Saltwater intrusion in coastal regions of North America

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Abstract Saltwater has intruded into many of the coastal aquifers of the United States, Mexico, and Canada, but the extent of saltwater intrusion varies widely among localities and hydrogeologic settings. In many instances, the area contaminated by saltwater is limited to small parts of an aquifer and to specific wells and has had little or no effect on overall groundwater supplies; in other instances, saltwater contamination is of regional extent and has resulted in the closure of many groundwater supply wells. The variability of hydrogeologic settings, three-dimensional distribution of saline water, and history of groundwater withdrawals and freshwater drainage has resulted in a variety of modes of saltwater intrusion into coastal aquifers. These include lateral intrusion from the ocean; upward intrusion from deeper, more saline zones of a groundwater system; and downward intrusion from coastal waters. Saltwater contamination also has occurred along open boreholes and within abandoned, improperly constructed, or corroded wells that provide pathways for vertical migration across interconnected aquifers. Communities within the coastal regions of North America are taking actions to manage and prevent saltwater intrusion to ensure a sustainable source of groundwater for the future. These actions can be grouped broadly into scientific monitoring and assessment, engineering techniques, and regulatory approaches.

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Introduction

Groundwater is a vital resource for sustaining the communities and economies of North America's coastal regions. Groundwater withdrawals for public supplies, agriculture, industry, and other uses in the Atlantic and Pacific coastal regions of the United States alone exceeded 618 m^3/s (14.1 billion gallons per day) in 2000 (US Geological Survey 2004), and in many coastal communities groundwater is the primary or sole source of drinking water. As groundwater use in coastal areas has increased, so has the recognition that groundwater supplies are vulnerable to overuse and contamination. Although groundwater overuse and contamination are not uncommon, the proximity of coastal aquifers to saltwater creates unique issues with respect to groundwater sustainability in coastal regions. These issues are primarily those of saltwater intrusion into freshwater aquifers and changes in the amount and quality of fresh groundwater discharge to coastal saltwater systems. This paper focuses on the first of these issues—saltwater (or seawater) intrusion into coastal aquifers of North America, which was recognized as a problem in the United States as early as 1854 on Long Island, New York (Back and Freeze 1983).

The objectives of this paper are threefold: to provide a summary of the extent and modes of saltwater intrusion along coastal regions of the United States, Mexico, and Canada; to describe the many approaches and tools that are used to monitor and manage saltwater intrusion in these coastal regions; and to provide a brief assessment of the prospects for addressing saltwater intrusion problems in the future. This paper is limited in scope to the Atlantic and Pacific coasts of Canada and the United States (excluding Alaska and Hawaii) and all of Mexico (Fig. 1). Previous reviews of saltwater intrusion in the United States have been done by Krieger et al. (1957), Task Committee on Saltwater Intrusion (1969), and Konikow and Reilly (1999). Barlow (2003) provides a detailed review of saltwater intrusion along the Atlantic Coast of the United States, and Barlow and Wild (2002) provide an extensive bibliography of publications related to

Fig. 1 Map of study area showing some of the locations discussed in the text

saltwater intrusion in that region. Surveys of saltwater intrusion on the Pacific Coast include California Department of Water Resources (1958), Dion and Simioka (1984), and Hanson et al. (2009). Cardoso (1993) provides an overview of saltwater intrusion in the 17 coastal states of Mexico.

Extent and modes of saltwater intrusion

In order to manage saltwater intrusion, one must first understand the extent of the problem and the physical mechanisms (or modes) by which saltwater intrusion occurs. This section briefly outlines what is known of the extent of saltwater intrusion in North America and gives examples of the many pathways by which saltwater intrusion has occurred.

The coastal regions of North America are characterized by a wide range of hydrogeologic settings. Although there are numerous types of geologic formations in the coastal regions, the most important water-bearing formations are unconsolidated and semiconsolidated silts, sands, and gravels of both marine and continental origin; and, among consolidated rocks, carbonates (primarily limestones), sandstones, and fractured crystalline rocks such as granites. Groundwater-flow systems within the coastal zones vary in size from single-layer aquifers that are a few square kilometers or less in areal extent to multilayer, regional-scale aquifers that are from hundreds to tens of thousands of square kilometers in areal extent. In many areas, unconfined aquifers that lie close to land surface are underlain by one or more confined aquifers that may be hydraulically separated from the land surface by confining units.

Groundwater flow systems along the coastal zones are characterized by flowpaths that range from a few kilometers to several hundred kilometers. The seaward limit of freshwater in the coastal aquifers is controlled by a number of factors, including the amount of freshwater flowing through each aquifer, the thickness and hydraulic properties of each aquifer and adjacent confining units, the current geographic distribution of saline surface water, and the geologic history of global sea-level fluctuations. In some of the confined aquifers along the Atlantic Coast, relatively fresh groundwater has been found tens of kilometers offshore; its presence has been attributed to freshwater recharge that occurred over at least the past 900,000 years during periods when sea levels were lower than at present (Meisler 1989). In other areas, such as southern Florida, confining conditions and sluggish groundwater flow are thought to have contributed to the presence of large inland areas of residual seawater that entered the aquifers during the Pleistocene when sea level was higher than its current level (Sprinkle 1989). Inland areas of saline water also can be found near estuaries, where saltwater carried up river channels by high tides has infiltrated into the adjoining freshwater aquifers. Examples of this type of naturally occurring intrusion have been

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documented for fractured sandstones of Prince Edward Island, Canada (Carr 1969), and permeable deltaic sediments near the Fraser River, British Columbia, Canada (Neilson-Welch and Smith 2001).

The transition zone between freshwater and saltwater ranges from less than 30 m thick in relatively thin aquifers to as much as 670 m thick and 60 km wide in thick, confined aquifers along the Northern Atlantic Coastal Plain where global sea-level fluctuations caused repeated advance and retreat of the landward position of the freshwater-saltwater interface. In California coastal aquifers, where saltwater intrusion tends to occur within coarse-grained layers of varying thickness, the transition zone can be relatively narrow (Land et al. 2004; Izbicki 1996; Hanson et al. 2009). Mixing within freshwater-saltwater transition zones is caused primarily by hydrodynamic dispersion that results from spatial heterogeneities in aquifer properties and from dynamic forces that operate over a wide range of time scales—from relatively short-term fluctuations in tide stages and groundwater recharge rates to millennial fluctuations in global sea-level position.

The variability of hydrogeologic settings, three-dimensional distribution of saline water, and history of groundwater withdrawals and freshwater drainage has resulted in a variety of modes of saltwater intrusion into coastal aquifers of North America. Saltwater can contaminate a freshwater aquifer through several pathways, including lateral intrusion from the ocean; upward intrusion from deeper, more saline zones of a groundwater system; and downward intrusion from coastal waters (such as embayments and estuaries) and storm or tidal-driven saltwater flooding of coastal lowlands. Although most saltwater contamination problems result from the movement of saltwater within aquifers, saltwater contamination also has occurred along open boreholes, abandoned wells, improperly constructed or corroded wells, and dredged channels that provide pathways for vertical migration across interconnected aquifers (see for example Metz and Brendle 1996).

The extent of saltwater intrusion into an aquifer depends on several factors, including the total rate of groundwater that is withdrawn from an aquifer compared to the total freshwater recharge to the aquifer; the distance between the locations of groundwater discharge—such as pumpage from wells and drainage to canals—and the source (or sources) of saltwater; the geologic structure of an aquifer or aquifer system (including structural features such as faults, folds, and bounding submarine canyons); the distribution of hydraulic properties of an aquifer (including the interconnectivity of coarse-grained units within multi-layered aquifer systems); and the presence of confining units that may prevent saltwater from moving vertically toward or within the aquifer. Many authors have recognized that there may be multiple sources of salinity to coastal aquifers, and that it can be difficult to unequivocally delineate the specific sources of salinity in a particular aquifer. Although there are concurrent sources of potential salinity in several of the cases discussed here, the discussion is focused on saltwater intrusion that has been shown to have been caused by the movement of saline water into or within coastal aquifers in response to anthropogenic stresses.

