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### Saltwater Intrusion in Two Population Centers of the United States

Coastal populations account for approximately 70% of the world total (Kulshan, 2006). More than half the population of the United States and many of its largest cities are located near the coast (Barlow, 2005). Some of the fastest growing counties in the nation are near the ocean and are showing signs of continued expansion (Barlow, 2005). This growing population needs a reliable source of freshwater to sustain itself, typically satisfied using groundwater (Barlow, 2005). Groundwater is an important resource to the populations, economies, and ecosystems inhabiting coastal regions (Barlow, 2005). In 1995, one quarter of the total freshwater used was groundwater (Barlow, 2005). Groundwater is the “primary or sole source of drinking-water” for many areas (Barlow, 2005). As populations and demand rise, groundwater resources are increasingly prone to overuse and contamination. Saltwater intrusion is one of the most common forms of groundwater contamination (Kulshan, 2006).

Understanding saltwater intrusion first requires an understanding of aquifers. Groundwater occurs in openings in geologic structures such as pores, fractures, and solution cavities (Barlow, 2005). The permeability of the material is described as its hydraulic conductivity (Barlow, 2005). There are two types of aquifers (figure 1): artesian and water-table (Barlow, 2005). In an artesian (also known as confined) aquifer pore spaces are totally filled with water and overlain by an impermeable confining unit (Barlow, 2005). A water-table or unconfined aquifer is only partially filled and the water level is free to rise and decline (Barlow,

2005). An unconfined aquifer may overlay one or more artesian aquifers, each separated by a confining layer (Barlow, 2005). The flow direction in aquifers moves from high water to low, which generally results in the seaward movement of freshwater (Barlow, 2005).

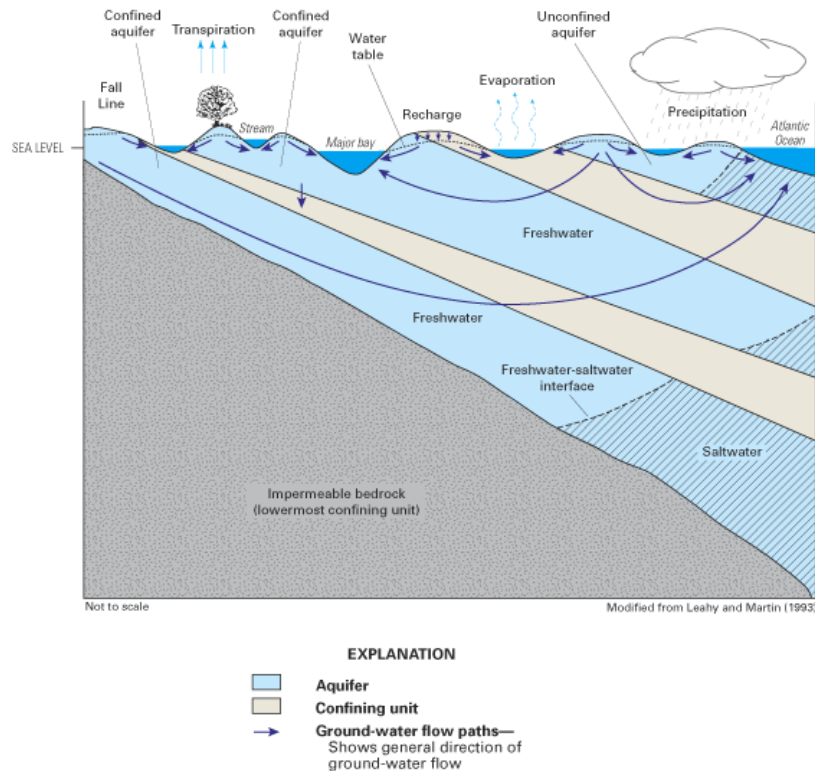


Figure 1: Illustration of confined versus unconfined aquifers (Barlow, 2005).

Saltwater intrusion is the result of a reversal of this offshore flow. Most simply defined, saltwater intrusion is the “movement of saline water into freshwater aquifers” (Barlow, 2005). Oceanic saltwater and groundwater encounter one another at a dynamic interface along coasts. The denser saltwater moves beneath the freshwater in a wedge shape (Sonenshein, 1995). Instead of existing with sharp limits, the boundary is a transition zone of gradually changing salinity, the thickness of which is determined by the aquifer’s hydraulic conductivity (Sonenshein, 1995). This interface moves laterally as water levels change (Sonenshein, 1995). An illustration of the interface in Biscayne Bay is shown as figure 2. Regional, long term water level changes have more important effects than seasonal ones and there is generally a time lag between level change

and the onset of intrusion (Sonenshein, 1995). Saltwater intrusion is driven by the lowering of freshwater levels in aquifers (Sonenshein, 1995). This occurs by three primary mechanisms. Subsurface, lateral movement of seawater from the ocean is the largest scale intrusion (Sonenshein, 1995; Barlow, 2005). Saltwater can also seep into aquifers through tidal canals and streams (Sonenshein, 1995). The third mechanism is the upward movement of more saline water from lower formations (Barlow, 2005), typically caused by well field withdrawals (Sonenshein, 1995), shown in figure 3.

