GROUNDWATER HYDRAULICS

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Summary

The flow in groundwater systems is part of the hydrological cycle. Groundwater constitutes an important component of water supply for domestic use, for process water in industry, and for irrigation water in agriculture. The intensification of human activities has caused an increased demand for pumped groundwater of an appropriate quality, but at the same time an increased input of pollutants. The development of groundwater resources and the remediation of polluted aquifers requires a profound knowledge of the various physical, chemical and biological processes involved, and careful exploration of the aquifer. Groundwater models are versatile tools for the assessment of the impact of human activities on groundwater; model theory and the modeling of various aspects of groundwater are described and discussed, as is groundwater exploration. The sustainable use of groundwater implies both the adequate management and the protection of groundwater resources, and remediation and protection are briefly discussed.

1. Groundwater Resources and their Significance

Groundwater as part of the hydrological cycle constitutes an important component of water supply for domestic use, for process water in industry, and for irrigation water in agriculture. The intensification of human activities has caused an increased demand for pumped groundwater.

1.1. What is Groundwater?

The term groundwater is used to denote in principal all the waters found beneath the ground surface. More precisely, it represents that part of the water, which circulates in interconnected pores or fractures, or more generally, in the interconnected void space of geological formations. Aquifers are geological formations, which allow significant amounts of water to move through it under ordinary field conditions. Sedimentary deposits, fractured rock, or karst (limestone and dolomitic) systems can be aquifers. Aquifers can be interconnected via semipervious layers thus forming multi-aquifer systems. Confined aquifers are bounded from above and below by impervious (or practically impervious) formations. In phreatic aquifers the water table serves as upper limit. Sometimes, the water in confined aquifers and below the water table of phreatic aquifers is denoted as groundwater. Since (practically) the complete void volume is filled with water, this zone is denoted as the saturated zone. The zone above the water table is referred to as the vadose or unsaturated zone thus reflecting the presence of air besides water. However, it has to be noted that the capillary fringe just above the water table can still be practically water saturated.

The flow in groundwater systems is part of the hydrological cycle. It consists of the following elements: recharge (natural or artificial recharge, infiltration, irrigation), underground inflow and outflow (including abstraction or infiltration of water), and evapotranspiration. The flow of groundwater is determined by various time-varying boundary conditions, and spatially varying flow parameters. A strong relationship can exist between groundwater and surface water (lakes, rivers, streams). Oases in arid countries are places where groundwater emerges at the ground surface. Groundwater is also part of the ecosystem. Wetlands, for example, are essentially influenced by the prevailing groundwater conditions. A schematic aquifer system is shown in Figure 1.