Saltwater intrusion has been documented along the coasts of the United States for more than 150 years, but the literature indicates that the extent of saltwater intrusion varies widely among localities and hydrogeologic settings. In many instances, the area contaminated by saltwater is limited to small parts of an aquifer and to specific wells and has little or no effect on overall groundwater supplies. In Washington State, for example, no large water-supply systems that rely primarily on groundwater have been affected by saltwater intrusion, although some wells and small community systems on Puget Sound shorelines have been affected, and groundwater resources on several islands in Puget Sound are threatened by saltwater intrusion (Dion and Simioka 1984; Sapik et al. 1988; Richard Dinicola, US Geological Survey, personal communication, 2008). Similarly, in Oregon there is relatively little use of groundwater in coastal areas, and hence no current saltwater intrusion (David Morgan, US Geological Survey, personal communication, 2008), though the potential for intrusion is recognized in the Coos Bay Dune sand aquifer (Jones 1992). In other instances, saltwater contamination is of regional extent and has substantially affected groundwater supplies such as in Cape May County, New Jersey; southeastern Florida; and Monterey, Ventura, Orange, and Los Angeles Counties, California.

The most extensive saltwater-intrusion problems in Mexico are concentrated in the western States of Sonora, Baja California Norte, and Baja California Sur (Fig. 1), with smaller problems along the Yucatan Peninsula (Yucatan and Quintana Roo States), Veracruz State along the Gulf of Mexico, and the western States of Sinaloa and Nayarit (Cardoso 1993; Marin 2002; Luis E. Marin, Universidad Nacional Autónoma de México, personal communication, 2009). In Sonora, lateral saltwater intrusion from the Gulf of California has occurred in several coastal irrigation districts in response to pumping for agriculture that exceeds the natural recharge rates that occur within this arid region; areas of substantial intrusion in Sonora occur near Caborca and in the Valleys of Hermosillo and Guaymas (Andrews 1981; Cardoso 1993; Steinich et al. 1998; Flores-Márquez et al. 1998). Groundwater withdrawals in the Valley of Hermosillo, which began in the 1940s, combined with the construction of a dam on the Sonora River that caused the river to go dry and substantially reduced recharge to the underlying aquifer (Steinich et al. 1998), has led to an area of saltwater intrusion in the unconfined alluvial aquifer that is as much as 30 km wide near the coast and extends inland approximately 20–25 km (Steinich et al. 1998; Flores-Márquez et al. 1998). The intrusion has forced the closure of several water-supply and irrigation wells (Andrews 1981; Steinich et al. 1998).

Much research has been done on the freshwater–saltwater relations within the unconfined karstic aquifer of the northwestern part of the Yucatan Peninsula (see, for example, González-Herrera et al. 2002; Steinich and Marin 1996; Marin et al. 2004; and references therein). The aquifer that underlies the northwestern part of the peninsula consists of a thin freshwater lens that 'floats' on denser saltwater that extends more than 40 km inland. Although there are a large number of groundwater withdrawal sites on the peninsula, groundwater flow has not been substantially altered because

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of the relatively high rates of recharge to the aquifer (as opposed to that in Sonora) and large transmissivity of the aquifer, thus preventing substantial problems of saltwater intrusion.

Few examples can be found in the literature of saltwater intrusion into coastal aquifers of Canada, and of those cases described, several relate to intrusion that occurs naturally (Carr 1969; van der Kamp 1981; Dakin et al. 1983; Neilson-Welch and Smith 2001). An exception is the intrusion of saltwater into the sandstone aquifers of Prince Edward Island (Tremblay et al. 1973) and nearby Magdalen Islands (Comte and Banton 2006), both of which are caused by groundwater pumping. On Prince Edward Island, two types of intrusion were identified: (1) a landward migration of saltwater from the coast into the upper 25 m of the aquifer due to large groundwater withdrawals and (2) upconing of saltwater at a depth of approximately 125 m due to intermittent pumping (Tremblay et al. 1973). Saltwater intrusion on the island is facilitated by fractures within the sandstone that increase the overall permeability of the aquifer. A few additional studies of saltwater intrusion along the Atlantic Coast of Canada are cited in a report by the Maritimes Groundwater Initiative (2003), but, overall, it appears from the lack of available references in the literature that saltwater intrusion is not currently a widespread issue in Canada.

Although groundwater pumping is the primary cause of saltwater intrusion in coastal regions of North America, lowering of the water table by drainage canals has led to saltwater contamination in a few locations, notably southeastern Florida. Other hydraulic stresses that reduce freshwater flow in coastal aquifers, such as lowered rates of groundwater recharge in sewered or urbanized areas, also could lead to saltwater intrusion, but the impact of such stresses on saltwater intrusion is generally small in comparison to pumping and land drainage.

Four examples are provided to illustrate the causes, modes, and complexity of saltwater-intrusion problems in coastal regions of North America. Examples along the Atlantic Coast are drawn from the States of New Jersey, Georgia, and Florida, which, with the possible exception of Long Island, New York, have experienced the most widespread problems of saltwater intrusion along the Atlantic Coast of the United States. Examples from the Pacific Coast are from the coastal basins of central and southern California, United States, which have experienced the most extensive saltwater intrusion along that coast.

Lateral encroachment of saltwater into confined freshwater aquifers from surrounding saline zones, Cape May County, New Jersey

Cape May County, New Jersey, is on a peninsula that is surrounded by the Atlantic Ocean and Delaware Bay (Fig. 2). The peninsula is underlain by a multilayer sequence of unconsolidated, predominantly sand and gravel aquifers separated by silt and clay confining units that extend offshore. Fresh groundwater in the aquifers beneath the peninsula is bounded laterally by saline groundwater that extends seaward toward the Atlantic Ocean and Delaware Bay. All of the county's potable water supply is obtained from the freshwater aquifers. Prior to the start of groundwater withdrawals, water levels in each of the aquifers stood above sea level, and groundwater flowed radially outward from inland recharge areas to low-lying streams, tidal wetlands, and saline surface waters. Withdrawals from the five aquifers, however, have lowered groundwater levels by as much as 30 m and have caused saltwater to encroach laterally within each aquifer. Saltwater intrusion in the county began about 1890 after the first deep wells were pumped and groundwater levels declined below sea level (Lacombe and Carleton 2002). Saltwater intrusion has forced the closure of at least 20 public- and industrial-supply wells and more than 100 domestic-supply wells in the county since the 1940s. One of the communities most affected by saltwater intrusion is Cape May City, where the history of saltwater contamination has been well documented (see for example Lacombe and Carleton 2002). The primary source of freshwater for the city has been groundwater withdrawn from five wells that tap the Cohansey aquifer. Pumping from these wells has led to saltwater contamination in four of the wells (Fig. 2a).

Vertical migration along fractures and other preferential flow conduits in the Floridan carbonate aquifer, southeastern Georgia and northeastern Florida

The Floridan aquifer system is one of the most productive aquifers in the world. It consists of a thick sequence of carbonate rocks (limestones and dolomites) that underlie all of Florida and southern Georgia and parts of South Carolina and Alabama—an area of about 250,000 km^2 (Fig. 3b). Withdrawals from the aquifer system totaled more than 158 m^3/s in 2000 (Maupin and Barber 2005), and in many areas it is the sole source of freshwater. Groundwater withdrawals from the Floridan aquifer system have caused long-term regional water-level declines of more than 3 m in several areas, including northeastern Florida and coastal Georgia.

