

The extent of saltwater intrusion in southern Baldwin County, Alabama

Dorina Murgulet · Geoffrey Tick

Received: 11 September 2007 / Accepted: 1 October 2007 / Published online: 30 October 2007
© Springer-Verlag 2007

Abstract Contamination of groundwater due to saltwater intrusion has become a major concern for coastal communities which rely on groundwater as their principal source of drinking water. The protection of groundwater resources from saltwater intrusion and groundwater overdraft is a critical concern in these areas as both groundwater resources and environmentally sensitive areas such as coastal wetlands and ecological coastal habitats may be at risk. A regional-scale study was conducted to assess the extent of saltwater intrusion for Baldwin County, Alabama. Groundwater wells were sampled and analyzed for salinity, chloride (Cl^-), total dissolved solids (TDS), and other parameters to determine the extent of saltwater intrusion, and the location of the freshwater/saltwater interface in the region. Spatial iso-concentration maps (i.e. salinity, Cl^- , and TDS) were constructed using ArcGIS software to determine the extent and severity of saltwater intrusion for the aquifers underlying southern Baldwin County. Concentration data show relatively low salinity levels in the central and northern extent of the study area. Elevated levels of salinity, Cl^- , and TDS were observed in the local aquifers A1 and A2 along the coastal areas adjacent to the Gulf of Mexico. The study provides an initial current data set of areas impacted or most vulnerable to saltwater intrusion and provides a scientific basis for effective management of the coastal aquifers in the study region.

Keywords Saltwater intrusion · Groundwater contamination · GIS · Southern Baldwin County

Introduction

The coastal regions of Baldwin County are characterized by a continuously increasing economy and rate of development. Protection of groundwater resources from seawater encroachment is a real concern for coastal communities in this area due to impacts associated with increasing population, development, local industries and tourism. In addition, predictions of increasing sea level and increased frequency, and intensity of tropical storms and hurricanes in the region may exacerbate the problem over the long term.

Seawater intrusion studies have been conducted on coastal aquifers in many areas adjacent to the Atlantic Ocean and the Gulf of Mexico. Although studies have been conducted in Baldwin County, regarding the hydrogeology of the area, relatively little research has been conducted on seawater intrusion and saltwater encroachment into the coastal aquifers in the region. A study by Walter and Kidd (1979) describes the groundwater chemistry and characterized the geology in detail. This study also presents management aspects for saltwater intrusion prevention, groundwater use, and the state of groundwater availability at the time. A 5 year study by Chandler et al. (1985) includes information and descriptions of the geologic, and hydrogeologic environments in southern Baldwin County as well as information about general groundwater quality. The report contains two sections on saltwater intrusion for Baldwin County revealing the freshwater/seawater interface and areas contaminated by the incursion of saltwater.

D. Murgulet · G. Tick (✉)
Department of Geological Sciences,
University of Alabama,
Tuscaloosa, AL 35487, USA
e-mail: gtick@geo.ua.edu

Gillett et al. (2000) published the most current study, assessing the groundwater vulnerability for the region.

The purpose of this study was to determine the extent and severity of saltwater intrusion in the aquifers underlying southern Baldwin County using the most recently collected geologic, hydrogeologic, and geochemical information. To meet these objectives, well surveys and groundwater analyses were conducted over a 1 year period (2005–2006) and integrated with existing data attained primarily from the Alabama Department of Environmental Management (ADEM), the Geological Survey of Alabama (GSA) well records, GSA Circular 199A (Gillett et al. 2000), and GSA Bulletin 126 (Chandler et al. 1985).

Site description

Location and extent of the study area

Baldwin County is the largest county in Alabama, comprising an area of approximately 4,130 km² (1,596 square miles). The study area comprises approximately 1,625 km² (628 square miles) of southern Baldwin County and is bounded by Interstate 10 in the north, by the Gulf of Mexico in the south, and by Mobile Bay, Perdido River, and Perdido Bay in the west, southeast and east, respectively. This region includes areas vulnerable to saltwater encroachment such as Fort Morgan Peninsula, Gulf Shores, Orange Beach, and Perdido Beach (Fig. 1).

The population of Baldwin County increased significantly from 2000 with the highest rates in Fort Morgan Peninsula, Gulf Shores, Orange Beach, and Ono Island. Baldwin County has one of the highest population increases in Alabama, second only to Shelby County. As a result of increasing population, tourism, and development, groundwater pumping in the region increased from 2.7×10^7 l/day to 1.6×10^8 l/day between 1966 and 1995 (Reed and McCain 1971; Robinson et al. 1996). Land use in Baldwin County varies considerably. The major types of land use include agriculture, recreation and tourism, seafood industries, and urbanization. Agriculture makes up approximately 40% of the land use/land cover of southern Baldwin County (Murgulet 2006, unpublished).

Hydrogeology and groundwater occurrence

The stratigraphy of southern Baldwin County as well as that of coastal and offshore Alabama consists of a relatively thick Jurassic to Holocene sedimentary rocks (Chandler et al. 1985). At relatively shallow depths, interbedded sands, silts, gravels and clays comprise the middle Miocene to Holocene sedimentary rocks, which

hosts the freshwater aquifer zones of Baldwin County area. The thickness of these sediments regionally decreases towards the Gulf of Mexico. The sediments are part of three widely recognized geologic units defined by Reed (1971) as (1) the Miocene Series undifferentiated; (2) the Citronelle Formation; and (3) alluvium, low terrace, and coastal deposits.

The aquifer system beneath southern Baldwin County that serves as the source of freshwater is divided into three distinct units at the most southern portion of the study area. However, the clay aquitards, which exist in the southern part of Baldwin County pinch out northward at which point the aquifer system consists of two distinct units through the central portion of the study area.

Aquifer zone A1

The upper unit, known as the Beach Sand aquifer or aquifer zone A1, is an unconfined aquifer consisting of white fine- to coarse-grained quartzose sands, silt, and locally sandy clay with a capability of producing more than 545 m³/day (100 gallons/min) locally. Regionally, Chandler et al. (1985) estimates that aquifer zone A1 can yield up to 1.5×10^5 m³/day; however, only a fraction of that amount can be exploited due to the potential risks of saltwater intrusion. The Beach Sands aquifer is roughly 6–20 m thick in the study area (Chandler et al. 1985). The primary source of recharge for this aquifer comes from precipitation infiltrating the surface sands. Fresh water is lost from the zone as a result of discharging by downward infiltration to underlying zones and to the Gulf of Mexico. Larger water table fluctuations may be observed during periods of minimal precipitation or drought, wherein depth to water may be as low as 5 m below the ground surface and as little as 1.2 m below the ground surface during periods of high precipitation and recharge. Water availability for aquifer zone A1 is limited as a result of its vulnerability to contamination from storm and flooding events, and salt-water spray effects, particularly in low-lying areas and from overdevelopment and irrigation practices (Chandler et al. 1985).

