3

Theory of Groundwater Flow

3.1 Scope

The terms *subsurface water* and *groundwater* have been given different meanings by different researchers all over the world. These terms have been used in a broader sense to include all waters below the surface of the earth in liquid, solid, or vapor forms, appearing as physically or chemically bound waters, as free water in the zones of aeration and saturation, and in a supercritical state in the zone of dense fluids extending below the zone of saturation having a pressure greater than 218 atm and temperature higher than 374 °C. These terms also have been used to refer only to the free water that can move through rock and soil, comprising water in the capillary fringe, gravitational water infiltered through the zone of aeration, and moving groundwater in the zone of saturation. Further, these terms have been used when referring to water in the zone of saturation only. The use of these terms in the United States, however, almost stabilized when in 1923 Meinzer defined subsurface water to designate all waters that occur below the earth's surface, and groundwater to designate the water in the zone of saturation. The *International Glossary of Hydrology*, prepared by WMO and UNESCO (1974), adopted the same meanings for these terms. Meinzer's concept of subsurface water as all varieties of water in the interior of the earth is very broad, something very similar to the present definition of subsurface hydrosphere. In the common sense, subsurface flow is meant to indicate water moving in the zones of aeration and saturation and the deep percolation.

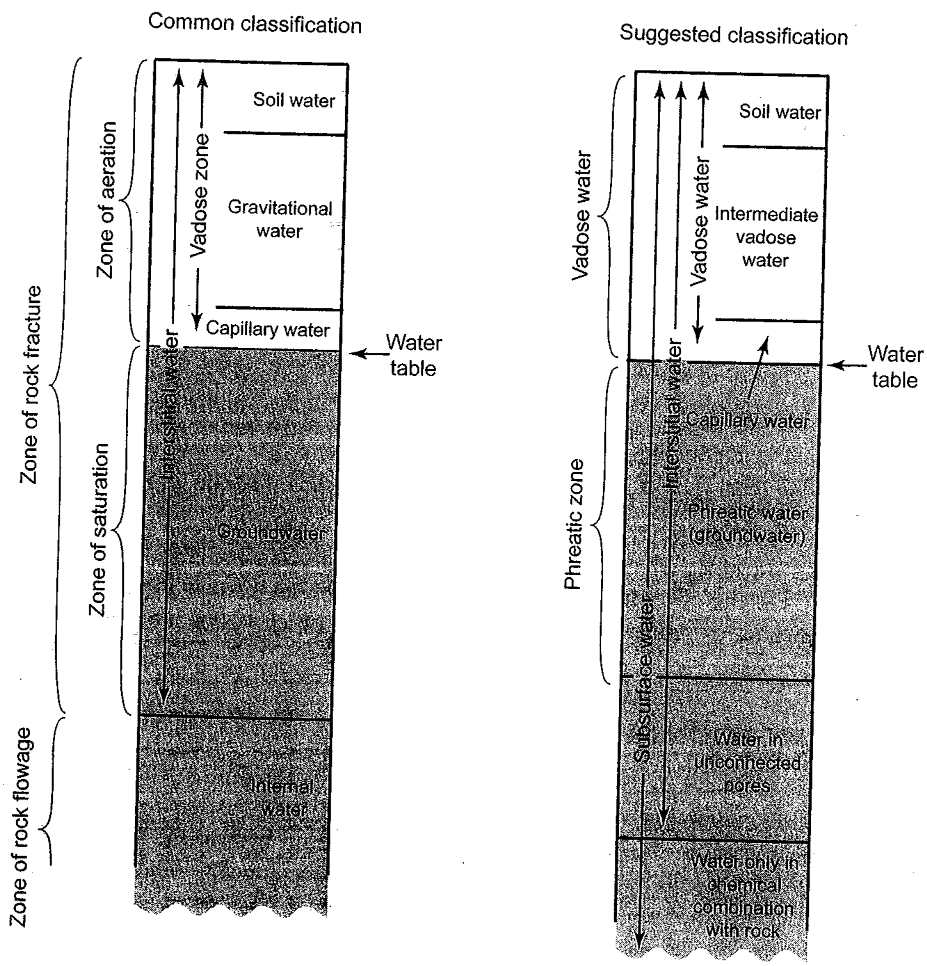
Hydrogeology covers the study of subsurface water in all its phases: origin, manner of deposition, laws of motion, distribution, physical and chemical properties, interrelationship with atmospheric and surface waters, effects of human activities, economic values, and so on. On the other hand, civil engineers are more concerned about the movement and distribution of groundwater and its application, which is the subject matter of this chapter.