In most places, the aquifer system consists of the Upper and Lower Floridan aquifers separated by a less permeable confining unit that restricts movement of water between the two aquifers. In northeastern Florida and southeastern Georgia, the Lower Floridan aquifer includes an extremely permeable, partly cavernous saline water-bearing zone called the Fernandina permeable zone. This zone is overlain by a low-permeability confining unit that in most places effectively separates it from shallower permeable strata (Miller 1986). However, in a number of locations, isolated geologic structures have breached the Floridan aquifer system and created preferential groundwater flow conduits that allow saltwater to migrate upward from the Fernandina permeable zone to overlying freshwater aquifers, especially in areas where groundwater levels have been lowered by pumping (Fig. 3a). Once the saltwater reaches the freshwater zones, it moves laterally downgradient within the freshwater zones toward areas of pumping. Geologic evidence indicates that the conduits

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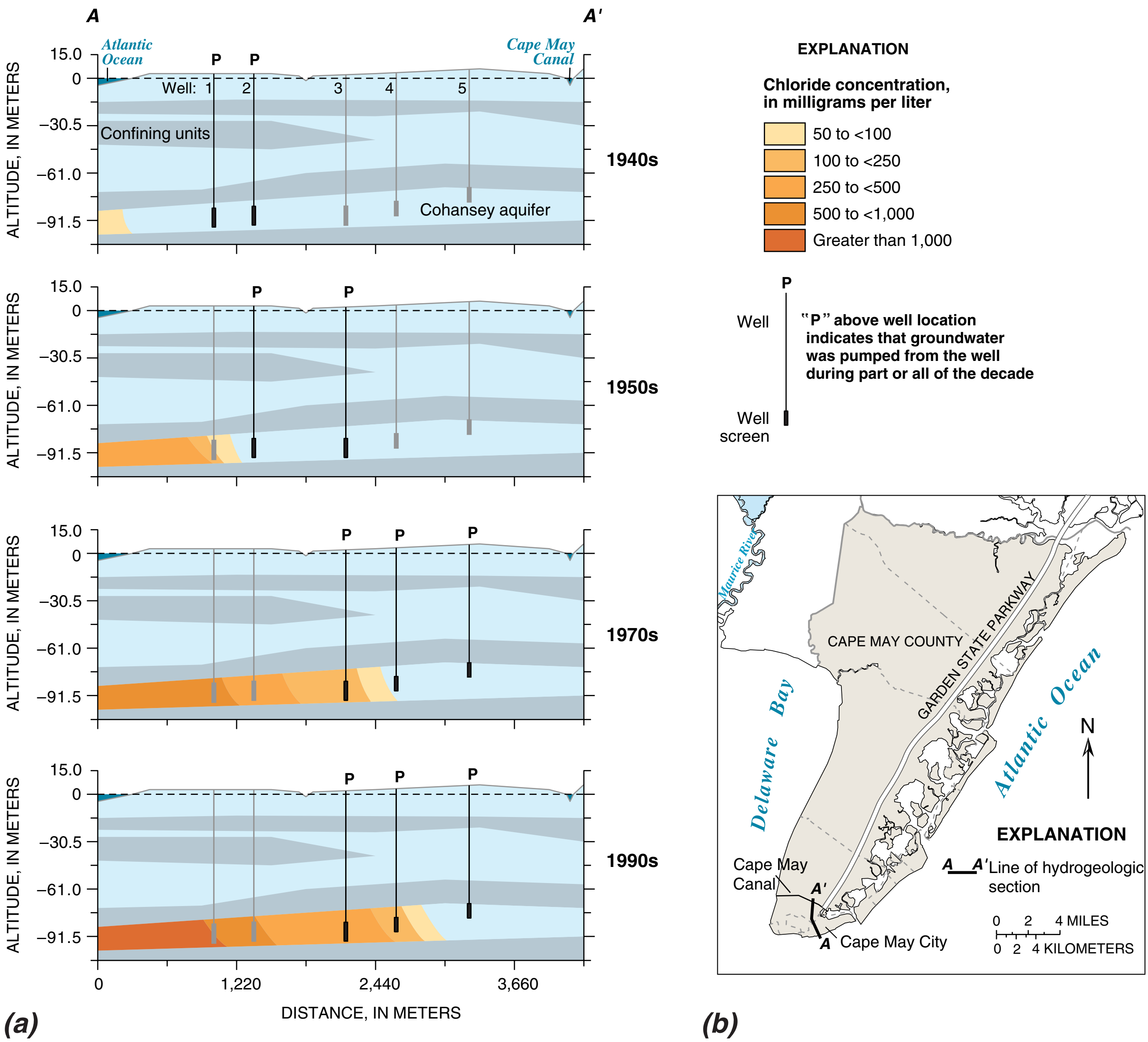

Fig. 2 **a** Hydrogeologic sections showing lateral encroachment of saltwater and contamination of supply wells in the Cohansey aquifer at the Cape May City (New Jersey) well field, 1940s to 1990s. **b** Map of Cape May County, New Jersey. (Modified from Lacombe and Carleton 2002)

are most likely fractures, joints, or faults that have been enlarged by dissolution of the carbonate strata in the fractured zone (see for example Spechler 1994). This type of contamination, which has occurred at Brunswick, Georgia, and at Fernandina Beach and near Jacksonville, Florida, has created localized, anomalous patterns of saltwater contamination that often are difficult to identify, explain, and monitor.

Regional saltwater intrusion due to large-scale drainage and pumping, southeastern Florida

Saltwater intrusion has been an issue of concern in southeastern Florida since the 1930s. Southeastern Florida is part of the region that once contained one of the largest wetlands in the continental US, the Everglades, which extended across the southern part of the Florida Peninsula south of Lake Okeechobee (Fig. 4b). Beginning in 1903 and continuing into the 1980s, an extensive network of canals was constructed between the lake and the Atlantic Ocean to drain the Everglades for agricultural and urban development, among other reasons. The canals are part of a highly controlled water-management system that has contributed to the growth of one of the largest urban areas of the United States.

An important component of southeastern Florida's hydrologic system is the highly productive Biscayne aquifer (Fig. 4b), which is the source of water supply in Miami-Dade, Broward, and Palm Beach Counties. Total withdrawals from the aquifer for irrigation and public

