GROUNDWATER FLOW IN POROUS MEDIA

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Contents

Summary

A life support system can be defined as a natural or human engineered system that furthers the life of the biosphere in a sustainable fashion. The fundamental attribute of life support systems is that, jointly considered, they provide all of the needs for continuance of life. Groundwater is an important life support system, as it represents an important reservoir for life in the biosphere.

The aim of this article is two-folded. On the one hand, the authors would like to highlight the importance of groundwater systems, as well as to persuade readers to be careful about decisions concerning them, as water is a scarce and necessary resource that should be protected and preserved.

On the other hand, groundwater flow is a very important research topic. The authors would therefore like to remark that this article sets up only the basic concepts for further reading, making special emphasis on groundwater quantity and quality. More specialized research will require the use of the suggested bibliography.

1. Introduction

Groundwater can be defined as the water stored underground in rock crevices (fractured media) and in the pores of geologic materials (porous media) that make up the Earth's crust. Nowadays, groundwater is considered an important life support system, both in terms of human water supply and sustenance of certain ecosystems. Wrong decisions about groundwater management can provoke undesired non-reversible effects, concerning quality and quantity. These concepts are strongly linked to groundwater movement.

Flow (movement of groundwater) in porous media is a common research topic, encountered in many branches of engineering, groundwater hydrology, etc. Obviously, this article cannot include everything related to this topic. Its objective is to present the basic principles of groundwater flow in porous medium and to set up a starting point for future studies.

The article is organized as follows. First, porous medium is defined and different classifications are presented. Section 3 shows the basic parameters controlling groundwater flow and the principles that will provide the base to establish the partial differential equations used to characterize groundwater motion. The latter will be presented in section 4. The work ends with a simple example illustrating the basic principles and some remarks about the status of this research topic.

2. The porous medium. Water reservoirs

The concept of porous medium is not only used in Hydrogeology (that branch of Earth Sciences devoted to the study of groundwater, with particular emphasis on its quality and quantity). Examples of porous media are numerous: soils, fissured rocks, even a filter paper, etc. In a hydrogeological framework, and depending on the type of medium, we will talk about fractured media (fractured or fissured rocks, where water flows mostly through fractures) and porous media (sands, gravels, etc., where water flows through pores).

The common characteristics among different types of porous media allow the construction of a standard definition: that portion of space occupied by heterogeneous matter (solid matrix, gas and/or liquid phase and void space). Moreover, a minimum number of voids must be interconnected, allowing fluid to flow. Otherwise, fluid would be trapped in isolated voids.

An aquifer or groundwater basin is a geologic formation that contains water and is capable of supplying significant amounts of water, this operation being economically feasible. This amount of water moves through the porous medium, flowing in the void space, fissures, fractures, etc. In this work, only flow of water in non-fractured media will be considered. Moreover, only the part of the aquifer filled with water (saturated zone, i.e. pores completely filled with water) will be taken into account.

This definition of an aquifer is somewhat subjective, as it is based on economic terms, given that to obtain a large amount of groundwater for industry supply can be as important as to obtain a small quantity to supply an arid region.

The opposite concept is the aquiclude, a geologic formation that contains water (even in considerable amounts), but is incapable of transmitting it, so that it is not susceptible to exploitation.
On the other hand, an aquitard is a semi-impervious geologic formation that transmits water at a very slow rate, so that, it is not capable of being directly exploited.

The most common aquifers are unconsolidated geologic formations, such as sands, gravels, etc., with different origins (fluvial, sedimentation processes, erosion, etc.) (See *Typical Hydrogeological Scenarios*).

The basic tool to understand the behavior of geologic formations transmitting (or not) groundwater is the well. It is not much more than an excavation, generally vertical and cylindrical in form and often walled in, drilled to such a depth as to penetrate the geologic material of study. If the latter is water yielding, the well should allow the water to be pumped to the surface. In any case, it allows the opportunity of taking measurements of groundwater depth.