Aquifer zone A2

The middle unit, known as the Gulf Shores Aquifer or aquifer zone A2, varies locally in thickness from 60 to 75 m throughout the entire study area. This aquifer varies from confined to semi-confined to unconfined throughout the extent of the study area. Along Gulf Shores and Orange Beach, the Miocene-shallow Pliocene aquifer is confined by a marine clay layer, which completely ends

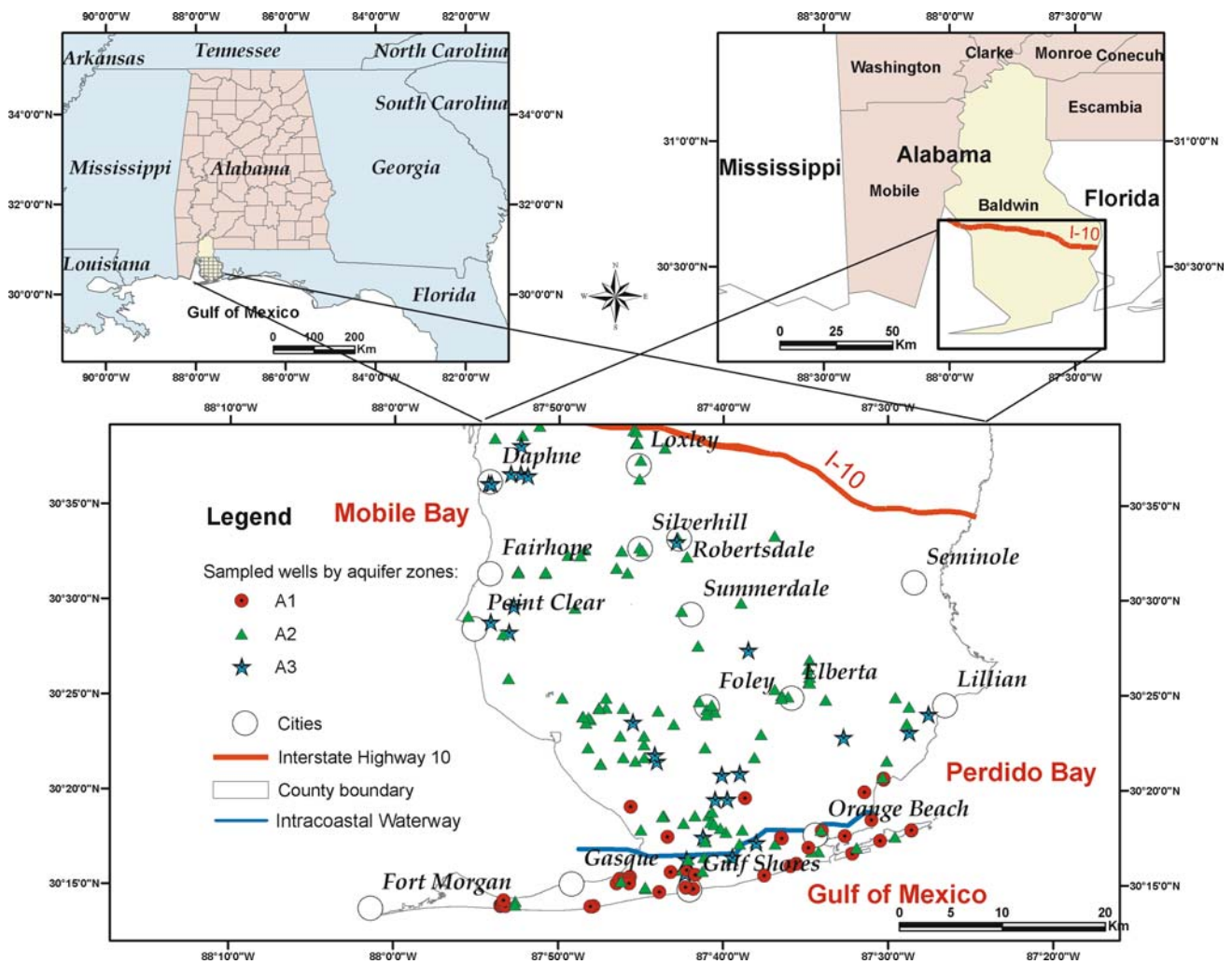


Fig. 1 Location of the study area and surveyed groundwater wells (2005–2006)

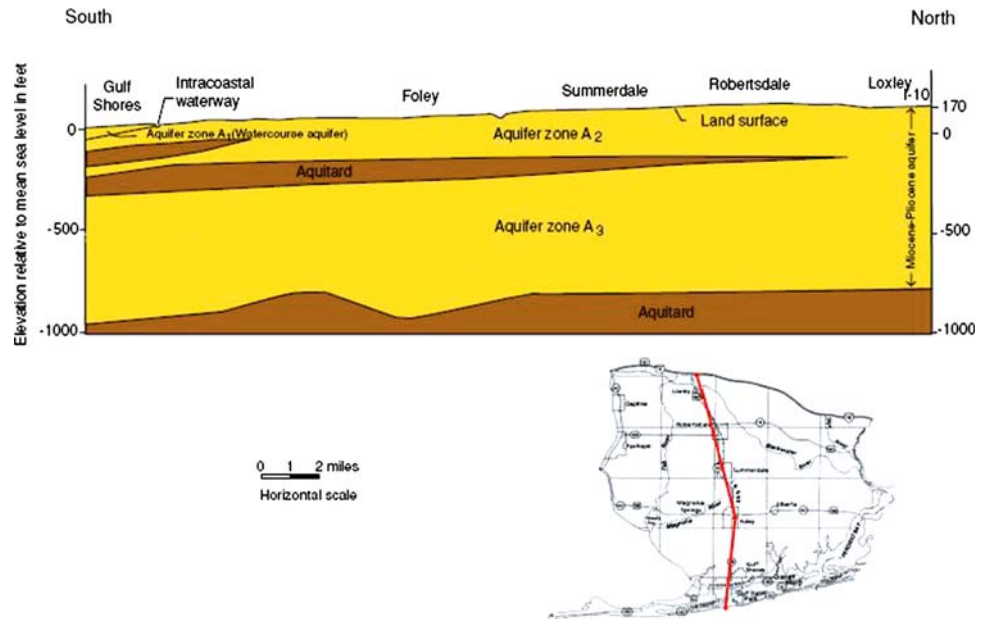
northward of the study area (Chandler et al. 1985). In the southern extent of the study area, the aquifer is approximately 20–30 m thick, and it is hydraulically separate from the Beach Sands water-table aquifer by a 10–15 m thick marine clay unit (Kidd 1988). The aquifer is extensively developed as a source of fresh water for municipal, industrial, private, and irrigation wells. Production rates from this unit range from 545 to 5,450 m³/day (100–1,000 gallons/min). Recharge to this aquifer zone primarily occurs from rainfall where the unit crops out to the north under unconfined conditions (Chandler et al. 1985). Aquifer A2 is vulnerable to surface contamination towards the north as it becomes unconfined.