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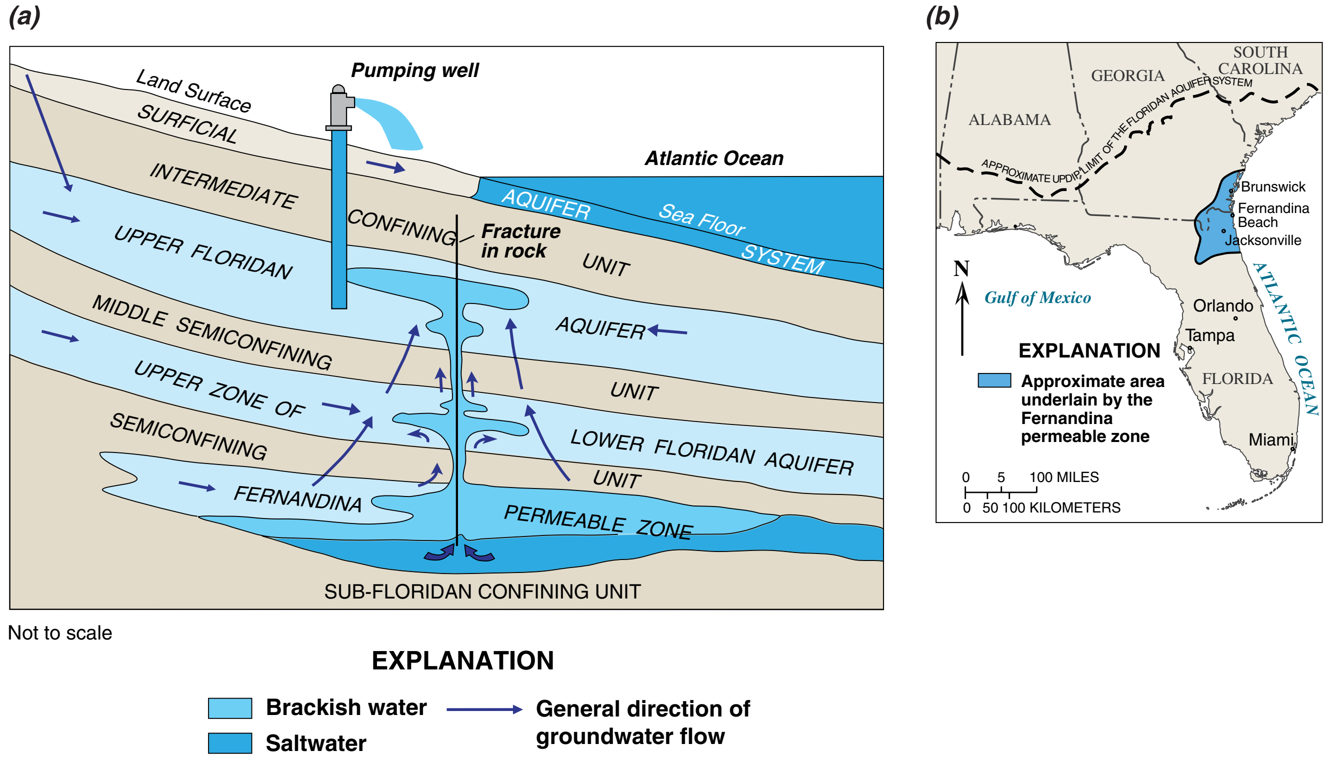

Fig. 3 **a** Simplified conceptual model of saltwater leakage along fractures in the Floridan aquifer system in southeastern Georgia and northeastern Florida. The fractures and other structural anomalies provide preferential conduits for saline water in the Fernandina permeable zone to flow upward into freshwater zones of the overlying aquifers in response to groundwater pumping in upper aquifers. **b** Approximate limit of the Floridan aquifer system and area underlain by the Fernandina permeable zone. (Modified from Krause and Randolph 1989; Miller 1990; Spechler 1994)

supply were about 35.5 m^3/s in 2000 (Maupin and Barber 2005). This surficial aquifer consists of highly permeable limestone and less-permeable sandstone and sand (Miller 1990). The aquifer is unconfined and the water table responds quickly to recharge, evapotranspiration, and pumping from supply wells. Moreover, in most places the aquifer and drainage canals are in direct hydraulic connection, which facilitates rapid interchange of water between them. Prior to 1945, flow within the canals was uncontrolled, causing overdrainage of the aquifer and periodically allowing seawater to move inland along the canals and subsequently into the groundwater system. Since 1946, gated canal control structures have been used to prevent inland migration of seawater along the canals and to control canal stages and groundwater levels.

Construction of the extensive drainage system, subsequent compaction and oxidation of inland peat and muck soils (with associated lowering of the water table within the peat mantle and underlying aquifer), and large-scale groundwater withdrawals have resulted in saltwater intrusion into coastal areas of the Biscayne aquifer (Renken et al. 2005) (Fig. 4a). Canal drainage appears to have had the most widespread impact on saltwater intrusion (Renken et al. 2005). The canals have lowered groundwater levels and induced lateral saltwater intrusion along the coast, and, at least prior to the construction of the canal control structures, conveyed seawater inland to the groundwater system. Movement of the freshwater/saltwater interface near Miami has been particularly well documented through the years (Fig. 5). In 1904, prior to construction of the regional drainage network and water-supply wells, very high water levels in the Everglades and Biscayne aquifer kept the saltwater interface limited to a narrow band along the coastline and to short tidal reaches of coastal streams (Fig. 5a). Beginning in 1909 and continuing into the early 1940s, construction of drainage canals that lacked control structures, as well as pumpage from coastal well fields, resulted in lowered water levels in the aquifer and substantial inland movement of saltwater along the coastline and into coastal tidal canals (Fig. 5b). Uncontrolled drainage in southeastern Florida was halted by the installation of the canal control structures beginning in 1946, which has slowed and in some areas reversed the inland migration of saltwater (Fig. 5c,d). The canals also are used to transfer freshwater from inland water-conservation (storage) areas to coastal reaches, where the water is artificially recharged to the aquifer to raise coastal groundwater levels and control saltwater intrusion.

Regional intrusion into multi-layer unconsolidated/semiconsolidated aquifer systems in central and southern California

In several important coastal basins in central and southern California, increased utilization of groundwater has played

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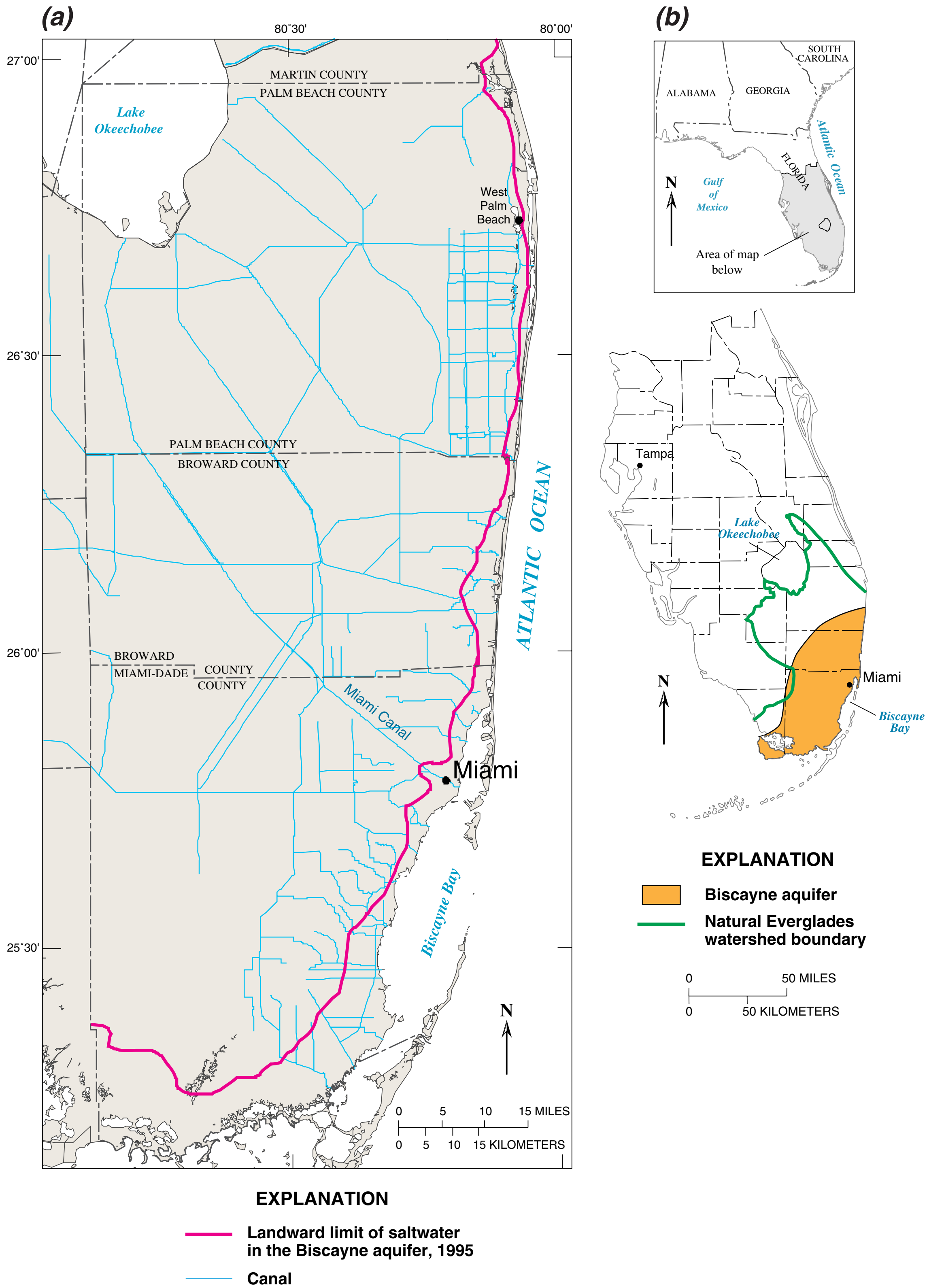

