established around drinking-water production wells, to avoid groundwater pollution. In addition, directives, guidelines and laws such as the Water Framework Directive in Europe (Chapter 4.9) are issued to assure groundwater protection.

Groundwater over-exploitation

If more groundwater is withdrawn from aquifers than can be renewed naturally, the groundwater resource is reduced with time. Declining groundwater levels are one consequence, leading to the installation of deeper wells until finally the entire reservoir is depleted or unusable because of qualitative restrictions such as the intrusion of saline water.

Even in some semi-arid or arid areas with very low present groundwater recharge rates, huge groundwater reservoirs are stored underground, which were deposited under wetter climates in the past thousands or ten-thousands of years (so-called »fossil« waters). If these groundwater deposits are mined, they are irretrievably lost, since they cannot be renewed within conceivable time spans. Because groundwater processes generally proceed slowly, over-exploitation is often only noticed after decades.

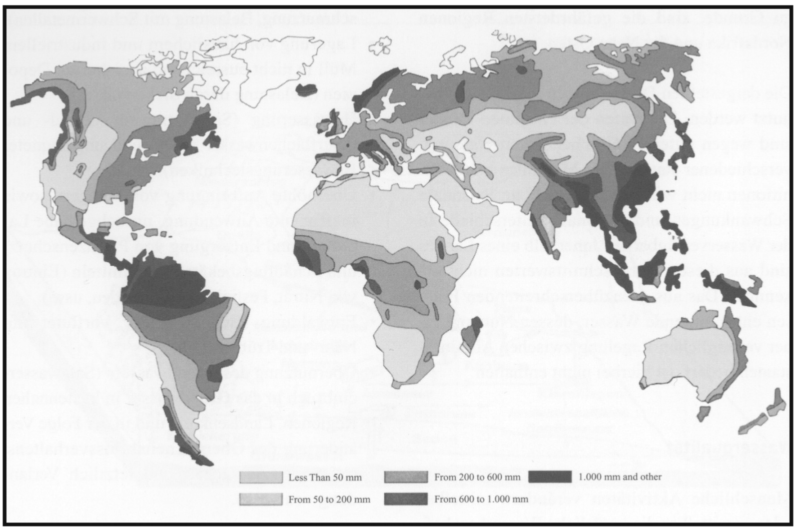

Fig. 1.8-1: Distribution of renewable groundwater reservoirs (World Resources Institute 1990; World Resources 1990–91).

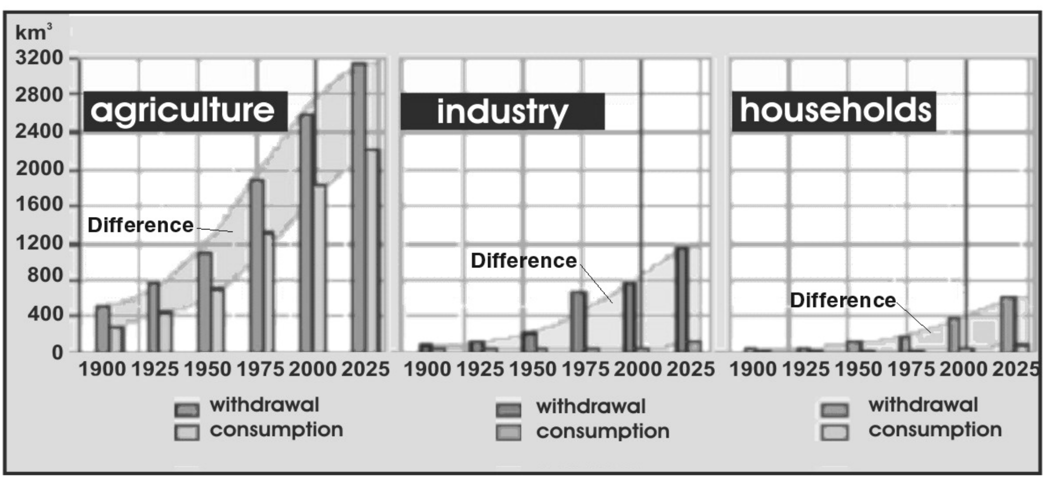

Fig. 1.8- 2: Global water consumption by agriculture, industry and private households from 1900 to 2025 (prognoses). Modified after Struckmeier et al. 2003.