Aquifer zone A3

The lower unit is known as the Deep Miocene Aquifer or aquifer zone A3. This hydrologic unit is similar to the Gulf

Shores aquifer (A2) in terms of lithology, with the exception that the sand and clay layers are more defined. The aquifer extends from the upper confining unit that underlies aquifer zone A2 to the top of the Pensacola Clay (200 m to more than 300 m below sea level). The aquifer ranges in thickness from roughly 90 to 175 m, and has a capacity of producing fresh water of more than 8,200 m³/day (1,500 gallons/min). Groundwater is typically present under confined or artesian conditions. The majority of public water supply wells are completed within this aquifer due to its limited exposure to sources of surface contamination. However, it has been mentioned in previous studies (Chandler et al. 1985; Gillett et al. 2000) that the unit is infiltrated with salt water in the area of Fort Morgan Peninsula. The aquifer receives much of its recharge from precipitation and resulting infiltration, where the confining unit thins out and the aquifer unit crops out into the northern part of the study area. A cross section of the study area illustrating hydrostratigraphic units is shown in Fig. 2.

Fig. 2 Hydrogeologic cross section of southern Baldwin County, Alabama (modified from Gillett et al. 2000)



Methodology

To meet the objectives of this paper, the first attempt was to link the hydrogeologic system and groundwater geochemical data of southern Baldwin County to spatial statistics and map modeling. Such integration allows, for example, meaningful identification of the seawater contaminated regions. For this purpose, geologic and hydrogeologic information, and groundwater quality parameters including salinity, Cl^- , and TDS concentrations were collected and compiled to generate spatial distribution and contamination maps. For the purposes of this study and consistency with current definitions, “freshwater” is considered to be water comprising concentrations no more than 500, 250, and 500 mg/l for salinity, Cl^- , and TDS, respectively (MCLs “maximum contaminant levels” are reported by USEPA 1992). Once these limits are exceeded, the water is no longer potable for drinking water purposes and additional water treatment is needed or well abandonment or discontinued operation is required. The relationships between the three parameters were examined as a means of assuring consistency between samples and verification of the saltwater source (i.e., intrusion from the Gulf of Mexico).

Advanced spatial analysis techniques were applied to raster data representing a set of constraints that may be encountered in a contamination project. Digital maps have been produced and used to construct a spatial database for the study area. Results obtained from this methodology have been incorporated with data collected for this project and used to create the final contamination digital maps.

Data collection

An extensive collection of geologic, hydrogeologic, and water chemistry data was conducted for southern Baldwin during a 1 year period between 2005 and 2006. Groundwater samples were collected from public supply wells, private supply wells, and industrial and irrigation groundwater wells during numerous field visits to the region. The spatial locations (i.e., longitude, latitude) of surveyed wells were recorded using GPS (Fig. 1). Surveyed wells were monitored for water level (hydraulic head) and well depth. In addition, a wealth of information and data was collected and gleaned from GSA, ADEM, local water utilities, golf courses, agricultural farms, and numerous other businesses and private well owners across southern Baldwin County (Fig. 2).

Sample analysis

Groundwater samples were analyzed for salinity, Cl^- , TDS, conductivity, resistivity, oxidation–reduction potential (ORP), pH, and temperature. All samples represent raw water samples collected from taps at the wellhead (after purging). Over 400 analysis measurements were determined for approximately 200 sampled wells during this 1 year period. As a means to assure consistency and confidence in the results of the sample analyses, Cl^- concentrations were independently measured using two different methods: a specific combination electrode (Denver Instruments) and an ion chromatograph (Dionex Instruments). Groundwater chemical field parameters

including conductivity, resistivity, ORP, pH, and temperature were measured using a portable field multi-meter (Ultrameter II 6P, Myron L Company). Salinity was measured using a portable field salinity meter (EC400, ExTech Instruments). Samples were analyzed for Cl^- at laboratory facilities housed within the Department of Geological Sciences at the University of Alabama.

Chloride specific electrode analyses were conducted in the Contaminant Hydrogeology Laboratory and ion chromatography (IC) analyses were conducted in the Geochemical Analytical Facility. For specific electrode analyses, samples were removed from the refrigerator, allowed to equilibrate to room temperature, and analyzed using a seven-point standard curve ranging from 1 to 1,000 mg/l. The samples were analyzed using a specific chloride electrode (Model # 300742.1, Denver Instruments Co.) coupled to a multi-meter (Model 250, Denver Instrument Co.). Samples were diluted as necessary to remain within the linear range of the instrument. The method detection limit for this method was approximately 1 mg/l. For IC analyses, concentrations of chloride were determined with a Dionex High Performance Ion Chromatograph (Model DX600, Dionex Corp., Sunnyvale, CA, USA) equipped with an autosampler, an anion-exchange column (7 mm; 4×250 mm; Dionex AS14A), and a conductivity detector (Dionex CD25). The lower detection limit of the method was approximately 0.01 mg/l.