Fig. 4 **a** Landward limit of saltwater in the Biscayne aquifer, 1995. **b** Maps of the State of Florida and extent of the Biscayne aquifer in south Florida (Fig. 4a modified from Renken et al. 2005; Part **b** modified from Miller 1990)

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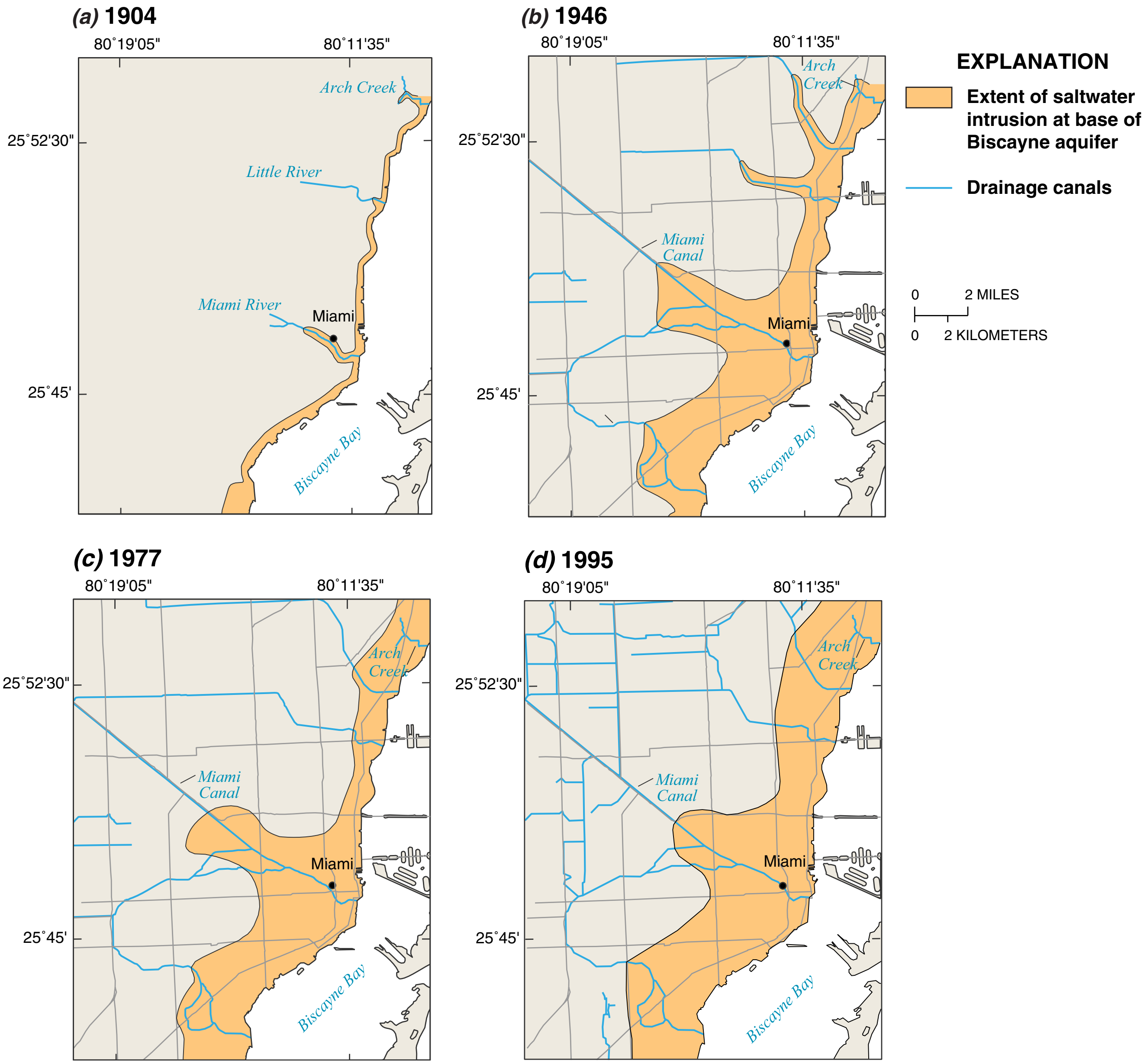

Fig. 5 Saltwater intrusion in the Biscayne aquifer in Miami-Dade County near the Miami Canal, **a** 1904, **b** 1946, **c** 1977, and **d** 1995. (Modified from Renken et al. 2005)

an essential role in large-scale agricultural and urban development. This includes the coastal basins of Santa Cruz and Monterey Counties in the Monterey Bay area of central California and Santa Barbara, Ventura, Los Angeles, and Orange Counties in southern California (Fig. 1). As development of these coastal basins escalated in the twentieth century, it was recognized that there was potentially a large amount of groundwater available in storage. Groundwater pumpage increased dramatically, which resulted in large water-level declines and associated impacts, including seawater intrusion. All of these basins have some similar characteristics in terms of their hydrostratigraphy, structural setting, and overall hydrologic setting. The hydrostratigraphy of these basins is the result of cycles of deposition and erosion, which have been driven by sea-level changes. This depositional history has resulted in multi-layer aquifer systems that contain sequences of both marine and terrestrial sediments. The sequences consist of sediment packages that can be either fining upward (deposited during periods of rising sea level) or coarsening upward (deposited during periods of falling sea level; Ponti et al. 2006). Zones of interconnected coarse-grained materials form the most productive aquifers for water supply, but also serve as the primary conduits for saltwater intrusion. In these coastal basins, the potential pathways for saltwater intrusion also are affected by faults (for example, the Santa Barbara area; Freckleton et al. 1998) and offshore bathymetric features such as submarine canyons (for example, the Ventura area; Nishikawa 1997; Hanson et al. 2003). Several specific

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aspects of saltwater intrusion in the Los Angeles and Monterey Bay areas are described in the next few paragraphs.

In the coastal Los Angeles region (Fig. 1), groundwater development began in the mid-nineteenth century. Groundwater pumpage increased substantially during the first half of the twentieth century as the population increased dramatically and the deep well turbine pump became widely used. Water levels below sea level were noted as early as the 1920s, and saltwater intrusion was documented all along the coast by the 1940s such as illustrated for the Los Angeles area in Fig. 6 (Poland et al. 1959). Since the 1950s, the problem of saltwater intrusion has been addressed on multiple fronts, including operation of injection barriers, increased artificial recharge in spreading ponds, and reductions in pumpage.

