

**AN ASSESSMENT OF GROUNDWATER-QUALITY
CONDITIONS AND CHLORIDE DISTRIBUTION IN THE
CHARLESTON AND GRAMLING AQUIFERS
IN BERKELEY, CHARLESTON, AND DORCHESTER
COUNTIES, SOUTH CAROLINA, 2020**

by

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An Assessment of Groundwater-Quality Conditions and Chloride Distribution in the Charleston and Gramling Aquifers in Berkeley, Charleston, and Dorchester Counties, South Carolina, 2020

by

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ABSTRACT

Seventeen wells screened in the Charleston and Gramling aquifers in Berkeley, Charleston, and Dorchester Counties were sampled during two or three sampling efforts between February–October 2020. Fifteen wells pump groundwater from the Charleston aquifer only and two wells pump groundwater from both the Charleston and the underlying Gramling aquifer. All wells were sampled following U.S. Geological Survey well-sampling protocols for the collection and analysis of field groundwater-quality constituents. Major cations, anions, alkalinity, and hardness were analyzed in the laboratory to determine the chemical composition of groundwater. Charleston aquifer groundwater is a sodium-bicarbonate type water, and groundwater from both the Charleston and Gramling aquifers is a sodium-chloride type water. Chloride ion concentration in groundwater is greater than 100 mg/L (milligrams per liter) in 92 percent of the wells sampled in Charleston County. Chloride concentrations greater than 250 mg/L were identified in one well at the northern end of the Isle of Palms that taps solely the Charleston aquifer, and in wells that tap both the Charleston and Gramling aquifers on the Isle of Palms and Kiawah Island. A map of equal chloride concentrations was created for the Charleston aquifer (formerly called the Middendorf aquifer). The documentation of the present-day (2020) distribution of chloride ions in the Charleston aquifer and underlying Gramling aquifer (formerly called the Cape Fear aquifer) can serve as a baseline for comparison to future groundwater-chemistry changes that may occur due to anticipated increased pumping. Such information is needed for coastal aquifer management and is in high demand by groundwater regulators and managers.

Introduction

The population of South Carolina’s Lowcountry region coastal counties is predicted to increase, as will the demands on potable water resources (Berezowska and Monroe, 2017). Groundwater quality is a critical factor that determines the suitability of groundwater for agricultural, industrial, and potable use. Several municipalities and industries in Berkeley, Charleston, and Dorchester Counties rely on groundwater as a source of water for public supply, irrigation, and industrial supply needs. The Charleston aquifer is a major source of groundwater and its development has driven substantial long-term regional groundwater-level declines from pre-development (1879) levels.

Groundwater development and management are necessary to support communities that rely on the resource. In response to groundwater-level declines, the South Carolina Department of Health and Environmental Control (SCDHEC) designated Berkeley, Charleston, and Dorchester Counties as the Trident Capacity Use Area (TCUA) in 2002. Capacity Use Areas are multi-county regions in which large groundwater withdrawals are regulated. A Groundwater Withdrawal Permit is required for any user withdrawing equal to or greater than 3 million gallons in any month during a year. For several years after the creation of the TCUA in 2002, groundwater use declined because of supplementation of water needs with surface-water sources, yet groundwater use remains high, and in recent years is again trending upward. Figure 1 shows the annual reported use of all groundwater (excluding power production) pumped in the TCUA from 2000 to 2019 (Craig and Monroe, 2020). Groundwater from the Charleston and Gramling aquifers accounts for approximately 72% of the total groundwater use in the TCUA.