Geographic information system (GIS)

All data relevant to the saltwater contamination of groundwater were collected, including for instance, but not exclusively, topography, geology, land-use/land-cover, hydrology, hydrogeology, and rainfall amounts, as well as existing aerial photographs and satellite imagery. ArcGIS was used to compile the geospatial data, to record and map well locations, well depths, hydrogeological information, and concentration data collected from fieldwork and allowed for the generation of iso-concentration maps, groundwater elevation maps, and groundwater flow maps. The spatial database for the project was built in the raster and vector formats inside the GIS. The output maps elaborated for this study are shown in Figs. 3, 4, and 5. Spatial features identified as the most sensitive (e.g., elevation, and geochemical and geological data) to this saltwater intrusion impact study have been gathered by categories and subsequently integrated into a raster map, which was created for each constraint. The grid layer for depth to water and saturated thickness of each aquifer zone was generated by computer subtraction of water-level elevation data sets from land surface elevation. Land surface elevations were derived from a Digital Elevation Model (DEM) for the southern Baldwin

County area. The water-level elevation data sets were obtained from field measurements and from the groundwater well records available at GSA and ADEM.

Iso-concentration and groundwater elevation maps were prepared to determine areas vulnerable to saltwater intrusion and the extent of saltwater intrusion for each of the developed aquifer zones. Specifically, salinity, Cl^- , and TDS concentration and groundwater level data were interpolated to construct the iso-concentration and groundwater elevation (potentiometric surface) maps. The *Geostatistical Analyst* extension was used to interpolate the data. For more confidence, the output maps were compared with output maps developed from interpolation of same data using *Surfer* software package (Golden Software, Inc.) and compared with the actual concentrations and water levels. The kriging interpolation method proved to be the most effective at simulating iso-concentration and potentiometric surface contours when compared to the observed data distribution.

The output concentration grid layers for each of the three parameters (salinity, Cl^- , and TDS) were reclassified using the binary masking method. The aim of this reclassification was to develop the final concentration maps that delineate only those sections affected by saltwater intrusion as indicated by concentrations of salinity, Cl^- , and TDS above regulatory MCLs. The reclassification process involved development of a new raster layer by changing the attribute values of the cells of the input layers. Through this process, critical areas such as those that exceed Cl^- concentrations of 250 mg/l, salinity concentrations of 500 mg/l and TDS concentrations of 500 mg/l were identified. A new grid based on the new criteria was developed for each aquifer using the *Spatial Analyst* extension, *raster calculator* tool.

Groundwater elevation maps were constructed to determine local and regional groundwater flow directions. Groundwater elevation contours (i.e., potentiometric surface contours) are shown in Figs. 3d, 4d, and 5d for aquifer zones A1, A2, and A3, respectively.

Results

An abundance of data (2005–2006) were collected and compiled into a user-friendly GIS database allowing for useful graphical visualizations (i.e., table and figures), data interpretation, data analyses, and current assessments of groundwater quality (i.e., saltwater intrusion) and availability (i.e., groundwater flow) for the region. Data from approximately 200 wells throughout Baldwin County were included in the database and analyzed in order to determine the extent of saltwater intrusion for the study area. Integration of hydrogeologic data and groundwater geochemical

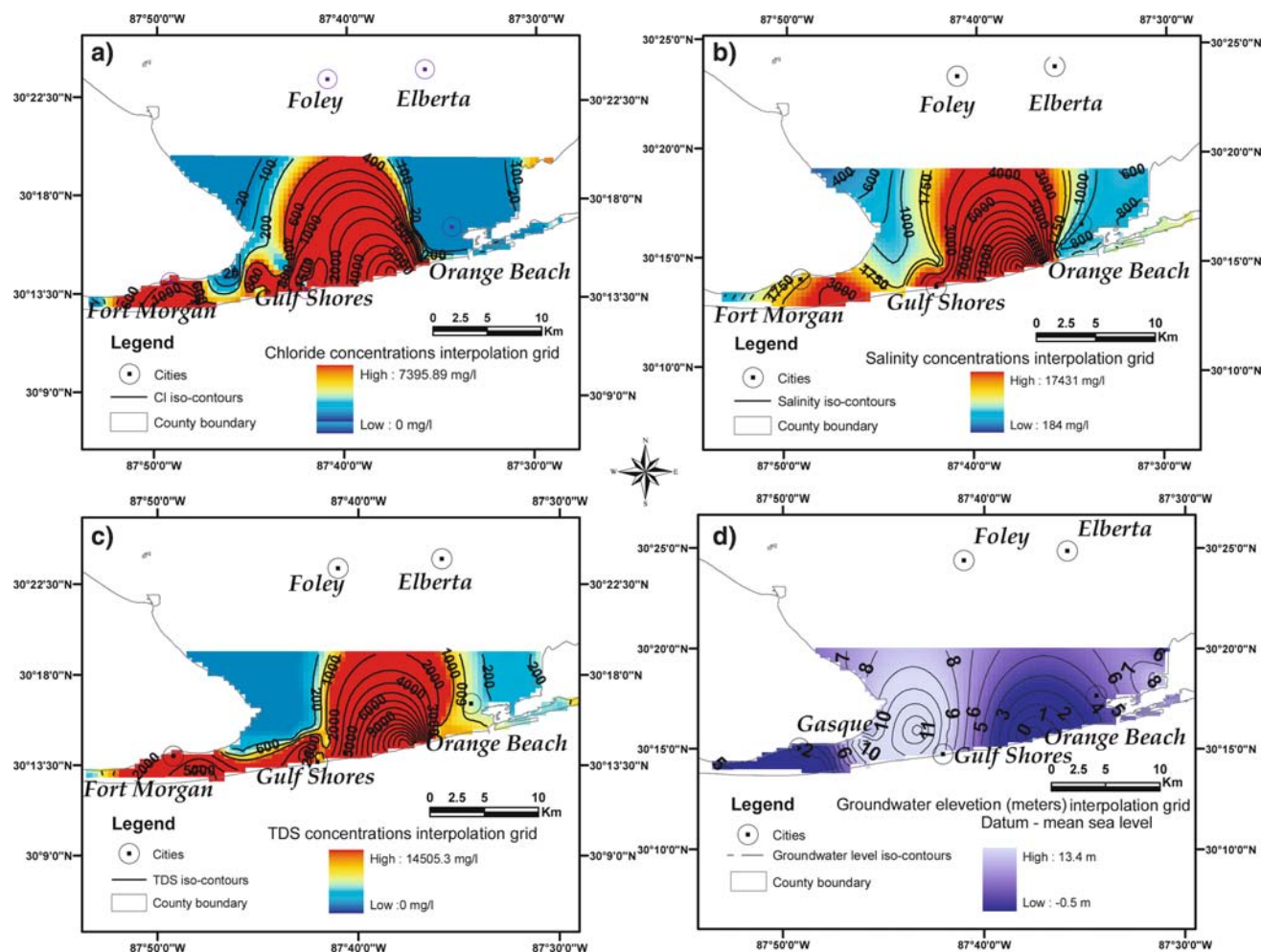


Fig. 3 Aquifer zone A1 (a) Chloride concentration map; (b) salinity concentration map; (c) TDS concentration map; (d) groundwater potentiometric surface and general flow directions. Concentrations are in mg/l; *contour lines* are labeled correspondingly

parameters (i.e., salinity, Cl^- , TDS, etc.) with spatial location and map modeling allowed for robust identification of the seawater contaminated regions. Examination of the salinity, Cl^- , and TDS parameters revealed the Gulf of Mexico to be the source of saltwater intrusion.

