Physical Properties

2

2.1 Introduction

Understanding how water moves in the subsurface requires knowledge of the physical properties of both water and the materials that it moves through. The physical properties of water along with the size and distribution of pore spaces determine how much water is stored in a given volume and how easily water moves through the material. In all groundwater investigations, understanding the distribution of these material properties is key to understanding the patterns of groundwater movement.

2.2 Properties of Water

Natural groundwater consists primarily of water molecules with trace amounts of other dissolved ions and molecules. In the liquid state, these molecules and ions are closely packed, but constantly moving and jostling each other. The physical properties of water have their basis in these molecular-scale interactions, so a brief mention of water's molecular properties is relevant here. Water molecules are polar, with more positive charge near the hydrogen atoms and more negative charge near the oxygen atom, as shown in Figure 2.1. This uneven charge distribution causes attraction known as hydrogen bonding, between the hydrogen atoms of one molecule and the oxygen atoms of another. The polarity and self-attraction of water molecules is the fundamental cause of viscosity, surface tension, and capillarity. Water chemistry is covered in much greater detail in Chapter 9, but this one point is relevant to several physical properties and deserves mention at this stage.

2.2.1 Density and Compressibility

The typical physical properties of fresh water are listed in Table 2.1. The mass density of fresh water ρ_w varies within a narrow range, and the figures in Table 2.1 are accurate enough for most analyses. English mass density units (slugs/ft^3) are almost never used, but instead the weight density lb/ft^3 units are used. Weight density $\rho_w g$ equals the mass density times the gravitational acceleration at the earth's surface, $g = 9.81$ m/sec^2 = 32.2 ft/s^2. It is simple to convert between mass density and weight density units when in the

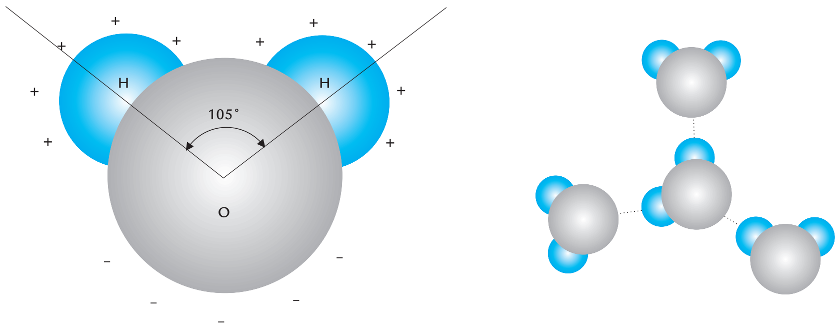

Figure 2.1 Geometry of a water molecule (left) and hydrogen bonding of water molecules (right).

Table 2.1 Typical Physical Properties of Fresh Water

Property	Symbol	Dimensions †	Value
Mass density	ρ_w	$[M/L^3]$	$1.00\ g/cm^3$ $1000\ kg/m^3$ $1.94\ slugs/ft^3$
Weight density	$\rho_w g$	$[F/L^3]$	$9810\ N/m^3$ $62.4\ lb/ft^3$
Compressibility	β	$[L^2/F]$	$4.5 \times 10^{-10}\ m^2/N$
Dynamic viscosity	μ	$[FT/L^2]$	$1.4 \times 10^{-3}\ N{\cdot}sec/m^2$

† L = length, M = mass, T = time, F = ML/T^2 = force.

vicinity of earth's surface, where gravitational acceleration may be treated as a constant. For general information on units and conversion factors, see Appendix A.

Water density does vary slightly with temperature, pressure, and chemistry if the concentration of solute molecules is high enough. The density of pure water at atmospheric pressure varies between 0.998 and 1.000 g/cm^3 in the range of temperatures typical for groundwater (0°C to 20°C). As the temperature of a liquid rises, it usually becomes less dense as molecules move with greater velocity and molecular attraction forces are overcome to a greater extent. Water is an unusual liquid because the maximum density does not occur at the freezing temperature, but instead slightly above freezing at 4°C.