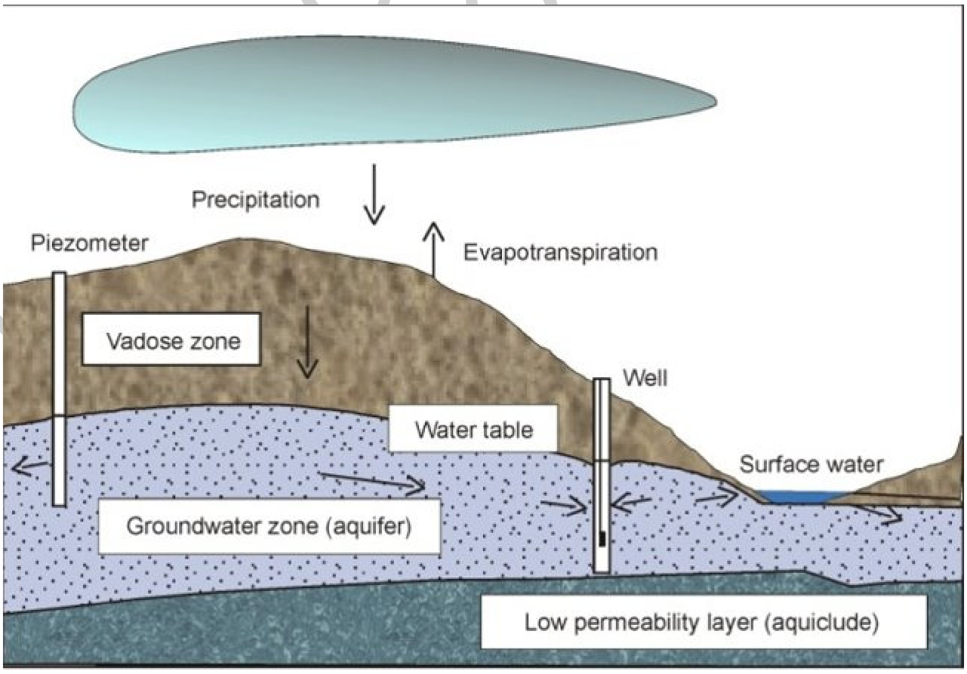

Figure 1. Schematic aquifer system

1.2. Groundwater Resources and their Utilization

Readily accessible fresh groundwater resources of the world comprise a total volume of about 4 million km^3. This represents about thirty times the volume of surface waters (rivers, lakes, swamps). Additionally, huge amounts of groundwater exist which are saline or inaccessible. Worldwide, more than 50% of the accessible and renewable water flux is utilized.

The utilization of groundwater comprises its use as drinking water, irrigation water, and process water for industry. Furthermore, the thermal properties of groundwater are used for the storage of heat and for cooling purposes. Historically, the early use of springs for drinking water supply is well known. The digging of wells in order to access artesian, confined or phreatic aquifers is an ancient technique. Already on a high technical level are the qanats of old Persia and neighboring countries. These are long underground galleries which collect groundwater along the foothills of mountains and conduct it to the cities in the plains. Nowadays, the exploitation of groundwater is widespread. In many parts of the world, springs and pumping wells are systematically developed and integrated into waterworks. There is a tendency towards a change in the use from surface water to groundwater or bank filtration for water quality reasons. The key questions of concern are both the quantity of groundwater (how much is available?) and its quality (how good is it?). These are the principal elements of a thorough water management strategy.

Aquifers are typically the result of a long and complex history of geological development. Many relevant characteristic properties of aquifers are highly heterogeneous, i.e., they are strongly spatially variable. This not only concerns the variability of permeability and porosity but also the mineral composition of the aquifer material. The latter is relevant for the chemical composition of groundwater and the adsorptive behavior of solutes. Aquifers are also the “playground” for microbial life, thus influencing the quality of groundwater. Seen altogether, groundwater research comprises various disciplines, including hydrogeology, engineering, chemistry, biology, and so forth.

2. Impact on Groundwater

Human impact on groundwater mainly concerns its abstraction and the deterioration of its quality, and therefore, it is characterized by both quantitative and qualitative aspects. From a quantitative point of view, unfavorable alterations of the storage capacity, of the flow rates, of the natural recharge, and of the level of the water table or the piezometric surface, are relevant. Questions of an overexploitation of natural groundwater resources are salient, mainly due to the long time scales of recovery involved. They are related to the sustainability of water resources utilization. In certain regions, the water table or piezometric surface has fallen by dozens of meters or even more. Over pumping can cause severe land subsidence. In other regions, however, a rise of the water levels due to the abandonment of wells and/or an increase of the infiltration can represent a threat to urban areas and the environment. Unfavorable alterations of groundwater flow caused by technical interventions also need to be mentioned. Examples are alterations of flow by underground constructions, or the clogging of the ground surface which reduces the availability of suitable recharge conditions.

Qualitative aspects mainly concern the chemical and microbial composition of the groundwater and its alteration. If groundwater is used for drinking water supply, it has to fit the quality requirements for food. Deterioration of groundwater quality can be caused by various factors, for example:

- infiltration of surface water polluted with various constituents;
- infiltration of sewage from sewers or other sanitary systems;
- inappropriate use of fertilizers and pesticides in agriculture (an example is the widespread pollution by nitrates);
- leachate from polluted sites (examples are waste landfills with inappropriate liner systems);
- inappropriate transportation, storage, and application of substances which can potentially endanger groundwater (examples are spillage from traffic accidents or the leakage of storage facilities of mineral oil or chlorinated hydrocarbons, or accidents occurring in deposits of radioactive waste); and
- deposition of air-borne pollutants on the ground surface and their subsequent infiltration.

Further impacts on groundwater which can influence water quality are:

- salt water intrusion in coastal aquifers, caused by an overexploitation of groundwater;
- thermal influences on groundwater, and the subsequent alteration of the physical, chemical and biological properties of groundwater;
- mixing of groundwater of differing origins, which may alter the physical, chemical and biological properties of groundwater; and
- impact of technical constructions.