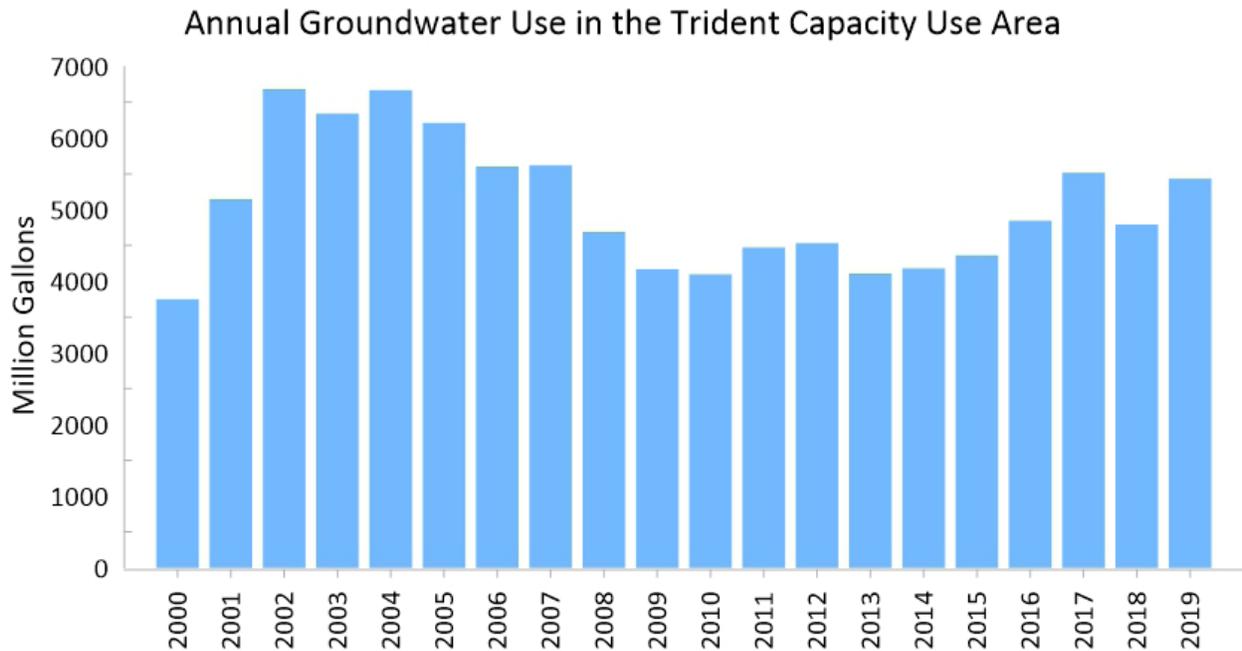


Figure 1. Annual reported groundwater use in the Trident Capacity Use Area from all aquifers (excluding power production), in millions of gallons. Source: SCDHEC (Craig and Monroe, 2020).

Prior to development, groundwater in the Charleston aquifer flowed in a general southeastward direction from the recharge area near the Fall Line to the Atlantic Ocean. Groundwater development has lowered the groundwater level by 50 to 100 ft (feet) in most of the Charleston aquifer, and a cone of depression has developed in the Mount Pleasant area owing to a decline of approximately 200 ft from pre-development levels (Aucott and Speiran, 1985). A recent potentiometric map created by the South Carolina Department of Natural Resources (SCDNR) indicates water level elevation near Charleston ranges between sea-level to -79 ft in the cone of depression centered at Mount Pleasant (Czwartacki and Wachob, 2020).

Because groundwater levels lie below mean sea-level in this Coastal Plain aquifer, the potential for saltwater intrusion is increased, making groundwater monitoring and management important for the protection of the resource. In 2017, SCDHEC developed and accepted a Trident Area Groundwater Management Plan (Berezowska and Monroe, 2017), the main goals of which are to ensure sustainable development of groundwater; protect groundwater quality from saltwater intrusion; and monitor groundwater quality and quantity. Ambient baseline groundwater-quality data (specifically, chloride ion concentration) are needed to evaluate the current distribution of chloride in the aquifer to achieve the goals of the Trident Area Groundwater Management Plan.

Saltwater Intrusion

In aquifers along the coast, the potential exists for dense saltwater to intrude and be overlain by less dense freshwater. A dynamic equilibrium of external factors separates the two along a zone of transition, called the freshwater-saltwater interface, defined by freshwater of less than 1,000 mg/L (milligrams per liter) of total dissolved solids (TDS) or approximately 250 mg/L chloride (Barlow, 2003). In a natural (non-pumping) setting, in predominately shallower unconfined and confined aquifers, groundwater recharge from the infiltration of precipitation into the soil and shallow aquifers keeps the freshwater-saltwater interface in the aquifers at some depth and at some distance offshore. When groundwater development exceeds the rate of recharge, freshwater pressures in the aquifer are lowered and the freshwater-saltwater interface can migrate upward and/or landward. As a result, saline water, including that from modern-day seawater, may reach pump intakes, render water unpotable, and require costly treatment.

