GROUNDWATER

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Contents

Summary

The term groundwater refers to that water stored naturally in the voids existing between underground rocks. It contributes about 30.10% of the total freshwater present in nature. Since 68.70% of freshwater present in the hydrosphere is in solid state, the necessary conclusion is that groundwater constitutes the most abundant liquid reserve of freshwater in our planet.

This Chapter presents a perspective of the field of groundwater and an overview of the important aspects of the subject such as, natural origin and distribution, characteristics under diverse climates and surrounding rocky environments, exploration and management, natural quality and human related sources of contamination, sustainable exploitation of resources, protection and current research trends.

The reader will find an answer to most questions arising from the study of groundwater in eight chapters presenting overviews of the main topics under the subject of groundwater. These are briefly as follows:

Origin, Distribution Formation, and Effects of groundwater in nature, as well as the aquifer properties of different types of rocks. Other topics within this level include the hydrological cycle, water balances, aquifer recharge and the importance of groundwater to ecological equilibrium.

Typical Hydrogeological Scenarios of groundwater with reference to mountainous regions, Great Plains, small islands, volcanic areas and karstic environments are discussed and climatic conditions, wetlands, and thermal springs are also discussed.

Transport Processes in Groundwater is an essential topic for the study of groundwater contamination. The theory of flux, responsible for advective transport, is covered for granular and fractured media, as well as for aquifers with high content of clays and heterogeneous media. Environmental isotopes, Subsurface Hydrobiology and a review on mathematical model of flow and mass transport in saturated porous media are another question within this topic level.

Transport Phenomena and Vulnerability of the Unsaturated Zone, including a study of the main physical characteristics of the vadose zone, and the existing relationship between saturation and capillarity are presented. Other topics about the unsaturated zone include groundwater and solute flux, its vulnerability, the role played by the unsaturated zone in the behavior of different types of contaminants, the attenuation of contamination effects and the modeling techniques of flow and transport in the unsaturated zone.

Groundwater Development is discussed, attending to study methods, groundwater exploitation, monitoring networks and groundwater development in coastal aquifers and hard rocks.

Groundwater Use and Protection is discussed, with an emphasis on the chemical composition and thermal regime of groundwater, its urban, agricultural and industrial use, contamination and protection of groundwater, aquifer remediation as well as recharge and discharge of aquifers and artificial recharge issues.

Groundwater Management is discussed, paying special attention to its basic aspects, sustainable use and overexploitation, economic and legal aspects of aquifer exploitation, groundwater exploitation impact and its remedies and the conjunctive use of surface and groundwater.

Finally **Special Issues in Groundwater** are discussed. These refer to groundwater and climatic change, urban hydrogeology, geostatistical applications, groundwater study related techniques and those problems related to the scale of the geological media with regard to groundwater flow and transport and in situ groundwater treatment.

Each of these chapters is expanded by further chapters characterized by presentations in depth and detail.

As an introduction to the above, the following pages cover some basic concepts necessary for a better understanding of this chapter. Comprehensive cross-referencing has been made to related chapters in order to facilitate access to a more detailed explanation of each concrete aspect.

Finally, it is important to note that the theoretical foundation of this introductory chapter is based on the author's experience and works, in addition to well known texts such as Davis & De Wiest (1966), Biswas (1970), Freeze & Back (1983), Back & Freeze (1983) and Fetter (2001).

1. Basic concepts on Groundwater

An *aquifer* (from the Latin *aqua* = water and *ferre* = to carry) is a geological unit which, regardless its lithology, allows for the storage and flux of water. This water is known as *groundwater*.

The distribution of water in the hydrosphere is as follows: 97.2% corresponds to saltwater, 2.14% is fresh water in solid state (glaciers as well as North and South Poles), water from lakes and rivers adds up to 0.009% whereas 0.005% is water retained in the soil and 0.001% is in the atmosphere in vapor state. Groundwater represents the highest volume of fresh water in liquid state, with about 0.645 % of the hydrosphere total.