Aquifer classification can be established in terms of the hydrostatic pressure (a close inspection of Figure 1 will help in the understanding of the above basic concepts):

- Unconfined or free aquifers, presenting a water table at atmospheric pressure (phreatic level). The water level at a well connected to this kind of aquifer is the same as the water table outside the well, under no pumping conditions. In this aquifer, one can find a “real” surface of water (the so called water table). When the water table reaches Earth surface, natural sources, wetlands, lakes, etc., appear. These systems are clear proofs of the existence of an important relationship between groundwater and surface water (see *Ground- and Surface-Water Interactions*).
- Confined aquifers, containing water between two relatively impervious boundaries. The water level in a well tapping a confined aquifer stands above the top of the confined aquifer and can be higher or lower than the water table that may be present in the material above it. In some cases, the water level can reach the ground surface, yielding a flowing well. In this case, one cannot talk about a “real” surface of water or water table, as water is only visible at a well tapping the confined aquifer. In this case, the correct term is piezometric level, as will be shown in the next section.
- Leaky aquifers, as a particular case of confined aquifers, where the confining stratum is an aquitard, permitting a very low water percolation from/to other connected formations.

Figure 1 still deserves further explanations:

- Wells are opened only at their innermost part, and this zone is depicted with a dashed thick line. If they were opened in a larger extension, the well will mix the water of several formations.
- Upper formation is a free aquifer, with a real water surface, depicted as WT_A (water table, aquifer A). Under no pumping conditions, well number 3, tapping this aquifer maintains water level at the water table level.
- The correct term for the real or virtual water surface (for unconfined or confined aquifers, respectively) is piezometric level (denoted by PL in the picture).
- One can find different piezometric levels in the same hydrogeological scenario (e.g. PL_C and PL_A in the system depicted in Figure 1).