Two issues in the Los Angeles area have relevance to saltwater intrusion in basins throughout central and southern California. First, the pathways of saltwater intrusion are affected by the complex geometry of the depositional sequences, the presence of alluvium-filled erosional gaps, offshore bathymetric features such as submarine canyons, and the presence of faults and folds (Planert and Williams 1995; Reichard et al. 2003). Geologic investigations and numerical simulations for the Dominguez Gap area, for example, have demonstrated that a series of faults and folds have allowed saltwater, which is moving preferentially through shallow coarse-grained sediments, to be transported vertically downward into deeper aquifers (Ponti et al. 2006; Nishikawa et al. 2009). Second, there are other sources of chloride besides seawater that affect groundwater quality in coastal Los Angeles. Land et al. (2004) used ion ratios (for example, chloride-iodide, chloride-bromide, chloride-boron), stable isotopes, other isotopic indicators (for example, strontium), and age dating to characterize mixing of water sources between seawater, native groundwater, oil-field brines, and imported water used for injection. Control of saltwater intrusion requires understanding the sources and movement of the different water components.

The Salinas and Pajaro Valleys are examples of groundwater basins in the Monterey Bay area in central California (Fig. 1) that face saltwater-intrusion problems. In contrast to southern California basins like Los Angeles, in the Pajaro and Salinas Valleys agricultural, rather than urban, development has led to saltwater intrusion in multiple aquifers. In both Pajaro and Salinas Valley basins, geologic units containing productive aquifers crop out in Monterey Bay (Yates 1988). The deeper aquifers crop out very close to shore along the Monterey Submarine Canyon. In both basins, there are distinct differences between intrusion in the upper and lower aquifers. In the Salinas basin, where saltwater intrusion has been recognized since the 1930s, there is much more extensive intrusion in the “180-ft” (upper) aquifer system than in the “400-ft” (deeper) system. The “400-ft” aquifer is threatened by downward migration of high salinity water from the “180-ft” aquifer (including, potentially, through wellbores; Monterey County Water Resources Agency 2004a). In the Pajaro Valley basin, high chloride concentrations in the upper aquifer system (within the shallow alluvium and upper Aromas Sand) are indicative of recent saltwater intrusion, as evidenced by measurable tritium. In contrast, the source of elevated chloride in the lower aquifer system (within the lower Aromas Sand) is seawater that has been in the groundwater system for thousands of years (Hanson 2003).

Monitoring and managing saltwater intrusion

Communities within the coastal regions of North America are taking action to manage and prevent saltwater intrusion to ensure a sustainable source of groundwater for the future. These actions can be grouped broadly into three general categories: scientific monitoring and assessment, engineering techniques, and regulatory (or legislative) approaches.

Scientific monitoring and assessment provide basic characterization of the groundwater resources of an area, an understanding of the different pathways by which saltwater may intrude an aquifer, and a basis for management of water supplies. Numerous water-level and water-quality monitoring networks have been established along the Atlantic and Pacific Coasts of the United States to monitor changes in groundwater levels, groundwater quality, and movement of the freshwater–saltwater interface. Water-quality monitoring networks are particularly important in serving as early-warning systems of saltwater movement toward freshwater supply wells, as well as providing information on the rates of saltwater encroachment. Dedicated wells that sample multiple intervals of an aquifer are invaluable for providing a three-dimensional characterization of the extent of saltwater within an aquifer system. These types of monitoring wells have been particularly important in the complex aquifer systems along the Pacific Coast, where saltwater may be present within relatively thin, discrete, coarse-grained zones (Hanson et al. 2009; Land et al. 2004).

The traditional approach for monitoring the location and movement of saltwater contamination has been to periodically collect groundwater samples from discrete sampling horizons for analysis of the chloride or dissolved solids concentration (or specific conductance) of the water. Recently, however, more innovative approaches have been developed to improve the spatial detail and frequency by which saltwater contamination can be monitored. One of these innovations is the use of borehole electromagnetic (EM) logs, which provide detailed, yet indirect, vertical profiles of conductivity through the entire well bore. Repeated EM logs at a monitoring location can also provide a detailed record of changing conductivity conditions within an aquifer. This is illustrated in Fig. 7, which shows the results of two sets of EM logs at three wells in Ventura County, California (Hanson et al. 2009). The EM logs are accompanied by gamma logs, which facilitate distinguishing between the zones of high and low permeability. EM measurements at all three wells

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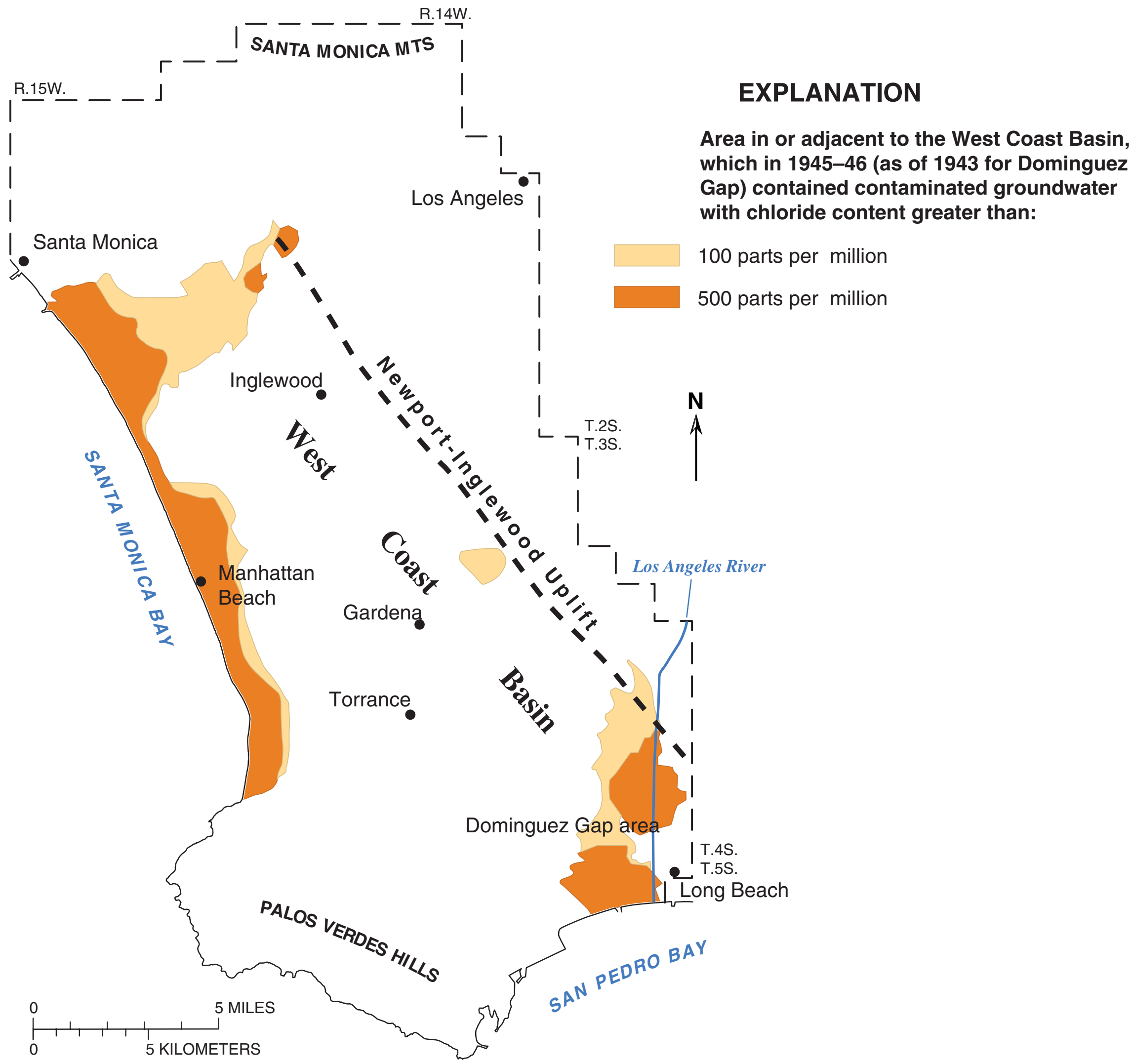

Fig. 6 Chloride concentrations in coastal Los Angeles (California) in the mid-1940s. (Modified from Poland et al. 1959, plate 16)

show evidence of reduced salinity in the shallower parts of the aquifer system over a 2-year interval (that is, the EM conductivity values in 1996 were lower than the 1994 values). However, the "Southern Oxnard Plain" well shows a significant increase in EM conductivity between 244 and 259 m (800 and 850 ft) below land surface. The increase in EM conductivity is indicative of an increase in salinity in the zone over the 2-year time period.

