Hydrology
Fresh water - Salt water interactions

Reading assignment: Fedder Chapter 9, pg. 364 - 377

Coastal Plain Aquifers

Long Island’s aquifers are developed in coastal plain strata that were deposited from the Cretaceous to the Pleistocene. These strata onlap onto the craton, dipping and thickening to seaward. These characteristics are common to coastal plain strata, many of which form important aquifers.

During deposition of coastal plain strata, sealevel rises and falls causing alternating onlap and offlap of marine and terrestrial deposition, or nearshore and offshore deposition.

Onlap and offlap tend to produce alternating intervals of strata that intertongue, with high permeability intervals separated by low permeability layers. The high permeability intervals become aquifers confined above and below by the low permeability aquiclude layers.

It is not unusual for there to be several confined aquifers within a single coastal plain stratigraphic sequence. For example, Baton Rouge LA has 10 confined aquifers stacked within 3000 feet of coastal plain sediments.

In many cases, deposition of the aquifer layers occurred in an offshore, marine environment, so that originally all pore waters were saline. Flushing of the saline water from aquifer layers occurs during low sealevel stands when the sediments are above sealevel and exposed to infiltration by meteoric waters.

Because of the seaward slope of coastal plain sediments, recharge tends to occur inland where the strata outcrop at the surface. Infiltrating fresh water also flows downward into the aquifer through leaky confining layers.

High values of hydraulic head in confined fresh water aquifers often forces fresh water deep into the aquifer, extending the zone of fresh water seaward of the shoreline. In a somewhat extreme example, test wells into a 900 foot deep confined aquifer off the coast of Nantucket Island in New England located fresh groundwater 40 miles out to sea!

Because of their density differences, fresh water and saltwater do not easily mix. The more dense salt water tends to move below the fresh water, creating a wedge of salt water bounded by a zone of diffusion where mixing is occurring.

This zone of diffusion, although allowing mixing, acts as a barrier to flow. Thus flow in both the freshwater and saltwater portions of the aquifer tends to be directed upward toward discharge along the boundary.
In confined aquifers, freshwater can move out of the aquifer through diffusion into the salt water and leakage through the upper confining layers. Depending the hydraulic head within the aquifer and the ease with which water can escape from the aquifer, different confined aquifers will be saturated with freshwater to different depths. It is not unusual for deeper aquifers to be under higher conditions of hydraulic head such that their freshwater portions may be overlain by other aquifers that are saturated with salt water.

**Saltwater intrusion**

The biggest water quality problem associated with coastal plain aquifers is salt water intrusion. The shape and the position of the fresh-salt interface is primarily a function of the amount of freshwater discharging from the aquifer. If discharge increases (i.e. more water is flowing through the aquifer) then the boundary will be pushed seaward. If discharge decreases, then the boundary will move landward.

**Active vs Passive encroachment**

Human actions that cause saline groundwater to enter a freshwater aquifer are called saline-water encroachment. Basically, saline-water encroachment occurs when discharge through the aquifer is decreased due to pumping or to a human induced reduction in recharge.

Note that saline-water encroachment is not only a problem in coastal areas. Many inland aquifers are underlain by strata containing saline water, either long residence groundwater or connate water that has acquired a high concentration of dissolved salts over time.

**Passive** salt-water encroachment occurs when the hydraulic gradient in an aquifer is reduced, yet the gradient still slopes toward the sea. In this case the s-f interface simply shifts landward in proportion to the reduction in the hydraulic gradient.

If pumping is of sufficient intensity to cause the cone of depression to intersect with the shoreline, then **active** salt-water encroachment will occur. In this case, the hydraulic gradient is reversed and saline water flows along the gradient toward the pumping well. In this case the boundary zone moves much more rapidly than in passive encroachment.

**The nature of the salt-water / fresh-water interface**

Fresh water grades into saltwater at the boundary between the two with a steady increase in salt concentration across a ‘zone of mixing’.

In many cases, the zone of mixing is very narrow relative to the extent of the aquifer. In these cases we can make the simplifying assumption that the fresh-water salt-water boundary is sharp, and predict the location and shape of the interface.
The shape and location of the fresh water interface is related to the hydraulic gradient in the freshwater near the salt-fresh boundary.

An equation to relate the height of the water table to the depth to the salt-water wedge in an unconfined aquifer was presented near the turn of the century by Ghyben and Herzberg:

\[ Z_{(x,y)} = \frac{\rho_w}{\rho_s - \rho_w} h_{(x,y)} \]

If the density of the saline water is that of normal marine ocean water, then \( \rho_s = 1.025 \) g/cc. This simplifies the Ghyben and Herzberg equation to:

\[ Z_{(x,y)} = 40 h_{(x,y)} \]

In other words, the depth to the saltwater wedge near the interface will be 40 times the height of the water table above sea level at any point. If the depth to the saltwater wedge exceeds the thickness of the aquifer at a point, then that point is beyond the extent of saltwater intrusion.

Likewise, if the water table is lowered by one foot, then the saltwater wedge at the interface will expand upward and inward 40 feet.

Really, the \( h_{(x,y)} \) of the Ghyben and Herzberg equation should be the hydraulic head at the points along the saltwater interface. However, if the Dupuit assumptions hold and the equipotential lines are vertical, then the hydraulic head and the water table height at any point along the interface will be the same.

The Ghyben and Herzberg equation tends to underestimate the depth of the saltwater-freshwater interface because it does not take into account the outflow of freshwater along the interface. A more accurate representation of the interface is given by a series of equations published by Glover (1964).

Knowing the hydraulic conductivity (\( K \)) and the flow per unit width (\( q' \)) through the aquifer at the coastline, the depth below sea level of the salt-fresh interface (\( z \)) is given by:

\[ z = \frac{Gq'}{K} + \sqrt{\frac{2Gq'x}{K}} \]

\( x \) is the distance inland from the shore (\( x = 0 \) at the shoreline).
\( G = \rho_w / \rho_s - \rho_w \) (= 40 for normal marine water).
Notice that when $x = 0$, $z$ is still a positive number. This is because there is an outflow face, that is, a zone beyond the shoreline where freshwater is discharging from the aquifer through the sea bottom.

The width of the outflow face is given by:

$$x_0 = \frac{Gq'}{2K}$$

**Tidal effects**

Aquifers located adjacent to the ocean (or any large, tidal body of water) are effected by the rise and fall of the tides. Hydraulic head measured in wells near the shoreline will rise and fall with the tides. The exact degree to which hydraulic head is affected by tides depends on a number of factors, including the storativity and transmissivity of the aquifer. However, some general relationships are observed:

The farther away from the shoreline, the less is the effect of tide on hydraulic head in an aquifer. This decrease is an exponential one.

The farther away from the shoreline, the greater is the time lag between a rise in tide and a rise in hydraulic head. The decrease is linear.

On Long Island, the Upper Glacial Aquifer does not show a response to tidal fluctuations, whereas the Magothy and Lloyd do.