The Charleston aquifer is susceptible to saltwater intrusion due to its proximity to the Atlantic Ocean. Declining groundwater levels from pumping coastal aquifers often lead to an increase in chloride ion concentration. While the mechanisms for saltwater intrusion are numerous, the likely sources in South Carolina include lateral encroachment from the sea where the deep aquifers may crop out, vertical upwelling (upconing) from deeper zones within the aquifer containing saline connate groundwater, and inter-aquifer transfer.

Drinking Water Quality

National primary and secondary drinking water regulations are set by the U.S. Environmental Protection Agency (EPA, 2020). Primary regulation standards are enforceable and apply to public health; secondary regulation standards are non-enforceable and apply to aesthetics (taste or odor), cosmetics (skin or tooth discoloration), and technical effects (corrosivity or scaling). Several contaminants having secondary standards—total dissolved solids (TDS), fluoride, pH, and chloride—were measured in this study. The secondary standard for TDS is 500 mg/L; fluoride is 2.0 mg/L; pH is 8.5 (high) or 6.5 (low); and chloride is 250 mg/L. Concentrations of these parameters greater than the established standards can indicate poor water quality. When these secondary standards are exceeded, groundwater may require additional treatment to remain potable.

Purpose of the Study

Past investigations have quantified chloride ion concentration and characterized groundwater of the Middendorf aquifer (Park, 1985; Speiran and Aucott, 1994), now referred to as the Charleston aquifer. The purpose of the current study is to update this information by delineating the present-day (2020) distribution of chloride ion concentration in the Charleston aquifer. Data collected from this study will provide baseline conditions that could be used as a comparison to future changes that may occur in groundwater chemistry because of continued groundwater development.

Study Area

The study area is the lower Coastal Plain of South Carolina, which is characterized by low topographic relief with numerous tidal saline water bodies and barrier islands. The study boundary is the TCUA, which consists of Berkeley, Charleston, and Dorchester Counties (Figure 2). Wells chosen for sampling are a mix of public supply, irrigation, and industrial wells that SCDNR periodically monitors for static (non-pumping) groundwater levels for the purpose of producing potentiometric maps.