Water level measurements were recorded to assess both local and regional groundwater flow and gradients for each aquifer zone. The encroachment of saltwater into coastal aquifers can be recognized by elevated salinity, Cl^- , and TDS concentrations. In addition, elevated measurements of resistivity and specific conductance were used to help in evaluating areas affected by saltwater intrusion.

Regional and local groundwater flow

Groundwater elevation maps constructed from the collected water level data provided the current state of

regional and local groundwater flow for the study (Figs. 3d, 4d, and 5d). Groundwater flow directions were determined to be predominantly south, south-southwest, and south-southeast. For aquifer zone A1, groundwater flow trended south and south-southwest with hydraulic gradients of approximately 0.001 and 0.0006, respectively and relatively steeper hydraulic gradients observed in the south-southwest direction. For aquifer zone A2, groundwater flow direction trended to east, southeast, south, and southwest with hydraulic gradients of approximately 0.0006, 0.0013, 0.0013, and 0.0016, respectively and relatively steeper hydraulic gradients observed in the south, southwest and southeast directions. For aquifer zone A3, groundwater flow direction trended to southeast, south-southeast, and southwest with hydraulic gradients of approximately 0.001, 0.00083, and 0.00016, respectively and relatively steeper hydraulic gradients observed in the southeast direction.

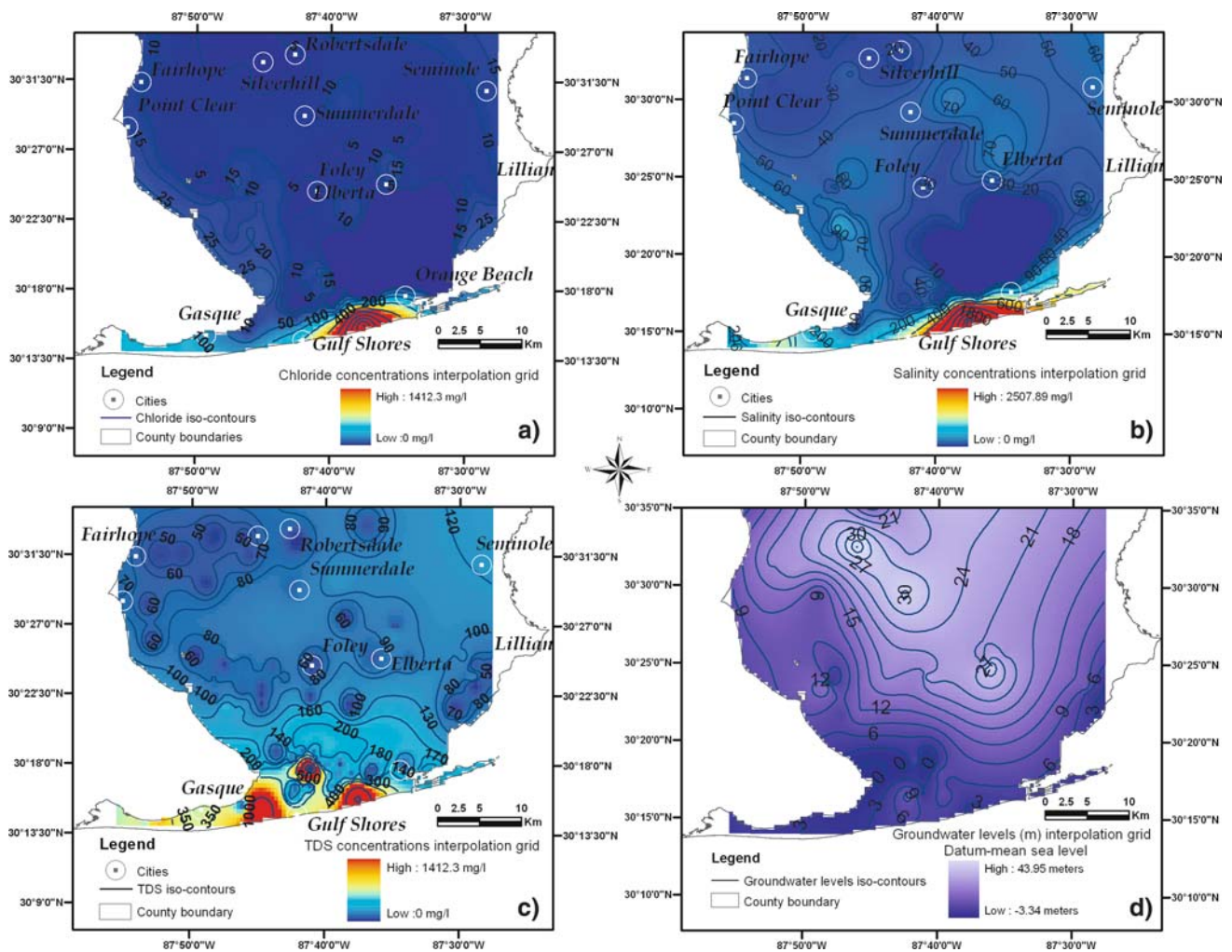


Fig. 4 Aquifer zone A2 (a) Chloride concentration map; (b) salinity concentration map; (c) TDS concentration map; (d) groundwater potentiometric surface and general flow directions. Concentrations are in mg/l; contour lines are labeled correspondingly

Groundwater chemistry and availability

The availability of groundwater for public and private use is primarily dependent upon the volume capacities of the aquifer itself. However, in regions that are vulnerable to contamination, such as coastal aquifers experiencing saltwater intrusion, large volumes of water can be rendered unsuitable for use due to degraded water quality (i.e., high salinity, TDS, Cl^- , etc.). Minimum, maximum, and average values of groundwater chemical concentrations for each respective hydrogeologic unit are included in Table 1. Iso-concentration maps are presented, displaying the zones impacted by saltwater intrusion (Figs. 3, 4, 5). It is important to recognize that the iso-concentration maps utilize interpolation schemes (i.e., kriging) based on available data. Due to the fact that some areas within the region lack any well data, concentrations of water quality parameters (i.e., salinity, Cl^- , and TDS) may not be revealed by the figures. Hence, it should be clear that these

apparently “non-impacted” regions may in reality possess elevated levels of salinity, Cl^- , and TDS.