Automated sampling systems have been developed to provide real-time monitoring of saltwater intrusion (see, for example, Granato and Smith 2002; Cherry and Clarke 2008). In the Brunswick, Georgia, area, a network of real-time monitoring wells completed in the Upper Floridan aquifer has been established around a plume of saltwater contamination to ensure that the contamination is contained. Wells in the network are equipped with satellite telemetry for real-time monitoring of water levels and specific conductance (Cherry and Clarke 2008).

Numerical modeling is an important tool that has been used to investigate the paths and rates of groundwater flow and saltwater intrusion in many regions of North America. Because of their complexity, density-dependent solute-transport models have not been used as extensively to evaluate coastal groundwater systems as have constant-density models that simulate only groundwater flow, although this will likely change in the future as computers become more powerful and familiarization with solute-transport simulation codes becomes more widespread. Optimization (management) models that are linked with numerical-simulation models have been used to determine strategies to better manage coastal groundwater systems and control saltwater intrusion (see Reichard and Johnson 2005, for a listing of recent optimization applications to saltwater intrusion problems).

Engineering and regulatory approaches for managing saltwater intrusion also include both traditional and innovative techniques. A common approach for managing saltwater intrusion has been to reduce the rate of pumping from coastal wells, or to move the locations of withdrawals further inland. Reductions in coastal withdrawals allow groundwater levels to recover from their stressed levels, and fresh groundwater to displace the intruded

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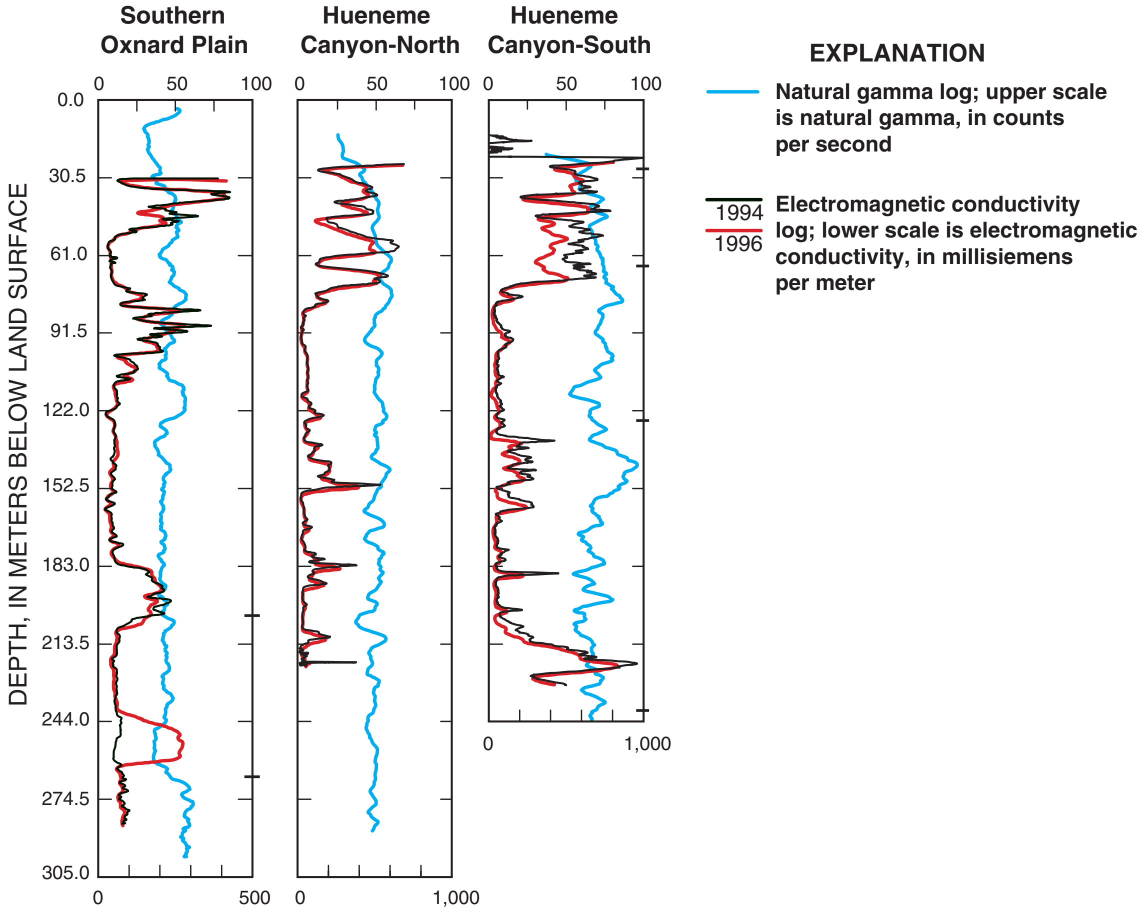

Fig. 7 Electromagnetic-conductivity borehole logs from three wells in Ventura County, California. Repeated measurement of the conductivity of the aquifer at the three wells indicates that conductivity decreased in the shallower parts of the aquifer during the 2-year interval. (Modified from Hanson et al. 2009)

saltwater. An example of a successful water-level recovery program is provided from central New Jersey, where water levels in four confined aquifers of the Northern Atlantic Coastal Plain have rebounded as a result of mandated reductions in groundwater withdrawals (and a shift to surface-water supply sources), begun in the late 1980s (Spitz et al. 2008). High rates of groundwater withdrawals from the four aquifers had caused steep declines in groundwater levels over an approximately 2,300 km^2 area, which posed a range of problems to water supplies within the affected areas, including depletion of groundwater supplies, reductions in groundwater discharge to streams, and saltwater intrusion. By 1988, groundwater levels in the aquifers had declined by as much as 60 m below sea level. In response to reductions in withdrawals in each aquifer that ranged from 40 to 50% of peak rates, water levels recovered by more than 24 m between 1988 to 2003 in some areas; typical recoveries ranged from 3 to 12 m over large areas of each aquifer.

An alternative (or supplement) to reducing groundwater withdrawals is to artificially recharge freshwater into an aquifer to increase groundwater levels and hydraulically control the movement of the intruding saltwater. Artificial recharge can be accomplished through injection wells or by infiltration of freshwater at land surface. In either case, the recharged water creates hydraulic barriers to saltwater intrusion. Perhaps the most prominent example of the use of artificial recharge to control saltwater intrusion on the Atlantic Coast is in southeastern Florida. As described previously, the extensive network of surface-water canals is used during the dry season to convey freshwater from inland storage areas to coastal areas, where the water is recharged through the canals to slow saltwater intrusion in the underlying Biscayne aquifer.