3.2 Classification of Subsurface Water

Hydrogeologists have classified subsurface water based on the fundamental ideas of geological structures containing such water. However, this classification scheme based on the manner in which water is deposited is widely accepted by both hydrogeologists and engineers. This scheme takes into consideration the fact that physical, geographical, geological, and thermodynamic conditions are responsible factors in the deposition of water in the interior of the earth. In this classification, zonal divisions of subsurface water are made. Nineteenth-century scientists noted that there existed a law of zonation of natural phenomena such as climatic zonation, soil zonation, and vertical zonation of the material of the globe. All natural water supply is distributed in three zones: atmospheric, surface, and subsurface waters.

The principle of zonation was traced in subsurface water as well. From 1910 onward, a number of classification schemes based on the manner in which water is deposited were proposed by Soviet and American scientists as well as by scientists in France, Germany, and other western European nations. A very original classification system suggested by Meinzer (1923) is still widely accepted today. This book adopts the same classification. This classification, shown in Figure 3.1, established two broader divisions: interstitial (rock voids) water and internal (deep-lying) water. Interstitial water is subdivided into suspended (vadose) water in the zone of aeration and groundwater in the zone of saturation. Suspended water has three further subdivisions: soil water zone, intermediate zone, and capillary zone. The water in the zone of saturation was divided by Meinzer into free water and pressure water.

Figure 3.1 Meinzer's classification and modification suggested by Davis and DeWiest (1966).



The French scientist Schoeller, in 1962, distinguished the following zones beneath the surface: (1) the evaporation zone, (2) the infiltration zone, (3) the capillary fringe, and (4) the zone of groundwater accumulation. In the last zone, free surface and pressure surface are recognized.

In Lange's classification of 1969, often used by hydrogeologists in the former USSR, three basic groups of water are recognized: soil water, subsurface water (in the former USSR this term is commonly used in the sense of groundwater) and interstratal water.

Davis and DeWiest (1966) of the United States suggested certain minor changes in Meinzer's classification. The original classification and suggested changes are shown schematically in Figure 3.1. Davis and DeWiest combined the collecting-rock properties, thus describing groundwater as (1) water of igneous and metamorphic rocks, (2) water of hard sedimentary rocks, (3) water of unconsolidated sediments, and (4) water of regions of extreme climatic conditions.

Pinneker (1983) considered that present classifications are concerned only with the distribution of water pertaining to land masses. Groundwater below the oceans and seas is not covered. Also, the deep-lying water in the zone of saturation that is acted upon by geostatic pressure or other internal forces is not identified in these classifications, although artesian water pressured by hydrostatic pressure has been recognized. Pinneker thus suggested a classification that included the process by which groundwater deposits are formed, while retaining Meinzer's concept (see Table 3.1). This classification has the following scheme:

- *Groups:* depending on the position of groundwater in the earth's crust
- *Sections:* according to the degree of saturation of rock formation with water
- *Types:* on the basis of hydraulic features
- *Classes:* basic varieties of groundwater according to the way in which they are formed
- *Subclasses:* on the basis of water-collecting properties of rocks
- *Special conditions:* specific nature of surroundings

3.3 Water-Bearing Formations

Formations that can yield significant quantities of water are known as *aquifers*. This characteristic is imparted to the formations by interconnected openings or pores through which water can move. Alluvial deposits are thus the best form of aquifers: probably 90% of all developed aquifers are in such formations. Such aquifers often have the advantage of direct replenishment by seepage from streams and land. Rock formations of a volcanic nature, limestone, and sandstone possess cracks, fissures, cavities, faults, caverns, and joints through which they yield water. The quality of such rocks as an aquifer depends on the extent of such openings; sometimes they form highly permeable aquifers. Generally, metamorphic and igneous rocks are in solid forms and serve as poor aquifers. Similarly, clays, although having a high level of porosity, prove to be poor aquifers because their pores are too small and not well connected.

