# The ground

To date we have discussed the atmosphere and its interaction with the sun. We have also briefly mentioned the interactions between the sun and the surface; albedo, evaporation of water, terrestrial radiation. We have not considered the surface of the planet in any more detail. The earth's surface is a complicated affair comprising oceans, deserts, cities, forests, tundra/savannah, ice-caps and so on. Each of these has a different albedo, rate of water evaporation/absorption, exchange of gases with the atmosphere and so on. The first problem is how to categorise the surface. This is done by *soil type*.

*Soils*
Soil is composed of both rock particles and organic matter (*humus*) - the remains of plants and animals in various stages of decomposition. The humus serves as food for many living organisms. Within the soil is a large population of animals (worms, ants. larvae), plants (*saprophytes* such as bacteria and fungi). These break down the humus into soluble substances that can be absorbed by the roots of larger plants.

Soils are categorised by the air, water, rock and humus content. The first consideration is the size of the particles that make up the soil. A set of typical sizes for various soils is given below.

| Fraction | particle diameter (μm) |
|---|---|
| gravel | > 2000 |
| sand | 60-2000 |
| silt | 2-60 |
| clay | < 2 |

Much of the soil consists of air and water; between 30% and 70% of soil is pore space. The fraction of soil that is occupied by solid is

$$\text{Fraction of soil volume occupied by solid} = \frac{\text{Mass of solids}}{\text{Volume of soil}} \times \frac{\text{Volume of solids}}{\text{Mass of solids}} \qquad (1)$$

$$= \text{bulk density} \times \frac{1}{\text{particle density}} \qquad (2)$$

Most minerals that make up the soil have very similar particle densities; a reasonable average value is 2600kg/m$^3$. Thus the fraction of soil volume occupied by the pores (the *porosity*) must be

$$\text{Porosity} = 1 - (\text{bulk density})/2600 \qquad (3)$$

| Soil Texture | Bulk density(kg/m$^3$) | Porosity |
|---|---|---|
| Sandstone | 2100 | 0.19 |
| Sandy loam subsoil | 1650 | 0.36 |
| Sandy loam plough layer | 1500 | 0.42 |
| Clay loam subsoil | 1450 | 0.44 |
| Recently ploughed clay loam | 1100 | 0.58 |

### Soil and the hydrologic cycle

The passage of water in and through the soil is an important part of the *hydrologic cycle* discussed above. There are two basic problems; how much water is in the soil, and how does it move through the soil. The porosity gives a measure of how much water the soil can hold. In fact, this is a gross overestimate. Water in large pores and cracks (greater than 60 microns diameter) cannot be held in the soil. This can be seen from the following argument. The flow of water through a tube depends on the tube radius, the viscosity of water and the pressure gradient trying to push the water through the tube. A simple dimensional analysis gives the Hagen-Poiseuille equation (except of course for the constant in front). This states that

$$Q = \frac{\pi}{8} \frac{r^4}{\eta} \frac{dP}{dx} \tag{4}$$

where $Q$ is the rate of flow of water (in $m^3$/sec), $r$ is the radius of the tube, $\eta$ is the viscosity (units of Pa-sec) and $dP/dx$ is the pressure gradient. The point is the strong dependence of the flow rate on the diameter of the tube. This badly overestimates the velocity; pores are not straight. Water velocities through pores typical of sand grains (diameter 1000$\mu$m) are about $10^8$ times those typical of clays (pore diameter about 0.1$\mu$m). There is an upper limit to the amount of water that a soil can hold in the long term. This is the *field capacity*. It is the water held in pores small enough so that friction and surface tension (see below) can resist the gravitational flow. There is also a lower limit to the amount of water that can be extracted by plant roots. If all the remaining water is held in very fine pore, the plant roots cannot extract it. This lower limit is called the *Permanent Wilting Point*.