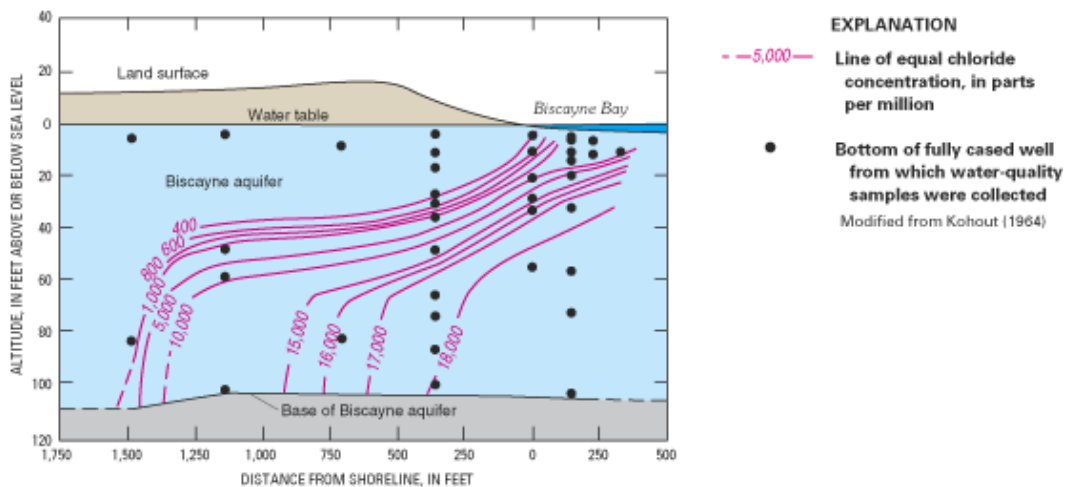


Figure 2: Illustration of the saltwater gradient in Biscayne Bay, Florida (Barlow, 2005).

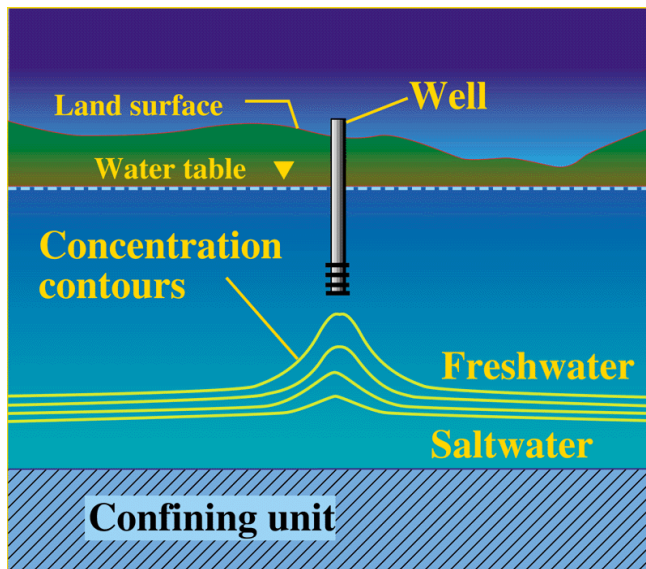


Figure 3: Illustration of connate upward movement of seawater due to well withdrawal (Barlow, 2005).

The extent of intrusion into an aquifer is controlled by several factors. The rate at which water is withdrawn compared to the rate at which the aquifer is recharged is one factor (Barlow, 2005). Recharge that closely compensates for withdrawal limits intrusion, while withdrawal that greatly exceeds recharge encourages inland movement of saltwater. The distance of stress from the saltwater source is another factor (Barlow, 2005). Wells and drainage canals closer to saltwater will lead to greater intrusion, while those farther away contribute less. The geologic structure of the aquifer and its geologic properties also affect the extent of intrusion (Barlow, 2005). Confining units may prevent saltwater from spreading through an aquifer (Barlow, 2005).

Saltwater intrusion is a problem for both human and environmental reasons. Saltwater is unfit for human consumption, as well as other anthropogenic uses (Barlow, 2005). Aquifers that are contaminated with saltwater are therefore unusable as freshwater resources. Wells into such aquifers are often abandoned (Barlow, 2005). Saltwater intrusion leads to an overall reduction in available freshwater (Barlow, 2005). Aside from human related issues, saltwater intrusion also has negative effects on coastal ecosystems (Barlow, 2005). Organisms along coasts adapt to very specific salinity conditions. Saltwater intrusion causes these conditions to change faster than the organisms can respond. A few potential results are red tides, fish kills, loss of seagrass habitat, and the destruction of coral reefs (Barlow, 2005).