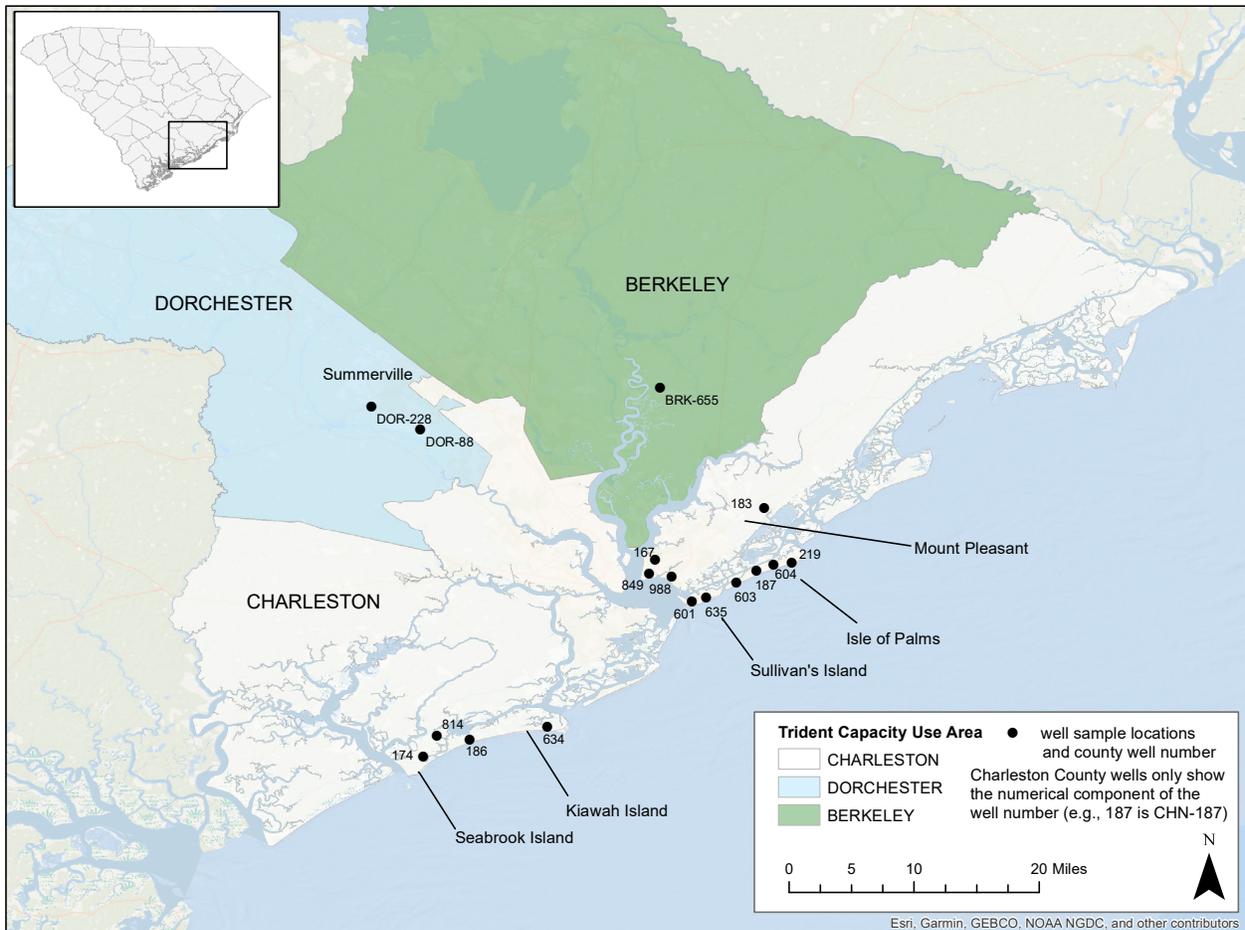


Figure 2. Map of study area showing the locations of sampled wells and the Trident Capacity Use Area.

Hydrogeologic Setting

The Charleston aquifer is a productive Upper Cretaceous-aged aquifer, formerly known as the Mid-dendorf aquifer in the study area (Gellici and Lautier, 2010), that occurs in the lower half of the Coastal Plain. In the study area, the aquifer lies between 1,700 and 2,200 ft below land surface and is composed of unconsolidated fine to very-coarse quartz sand, clayey sand, and clay (Figure 3). Transmissivity values from tests in Mount Pleasant (Charleston County) average 1,800 ft²/d (feet squared per day) (Gellici and Lautier, 2010). The aquifer is believed to be hydraulically connected to the overlying McQueen Branch aquifer updip of the study area. In these updip areas, the McQueen Branch aquifer is composed of unconsolidated, medium to very-coarse grained sand and is very productive; downdip, however, it becomes very-fine grained and is generally unused owing to low yields (Gellici and Lautier, 2010).

The Gramling aquifer, formerly known as the Cape Fear aquifer, is the basal aquifer of the Coastal Plain aquifer system and occurs at a depth of 2,300 to 2,500 ft in the study area. It consists of unconsolidated to semi-consolidated interbedded quartz sand, clayey sand, silt, and clay (Gellici and Lautier, 2010). There are no wells completed solely in the Gramling aquifer in the study area; the nearest wells are in southern Beaufort County, where transmissivity values range from 200 to 1,200 ft²/d (Gellici and Lautier, 2010).

In the study area, wells are deeper at Seabrook Island to the south and shallower at Isle of Palms to the north. The orientation and elevation change of the hydrogeologic units along strike is due to the lifting of the Cape Fear Arch. The generalized cross section diagrams in Figure 3 show the completed depth and screen intervals of most wells sampled during this study and two test holes.

Materials and Methods

A total of 17 wells were sampled between the months of February and October 2020. Most wells were sampled twice; one well was sampled three times. All wells chosen for sampling are permitted wells within the TCUA and are also periodically measured by SCDNR to create potentiometric groundwater-level maps. Well location, construction details, and ownership are detailed in Table 1.