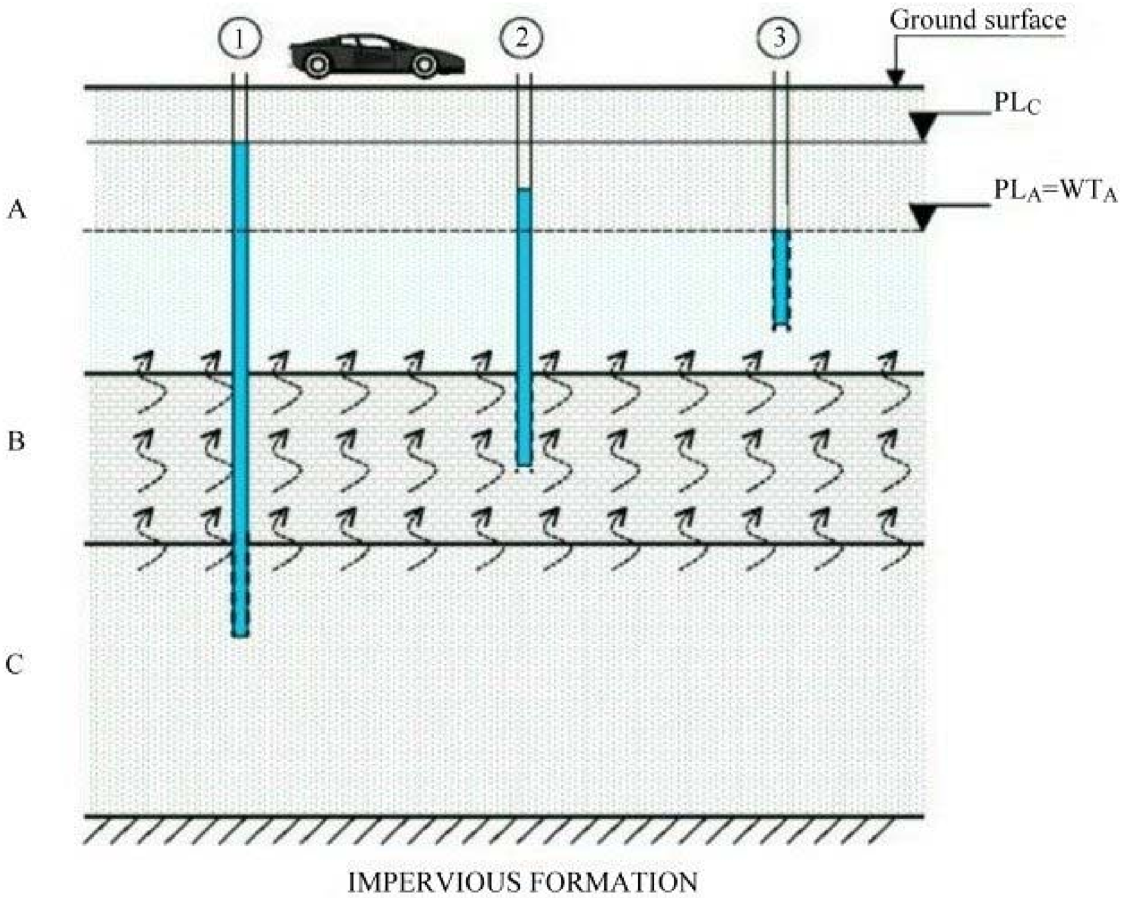

Figure 1. Classification of aquifers in terms of hydrostatic pressure (no pumping conditions)
A) Unconfined/free aquifer. Water table denoted by WT_A. It coincides with the limit of the saturated zone of aquifer A.
B) Confining formation of aquifer C. Aquitard presenting flow from formation C to formation A (dashed arrows), because the piezometric level in aquifer C is larger than the piezometric level in aquifer A.
C) Leaky (semi-confined) aquifer with head level PL_C. If formation B is an aquiclude (impervious formation, so there is no flow between formations C and A), then formation C is a confined aquifer. Notice that PL_C could reach the ground surface.
1) Well tapping formation C. Water height at well corresponds to PL_C. If PL_C reaches the ground surface, this well is also known as a “flowing well”.

2) Well tapping formation B. Water height at well is an intermediate value.
3) Well tapping formation A. Water height at well corresponds to PL_A.

Once the relationship between groundwater and the medium has been presented, the basic principles controlling groundwater motion can be set up.

3. Basic principles of groundwater flow in porous media

The microscopic study of a porous medium is extremely complex, given the complicated shape of the pores and the fanciful disposition of the flow paths. Fortunately, some macroscopic properties can be established, treating the porous medium as a continuum with well-defined average properties.

These properties are fully characterized by three parameters: permeability, porosity and storativity. Darcy's law establishes the fundamental macroscopic relationship and sets up the starting point to formulate the partial differential equation that controls groundwater flow.

3.1. Dynamics of fluids in porous media

The fluid occupying the pores can be characterized by a pressure p, in such a way that in a vertical tube contacting the aquifer (piezometer), the height L of the water column (assuming equilibrium pressure) will be:

$$L = \frac{p}{\gamma} \qquad (1)$$

where γ is the specific weight of the fluid ($\gamma = g \cdot \rho$, where g is gravity and ρ is fluid density).

As mentioned before, water depth can be measured in a well, but also in a piezometer (similar to a well but, generally, with a smaller diameter, and considered just for measurement, not for water-pumping purposes).

Considering a given reference horizontal plane, the water level (piezometric head level) in the piezometer is (see Figure 2):

$$h = z + \frac{p}{\gamma} \qquad (2)$$

where z is the height of the point with respect to the reference plane (this plane or height reference is often taken to be equal to the mean water sea level). One can observe that head level defines the energy of the water per unit weight. For instance, the first term "z", can be expressed as potential energy (m·g·z, being m fluid mass) per unit weight (m·g). In a static system, all points have the same head level (but not the same pressure), as depicted in Figure 2.

Aquifer dimensions can be huge. The separation between confined or unconfined is not so strict as the previous definition may say, because its behavior can vary in space. Figure 2 shows this change. On the left and right zones (depicted in blue), aquifer behaves as a free aquifer. Therefore, one could observe a "real" surface of water (water table). Once the aquifer is over-pressured (zone marked with dashed line), aquifer behaves as confined. However, if the system is static, the water table/piezometric level (depending on the zone) remains unchanged within the whole aquifer (free or confined) extension. Therefore, piezometric levels do not change and the aquifer is under no flow conditions.

