Water Supply Well Coastal Hydrogeology

G. Zemansky

GNS Science Consultancy Report 2007/39

February 2007

CONTENTS

FIGURES

BACKGROUND DISCUSSION

The general case in coastal environments is that fresh groundwater flows towards the coast and enters saline seawater. The physical force driving this movement, as with all groundwater, is the sum of the kinetic, pressure, and elevation energy of the groundwater or its force potential. Because the velocity of groundwater flow is relatively small, the kinetic energy component of force potential is negligible and at the water table in an unconfined aquifer the pressure component will be zero. Therefore, in these circumstances, the force potential can be assumed equal to the product of hydraulic head (i.e., elevation above sea level datum) and the acceleration of gravity. Both force potential (energy/unit mass) and hydraulic head (energy/unit weight) are forms of potential energy (Fetter, 1994 and Freeze and Cherry, 1979).

The general case of groundwater flow at the coast, absent human intervention, is illustrated in Figure 1. It can be seen in Figure 1 that there will be a wedge of saline groundwater underneath fresh groundwater at the coast that reflects the influence of seawater and that there is an interface between fresh and saline groundwater. The position of this interface under conditions of hydrostatic equilibrium is a function of the density difference between the two fluids (i.e., fresh and saline groundwater) and can be estimated using the Ghyben-Herzberg (G-H) relationship. The G-H relationship is expressed as (Fetter, 1994 and Freeze and Cherry, 1979):

$$z = \frac{\rho_f}{\rho_s - \rho_f} h_f$$

Where:
- h_f = Height (m) of fresh groundwater above sea level (hydraulic head)
- z = Depth (m) below sea level to the interface (i.e., column of saline groundwater equivalent to hydraulic head)
- ρ_f = Density of fresh groundwater (1.0 g/cm^3 = 1,000 Kg/m^3)
- ρ_s = Density of seawater or saline groundwater (1.025 g/cm^3 = 1,025 Kg/m^3)

This relationship predicts that the interface will be at a depth below sea level of approximately 40 times the hydraulic head.

The nature of the fresh and saline groundwater interface is not as sharply defined as the G-H relationship would imply. Instead, as illustrated in Figures 1 and 2, the interface tends to consist of a brackish transition zone that develops from dispersion through fresh water flow, diffusion from higher concentration saline groundwater, and such unsteady natural displacements as tides and groundwater recharge. Observed thicknesses of such transition zones vary from less than 1 to greater than 100 m (Todd, 1980). As can be seen in Figure 2, transition zones can be well defined by isoconcentration contours for such characteristic components as chloride levels. The elongated shape of the transition zone in Figure 2 is a function of limited variation in hydraulic head (i.e., relatively flat topography) and horizontal flow paralleling the base of a highly permeable aquifer (Todd, 1980).

As noted above, the shape and position of the transition zone may be impacted by a number of natural factors. Anthropogenic factors, particularly the pumping of water supply wells, may also be important. A pumping well can contribute to the drawing of saline groundwater inland from the coast in two ways: (1) through interception of fresh inland groundwater flowing towards the coast; and (2) by its cone of depression producing horizontal or vertical hydraulic gradients toward the well from zones of saline groundwater (horizontally at or near the coast or vertically from the underlying wedge). These two cases are illustrated in Figure 3.

An important aspect of the second case above is the potential for upconing of saline groundwater when a well having its open interval or screen located in overlying fresh groundwater is pumped. A simplified diagram of this case if presented in Figure 4. “An approximate analytical solution” for it “based on the Dupuit assumption and the G-H relation” is given by (Todd, 1980):

$$z = \frac{Q}{2\pi dK(\Delta\rho / \rho_f)}$$

Where:	z =	Upconing rise distance (m) above initial fresh-saline groundwater interface under static conditions
	Q =	Well pumping flow rate (m^3/sec)
	d =	Distance (m) between bottom of well and initial fresh-saline groundwater interface under static conditions
	K =	Hydraulic conductivity (m/sec)
	$\Delta\rho$ =	Density difference between saline and fresh groundwater (ρ_s – ρ_f) or 0.025 g/cm^3 for below assumptions
	ρ_f =	Density of fresh groundwater (1.0 g/cm^3 = 1,000 Kg/m^3)
	ρ_s =	Density of seawater or saline groundwater (1.025 g/cm^3 = 1,025 Kg/m^3)