Along the narrow coastal zones of the study area, elevated concentrations of salinity, Cl^- , and TDS were observed for both aquifer zones A1 and A2. Groundwater samples from aquifer zone A1 exhibited elevated concentrations of salinity, Cl^- , and TDS in the close coastal proximity of Gulf Shores, Orange Beach, Ono Island, and Laguna Keys (Fig. 3a, b, c). The average salinity concentration for aquifer zone A1 was determined to be 1,153.9 ppm (mg/l) with a maximum concentration of 18,000 ppm (mg/l) in close proximity to the coastline. The average chloride concentration for aquifer zone A1 was determined to be 486.2 mg/l with a maximum concentration of 7,758.3 mg/l in close proximity to the coastline of Gulf Shores. Similarly, along the southern coastal boundary of Baldwin County, the groundwater samples in aquifer zone A1 revealed relatively high TDS concentrations. The average TDS concentration for aquifer zone A1 was

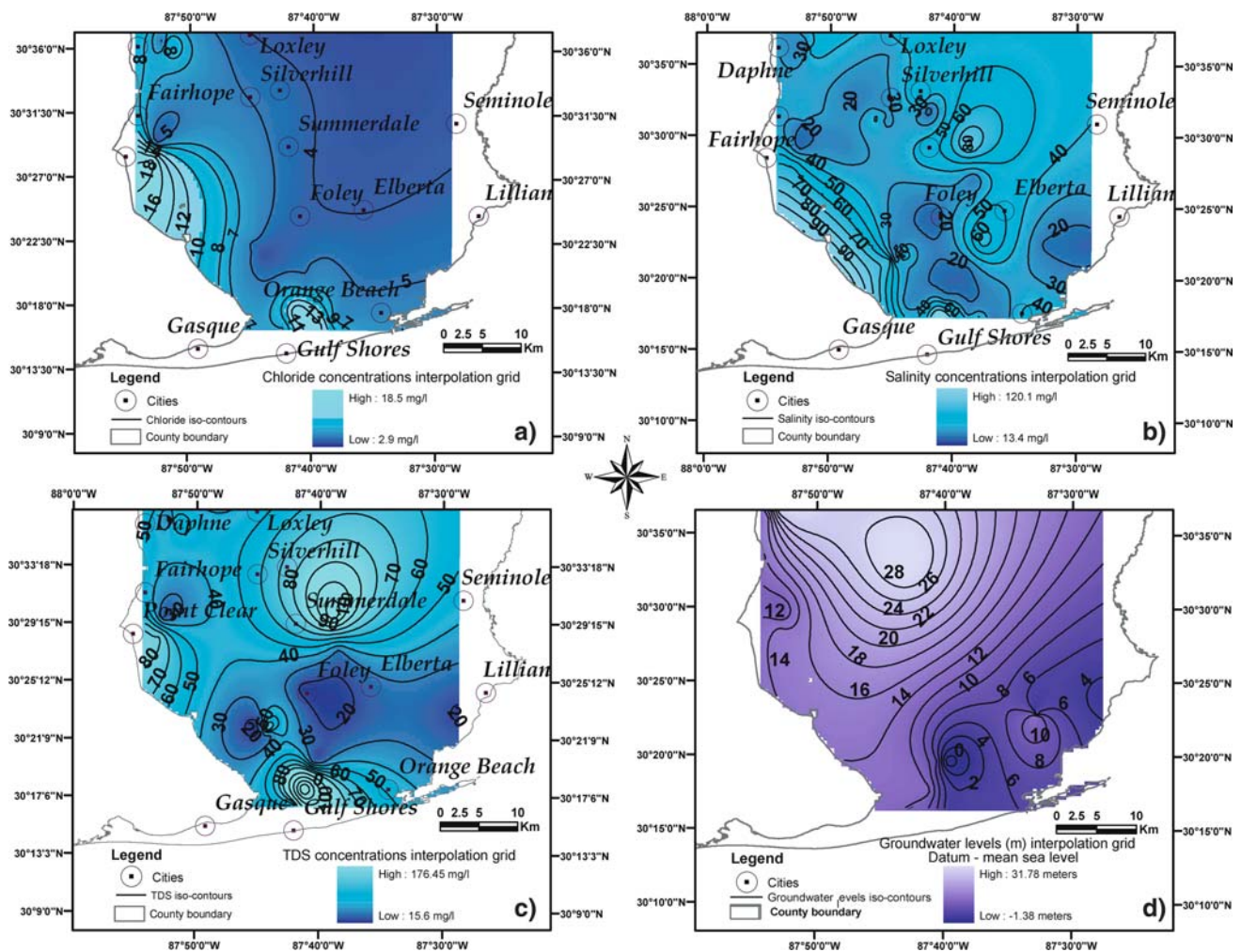


Fig. 5 Aquifer zone A3 (a) Chloride concentration map; (b) Salinity concentration map; (c) TDS concentration map; (d) Groundwater potentiometric surface and general flow directions. Concentrations are in mg/L; contour lines are labeled correspondingly

determined to be 1,359.3 ppm (mg/l) with a maximum concentration of 14,590 ppm (mg/l).

Aquifer zone A2, a principal water bearing aquifer for Baldwin County, has been extensively developed for domestic, agricultural, municipal, and industrial uses. Groundwater in aquifer A2, near the coastal margin, was determined to possess lower water quality with relatively high salinity, Cl^- , and TDS concentrations (Fig. 4a, b, c). The average salinity concentration for aquifer zone A2 was determined to be 96.8 ppm (mg/l) with a maximum concentration of 2,590 ppm (mg/l) just north of Highway 182 in Gulf Shores. The average chloride concentration for aquifer A2 was determined to be 28.2 mg/l with a maximum concentration of 1,460.4 mg/l north of Romar House in Gulf Shores. The average TDS concentration for aquifer zone A2 was determined to be 146.8 ppm (mg/l) with a maximum concentration of 3,610 ppm (mg/l) at the same location in Gulf Shores.