Water molecules, though electrically neutral, present their positive and negative charges distributed in an asymmetrical manner. The immediate consequence of this chemical structure, known as a *dipole*, is the mutual attraction between molecules. When solar radiation acts with enough intensity to break this attraction between the surface molecules of a water body, these separate from one another. Water then passes from liquid to gas state, that is, it *evaporates* into the atmosphere, making up clouds. Clouds are blown by the wind towards land masses, where they precipitate as a consequence of a series of thermodynamical processes.

Part of this precipitation evaporates again before it reaches the ground. Another part, reaches the ground to flow as surface runoff, in streams and rivers towards the sea, where it evaporates again as explained above, stating the cycle all over again. The rest infiltrates through the soil (*Soil* is the uppermost layer of the Earth's crust. This superficial layer is of variable thickness, and allows for the physical, chemical and biological processes necessary for the occurrence of vegetation) and contributes to the nourishment of vegetation. It finally returns to the atmosphere through the process known as *transpiration*.

Once the soil is saturated, and if external contribution continues, part of the water contained in the soil flows by gravity through the pores and fissures of the an *unsaturated* zone (vadose zone). Water co-exists there with air and other gases. This water can reach the saturated zone, where all pores and fissures remain full of water (see *Physical properties of solid and fluid matrices and Volumetric water content – Matrix potential relationship*). The thickness of this unsaturated zone ranges from hundreds of meters in arid regions to non-existence in groundwater discharge areas or humid regions where the water table is very close to the surface.

Groundwater recharge is the volume of water that infiltrates and flows towards the saturated zone, thus contributing to increase the volume of water stored in the aquifer (see *Groundwater Recharge*). The upper limit of the saturated zone is known as the water table, and corresponds to the set of points where the water is in equilibrium with the atmospheric pressure. Underneath the water table, water flows as underground runoff.

Over the last two decades, hydrogeologists have focused their research on the role played by the unsaturated zone in aquifer recharge and on contaminant transport into the saturated zone (see *Transport Phenomena and Vulnerability of the Unsaturated Zone, Water and Solute Transport in the Vadose Zone, Biodegradation in the Vadose Zone and Organic Compounds in the Vadose Zone*).

2. Evolution of the Hydrological Cycle Concept

Water in nature is in a perpetual state of motion due to the action of gravity and solar energy. This results in a cycle in which not all particles complete.

Except for small volumes of magmatic origin, all freshwater existing in the hydrosphere is a result of precipitation. Freshwater is employed by plants in their biological functions; it gives rise to lakes and rivers and constitutes glaciers and ice sheets, it also constitutes the recharge of underground reservoirs and the water that ends up in the sea to give rise to rain clouds again (see *Groundwater origin and distribution*).

The following equation always holds for a given period of time, whether it applies at a global scale or to a small catchment:

$$P - (E + T + R_s + R_u) = \Delta$$

Where:

P = Precipitation
E = Evaporation
T = Transpiration through vegetation
R_s = Surface runoff
R_u = Underground runoff
Δ = Volume storage increment (+/-) for the catchment

This equation is known as Hydraulic Balance, and corresponds to Lavoisier's principle of mass conservation (see *Origin, distribution formation and effects and Groundwater balance, climate and groundwater*).

This fact, evident today, was first accepted by science when Perrault (1608-1680) and Mariotte (1620-1684) separately measured the Seine river contribution and proved that these represented about one-sixth of the precipitation over their control catchment. Later on, Halley (1656-1742) showed that the volume of water evaporated from the Mediterranean sea was enough to explain the total contribution of all rivers to that sea.

Arriving at this conclusion was a task that lasted for ceturies. Ever since primitive times, water has played a key role in the development and evolution of the human kind. Practically every nation has been born as a reduced community of people gathered around fresh water resources. Take for instance the Nile, Indus or Yellow river, cradles of ancient civilizations such as the Egyptian, Indian and Chinese. It is only logical that this is the case, although ancient people considered water as a resource for subsistence, rather than as a scientific issue.