In general, the main impacts on groundwater are the overexploitation and the release of pollutants. The latter can be present as long term sources of pollutant release. Consequently, the groundwater systems often play a prominent role in environmental impact studies. The protection of groundwater resources represents a necessary measure to guarantee a sustainable use. Therefore, the flow of groundwater and the migration and fate of dissolved substances, of non-aqueous-phase liquids, and of colloidal particles in the subsurface are of primary concern. It should be kept in mind that aspects of water quality are strongly related to flow, since the advective motion represents the main process for the migration of dissolved substances and of energy.

3. Basic Theory of Groundwater Flow and Transport

For the sake of simplicity, the basic theory is restricted to the most widely used concepts and models of flow and transport. The main purpose of this chapter is to list the parameters and conditions which are necessary for characterizing flow and transport processes.

3.1. Flow Equations

The equation, which describes the flow of groundwater in most applications, is Darcy's law. It relates the water discharge rate Q through a cross sectional area A to the hydraulic head gradient $\Delta h/\Delta l$. The one-dimensional form is:

$$Q = AK\frac{\Delta h}{\Delta l} \qquad (1)$$

The variable h is the piezometric head, which is identical to the water level in a piezometer. The symbol Δh denotes the head difference due to energy loss over the length Δl of the flow segment between two cross sections. The parameter K is the hydraulic conductivity which depends on the permeability of the aquifer material and on the physical properties of water. Note that the discharge Q is only meaningful if a macroscopic area A comprises many pores or fractures. This continuity concept is related to the idea of a representative elementary volume which contains so many pores or openings, that stable values for the average of the considered quantity are obtained. In granular porous media a sufficient number of grains are necessary whereas in fractured media a sufficient number of interconnected fractures are required. This may be also applicable to karstic aquifers if many interconnected small openings or tubes are considered. Darcy's law for homogeneous fluids is written as:

$$\boldsymbol{q} = -\boldsymbol{K}\nabla h \qquad (2)$$

where $\boldsymbol{q}$ is the specific discharge vector with the components in the direction i:

$$q_i = \frac{Q_i}{A_i} \qquad (3)$$

and A_i is the area perpendicular to the i-direction. $\boldsymbol{K}$ is the hydraulic conductivity tensor. The tensorial property of $\boldsymbol{K}$ is necessary to allow description of an anisotropy of the hydraulic conductivity. It is often observed that the horizontal hydraulic conductivity of aquifers is higher than the vertical one due to the prevailing heterogeneous (layered) structure (lenses, layers). For isotropic media the tensor reduces to a scalar quantity K. The symbol ∇ is the gradient operator, and the vector ∇h is the head gradient. More generally, if water density may be variable, Darcy's law is stated as:

$$q = \frac{\boldsymbol{K}}{\rho\nu}\left[-\nabla p - \rho g\right] \qquad (4)$$

This form is applicable if density effects due to concentrations and/ or temperature are relevant. The tensor k is the permeability. It is related to the hydraulic conductivity of the aquifer material and the kinematic viscosity ν of water by the expression:

$$k = K\frac{\nu}{g} \qquad (5)$$

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Biographical Sketches

Fritz Stauffer (Dr.Sc.Techn., Switzerland). Senior Research Associate and Lecturer. Awarded the title of Professor. Chairman of the Groundwater Hydraulic Section of the IAHR (1997-2000). Researcher in modeling flow and transport in saturated and unsaturated porous media, stochastic numerical groundwater modeling. Author or coauthor of many publications in the field of groundwater flow and transport on nonequilibrium, and hysteresis effects in unsaturated aquifers.

Wolfgang Kinzelbach (Doctorate received from University of Karlsruhe, Germany). Studied Physics and Environmental Engineering. Professor of Technical Hydraulics and Hydrology at the University of Kassel (1988), Professor of Environmental Physics at the University of Heidelberg (1993), and Professor of Hydromechanics at ETH Zurich (1996). Research on flow and transport processes in the environment with practical applications in water resources management, pollution control and remediation. Current focus is on soil and groundwater studies. Author or coauthor of many publications on groundwater flow and transport. Winner of three prestige prize awards for research.