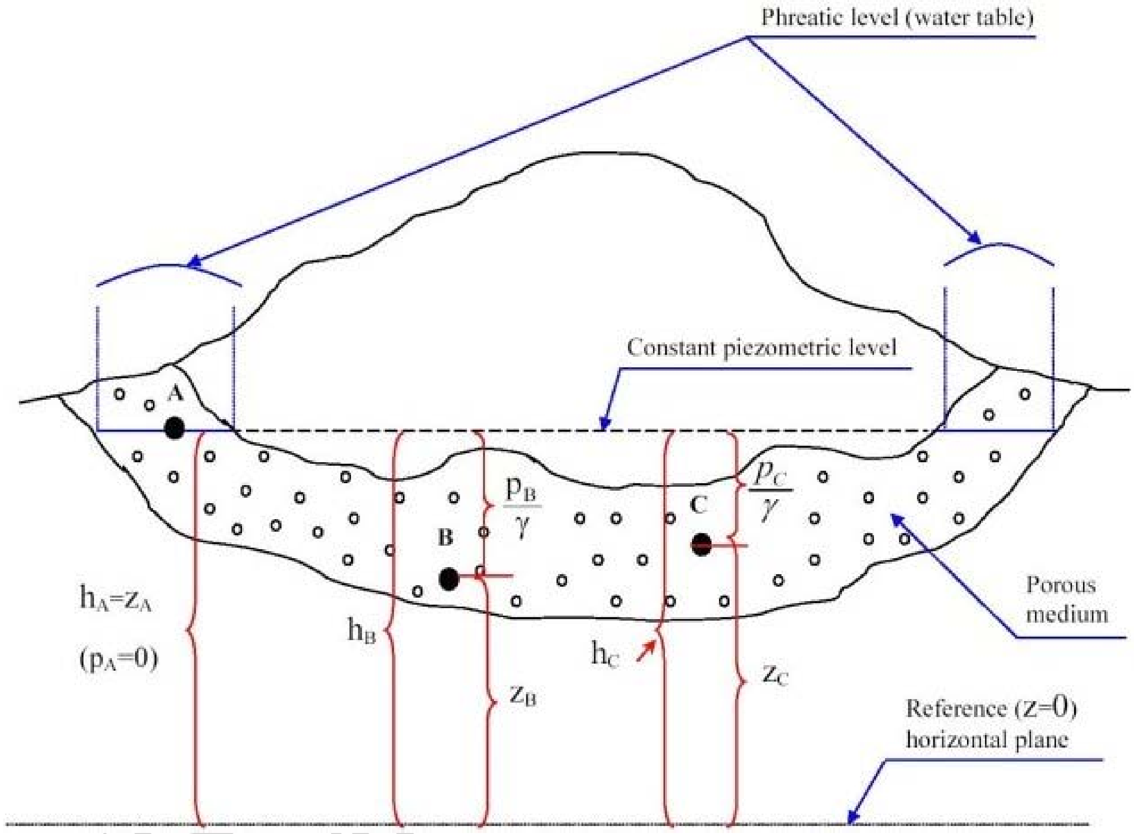

Figure 2. Aquifer under no flow conditions (static system). Observe that points A, B and C have the same head level, but a different pressure. Point A has atmospheric pressure (taken as 0).

Let us make a step further to include the fluid movement. Consider for this purpose a pseudo-cylinder of porous medium, as indicated in Figure 3, with a fluid moving through it. Bernouilli's equation can be written for two points A, B, in the same flow path and separated by a distance d_{AB}:

$$\frac{p_A}{\gamma_A}+z_A+\frac{v_A^{*2}}{2g}=\frac{p_B}{\gamma_B}+z_B+\frac{v_B^{*2}}{2g}+\Delta h_{AB} \qquad (3)$$

where v^* is the real velocity of the fluid, Δh_{AB} is the head loss between A and B (due to frictions) and γ is the specific weight of the fluid. Again, all terms in (3) can be viewed as energy per unit weight (pressure, potential and kinetic energy). The hydraulic gradient between A and B is:

$$\text{grad } h = \nabla h \approx \frac{\Delta h_{AB}}{d_{AB}} \qquad (4)$$

being d_{AB} the distance between A and B, following a flow line connecting A and B. A common mistake, while calculating hydraulic gradients is to consider the geometric distance between A and B, instead of using the distance that the fluid particle has to cover to reach point B from point A (i.e. distance along a flow path).

Usually, groundwater velocities are negligible, so that (3) can be expressed as:

$$\frac{p_A}{\gamma_A} + z_A = \frac{p_B}{\gamma_B} + z_B + \Delta h_{AB} \qquad (5)$$