Because of the negative effects associated with saltwater intrusion humans have begun to take steps to mitigate and prevent its occurrence. Management and prevention approaches fall into three broad categories and efforts usually involve a combination of strategies (Barlow, 2005). Engineering techniques include physical efforts to recharge aquifers and limit the spread of saltwater (Barlow, 2005). Regulatory approaches involve legislation to limit freshwater withdrawals and affect human behavior (Barlow, 2005). The third category is scientific

monitoring and assessment (Barlow, 2005). Both engineering and regulatory approaches can be more effectively implemented when the extent and rate of intrusion is known. Saltwater intrusion is generally considered to exist at chloride concentrations greater than 100 mg/L (Sonenshein, 1995).

Saltwater intrusion is a problem for many coastal communities. To understand the causes and methods used to manage saltwater intrusion it is useful to look at two differing case studies. Miami-Dade County, Florida and Los Angeles County, California both suffer from saltwater intrusion. Both include large cities and have growing populations. The differing causes and geologic settings have necessitated very different responses in the affected areas.

Saltwater intrusion is a “major threat” to the freshwater resources of coastal Southeastern Florida (Sonenshein, 1995). The region is characterized by high rainfall and low, flat topography (Barlow, 2005). Although now it has been drained by canals, the area once contained the largest wetland in the continental United States: the Everglades (Barlow, 2005).

Underlying Miami-Dade County (as well as Broward and part of Palm Beach Counties) is the Biscayne Aquifer (Barlow, 2005), shown in figure 4. The aquifer is unconfined and responds quickly to changes in water level due to recharge, evapotranspiration, and well withdrawals (Sonenshein, 1995; Barlow, 2005). Three major factors have contributed to the lowering of freshwater levels in the Biscayne Aquifer: coastal urbanization, municipal well fields, and the construction of drainage canals (Sonenshein, 1995). The aquifer supplies over 3 million people with freshwater, with total withdrawals in 1995 amounting approximately 870 Mgal/day (Barlow, 2005). Withdrawals in Miami-Dade County alone were greater than in any other county in the United States (Barlow, 2005). The greatest proportion of withdrawal is for the public water supply, with agricultural needs creating the second largest demand (Figure 5)

(SFWMD, 2006). The high percentage of water used for municipal demand shows that it is the growth of the local population that has placed increasing pressure on the aquifer, rather than global population growth manifesting in agricultural pressure.

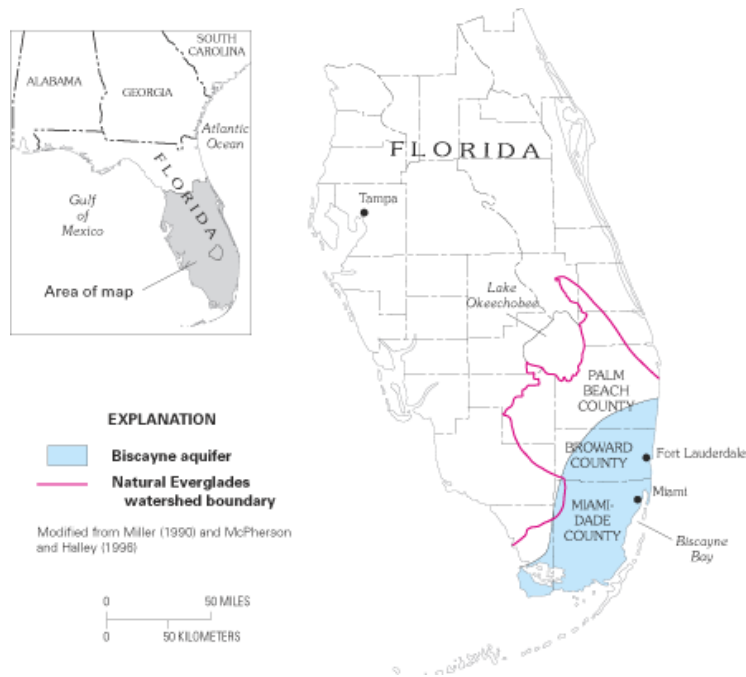


Figure 4: Location of the Biscayne aquifer (Barlow, 2005).