Samples were collected according to standardized U.S. Geological Survey (USGS) techniques described in Book 9 of the USGS National Field Manual for the Collection of Water-Quality Data (<http://pubs.water.usgs.gov/twri9A>). At most wells, raw groundwater samples were collected at a spigot with tubing attached to a flow-through cell connected to a YSI® multi-parameter probe, which continuously measures temperature, specific conductance, pH, and TDS (Figure 4). Pumping rates (gallons per minute) and length of time the pump had been running were recorded. At most sites, three well volumes were removed prior to sampling. Well volume was calculated using the diameter(s) and length of the well casing and the assumption that the entire length of casing was filled with water. Prior to the collection of groundwater samples, readings were periodically monitored until temperature and specific conductance stabilized (defined by USGS standards). Two well sites did not have a spigot; at those sites, raw groundwater was collected in a 5-gallon bucket and the probe was suspended in the bucket to obtain field measurements. Immediately before collecting groundwater in sample containers, field water-quality measurements were recorded in one-minute intervals over a period of five minutes. Groundwater was collected in previously prepared containers and kept on ice or refrigerated until transported to a South Carolina-certified laboratory (GEL Laboratory, LLC; SCDHEC Certificate Number 10120001). Samples were analyzed for major cations and anions (EPA 300.0/EPA 200.7), alkalinity (SM 2323 B), and hardness (SM 2340 B) following laboratory quality assurance procedures. One duplicate sample was collected as part of this study. A chain-of-custody form accompanied each sample set sent to the laboratory.