Surface water infrastructures such as dams have been dated back as early as 5000 B.C., mainly in the eastern civilizations of Persia, Babylon and China. Examples of artificial structures for the obtention of groundwater appear somewhat later (800 B.C.) in the Arab world. These are the famous “khanats”: inclined galleries drilled along the saturated zone, which act as a drain from the groundwater system.

Such was the utility of khanats, that their use soon became widespread. Thus, Custodio and Llamas (1976) quote that the Assyrian king Sargon II imported the technique to his own country after witnessing it when he invaded Armenia in 714 B.C. Moreover, the Arab takeover of Spain (from 711 A.D.) resulted in the implementation of khanats in this country. Khanats became important to the point that the name of the capital, Madrid, seems to come from the Arabic word “mayrit” or “galleries of water”, which served the city until the 19th Century. Khanats are still today operational in many countries of the Middle East. Furthermore, wells up to 1500 metres deep have been known to exist in China from 400 A.D. It appears that these were drilled with similar percusion techniques to those employed today, although human-powered.

However, it was probably not until the 7th Century B.C. when humans being began to wonder about the peculiarities of groundwater. People from early Greek civilizations, who were the first to inquire into the principles of groundwater source and motion, can thus be considered to be the first “hydrogeologists”. Different theories, more or less in accordance with those of the *natural philosophers* had been postulated. Indeed, through the observation of the surrounding environment (mediterranean climate, karstic geology, undeveloped fluvial networks and abundant springs), the philosophers of Ancient Greece claimed that spring water had an origin other than precipitation.

Thus, sea water was thought of as the source of fresh water. According to Thales of Miletos (640-546Bb.C.), the winds carried sea water into the rocks wherefrom it somehow found its way through the earth and sprang back out to form rivers and other fresh water bodies. Thales claimed that salinity was lost somewhere along the process.

Anaximenes (570-526 B.C) observed precipitation phenomena, and thought that water was nothing but condensed air. He also believed water would turn into earth by reaching a more advanced state of condensation. This he probably inferred by looking at the walls and the stalactites and stalagmites of the karstic caves he visited. He would have explained thus the origin of earth, but not that of springs and rivers.

Plato (428-347 B.C.) thought similar to Thales of Miletos. He stated that sea water was carried by the wind into the depths of Earth, it was stored there in a huge cave (Tartarus) and rose to the surface through fissures (the veins of Earth), thus giving rise to springs. This is probably the explanation for the name of *veneros* (*veins of water*), which is given to karstic conduits in Spanish speaking countries. Neither Thales nor Plato was able to explain the process which turned sea water into fresh water or the surging of springs in high mountains.

Aristotle (384-322 B.C.), perhaps after Anaximenes, thought of Earth as a massive sponge full of holes, similar to the karstic environment he observed in Greece. He claimed that air condensed within these holes, turning into water which came out in springs. According to him, the origin of air was probably within the very Earth, although he did not discard other alternatives.

Roman thought continues along the same lines as the Greeks. Seneca (4 B.C. – 65 A.D.) generally follows Aristotle. However, he rejects rain water infiltration, and thus rejects the idea that rain is enough to justify the amount of water present in streams. Seneca's contemporary, Vitruvius, points out that snow infiltration at the top of mountains can give rise to springs at their toe. His ideas did not gain much acceptance.

During the Middle Ages, the human beings had a utilitarian view of freshwater resources which led to important advances in the construction of wells. In the first decades of the 12th Century, a series of wells are made in Europe (England, France and Italy mainly). These happen to be surging wells, and they are named Artesian wells, after the French region of Artois. It is not until 1615 that Vallisnieri provides a satisfactory explanation to this phenomenon, based on the geological structure of aquifers. A new distinction between confined and unconfined aquifers is accepted since then.