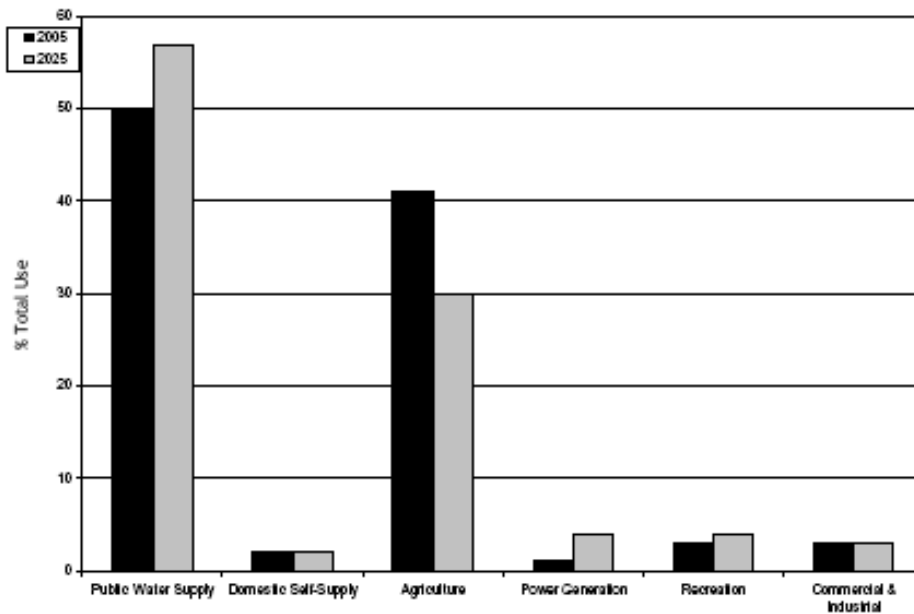


Figure 5: Graph of water withdrawal in Miami-Dade, Monroe, Palm Beach, and Broward Counties, Florida. Each use category is shown as a percentage of total withdrawal (SFWMD, 2006).

Human interactions with the freshwater-saltwater system in Miami-Dade County are well documented over time. Human manipulation of the system started in the early 1880's when drainage canals were constructed to reclaim land north of Lake Okeechobee (Barlow, 2005). In 1904 the Everglades still had naturally occurring high freshwater levels (Sonenshein, 1995). Freshwater flowed offshore to such an extent that it was used as a water source for passing ships (Sonenshein, 1995). 1909 saw artificial expansion of the Miami River (Sonenshein, 1995). By 1926, saltwater intrusion forced the closure of the Spring Gardens Well Field, which stood 1.5 miles from Biscayne Bay (Barlow, 2005). In the 1930's, drainage canals without control structures were installed on a large scale (Sonenshein, 1995). The drainage combined with water withdrawals at coastal well fields acted to lower the water level, inducing movement of saltwater inland (Sonenshein, 1995; Barlow, 2005). Seawater driven by tidal forces moved inland along the drainage canals and subsequently seeped into the aquifer (Sonenshein, 1995). By 1941 the Coconut Grove Well Field, lying 1 mile from the bay, was also forced to close (Barlow, 2005).

The uncontrolled flow of water through the drainage canals caused over drainage of the aquifer and allowed seawater to periodically flow into the groundwater system until 1945 (Barlow, 2005). By that time, thousands of private wells had been abandoned due to saltwater intrusion (Barlow, 2005). In 1946, salinity control gates were constructed on primary canals as far seaward as possible to prevent the inland movement of seawater (Sonenshein, 1995; Barlow, 2005). During the wet season, the gates are opened to drain off flood waters (Barlow, 2005). They are closed during the dry season to raise water levels in the canals and cause freshwater to seep into the aquifer (Barlow, 2005). The canal water artificially recharges the aquifer and slows the progress of saltwater intrusion (Sonenshein, 1995; Barlow, 2005). The canal system can be used to transfer freshwater from inland to the coast and serve as a freshwater source for coastal

well fields in addition to helping control the extent of saltwater intrusion (Barlow, 2005). An illustration of saltwater intrusion before and after the installation of the canals is shown as figure 6.