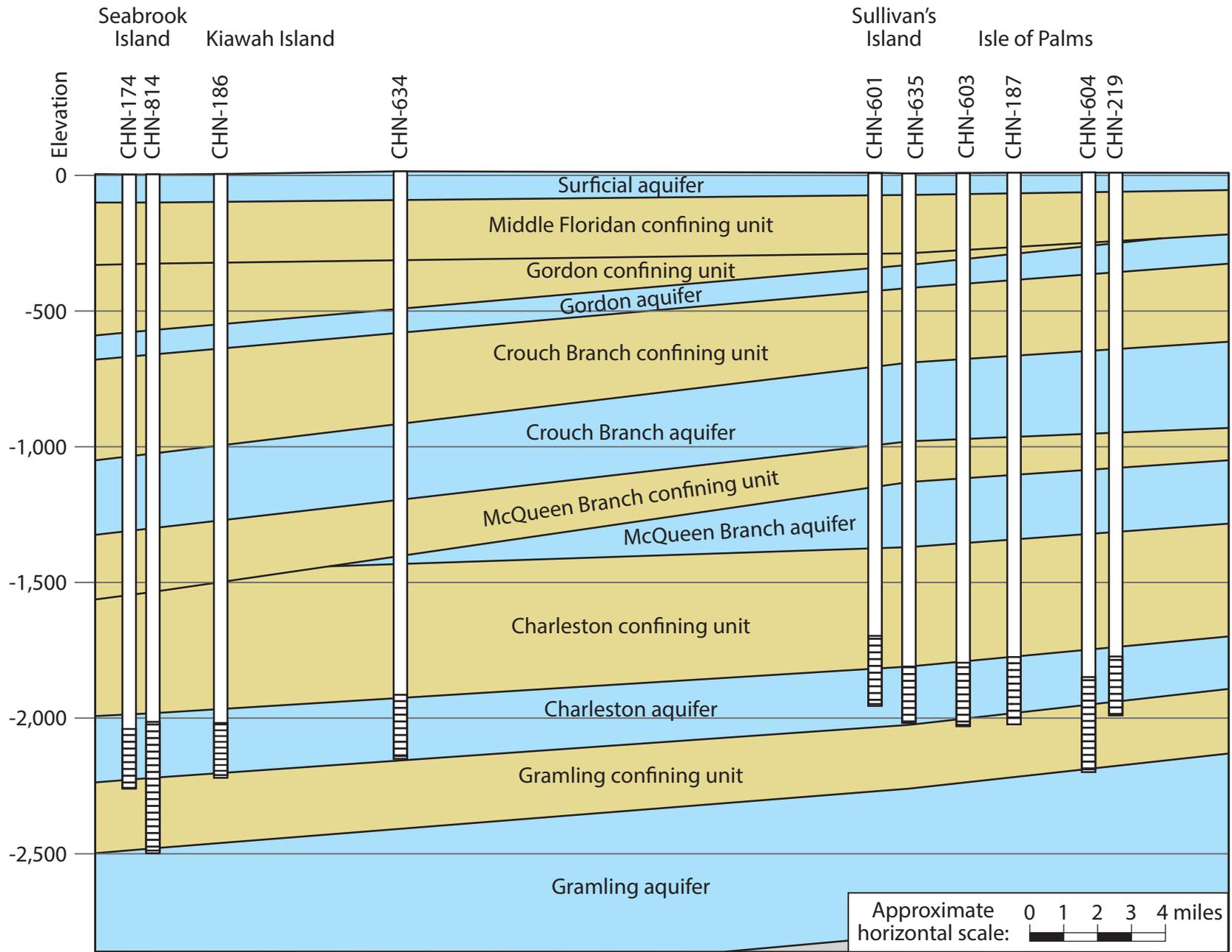


Figure 3A. Simplified hydrogeologic cross section of coastal Charleston County, showing major aquifers and approximate locations of some wells sampled during this study. Because elevations in the study are close to sea level, elevations shown approximate the completed depth and screened intervals of wells.