Water is often considered incompressible, but it does have a finite, low compressibility. As water pressure P rises an amount dP at a constant temperature, the density of water increases $d\rho_w$ from its original density ρ_w, and a given volume of water V_w will decrease in volume by dV_w in accordance with

$$\begin{aligned} \beta dP &= \frac{d\rho_w}{\rho_w} \\ &= -\frac{dV_w}{V_w} \end{aligned} \tag{2.1}$$

where β is the isothermal compressibility of water. Water compressibility varies only slightly within the normal range of groundwater temperatures, from $\beta = 4.9 \times 10^{-10}$ m^2/N at 0°C to $\beta = 4.5 \times 10^{-10}$ m^2/N at 20°C (Streeter and Wylie, 1979).

Example 2.1 To illustrate just how incompressible water is, use Eq. 2.1 to calculate the water density at the bottom of a well 500 m deep. Assume

$\rho_w = 1000.0\ \text{kg/m}^3$ and $P = 0$ (atmospheric pressure) at the top of the well, and that the water temperature is 10°C.

At the bottom of the well, pressure equals the weight density of water times the height of the water column H,

$$P = \rho_w g H = 9810\ \text{N/m}^3 \times 500\ \text{m} = 4.905 \times 10^6\ \text{N/m}^2$$

Since the pressure at the top of the well is zero, the change in pressure from top to bottom is $dP = 4.905 \times 10^6\ \text{N/m}^2$. Using $\beta = 4.7 \times 10^{-10}\ \text{m}^2/\text{N}$, Eq. 2.1 gives

$$d\rho_w = \beta dP \rho_w = 2.31\ \text{kg/m}^3$$

The water density at the bottom of the well is therefore $1002.3\ \text{kg/m}^3$.

2.2.2 Viscosity

Viscosity is friction within a fluid that results from the strength of molecule-to-molecule attractions. Thick fluids like molasses have higher viscosity than thin, runny fluids like water or gasoline. To grasp what viscosity means, consider the two flat plates separated by a thin film of fluid as shown in Figure 2.2. When you try to slide one plate laterally relative to the other, the fluid resists shearing; the faster you slide the plate, the greater the resistance. The resisting force F in this case is proportional to the area of the film between the plates A, a fluid property called **dynamic viscosity** μ, the velocity of the plates relative to each other dv, and inversely proportional to the thickness of the fluid separating the two plates dz:

$$F = A\mu \frac{dv}{dz} \tag{2.2}$$

This resistance to internal shear causes water to resist flow through geologic materials. In order to flow through pores or fractures, a packet of water must change shape and shear as it flows. Note that pore size is analogous to dz in Eq. 2.2, so that water encounters greater viscous resistance flowing through materials with smaller pores.

The viscosity of a liquid generally decreases with increasing temperature, and water is no exception in this respect. The dynamic viscosity of water ranges from $\mu = 1.79 \times 10^{-3}$ N·sec/m^2 at 0°C to $\mu = 1.01 \times 10^{-3}$ N·sec/m^2 at 20°C. The unit N·sec/m^2 is equivalent to kg/(sec·m) in more fundamental SI units. Dynamic viscosity is also given in poise (1 poise = 1 g/(sec·cm)).

A related parameter, the kinematic viscosity ν, is proportional to dynamic viscosity:

$$\nu = \frac{\mu}{\rho} \tag{2.3}$$

where ρ is the fluid density.

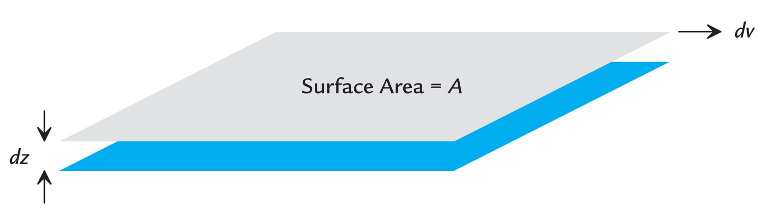

Figure 2.2 Picturing the meaning of viscosity. Two parallel plates with surface area ***A*** are separated by fluid of thickness *dz*. The upper plate moves with velocity *dv* relative to the lower plate.