This relationship has been empirically shown to hold only if the upconing rise (z) is limited to about 30 to 50 percent of the distance (d) between the bottom of the well and the fresh-saline groundwater interface. After that, upconing “accelerates upward to the well” (Todd, 1980 and Domenico and Schwartz, 1998). Therefore, a conservative estimate of the maximum pumping rate to prevent saline groundwater intrusion from upconing would be (Domenico and Schwartz, 1998):

$$Q_{\max} = 0.6\pi d^2 K(\Delta\rho / \rho_f)$$

Where: Q_{max} is the maximum pumping rate (m^3/sec) and all other variables are as defined above

For the assumed densities of fresh and saline groundwater, this equation simplifies to:

$$Q_{\max} = (0.0471)(d^2 K)$$

Although it should be recognized that the above equations have their limitations, with appropriate data and/or assumptions they can be utilized as a first approximation that can provide a rational context in which to consider prevention of saline groundwater intrusion for water supply wells near the coast. Examples of the limitations of these equations include (Todd, 1980):

1. The equations assume isotropic aquifers. For anisotropic aquifers in which the vertical hydraulic conductivity is less than the horizontal (a likely case), a larger maximum pumping rate would be possible.

2. As noted above, their will not be a sharp interface between saline and fresh groundwater. Instead, there will be a transition zone of finite thickness containing brackish water having less density than seawater. When pumping occurs continuously over a long period of time, empirical data indicates that this can result in increasing the salinity of well water to about 5 to 8 percent of that in the saline groundwater.

POSSIBLE REGULATORY APPROACH

The above information could be applied to consideration of an existing water supply well near the coast in the following manner:

1. At the well location under consideration, measure groundwater elevation (h_f) above sea level datum.

2. Calculate the depth below sea level datum to the fresh-saline groundwater interface (z) using the G-H relationship above (assume the default densities for fresh and saline groundwater shown).

3. Using the well location ground level elevation (from item 1 above), information on total well depth from well construction information, and the depth below sea level data to the fresh-saline groundwater interface (item 2 above), calculate the distance from the bottom of the well to the fresh-saline groundwater interface (d).

4. Determine a value for hydraulic conductivity (K). K is best determined from site-specific testing. If such data are unavailable, it can be estimated from lithologic information obtained when the well was drilled (i.e., the boring log) using general relationships from the literature. Since Q_{max} is directly proportional to K, a conservative approach would be to intentionally underestimate K. A value for K of 1×10^{-6} m/sec would be such a conservative estimate. This value for K would be consistent with the lower end of the range for silty sand and would be below the range for clean sand (Freeze and Cherry, 1979). It is unlikely that a water supply well would be installed in an aquifer having a smaller value of K even for intermittent residential purposes.

5. Calculate Q_{max}.

6. Because the interface is really a transition zone of brackish water rather than a sharp contact, continuous pumping would be undesirable in any case. There is no good way to calculate what level of intermittent pumping is appropriate. One approach might be to specify that pumping not occur for greater than 12 hours/day and that water quality be monitored. Chloride or conductivity would be good variables to monitor. If an increasing trend was observed over time, measures could be taken to control impact by some combination of reduced pumping rate and/or reduced hours/day of pumping.

Example Calculation

1. Assume that a well having a total depth of 20 m is installed near the coast at a residence located on land 10 m elevation above mean sea level. Assume also that the well top of casing reference point for water level measurements is 1 m above ground level. The water table is measured in this well at a depth of 6 m below ground level. This would be an elevation of 5 m above mean sea level.

2. The water table indicates a value for h_f of 5 m. Using the G-H relationship, this yields a value for the fresh-saline groundwater interface (z) of 200 m below mean sea level.

3. Since the bottom of the well is 10 m below mean sea level, and the fresh-saline groundwater interface is 200 m below mean sea level, the distance between the bottom of the well and the interface (d) is 190 m.

4. Conservatively assume K = 1 x 10^{-6} m/sec.

5. The calculated Q_{max} is 0.0017 m^3/sec or 1.7 L/sec.

REFERENCES CITED

Domenico, P.A. and F.W. Schwartz. 1998. Physical and Chemical Hydrogeology, 2nd Ed., John Wiley & Sons, Inc., New York, 506 pages.

Fetter, C.W. 1994. Applied Hydrogeology, 3rd Ed., Prentice Hall, Englewood Cliffs, NJ, 691 pages.

Freeze, R.A. and J.A. Cherry. 1979. Groundwater, Prentice-Hall, Inc., Englewood Cliffs, NJ, 604 pages.