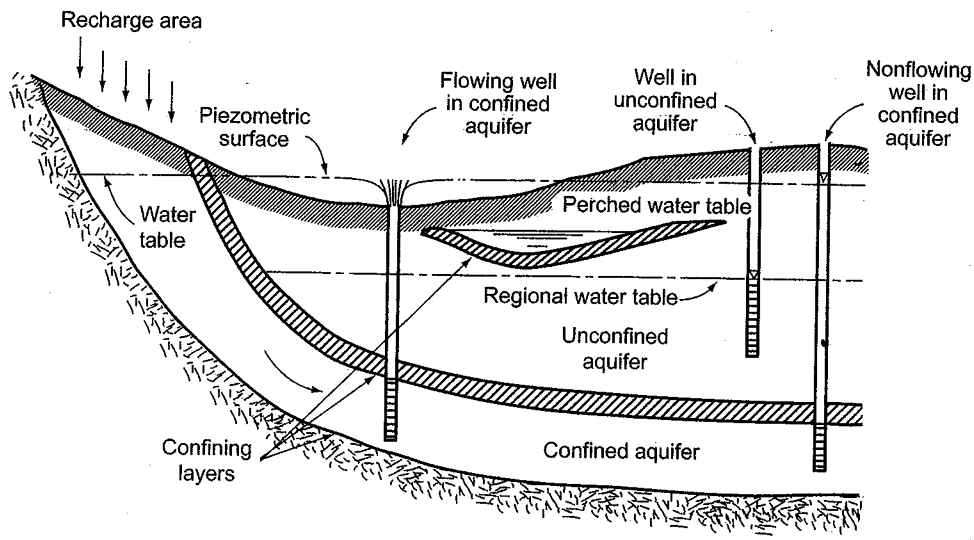
Types of aquifers are shown schematically in Figure 3.2. Mainly there are two types: unconfined aquifers and confined aquifers. In unconfined aquifers, the upper surface of the groundwater body is exposed to atmospheric pressure or a *water table* exists. Confined aquifers, also known as pressure or artesian aquifers, occur where groundwater is under

Table 3.1 Groundwater Classification According to the Manner in Which it Has Been Formed

Group	Section	Type	Class	Subclass		Special Conditions	
				Water in strata of porous rocks (pore and stratal water)	Water in fissured cavernous rocks (fissure and vein-fissure water)	Water in permafrost regions	Water in volcanically active regions
Continental groundwater	Groundwater of the zone of aeration	Suspended water	Perched water (in the broad sense)	Salt water and infiltrating water, perched water	Salt water and infiltrating water, perched water	Active layer	Upper part of lava cover
						Suprapermafrost	Lower part of lava cover
	Groundwater of the zone of saturation on continents	Mainly nonpressure water	Groundwater	Aquifer nearest to the surface on stable impermeable layer	Upper parts of the zone of intensive fissuring and karst massif	Interpermafrost and intrapermafrost	Water of hydrothermal systems underhydrostatic pressure
		Pressure water	Artesian water	Industrial water under hydrostatic pressure	Buried fissured zone under hydrostatic-pressure	Subpermafrost	
			Deep-lying	Sedimentary layers, which are subjected to the action of geostatic pressure and endogenic forces	Water of deep-lying faults within the sphere of activity of endogenic forces	Absent	Water of volcanic structures and hot spring systems, connected with a rising stream from the magma chamber
Groundwater below seas and oceans	Groundwater of the submarine zone of saturation	Mainly pressure water	Water connected with the land mass	Shelf and marine deposits	Karsted rock of the shelf and fault zones	Subpermafrost shelf of the northern seas	Submarine volcanic structures and marine hot spring systems
			Water not connected with the land mass	Water of deep basins	Trenches and mid-oceanic rifts	Absent	

Source: Pinneker (1983). Used with permission of Cambridge University Press.

Figure 3.2 Types of aquifers.



greater-than-atmospheric pressure due to an overlaying confined layer of a relatively impermeable medium.

A special case of unconfined aquifers involves perched aquifers, where a stratum of relatively impermeable material exists above the main body of groundwater. The downward-percolating water is intercepted by this stratum and a groundwater body of limited areal extent is thus formed. The zone of aeration is present between the bottom of the perching bed and the main water table.

A special case of confined aquifers is the leaky aquifer, also known as a semi-confined aquifer. Such an aquifer is either overlain or underlain by a semipervious layer through which water leaks in or out of the confined aquifer.

3.4 Fluid Potential and Hydraulic Head

Just as the energy head is the energy quantity per unit weight of fluid, the fluid potential is the energy quantity per unit mass. Thus,

$$\Phi = gh \quad [L^2T^{-2}] \tag{3.1}$$

where

Φ = fluid potential at any point
h = hydraulic head at that point

Flow of any kind occurs from a region in which the potential has a higher value towards the region of a lower value. Thus, the flow of heat, electricity, or water requires existence of a potential gradient. For a porous medium, the flow velocity and, hence, the kinetic energy are extremely small and can be ignored. Thus, the fluid potential and the hydraulic head are comprised of the elevation head and the pressure head. With reference to Figure 3.3:

$$h = Z + \psi \quad [L] \tag{3.2}$$

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