In addition to these more conventional methods, innovative approaches are now used to manage saltwater intrusion. These include aquifer storage and recovery (ASR) systems, desalination systems, and blending of waters of different quality. ASR systems have been developed in New Jersey, Virginia, South Carolina, Florida, and California. Desalinization systems are becoming more widespread in the United States as desalination technologies improve, costs decrease, and new sources of freshwater become more difficult to develop. An example in which desalination and blending of waters have been implemented to reduce the rate of saltwater intrusion and meet projected increases in peak water-supply demands is provided by the City of Cape May, New Jersey, where saltwater intrusion has contaminated supply wells in the

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Cohansey aquifer (Fig. 2a). Since 1998, the city has operated a desalination system that consists of two new supply wells installed in a brackish confined aquifer that underlies the Cohansey aquifer. The two wells have a combined capacity of $8.8\times10^{-2}\,m^3/s$ (2 million gallons per day, Mgal/day). The brackish groundwater pumped from the aquifer is desalinated by use of reverse-osmosis membrane filtration systems designed to treat water with concentrations up to 2,000 mg/L dissolved solids. The desalinated water is then blended with freshwater pumped from the Cohansey aquifer. The desalinated water has reduced the city's reliance on imported water and groundwater pumped from the Cohansey aquifer, and is expected to reduce the rate of saltwater intrusion in the Cohansey aquifer.

Often, several actions are taken simultaneously to control saltwater intrusion or are taken as part of a comprehensive strategy for managing the groundwater and surface-water supplies of coastal areas. The State of Georgia provides an example in which a multicomponent strategy has been used to manage saltwater intrusion. Groundwater withdrawn from the Upper Floridan aquifer is the principal source of water supply for 24 counties of coastal Georgia, an area of rapid population growth, increased tourism, and sustained industrial activity. Extensive withdrawals in the area for industry, public supply, and irrigation have resulted in substantial water-level declines in the coastal zone, decreased fresh groundwater discharge to springs and other surface-water features, and saltwater contamination in the city of Brunswick, Georgia, and on Hilton Head Island (and nearby offshore areas) in adjacent South Carolina. In response to the saltwater contamination and related water-supply issues, the State of Georgia has developed a comprehensive plan to stabilize or halt saltwater intrusion into the Upper Florida aquifer (Georgia Environmental Protection Division 2006). The basis of the plan is the establishment of three management subregions within the state's coastal zones, with each subregion having a varying degree of vulnerability to saltwater intrusion. Within the area closest to Hilton Head Island, the plan includes restricting withdrawals from the Upper Floridan aquifer to 2004 pumping rates and eventually reducing withdrawal rates within the area by $2.2\times10^{-1}\,m^3/s$ (5 Mgal/day). The plan also encourages blending of groundwater and surface-water sources to meet increased demands within this area. In the Brunswick area, the plan prohibits new wells within the area of saltwater contamination and management of existing withdrawals to avoid further expansion of the saltwater plume. The plan also calls for the implementation of water-conservation, water-efficiency, and water-reuse strategies within the entire coastal zone of the state, and continued monitoring of groundwater levels, chloride concentrations, and streamflow within the coastal zone to determine how the hydrologic system responds to management actions.

Comprehensive integrative management strategies also are in place in many of the basins of central and southern California. In all of these areas, it is recognized that although saltwater intrusion directly affects only a portion of the groundwater basin, control of saltwater intrusion must be considered within regional-scale groundwater and surface-water management. In Los Angeles, local agencies began installing experimental wells near Manhattan Beach (Fig. 6) in the early 1950s to evaluate the effectiveness of injection in creating an hydraulic barrier to control intrusion. Today, three sets of barrier injection wells operate along coastal Los Angeles, injecting approximately $30.8\times10^6\,m^3$ (25,000 acre-feet) annually. There have been several other key developments that enabled at least partial control of seawater intrusion. First, the coastal Los Angeles groundwater basins were adjudicated in the early 1960s, which enabled imposition of controls on pumping. Second, additional surface water has been imported to replace groundwater pumpage and as source water for the coastal injection wells and upgradient artificial recharge ponds. Finally, highly treated recycled wastewater is increasingly used for injection. Johnson and Whitaker (2004) provide an extensive overview of the several management approaches that have been used to mitigate saltwater intrusion in Los Angeles County, particularly the history and operation of the saltwater barrier wells. Although all these actions have had substantial impacts on saltwater intrusion in the area, water levels remain below sea level in many areas near the coast, and elevated chloride concentrations persist (Land et al. 2004). In the Los Angeles area, water managers are continually evaluating strategies for reducing the costs and increasing the reliability of saltwater-intrusion control (Reichard and Johnson 2005). This includes increasing use of recycled water for injection; operation of small-scale, localized desalination systems; and developing ASR projects. The ASR projects would store additional imported water during wet years (either delivered directly to users to be used in lieu of groundwater, or as injection) and extract additional groundwater during dry periods.

In Orange County, California, the Orange County Water District recently (2008) began operating the "Groundwater Replenishment System." This system incorporates a large-scale ($3.1\ m^3/s$, or 70 Mgal/day), multi-phase treatment (reverse osmosis, microfiltration, and ultraviolet light with hydrogen peroxide) disinfection plant, which processes tertiary-treated sewage. About half of this highly treated water is injected into saltwater-intrusion barrier wells; the remaining water is transported upgradient to spreading grounds in the unconfined/semiconfined part of the basin (Orange County Water District 2004).

In the Salinas and Pajaro basins, saltwater intrusion is addressed through a range of actions, including replacing pumpage with diverted streamflow and increasing use of recycled water. In Pajaro, an ASR project is being implemented in conjunction with the use of recycled water. In Salinas, strategies for controlling intrusion include coordinated operation of two upstream surface-water reservoirs (Naciemento and San Antonio). Current plans include modifying the spillway of one of the reservoirs (Naciemento), which will allow modification of the joint reservoir operation to increase the amount of water available for instream recharge and direct delivery. A new diversion structure is

 DOI 10.1007/s10040-009-0514-3

planned to allow increased diversion of Salinas River water to replace pumpage near the coast (Monterey County Water Resources Agency 2004b).

Future prospects

Much progress has been made in understanding the pathways and processes that affect saltwater movement in freshwater aquifers in coastal regions of North America. In addition, a wide range of traditional and innovative monitoring and management approaches are being used to control and reverse saltwater intrusion where it has occurred and to prevent it from occurring in other areas. In the future, new tools are likely to be developed to monitor and model saltwater intrusion, and new approaches will likely be applied to more efficiently manage intrusion. Accurate three-dimensional characterization of intrusion will require increased use of depth-dependent monitoring wells, supplemented by innovative applications of surface and borehole geophysics. Because of the often complex pathways of saltwater movement, predicting the dynamics of intrusion will require solute-transport models that more completely incorporate the details of the hydrostratigraphy of coastal groundwater systems and the dynamics of multiple sources of chloride than present models can. Sustainable management responses to saltwater intrusion will require multi-component strategies that consider intrusion in the broader context of basinwide, integrated groundwater and surface-water management. New engineering approaches will need to be considered (for example, utilizing physical barriers) and there will likely be increased use of recycled water for recharge and direct delivery to users. In addition, sophisticated decision-support systems will likely be developed that can link monitoring data with simulation and optimization models, and that provide for improved communication of simulation results to water-resource managers. Desalination is expected to become more widespread as the treatment methods become more energy efficient and the challenges of environmentally sound brine disposal are addressed. Finally, water managers will need to consider how saltwater intrusion may be affected by potential rises in sea level due to climate change.

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