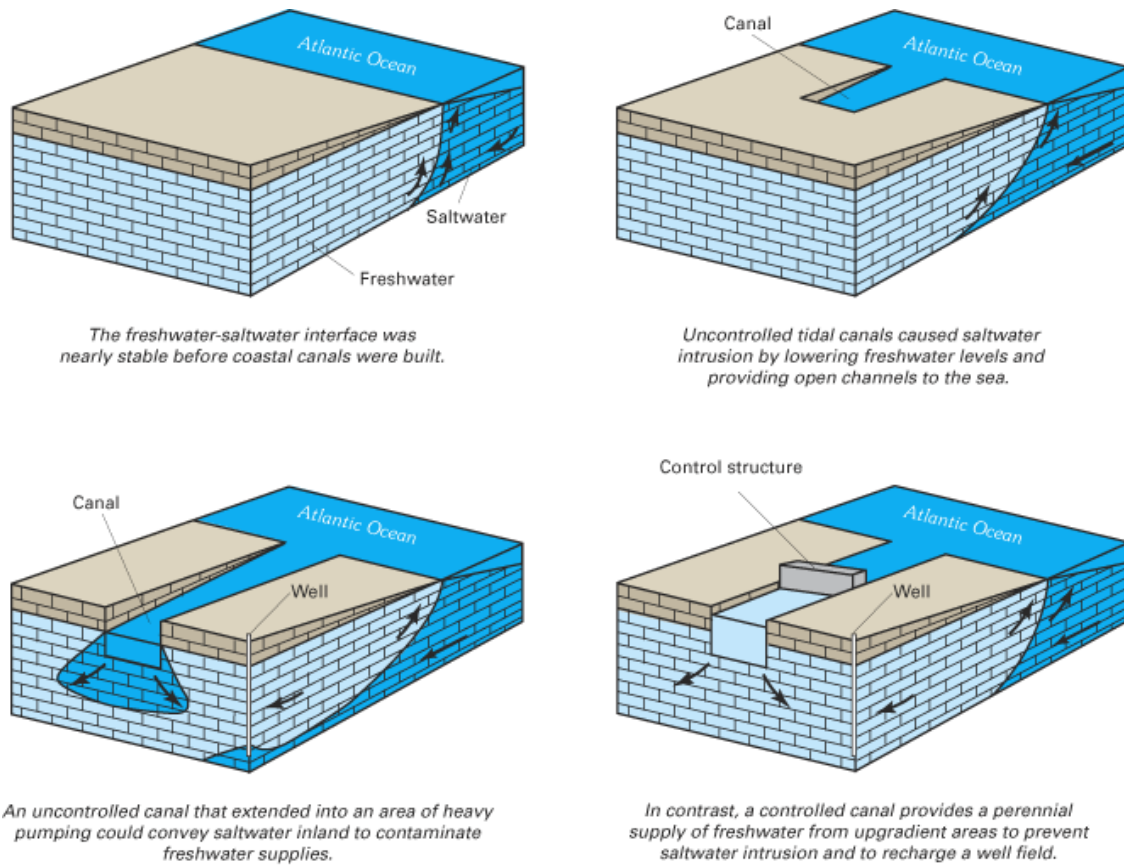


Figure 6: Illustration of saltwater intrusion before and after the construction of canals and control structures (Barlow, 2005).

In the early 1960's the canal system was expanded for use as flood control and the canals were equipped with flow control devices (Sonenshein, 1995). The water levels can be stepped down between structures to prevent excess drainage (Sonenshein, 1995). However, the design and operation of the structures has continued to lower the freshwater levels in the Biscayne aquifer (Sonenshein, 1995). 1970-1971 were years of drought, prompting further progression of saltwater intrusion (Sonenshein, 1995). Additional water was routed to the area in 1976, raising



water levels along the coast and helping to slow or reverse the inland movement of saltwater (Sonenshein, 1995).

The canal system is currently the primary method of control over the water level in the Biscayne aquifer (Sonenshein, 1995). Water levels are generally represented by the canal stages (Sonenshein, 1995). Freshwater is detained landward of the control structures to help sustain what remains of the Everglades (Sonenshein, 1995). Water is also held in “conservation areas” for use during dry seasons (Sonenshein, 1995; Barlow, 2005). The freshwater is pumped through the canal system to release excess during periods of high water and to control intrusion during low periods (Sonenshein, 1995).

Plans for future efforts to control saltwater intrusion in Miami-Dade County all aim at raising the level of freshwater (Sonenshein, 1995). There has been a general inland shift in the construction of new well fields (Barlow, 2005), decreasing coastal freshwater withdrawals (Sonenshein, 1995). There has also been an increase in freshwater delivery from inland areas to the coast (Sonenshein, 1995). The construction of further control structures would also help mitigate intrusion (Sonenshein, 1995).

While saltwater intrusion is still an issue in Miami-Dade County, prevention and mitigation attempts have met with a degree of success. Figure 7 shows the progress of intrusion over time. The inland movement of seawater has slowed and in some areas even reversed (Barlow, 2005). The control structures are working to, at the very least, decrease the rate at which intrusion progresses.