Island County. 2005. Seawater intrusion topic paper (final). WRIA 6 Watershed Planning Process, Island County, Washington (USA). Available at: http://www.islandcounty.net/health/Envh/wrac/TopicPapers/Seawater%20Intrusion%20_Final_.pdf.

Todd, D.K. 1980. Groundwater Hydrology, John Wiley & Sons, Inc., NY, 535 pages.

FIGURES

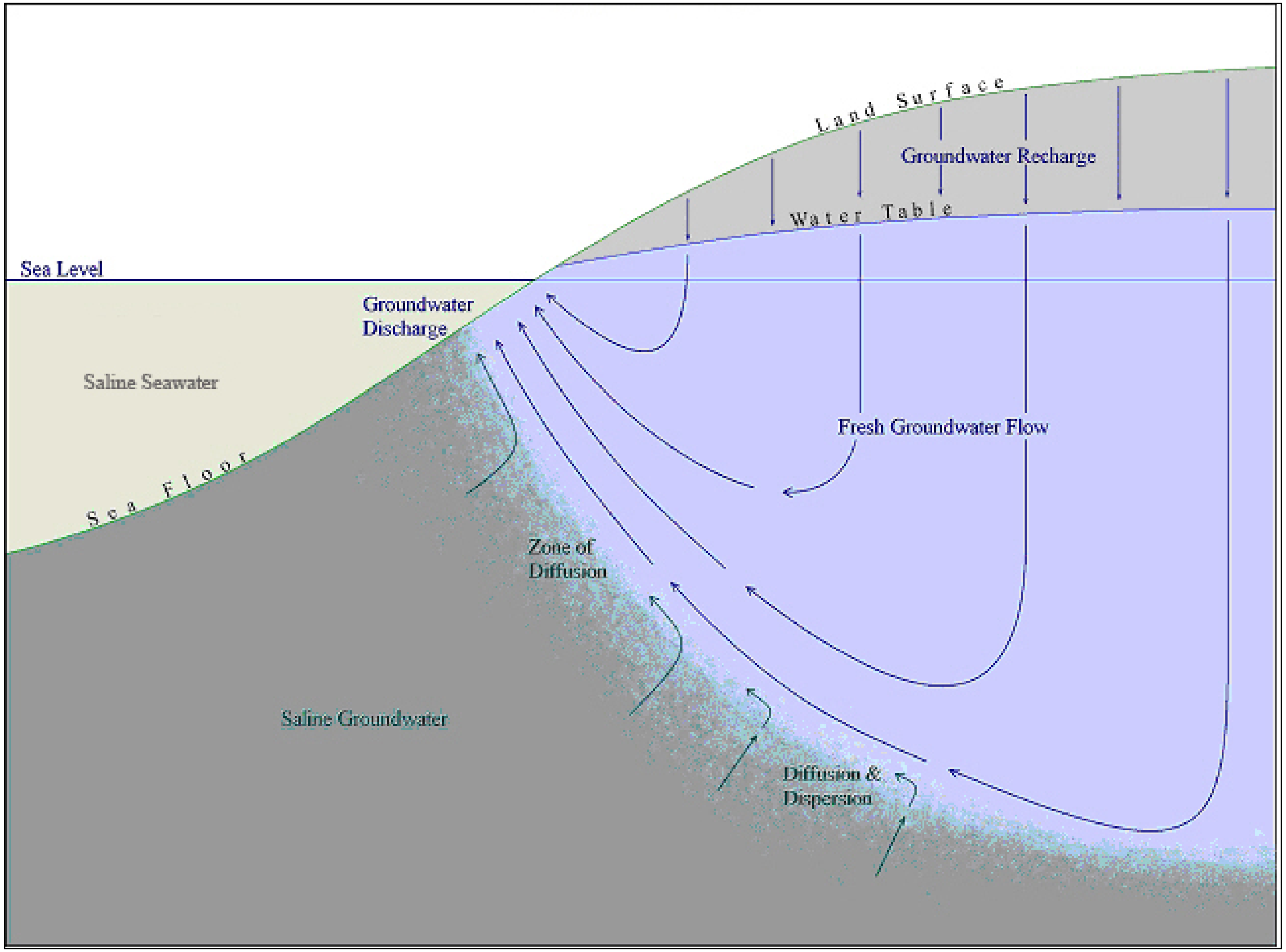

Figure 1. General Coastal Hydrogeology Diagram (Island County, 2005)