Globally, the average annual amount of renewable water is estimated to be 43,000 km³ (STRUCKMEIER et al. 2003). Hence, theoretically, the global renewable water resources are sufficient and exceed the demand. However, there are significant differences in the real availability in different areas of the world, since the resources are not equally distributed. For example in Asia, where 60% of the world's population live, only 36% of the globally accessible water resources are stored (UNESCO 2003). The problem is further aggravated by the fact that the world's population has approximately tripled in the past century, while water consumption rose sixfold. Water shortage is currently reported from more than 30 countries in the world (STRUCKMEIER et al. 2003).

Locally declining groundwater levels as a consequence of over-exploitation have been observed in many places in the world, for example China (ZAISHENG 2002), Australia (GERGES et al. 2002), Spain (ESCALANTE & GUITÉRREZ 2002) or Italy (LANDINI & PRANZINI 2002). ZAISHENG (2002) reports groundwater levels declining at a rate of more than a metre per year in large areas of the densely populated lowlands of North China (more than 30 m in the past decades). Another example is a groundwater depression of up to 75 m caused by intensive groundwater withdrawal from a confined aquifer near Adelaide in South Australia (GERGES et al. 2002).

The problems associated with groundwater over-exploitation will be intensified, should the expected climate change cause an increase of aridity in areas with already low precipitation. One approach to solve the increased water demand of the growing population of the world is the application of artificial groundwater recharge, which appears to be gaining world-wide importance.

Artificial groundwater recharge

There are various types of (artificial) aquifer recharge, including induced bank filtration next to natural surface water bodies (HISCOCK & GRISCHEK 2002), aquifer storage and recovery via injection wells (ASR; PYNE 1995), surface infiltration via artificial ponds, ditches or wetlands (BOUWER 2002), dune filtration or others (DILLON 2005). Besides the increase of the groundwater reservoir, objectives of the application of artificial recharge may be to prevent salt water intrusion, to ensure intermediate water storage and to improve water quality (BOUWER 2002). Beneficial effective attenuation processes during artificial groundwater recharge include the elimination of suspended solids, particles, biodegradable compounds, bacteria, viruses and parasites and the partial elimination of absorbable compounds (HISCOCK & GRISCHEK 2002).

Bank filtration is the infiltration of surface water into the groundwater which is caused by a hydraulic gradient from the surface water to the groundwater which may exist

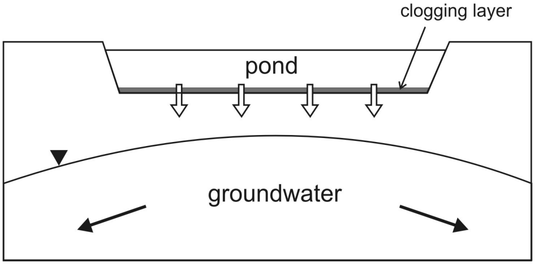

Fig. 1.8-3: Scheme of an artificial recharge pond in Berlin (MASSMANN et al. 2006).

naturally or as a consequence of groundwater extraction via production wells close to the surface water bodies (induced bank filtration; BOUWER 2002). Another requirement for a successful bank filtration scheme is a sufficiently permeable river bed. HISCOCK & GRISCHEK (2002) reported that the Slovak Republic depends on bank-filtered water for 50% of its potable water supply, Hungary for 45%, Germany for 16%, and the Netherlands for 5%. In Berlin, at least 70% of the drinking water originates from bank filtration and aquifer recharge via ponds (PEKDEGER & SOMMER-VON JARMERSTEDT 1998).

Artificial groundwater recharge can be achieved by building dams in seasonally or permanently flowing water bodies to increase the surface area. Another common technique is the installation of special infiltration systems such as lagoons, ponds, former gravel pits, flood plains, perforated pipes or any other designed system which enables water percolation into the unsaturated or saturated zone (BOUWER 2002) (s.*Abb. 1.8-3*). The advantages and the use of artificial infiltration systems are similar to those of bank filtration schemes. Clogging and the consequent decrease of the infiltration capacity are often a problem in these systems and artificial infiltration sites often require regular maintenance such as pre-treatment of the water or redevelopment of the pond bases.

Artificial recharge of water via injection wells (ASR, aquifer storage and recovery) is practised mainly in the more arid regions of the world (PYNE 1995). It is, however, also practicable where permeable soils are not available, when land for ponded infiltration is not accessible, or if aquifers are very deep or confined. Besides the seasonal storage, benefits can be reduction of groundwater salinity, prevention of salt water intrusion, improvement of water quality, storage of thermal energy and avoidance of land subsidence or floods (DILLON & PAVELIC 1996). If available, excess storm water or even treated wastewater is injected into mostly unusable aquifers to be recovered in times of water shortage (BOUWER 1996). One advantage is the negligible evaporation loss compared to overground storage in dams.