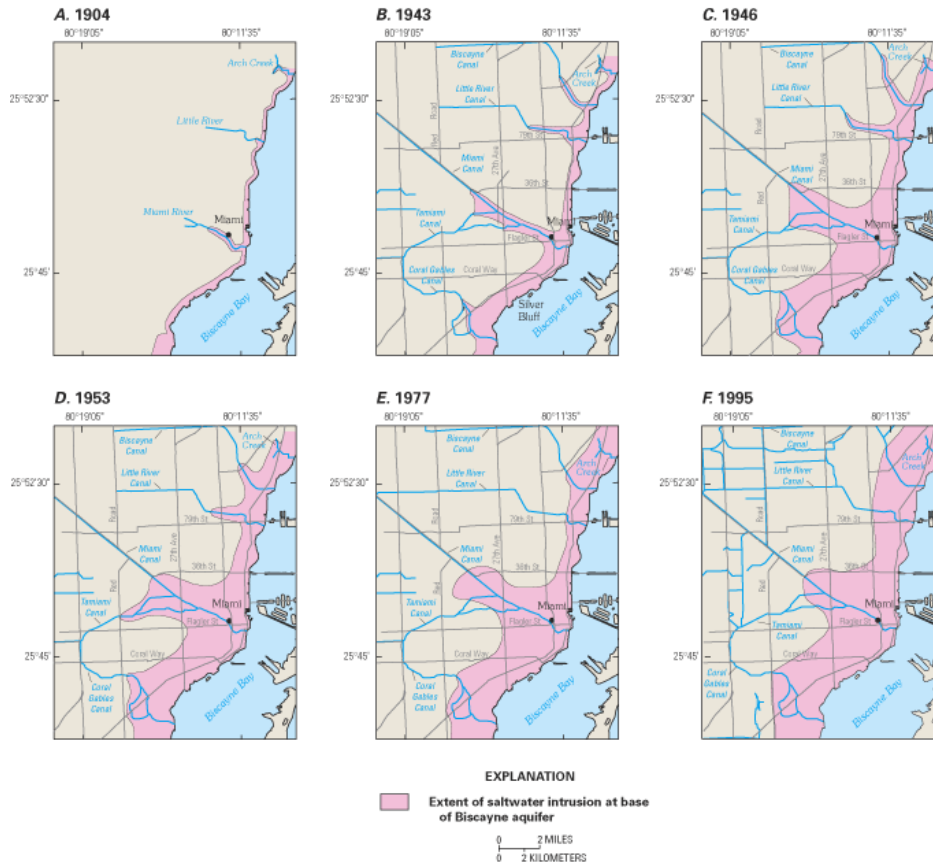


Figure 7: Illustration of the extent of saltwater intrusion in the Miami area through time (Barlow, 2005).

Saltwater intrusion is also a problem in Los Angeles County, California. However, the situation differs considerably from that of Miami-Dade County. Los Angeles is a critical population center and one of the most densely populated areas in the United States (Kulshan, 2006). The large population creates a correspondingly high freshwater demand (Kulshan, 2006) with approximately 500 extraction wells existing in Los Angeles County alone (Johnson and Sim, 2006). As the population in the area increases, so do freshwater withdrawals. A graph of population through time with significant groundwater events marked is shown as figure 8. Unlike the Biscayne, the aquifer underlying Los Angeles County was under artesian pressure prior to development (Kulshan, 2006).

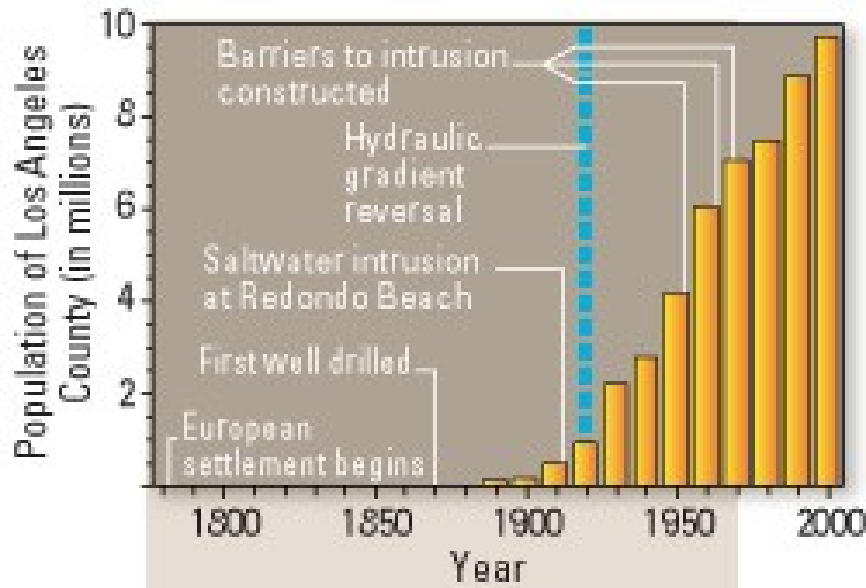


Figure 8: Graph of population increase with significant groundwater events marked. The blue dashed line marks the reversal of water flow direction in the 1920's, allowing saltwater to migrate inland (Edwards and Evans, 2005).