### Surface tension and soils

Moreover, some of the water is tightly held in the soil. This is because of the effect of *surface tension*. A liquid behaves as if its surface is enclosed by a skin. A molecule in the interior of a liquid experiences forces from all directions since the liquid molecules are in all directions. A molecule at the surface experiences forces only from the lower hemisphere, since above the molecule is air or vacuum (and the effect of air molecules is negligible). It therefore costs energy to make a surface (usually expressed as energy per unit area). This can also be looked at in terms of a force; the surface tension. The surface tension is thus the force acting across the surface pulling the molecules into the liquid. The same applies to interfaces between liquids and solids (and liquids and other liquids) since the forces between molecules in different materials are different. If the attraction between the molecules of a liquid is less than the attraction between the molecules of the liquid and that of a solid, the liquid will wet the solid. This determines the shape of the meniscus in a tube (concave or convex). Let us consider the case where the meniscus is convex (as it almost always is for water.

Let us assume that we are trying to push the water down the pore (say by forcing air into it) with a pressure $S$. Then the force is the pressure multiplied by the area of the tube; i.e. $\pi r^2 S$.
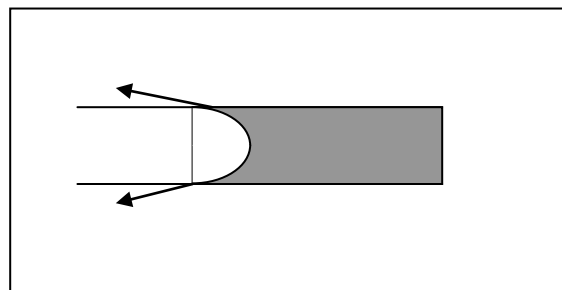
Opposing this is the surface tension, $\gamma$, shown by the arrows. If the *angle of contact* between the liquid and the wall is given by $\theta$, then the total force is $2\pi r \gamma \cos\theta$. If the system is equilibrium, this gives the result $S = 2\pi \cos\theta / r$. It is often reasonable to set $\cos\theta$ to unity, giving

$$S = 2\gamma / r \tag{5}$$

In the absence of an external pressure, $S$ represents the tendency of water to creep along a pore from the wet to the dry end and is often called the *suction*. A case of particular importance is when a column of water is supported against gravity by surface tension. In this case it can be shown that the height of the column is given by $h = 2\gamma / r\rho g$ where $\rho$ is the density of the liquid.

*Osmotic Pressure*
When two solutions with different concentrations of solute are separated by a *semi-permeable membrane* (one that lets only one component through) the mobile component moves to equalise the chemical potentials of the *mobile component* on each side. The pressure required to stop this is the *osmotic pressure.* Consider solutions (1) and (2), with different concentrations of solute in them and assume (as is usual) that the mobile component is also the solvent. Then the chemical potential of the solvent on the two sides is given by $\mu(P_1) + RT \ln x_1$ and $\mu(P_2) + RT \ln x_2$ where $\mu(P)$ is the chemical potential of the solvent at a pressure $P$ and $x$ is the partial molar fraction (strictly speaking the activity) of the solvent in the presence of the relevant amount of solute. These must be equal, and therefore

$$\mu(P_1) + RT \ln x_1 = \mu(P_2) + RT \ln x_2 \text{ or equivalently } \mu(P_1) - \mu(P_2) = RT \ln x_2 - RT \ln x_1$$

From the Gibbs-Duhem equation, we know that $\partial\mu / \partial P = \Omega$, the partial molar volume of solvent. Most cases are sufficiently dilute that this can be identified with the molar volume of the solvent. The osmotic pressure $\Pi$ is defined as $P_2 - P_1$ (provided that $x_2 < x_1$ i.e. that solution (2) is more concentrated. We can then write the osmotic pressure equation,

$$\Pi\Omega = -RT \ln(x_2 / x_1) \tag{6}$$

For very dilute solutions, we can go further. If (1) is the pure solvent (i.e. $x_1 = 1$) and (2) is dilute, we can write the mole fraction of *solute* in solution (2) as $x_s = 1 - x_2$ which for small enough values of $x_s$ gives
$\Pi\Omega = RTx_s$, the original form that was guessed on the basis of a simple kinetic model.

Clay can often act as a semi-permeable membrane, stopping ions but letting water go through. Thus two salt aquifers separated by a layer of clay can develop significant osmotic pressures between them. These are often removed by water flows.

