Hydrology
Physical Quantities and Qualities of Water

Matter and Energy

Before getting into the fundamentals of groundwater, Fedder reviews the basic units of Newtonian Physics. I think that this is a good idea. **Force, Work, Pressure, and Density** are all fundamental aspects of the behavior and movement of groundwater. If we are going to be manipulating these quantities, we had best review what they are.

**Force**

Force is the physical capacity to cause movement in an object.

Force equals mass X acceleration (Newton’s Second Law):

\[ F = M_{kg} \times A_{m/s^2} \]

**Weight:** force due to gravitational acceleration. \( A = g = 9.8 \, m/s^2 \) or \( 980 \, cm/s^2 \)

Moving from the surface of the Earth to outer space to the moon your weight changes but your mass does not. What is really changing is your acceleration due to gravity.

Force is measured:
Kg m / sec\(^2\) = Newton (N)
g cm / sec\(^2\) = dyne (d)
slug foot / sec\(^2\) = pound (lb)

**Work**

If a force causes an object to move over a distance, then work has been done.

Work = force X distance

\[ W = F_{kgm/s^2} \times D_m \]

Work is measured:
Kg m\(^2\) / sec\(^2\) = Joule or newton-meter (J)
g cm\(^2\) / sec\(^2\) = erg or dyne-centimeter (e)
slug foot\(^2\) / sec\(^2\) = foot-pound (ft-lb)

**Density**

Density is a measure of mass / volume. It is usually abbreviated \( \rho \) (rho).

There are no units particular to density. A standard metric density is g / cm\(^3\).
The English system units of density would be slugs / ft³. Pounds are not used because the pound is a unit of force (weight) and not mass.

Specific Gravity

Specific gravity is the density of a substance normalized to the density of pure water. Water has a specific gravity of 1.00. A substance with a specific density of two is twice as dense as water. What is the difference between specific gravity and density? Not much, if density is measured in grams / cc then density and specific gravity are equivalent.

Specific Weight

Specific weight is weight per unit volume. weight / volume = (mass x g) / vol = \( \rho \times g \)

Pressure

Pressure is the force applied to a unit area perpendicular to the plane of the area.

\[ P = F \frac{kg m/s^2}{m^2} \div A \]

Newton / m² = kg / m s² = pascal (Pa)

Dyne / cm² = g / cm s² = millipascal (mPa)

lb / ft²

1 millibar = 10³ dyne / cm²

millimeter of mercury = 133.3 pascals

1 Atmosphere = 2116 lb / ft² = 14.70 lb / in² = 1.013X10⁵ Pa = 760 mm Hg

Properties of Water

Polarity of Water

Water (H₂O) is a polar molecule with a net positive charge at one end and a net negative charge at the other end. This results from the "Y" shape of the molecule, wherein both
relatively weak hydrogen nuclei are clustered on one side of the large oxygen nucleus. The polarity of water gives it several unusual properties.

**Freezing expansion**

Water is unusual in that it expands by 9\% in volume as it freezes. This occurs because the polarity of water causes the molecules to take up more space when they form a crystal structure. Because ice is less dense than water, bodies of surface water do not freeze solid in the winter. The floating ice insulates the liquid water beneath.

**Surface tension**

The polarity of water molecules gives them a high surface tension because they tend to attract one-another where the water is in contact with air. This causes water to cling to surfaces, such as grains of sediment. If a given quantity of water is used to saturate a material, the amount of water that drains away under gravity will be less because some of the water remains as **pendular water**.

**Dynamic viscosity**

Water resists flowing to a degree proportional to a fluid property known as dynamic viscosity.

\[ \mu \] (mu)

Dynamic viscosity is measured in units of N s / m\(^2\) or lb s / ft\(^2\).

These units condense down to Kg / m s, g / cm s, or slug / ft s.

**One can think of viscosity as the internal friction of a fluid.** Molasses has a high viscosity, acetone has a low viscosity. Viscosity is effected strongly by temperature (thick of pouring hot vs cold maple syrup). Viscosity is caused by the mutual attraction between the molecules of a liquid. Increased temperature in the liquid weakens this attraction, lowering viscosity.

Although one doesn’t always realize that water has a viscosity, it does. **Water is about three times more viscous at 20°C (68°F) than it is at 80°C (176°F).**

Why is this important? Let me give you an example from a groundwater infiltration system built some years ago in Washington State. Water from the local river was collected as it percolated down through gravels beneath the river bed. This was accomplished by digging a shaft deep into the river bank and emplacing perforated pipes in the gravel. Differences in flow into the pipes could be accounted for by two variables, the river level and the change in temperature = viscosity of the water. Even when the river level was the same, the summer yield was about 6 million gallons per day, while the winter yield was about 5 million gallons per day. The difference of one million gallons per day was due entirely to a change in water viscosity.
Bulk Modulus and Compressibility

When pressure is applied to an elastic material it compresses so that the same mass of material is contained within a smaller volume. In other words, the density of the material increases. The proportion of density change to change in pressure is called the bulk modulus.

\[ B = \frac{-V\Delta p}{\Delta V} \]

The bulk modulus is in units of N / m\(^2\) or lb / ft\(^2\) the same units as pressure (V and delta V units cancel out in the equation).

For our purposes, a more useful measure is the reciprocal of the bulk modulus (1/B), which is called compressibility.

\[ \alpha = \frac{-\Delta V}{V\Delta p} \]

Where V is the original volume, delta V is the change in volume, and delta p is the change in pressure causing the change in volume. The smaller the compressibility, the more difficult it is to compress the substance.

Compressibility is in units of 1 / N / m\(^2\) or 1 / lb / ft\(^2\) (units of 1/pressure)

Water and other liquids are normally considered incompressible. How else could hydraulic systems function? For all practical purposes at small volumes water can be considered incompressible.

The compressibility of water is 0.0000034 lb/ft\(^2\). For a change in pressure of one pound per square inch, water is only compressed by about 3 one-millionths of its original volume.

However, at very large volumes, this small compression can become significant. For example, if water were truly incompressible, the oceans would stand about 100 feet higher than they do today. Compression of water in the ocean basins reduces global sea level by 100 feet. Likewise, in large underground aquifers, the compressibility of water can significantly increase the storage capacity of the aquifer.