Europeans began to settle the area in the late 1700's (Edwards and Evans, 2005). By 1905 the artesian area of the aquifer had been greatly reduced (Kulshan, 2006). Prior to 1960, withdrawals from the aquifer were double what would be considered a natural or safe yield (Johnson and Sim, 2006). The basin was severely overdrawn with water levels falling approximately 3 meters per year. By the 1950's, the groundwater level was 30 meters below sea level (Johnson and Sim, 2006). Saltwater intrusion reached 20 meters in land and contaminated many coastal wells (Johnson and Sim, 2006).

Management efforts began in the 1950's. A replenishment district was created to artificially recharge the basin at percolation ponds and injection wells in an effort to reduce overdraft (Johnson and Sim, 2006). Administratively, allowable extractions were capped at  $310 \times 10^6 \text{ m}^3/\text{year}$  in the early 1960's (Johnson and Sim, 2006). The Los Angeles Flood Department also successfully tested and installed injection wells to recharge the aquifer (Johnson and Sim, 2006).

The injection wells were arranged to create a barrier to saltwater intrusion, which can be seen in figure 9 (Johnson and Sim, 2006). The wells inject water into the aquifer to restore the artesian pressure (Johnson and Sim, 2006). The water itself replenishes the freshwater supply and therefore recharge requires very high quality water to protect the usability of the aquifer (Kulshan, 2006; Johnson and Sim, 2006). Much of the water for the area is imported through aqueducts (Kulshan, 2006). From the 1950's until the present, treated drinking water was used in the injection wells (Johnson and Sim, 2006). However, starting in the mid 1990's advance treated reclaimed waste water was also used (Johnson and Sim, 2006). The reclaimed waste water is very high quality and is a reliable, local source of freshwater (Johnson and Sim, 2006). It also reduces the use of limited and expensive drinking water (Johnson and Sim, 2006).

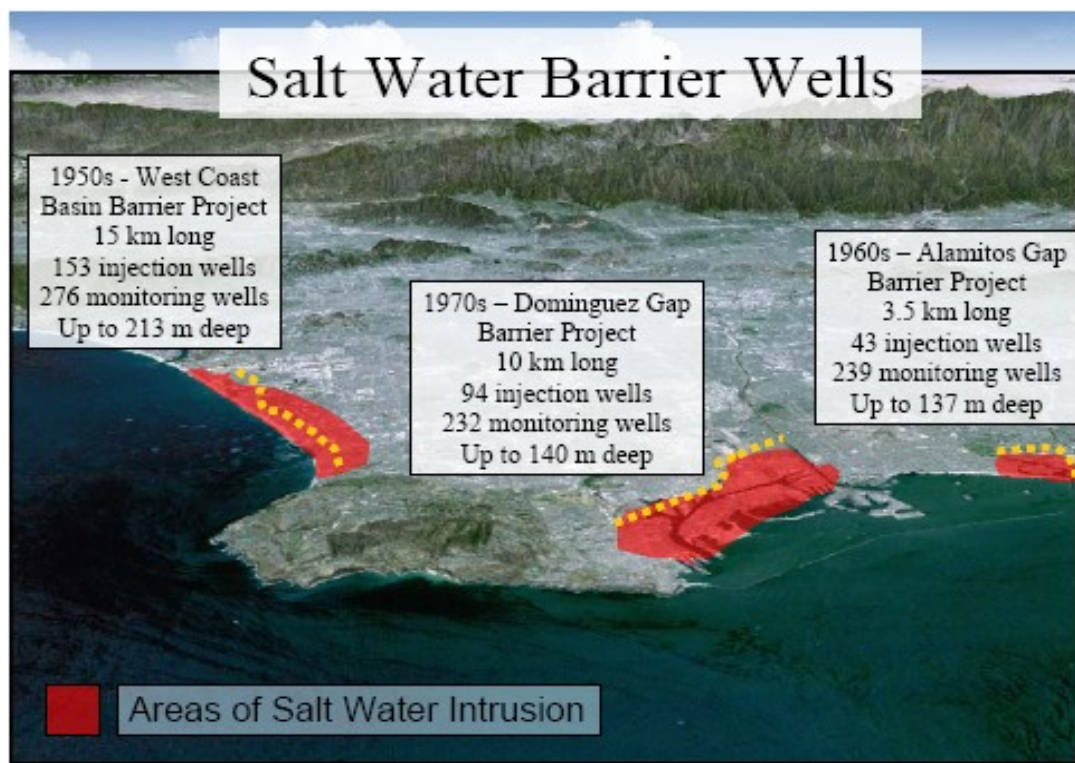


Figure 9: Illustration of the layout of barrier wells in Los Angeles County, California (Johnson and Sim, 2006).