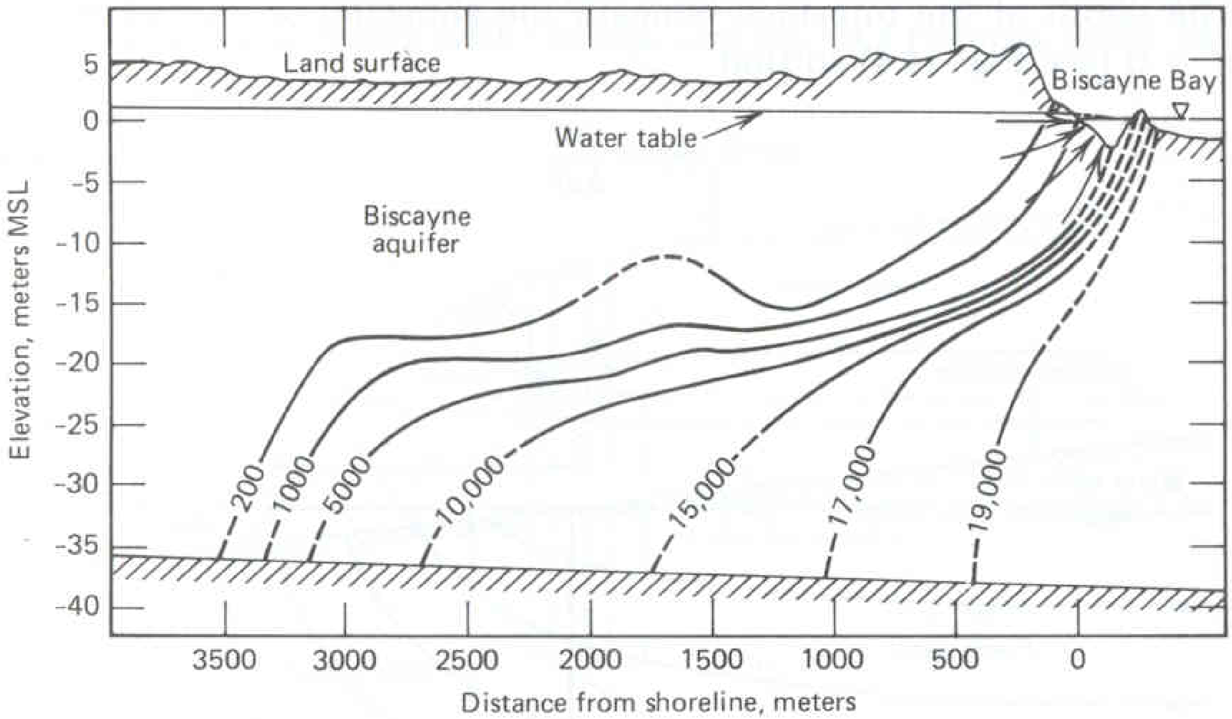

Fig. 14.5 Cross section through the transition zone of the Biscayne aquifer near Miami, Florida. Numbered lines are isochlors in mg/l (after Cooper, et al.[18]).

Figure 2. Saline-fresh Groundwater Transition Zone (Todd, 1980).