Aquifer zone A3 has been extensively developed for municipal uses. The majority of the public water supply wells are completed within this aquifer unit due to its limited vulnerability to sources of surface contamination. However, as Chandler et al. (1985) points out, it is important to note that this aquifer can be affected by saltwater contamination due to saltwater intrusion, as evidenced by elevated salinity levels in the lower portion of the aquifer and extending a considerable distance inland (Chandler et al. 1985, Fig. 2). As part of this current study, groundwater samples obtained from wells completed in aquifer zone A3 exhibited low concentrations of salinity, Cl^- , and TDS (Fig. 5a, b, c). The average salinity concentration for aquifer zone A3 was determined to be 39.5 ppm (mg/l) with a maximum concentration of 136 ppm (mg/l) north of the Intracoastal Waterway in Gulf Shores. The average chloride concentration for aquifer zone A3 was determined to be 13.6 mg/l with a maximum

Table 1 Results of water analyses by hydrogeologic unit

Water analysis parameter (unit)	Limits for fresh water (USEPA 1992)		Hydrogeologic unit								
	Human consumption	Irrigation	Aquifer zone A1			Aquifer zone A2			Aquifer zone A3		
			Low	High	Average	Low	High	Average	Low	High	Average
Chloride (mg/l)	250	250	6.9	7,758	486	1.8	1,460	28.2	2.9	18.2	13.6
Salinity (mg/l)	500 ^a	500–1,000 ^b	32.3	18,000	1,153	13.2	2,590	96.8	12.6	136	39.5
TDS (total dissolved solids (mg/l))	500	500–1,000 ^b	45.6	14,590	1,359	18.5	3,610	146.8	14.8	190	51.4
pH	6.5–8.5	–	4.7	7.6	6.5	4.5	8.0	5.1	4.6	8.0	5.8
Specific conductance (µS)	–	–	64.9	25,700	2,020	26.6	5,170	181.2	53.0	151.9	81.6
Resistivity (kΩ)	–	–	11.9	16.4	13.4	10.1	38.4	18.0	18.9	38.4	27.8

Chloride is the chloride concentration in water; salinity is the concentration of mineral salts and solids dissolved in water; specific conductance is the water capacity to carry an electrical current; resistivity is a measure of how strongly water opposes the flow of electric current (pure water is not considerably conductive)

TDS total dissolved solids is an expression for the combined content of all inorganic and organic substances contained in a liquid, pH a measure on a scale from 0 to 14 of the acidity or alkalinity of a solution (where 7 is neutral, greater than 7 is more basic, and less than 7 is more acidic)

^a MCL not reported by USEPA

^b Dependent upon crop sensitivity

concentration of 18.2 mg/l at the same location in Gulf Shores. The average TDS concentration for aquifer zone A3 was determined to be 51.4 ppm (mg/l) with a maximum concentration of 190 ppm (mg/l) north of the Intracoastal Waterway in Gulf Shores, at the same location where the highest chloride and salinity concentrations were observed.

Obtaining data from this aquifer unit (A3) proved to be difficult, especially along the coastal zones of the study area, as wells that were established within this aquifer, in close proximity to the coastline, have for the most part been shut down, abandoned, or have limited access (Blakeney Gillett, GSA, personal communication, 2006). This may suggest that these wells are either established in a relatively shallow portion of the aquifer zone A3 or that aquifer A3 in that region has not been infiltrated with saline water.

Discussion

The groundwater system of southern Baldwin County comprises three hydraulically distinct aquifers that will likely provide ample supply if properly managed. However, saline water intrusion from aquifer overproduction or storm events is a potential problem for the coastal region of the study area. The results of this study indicate that saltwater intrusion may have occurred in aquifer A1, especially in regions relatively close to the Gulf of Mexico. The elevated salinity, Cl⁻, and TDS concentrations may be the result of a combination of both saltwater intrusion and surface contamination. Aquifer zone A1 is vulnerable to

saltwater intrusion, in the close proximity of the Gulf of Mexico, from storm events due to seawater surface infiltration. Another source of contamination of aquifer A1 may be due to the direct infiltration from the Intracoastal Waterway, which crosses the southern part of the study area from east to west (Figs. 1, 2) and from saltwater ponds located along the intracoastal waterway. Aquifer zone A2 is vulnerable to saltwater intrusion, particularly in areas where wells are in close proximity to the Gulf of Mexico. The results of this study indicate that saltwater intrusion has occurred in aquifer A2, specifically in close proximity to the Gulf of Mexico. The results are confirmed by field data that exhibited elevated levels of salinity, Cl⁻, and TDS for these noted areas. Saltwater contamination of aquifer zone A2 might be the result of aquifer overdevelopment and infiltration from aquifer A1. Groundwater samples and iso-concentration maps revealed that aquifer zone A3 did not exhibit significant degradation of water quality due to saltwater intrusion. As it might be expected, the groundwater concentration data suggest that aquifer zone A3 is less vulnerable to saltwater intrusion. However, this does not mean that saltwater intrusion has not occurred or exists within this aquifer zone. It may be that the relatively low number of wells and depth of these wells were too shallow to capture high concentration regions of salinity, Cl⁻, and TDS within this aquifer (A3). The potential extent of saltwater intrusion for the study area can be observed from the groundwater contamination (iso-concentration) maps (Fig. 6). These maps reveal the regions that exceed regulatory limits for salinity, Cl⁻, and TDS.