When the water present in the pores of the saturated zone is directly in contact with the atmosphere, the aquifer is said to be free or *unconfined*. Thus all points along the water table are at a pressure equal to that of the atmosphere. This surface, known as *phreatic surface*, separates the saturated and the unsaturated areas within the aquifer.

If an aquifer is isolated by impervious layers, then it is known as *confined*. A confined aquifer is always saturated, and everywhere within it, the water is at a pressure higher than that of the atmosphere (if this condition is not fulfilled, then the aquifer is unconfined by definition). The level to wich water would rise if a hole was to be drilled through the upper confining layer is known as the *piezometric level*. The surface formed by the piezometric levels of all points in an aquifer is known as the *piezometric surface*. Since the pressure at every point is higher than the atmospheric pressure, the piezometric surface is always above the aquifer top and is therefore a virtual surface. If the confining units allow for a certain degree of flow, the aquifer is known as semi-confined.

Greek ideas, doubtlessly supported by the prestige of such cultured civilization, remain virtually unchallenged for more than 2000 years. Only Kepler (1571-1630), a contemporary of Perrault and Mariott, attempted to compare Earth to a gigantic beast that drinks saltwater and yields freshwater as a result of physiological processes. However, later on Kircher (1602-1680) strictly believed in Aristotle's ideas. Even today, all that which surrounds hydrogeology is regarded as mysterious in certain circles.

3. Hydrogeology as Science

From a scientific point of view, the most difficult concept to explain in hydrogeology was the theory of groundwater flow. Whereas free flow through a conduit equals the wet perimeter area times the velocity of the water, it is not so easy to characterize the flow through a porous medium. Indeed, the different characteristics of each one of the pores imply the necessity to define an infinite number of velocity vectors, and as a result, flux through a porous media would be a random phenomenon. It would thus be impossible to quantify the flux or to carry out water balances.

In 1856 Henry Darcy, a French engineer, enunciated an empirical law that defined water motion through different types of sand. He stated that the flux through a pipe full of sand was directly proportional to the section of the pipe and to the loss of pressure potential along the pipe. The proportionality constant, or *hydraulic conductivity*, was defined as dependent on the characteristics of sand (texture and structure) *intrinsic permeability*, and of water (density and viscosity); this is meant to provide a physical description of the ease with which water circulates through a porous medium.

Darcy's Law thus allows us to define a velocity vector which holds for the velocity of water at all points of the porous medium under consideration. Thereupon began the development of new concepts and methods to quantify processes which involve flow through porous media. A brief history of these is provided below.

Seven years later, Dupuit was able to quantify the flux from an unconfined aquifer to a well based on Darcy's principles. Moreover, in 1870 Thiem presented the depression cone equation (a cone of depression is produced by a pumping well working at a constant rate on a stationary regime aquifer, that is, when inputs equal outputs), which was able to quantify the ability of a confined aquifer to transfer water.

Forchheimer (1886) and Slichter (1899) arrive separately at the general equation of flux in permanent regime (Laplace equation). To this effect they applied Darcy's Law to the principle of mass conservation (continuity equation), defining the flow velocity of water according to a three dimensional Cartesian system of coordinates, and taking into account permeability and the variation in water pressure along the three directions.

The set of points with identical hydraulic potential is known as an *equipotential surface*. The intersection of the phreatic (or piezometric) surface of an aquifer with a series of imaginary, uniformly-separated horizontal sheets yields a series of equipotential lines known as isopieces. Since phreatic and piezometric surfaces vary over time, isopiece maps can only strictly accepted as true at a given point of time.

Boussinesq (1842-1929) found the general flow equation for a non-permanent, or *transient* regime (a regime is known as *transient* when the volume of stored water varies over time, that is, inputs and outputs are not equal). Later on, in 1899, Franklin H. King was able to represent the phreatic surface of an aquifer as equipotential curves (isopieces), and then defined flow through a series of flowlines perpendicular to the isopieces.