Because injection wells are very expensive, several alternative mitigation techniques have been proposed for the area. One option is the construction of underground dams (Johnson

and Sim, 2006). Another idea is to inject gas, such as nitrogen, into the aquifer (Johnson and Sim, 2006). Gas injection would reestablish the pressure in the aquifer without replenishing the freshwater supply. Modeling pumping patterns to find the optimum configuration to minimize intrusion is a further option (Johnson and Sim, 2006). Another possibility is varying the vertical profile of the injection wells (Johnson and Sim, 2006).

Despite their large expense, injection wells are working to stop saltwater intrusion in Los Angeles County (Johnson and Sim, 2006). A comparison of chloride concentrations before and after injection is shown as figure 10. The amount of freshwater increased dramatically and the upper salinity limit was reduced inland. The injection wells have been successful at reestablishing pressure in artesian aquifers to impede saltwater intrusion and replenishing the freshwater (Johnson and Sim, 2006).

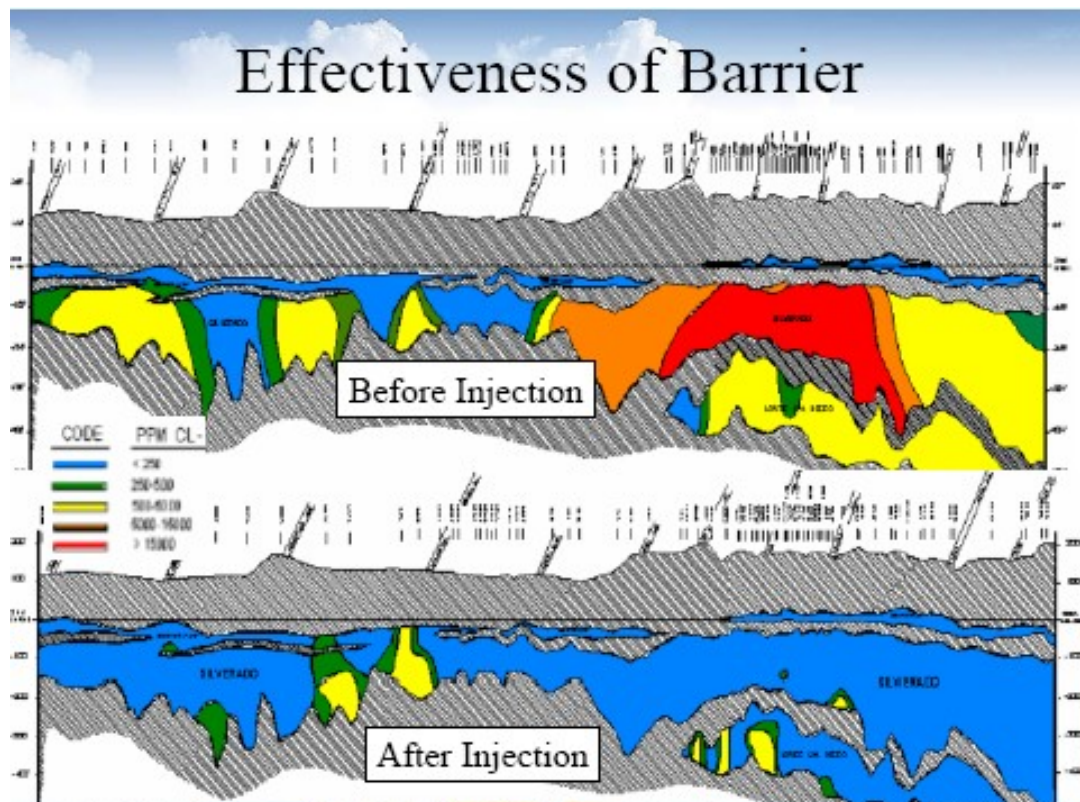


Figure 10: Illustration of chloride concentrations before and after freshwater injection. Blue represents freshwater, while red is highly saline (Johnson and Sim, 2006).

Looking at both case studies, several larger conclusions can be drawn. The first is the importance of mitigation efforts tailored to the specific situation. Because the two aquifers studied had different geologic settings they required different strategies to control saltwater intrusion. The canals were part of the problem in the unconfined Biscayne aquifer in Miami-Dade County, and therefore had to be included in the solution. For the artesian aquifer in Los Angeles County, rebuilding the pressure was a necessary component to mitigation efforts. For both cases, growing populations were key triggers to saltwater intrusion because of the consequent increase in freshwater demand.

Saltwater intrusion promises to continue to threaten the freshwater resources of coastal communities. As global warming raises sea level, the freshwater-saltwater interface will move inland and communities that were previously safe may soon face saltwater contamination. As populations continue to grow withdrawal pressure on threatened aquifers will also continue to rise. Human actions have induced saltwater intrusion and therefore it is our responsibility, as Miami-Dade and Los Angeles Counties have attempted, to preserve and protect our crucial freshwater resources.