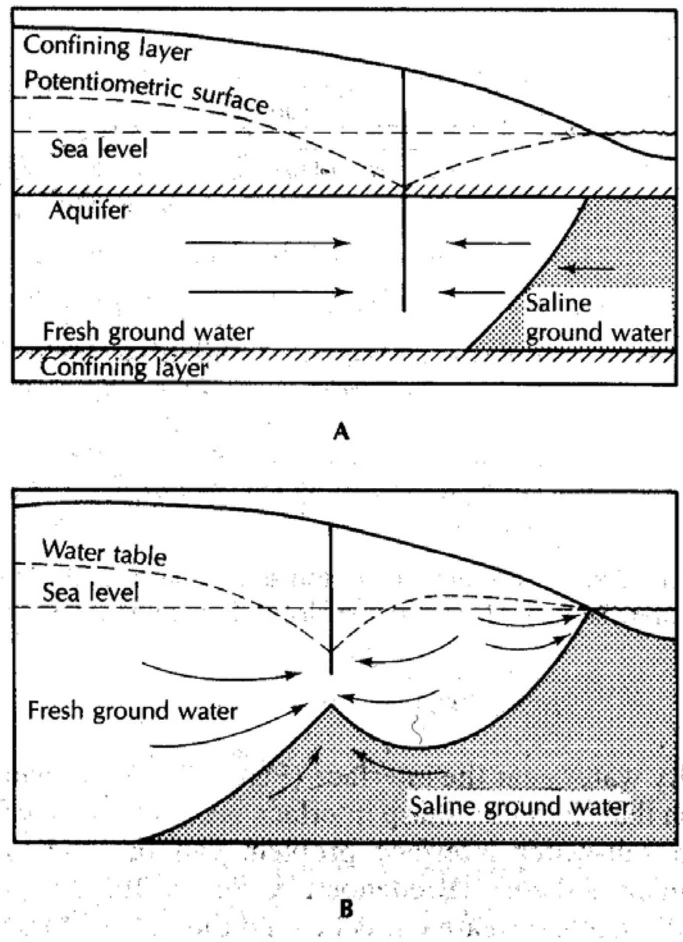

FIGURE 9.33 A. Active saline-water encroachment in a confined aquifer with the potentiometric surface below sea level. **B.** Active saline-water encroachment in an unconfined aquifer with the water table drawn below sea level.

Figure 3. Saline Intrusion Caused by Pumping Wells (Fetter, 1994).

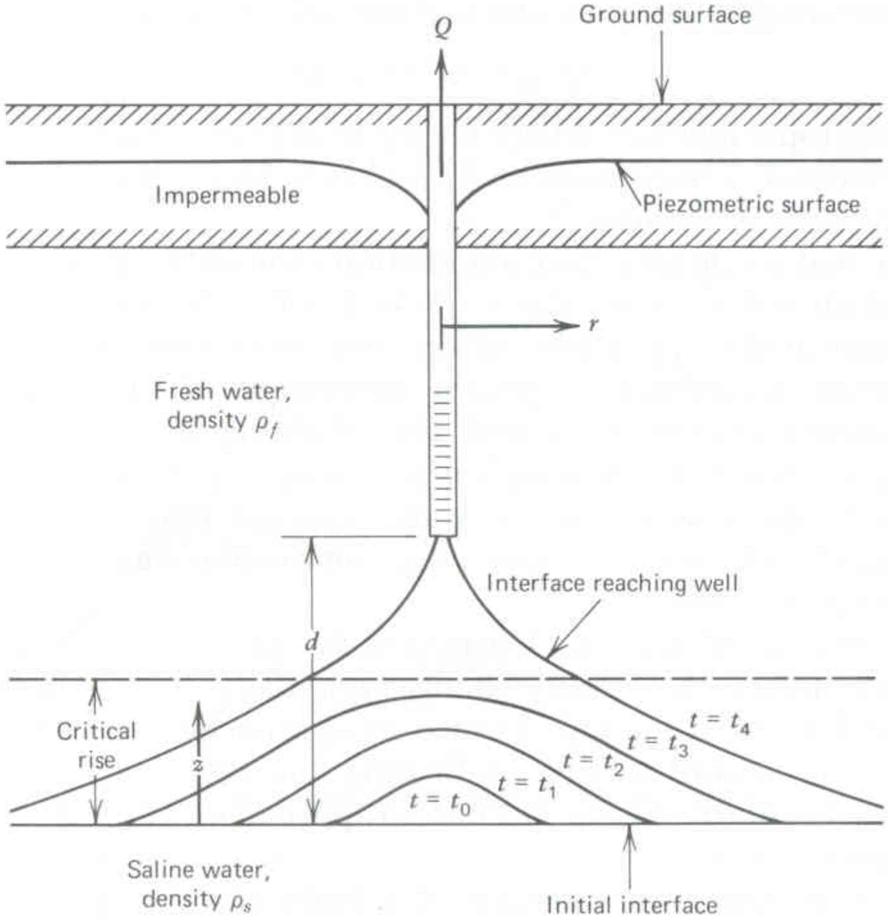

Fig. 14.8 Diagram of upconing of underlying saline water to a pumping well (after Schmorak and Mercado[79]).

Figure 4. Upconing Diagram (Todd, 1980).

www.gns.cri.nz

Principal Location

1 Fairway Drive
Avalon
PO Box 30368
Lower Hutt
New Zealand
T +64-4-570 1444
F +64-4-570 4600

Other Locations

Dunedin Research Centre
764 Cumberland Street
Private Bag 1930
Dunedin
New Zealand
T +64-3-477 4050
F +64-3-477 5232

Wairakei Research Centre
114 Karetoto Road
Wairakei
Private Bag 2000, Taupo
New Zealand
T +64-7-374 8211
F +64-7-374 8199

National Isotope Centre
30 Gracefield Road
PO Box 31312
Lower Hutt
New Zealand
T +64-4-570 1444
F +64-4-570 4657