In 1935, Charles V. Theis obtained an analytical solution to the general flow equation in transient regimes. The resulting equation defines the effect over time of a constant-rate pumping well on the piezometric surface of a confined aquifer. Based on this equation, Jacob published in 1940 a simplified method to calculate the parameters of a confined aquifer. Theis-Jacob equations allow us to calculate both the ability to transmit water and to store it in a confined aquifer.

After stating the concept of anisotropy (variation of permeability with spatial direction) in 1940, Hubbert defined *hydraulic potential* (*h*) as the energy groundwater possesses at a given point. This energy results from the sum of potential energy, the energy due to pore water pressure, and kinetic energy at the chosen point. Due to the slow nature of porous groundwater flow, kinetic energy is often neglected.

Within the saturated zone, water naturally tends to flow from high-energy to low-energy areas until groundwater finds its way back out to the surface. This discharge can occur directly into rivers or into the sea as well as due to spring phenomena. If there is no groundwater flow, the system is referred to as *static*, as water has the same energy at all points.

The hydraulic potential at a given point is defined by the level water rises to when a hole is drilled through the upper confining layer at that point. Hydraulic potential is thus measured in length units. The energy loss per unit of distance covered is known as *hydraulic gradient*, and it is a dimensionless quantity.

The set of points with identical hydraulic potential is known as an *equipotential surface* or *equipotential line*.

The complete set of positions of a particle of water in its course through an aquifer is known as its *trajectory*. The velocity vector envelope curve is known as *flowline*, under laminar flow condition.

In a homogeneous (identical permeability at all points) and isotropic medium, equipotential lines and flow lines must be mutually perpendicular, since the velocity and gradient vectors are parallel, and the gradient vector is by definition perpendicular to the equipotential lines. The network constituted by equipotential and flow lines is known as a *flownet*.

It is possible to draw a flownet or an isopiece map once the limit conditions of an aquifer have been established (constant potential, constant flux, flux as a function of potential variation). This allows us to define and quantify a flow system by applying Darcy's Law.

If the flow is horizontal, an aquifer has one single piezometric surface, whereas the equipotentials are vertical surfaces or lines. If the flow is not horizontal, an aquifer presents an infinite number of equipotential surfaces. This must be born very much in mind in the task of interpreting field data. Hantush and Jacob (1955) and Hantush (1959, 1960) found a solution for the problem of flow from a semi-confined aquifer in transient regime to a well. As a result, they found it possible to calculate the ability to transmit and store water of the aquifer, as well as the vertical transmissivity of the aquitard.

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Biographical Sketch

Pedro Emilio Martínez Alfaro was born in Murcia, Spain, in 1947. He undertook his studies of Geology at the University of Murcia and the Complutense University of Madrid, graduating in 1974. He completed his PhD on Economic Geology in 1977 obtaining the University Extraordinary Award. That very year, he became part of the teaching staff at the university, lecturing first year *Geology* while also fulfilling the role of First Year Course Coordinator.

Between 1978 and 1982, he became a member of the Geological Research Service of the Public Works Ministry, taking part with the University of Arizona in the “Hydrogeology of Great Sedimentary Basins” project. He received the Award of the Spanish Royal Academy of Exact, Physical and Natural Sciences for this work in 1982.

In 1982, he became an assistant lecturer of the Complutense University Geodynamics Department. Between then and 1991, he taught surface and groundwater hydrology. In 1991 he obtained the Hydrology Professorship of his Department, where he has worked since, teaching Hydrogeology, Hydrogeochemistry and Digital Models of Aquifer Flux and Mass Transport.

He has authored about a hundred academic publications in the field of groundwater. He has also directed and contributed to many research projects, also supervising over ten PhDs.

He is married to Begoña since 1978 and they have six children: Pedro, Paula, Antonio, Josemaría, Juan and Álvaro.