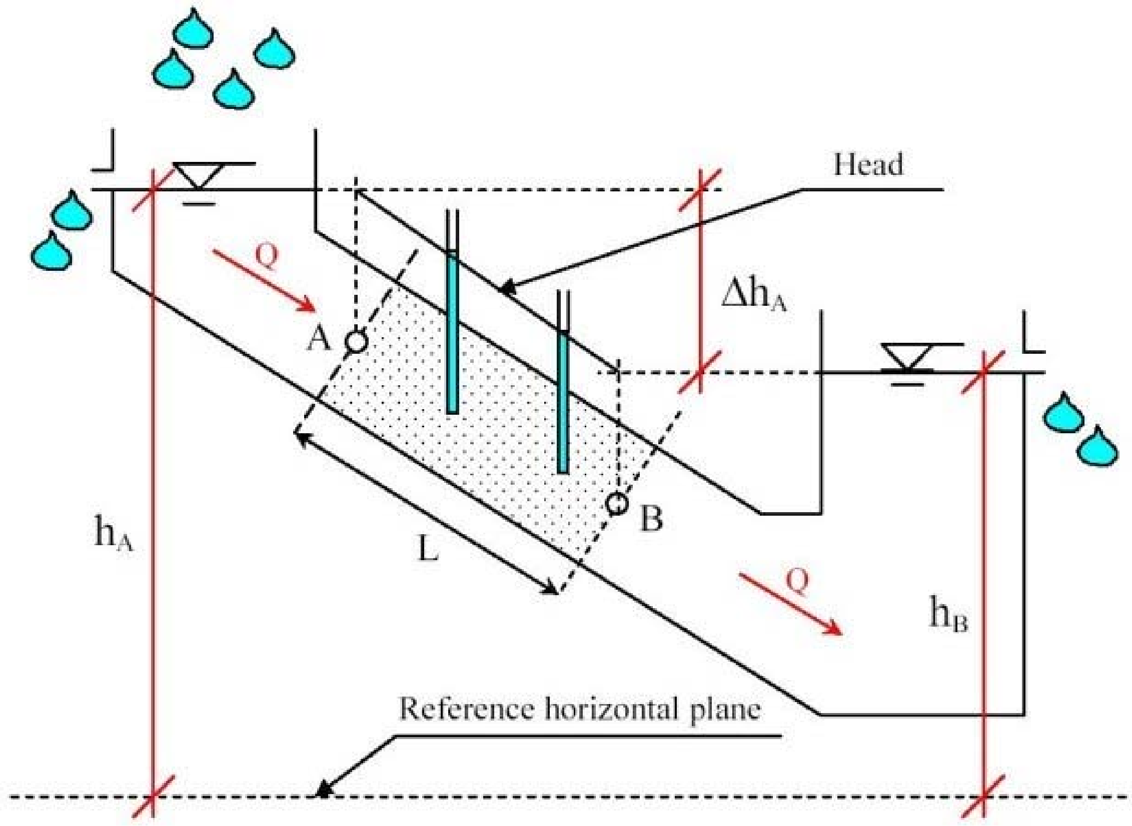

Figure 3. Hydraulic system in a porous medium with fluid motion from A to B (from higher to lower head levels).

All fluids move from higher to lower energy states. In a porous medium water starts moving when a head variation exists and moves always from a high-energy state (high head level) to a lower energy state (low head level). Another common mistake is to consider that fluids move from high to low pressure zones. This affirmation is only valid for gases, where position energy (z) is negligible against pressure energy (p/γ). Notice that water can move from low to high-pressure zones, if the head loss is positive.

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Biographical Sketches

Andrés Alcolea was born in Barcelona, Spain in June 1974. He studied civil engineering from 1992 to 1999. He started work at the Department of Geotechnical Engineering and Geosciences in 1997, specializing in work related to optimization methods and design of geochemical barriers. In 2000, he took a six-month international postgraduate course, for deepening his knowledge in groundwater hydrology. Since 1999 he has been working on a PhD, related to geostatistical methods.

He has participated in numerous projects concerning: optimization methods, design of geochemical barriers, urban hydrology, geochemistry, and numerical modeling, and has assessed a large number of private projects. On the other hand, he has cooperated in many public projects, directed by ENRESA (Spanish Enterprise devoted to residuals management), NATO and UNESCO.

He likes listening to traditional Spanish music (and plays in a Spanish folk group). In his free time he builds puzzles, reads, paints, and enjoys the company of his wife Iryna (married in April 2003).

Agustín Medina Sierra was born in Vilanova i la Geltrú (Barcelona), Spain in December 1962. He studied Mathematics (speciality in applied mathematics) at the University of Barcelona. Prior to finishing these studies, he won a scholarship to work in numerical methods in groundwater at the Technical University of Catalonia (UPC). After finishing mathematics, he worked with people of the Soil Engineering Department in the area of groundwater. He worked in several projects related to radioactive waste and in 1993 he defended his Ph.D. thesis on "The coupled flow and solute transport inverse problem", at the UPC. Today, he is Titular Professor of the Department of Applied Mathematics. His main academic and professional interests are groundwater modeling, numerical methods and inverse problem. In his free time he likes photography, fiction, movies, and travel.