*Water flow and Darcy's Law*
In most cases, the two most important forces in the soil tending to move water are gravity and the changes in the suction from one area to another. It is often convenient to express these in terms of a potential. the *soil-water potential*, $\Psi$, defined as

$$\Psi = -(\text{depth} + \text{suction}) \tag{6}$$

The sign states that the potential becomes more *negative* with depth or as the suction increases. This is related to the rate of water flow by Darcy's Law. The combination of gravity and surface tension (and also osmotic pressure) sets up a potential difference in the soil. This potential difference determines the volume of water that can pass through unit cross-sectional area of soil. We write

$$Q_W = -\kappa \frac{d\Psi}{dx} \tag{7}$$

where $Q_W$ is the volume of water per unit cross-section and $\kappa$ is the effective permeability of the soil (often known as the hydraulic conductivity). The value of $\kappa$ depends on the soil type and structure (in particular on the size and distribution of pores). $\kappa$ decreases rapidly as the soil gets drier. The sign ensures that water flows down the potential gradient. The balance of the effect of gravity and suction ensures that there will always be some moisture at the top of the soil where it is in contact with the air and can evaporate. Water is also returned to the atmosphere from the leaves of plants (*transpiration*)

The amount of water stored in the soil, the *soil profile*, $S$, is a balance between a number of factors:

$$\Delta S = P - E_s - T - D - R \tag{8}$$

where the contributions are $P$ from the precipitation, $E_S$ from the evaporation from the soil surface, $T$ from transpiration, $D$ from deep drainage out of the soil layer and $R$ from runoff. This balance is important when investigating the leaching of pollutants into the soil. The penetration of a leachant is, in fact, rather complex. The dependence of water flow rate on pore size means that the water moves faster down cracks than the surrounding small pores. This effect is *hydrodynamic dispersion.*

A major pollutant in groundwater is the nitrate ($NO_3^-$) ion. In surface water the main problem is eutropication ( the water has too much nutrient, grows algal mats and reduces the oxygen levels to the point where fish die). In groundwater, presence of nitrate can cause methaemoglobinaemia (blue baby syndrome) in high concentrations. In very young children, nitrate is converted to nitrite ($NO_2^-$) in the gut and interferes with oxygen absorption. Very high doses of nitrate have caused cancer in laboratory animals but there are no known human examples.

Evaporation of water from the soil is an important part of the hydrologic cycle. Most of the incident solar radiation is radiated back at infra-red frequencies. Of the remainder, some is conducted into the earth, some is transferred to the overlying air and some (up to 60%) evaporates water. The principal mechanism for removing water from the land surface is turbulent transfer. It is possible to derive an expression for the evaporation rate for a simple case such as a lake surface. The *Penman equation* gives

$$\text{Evaporation Rate} = aR + b(c_0 + c_1 W)D \tag{9}$$

where $R$ is the net radiation flux into the soil, $W$ is the windspeed, $D$ is the saturation deficit of the air and $a, b, c_0 c_1$ are disposable coefficients. Evaporation from land is much harder to describe with a simple expression; it depends strongly on the vegetation cover

### *The soil and the sun*
The temperature range across the earth's surface is large. The most obvious causes of variation are latitude and season. The seasonal changes are particularly big in the centres of continents (for example Chicago mean temperatures vary from $-10^0$C (winter) to $+25^0$C (summer)). However, variations of $10^0$C in a single day are possible. Even slight topographic features affect the temperature. Low spots in fields have lower crop growth (by 33-50%) than other parts of the same field because frost formation is more likely. Small hills, depressions, exposure to sun, all affect the local temperature. The differences in air temperature just above the ground only affect the topmost layers of the soil because soil is a very poor conductor. An annual temperature variation of $30^0$C in air is reduced to $15^0$C at a depth of 1m and $0.5^0$C at 8m. Indeed, the heat conduction through the soil is so slow that the temperature cycle deep within the soil is the reverse of the seasonal variation at the surface. In the Northern hemisphere,

- At 3m; minimum temperature is March/April, maximum temperature is September/October
- At 7-11m minimum temperature is August, maximum temperature is February (but the variation is very small – see above).

Vast areas of Canada and Siberia (20% of the earth's surface) have frozen soil (permafrost).Intrusion of frost into the ground is so effective that summer heat cannot thaw the ground below 1m depth. Hence rain cannot sink into the soil and such regions become swamps in summer. Oil cannot easily be pumped through pipes laid in permafrost – the viscosity is too high.