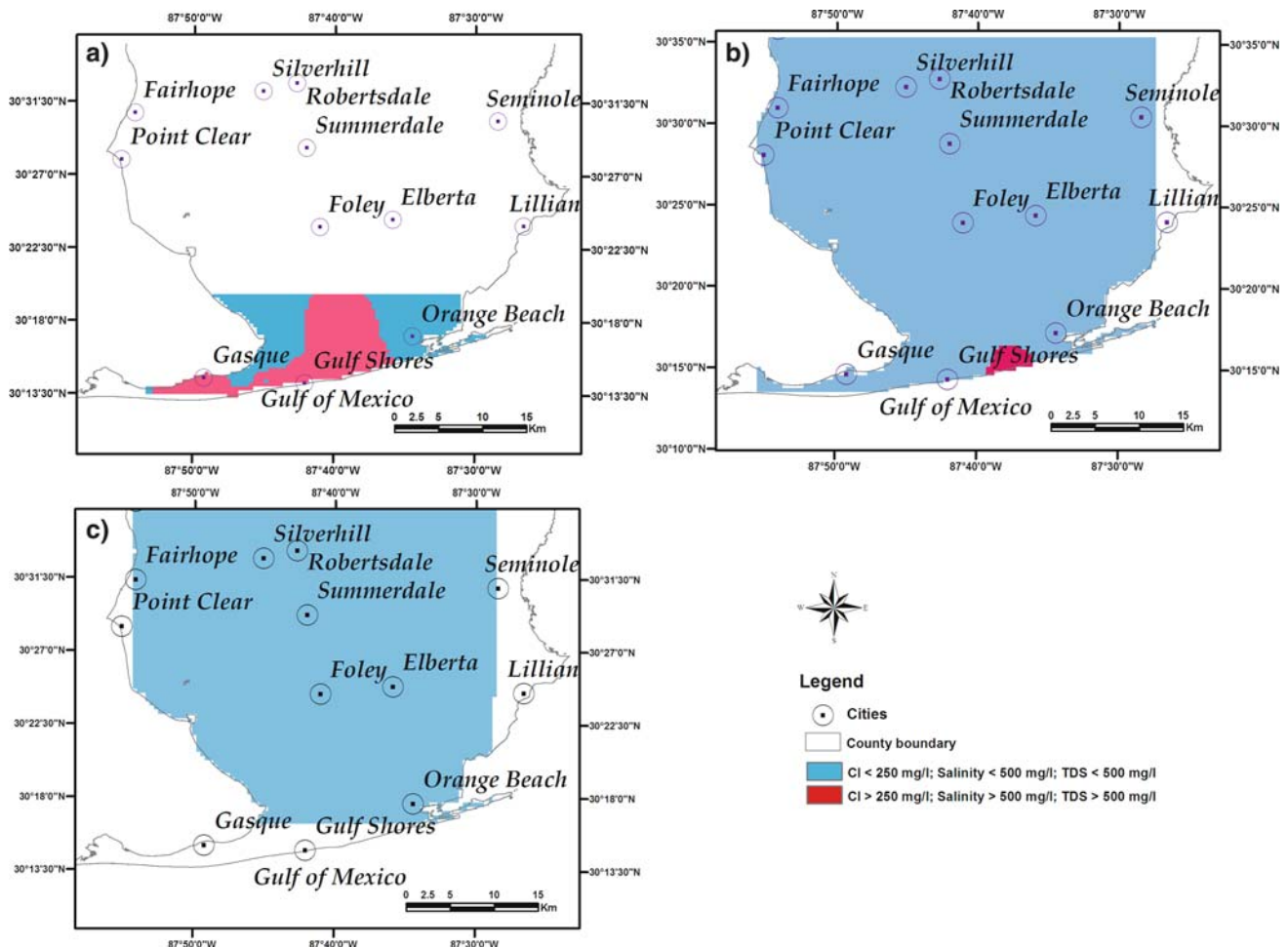


Fig. 6 Contamination maps. (a) Aquifer zone A1; (b) Aquifer zone A2; (c) Aquifer zone A3

To define the extent of saltwater intrusion along the entire coastal region, more wells need to be constructed in areas that lack data. This will improve the current iso-concentration maps; however, the addition of wells to these sparsely populated areas may be too costly and/or not feasible to implement. Further monitoring of the salinity and chloride levels in this aquifer, especially near the coastal margin of the study area, is necessary to evaluate the evolution of the saltwater and water quality conditions over time. Proper well placement and regulation in terms of groundwater withdrawal is important to prevent aquifer zones A2 and A3 from experiencing such problematic conditions associated with saltwater intrusion.

ArcGIS proved to be a valuable tool used to determine the spatial extent of saltwater intrusion. ArcGIS was effectively used to produce groundwater elevation (potentiometric surface) maps and assess groundwater flow conditions for the study area. The method used to determine regions affected by saltwater intrusion includes those areas that revealed concentrations exceeding the maximum contaminant level (MCL) for salinity, Cl^- , and

TDS (Table 1; USEPA 1992). In addition, the use of GIS makes it possible to view the data in a viable format for those who make regulatory decisions, whereas such data in the past has been much less accessible. Furthermore, the use of these tools provides an opportunity to assemble, standardize, and analyze scientific data that comes from a variety of sources, making it available to others who may be able to continue with further research studies.

Acknowledgments Funding for this project was provided in part by Award Number NA#04NOS4190029 through the Coastal Zone Management Act of 1972 (as amended), administered by the Office of Ocean and Coastal Resource Management, National Oceanic and Atmospheric Administration and in conjunction with the Alabama Department of Conservation and Natural Resources (ADCNR), State Lands Division. We would like to extend our gratitude to Mr. Carl Ferraro from ADCNR who played a primary role in initiating the funds for this project and providing invaluable assistance along the way. We would also like to thank Dr. Enid Probst from (ADEM), the Geological Survey of Alabama, and Weeks Bay Reserve for providing assistance and guidance along the process. We would especially like to thank the people of Baldwin County who generously provided access to their wells.

References

- Chandler RV, Moore JD, Gillett B (1985) Ground-water chemistry and salt-water encroachment, Baldwin County, Alabama. *Geol Surv Ala Bull* 126:1–86
- Gillett B, Raymond DE, Moore JD, Tew BH (2000) Hydrogeology and vulnerability to contamination of major aquifers in Alabama: area 13. Geological Survey of Alabama circular 199A
- Kidd RE (1988) Hydrogeology and water-supply potential of the water-table aquifer on Dauphin Island. United States Geological Survey water-resources investigation report, pp 87–4283
- Reed PC, McCain JF (1971) Water availability of Baldwin County, Alabama. Geological Survey of Alabama, Division of Water Resources, map 96
- Reed PC (1971) Geologic Map of Baldwin County, Alabama: Alabama Geological Survey Special Map 94, p 55
- Robinson JL, Moreland RS, Clark AE (1996) Groundwater resources data for Baldwin County, Alabama, U.S. Geological Survey Open-file Report, pp 96–487
- U.S. Environmental Protection Agency (1992) Groundwater and drinking water: secondary drinking water regulations: EPA 810/K-92-001 (<http://www.epa.gov/safewater/consumer/2ndstandards.html>)
- Walter GR, Kidd RE (1979) Ground-water management techniques for the control of salt-water encroachment in Gulf Coast aquifers: a summary report. Alabama Geological Survey open-file report