Mount Pleasant

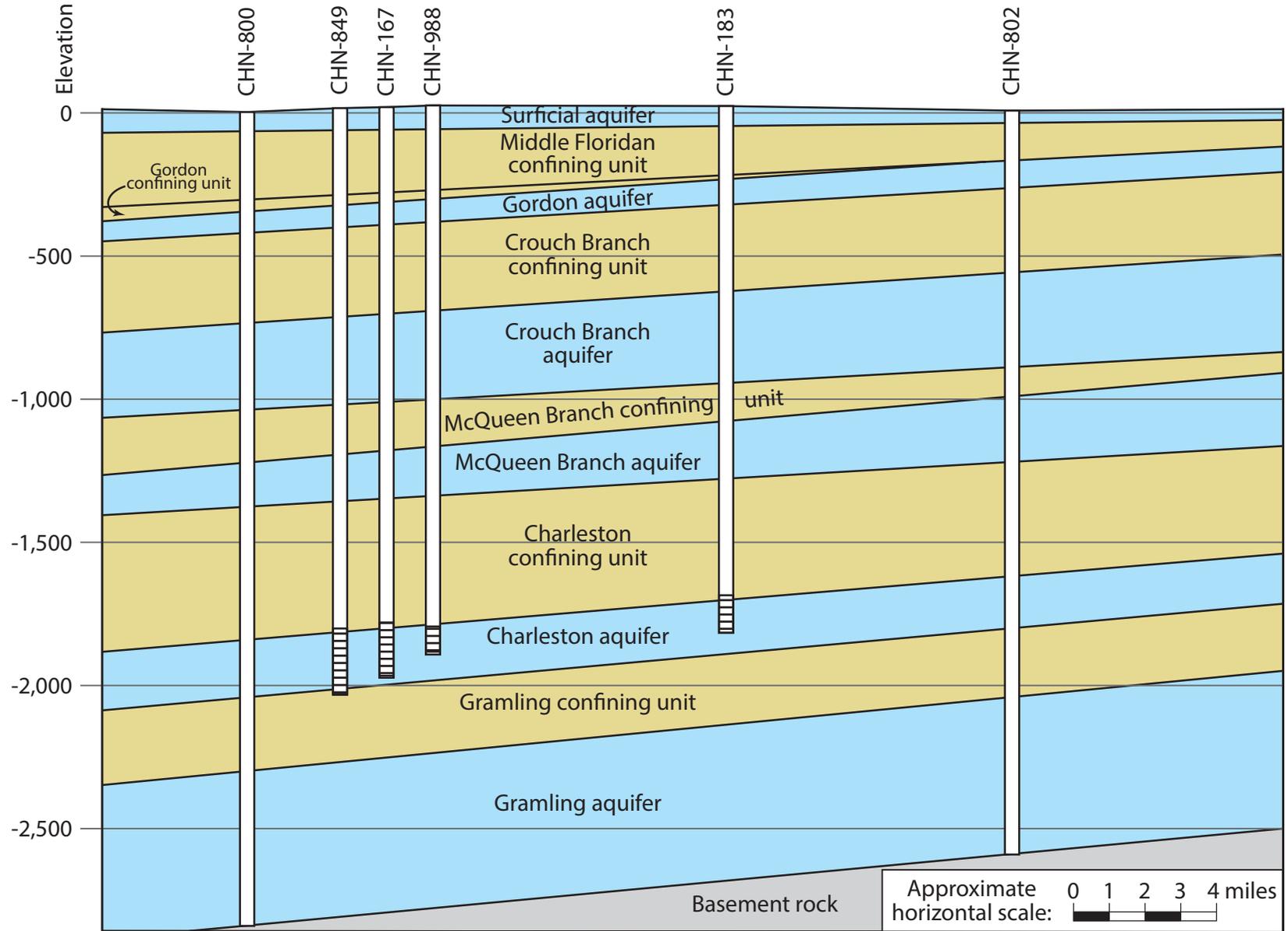


Figure 3B. Simplified hydrogeologic cross section of inland Charleston County, showing major aquifers and approximate locations of some wells sampled during this study. Because elevations in the study are close to sea level, elevations shown approximate the completed depth and screened intervals of wells. CHN-800 and CHN-802, two cored test holes used to determine local hydrostratigraphy, are also shown for reference.

Table 1. Wells sampled in this study including location, ownership identification, primary use, construction specifications, and sampling information

SCDNR Well ID	Well Location	Well Owner and Identification	Well Use	Well Depth (ft)	Top of Screen (ft)	Bottom of Screen (ft)	Aquifer	Pump Rate (gpm)	Sample Date 1	Sample Date 2 & 3
BRK-655	Huger	Industrial Well 2	IND	1,771	1,345	1,761	Charleston	900	7/23/2020	N/A
CHN-167	Mount Pleasant	MPW Deep Well 2	PS	1,993	1,800	1,986	Charleston	460	2/11/2020	6/24/2020
CHN-174	Seabrook Island	Fire Station Well	IRR	2,261	2,040	2,260	Charleston	500	6/18/2020	N/A
CHN-183	Mount Pleasant	MPW Deep Well 6	PS	1,840	1,709	1,840	Charleston	540	2/11/2020	6/24/2020 9/18/2020
CHN-186	Kiawah Island	KIU Plant	IRR	2,220	2,018	2,210	Charleston	525	6/8/2020	10/30/2020
CHN-187	Isle of Palms	IOPWSC Well 1	IRR	2,023	1,775	2,000	Charleston	800	2/12/2020	6/26/2020
CHN-219	Isle of Palms	IOPWSC Well 3	PS	1,990	1,773	1,985	Charleston	500 (est)	6/26/2020	9/18/2020
CHN-601	Sullivan's Island	SIWSD Well 1-A	UNU	1,955	1,697	1,948	Charleston	360	2/12/2020	6/25/2020
CHN-603	Isle of Palms	IOPWSC Well 2	IRR	2,030	1,796	2,025	Charleston	800	2/12/2020	6/26/2020
CHN-604	Isle of Palms	IOPWSC Well 4	PS	2,200	1,850	2,190	Charleston/ Gramling	800	6/26/2020	9/18/2020
CHN-634	Kiawah Island	Ocean Golf Course Well 2	PS	2,150	1,914	2,140	Charleston	450	7/23/2020	N/A
CHN-635	Sullivan's Island	SIWSD Well 2	UNU	2,018	1,810	2,013	Charleston	620	2/12/2020	6/25/2020
CHN-814	Kiawah Island	KIU Cassique Golf Course	IRR	2,498	2,014	2,488	Charleston/ Gramling	800	6/8/2020	10/30/2020
CHN-849	Mount Pleasant	Patriot's Point Golf Course	IRR	2,033	1,801	2,027	Charleston	500 (est)	6/24/2020	N/A
CHN-988	Mount Pleasant	MPW Deep Well 1	PS	1,918	1,820	1,908	Charleston	460	2/11/2020	6/24/2020
DOR-88	Summerville	SCPW Well 3	STB	1,760	1,644	1,750	Charleston	900	6/1/2020	N/A
DOR-228	Summerville	SCPW Well 5	STB	1,830	1,658	1,824	Charleston	700	6/1/2020	N/A

Well Owner abbreviations: MPW, Mount Pleasant Waterworks; KIU, Kiawah Island Utility; IOPWSC, Isle of Palms Water and Sewer Commission; SIWSD, Sullivan's Island Water & Sewer Department; SCPW, Summerville Commissioners of Public Works.

Well Use abbreviations: IND, industrial; PS, public supply; IRR, irrigation; UNU, unused; STB, standby.



Figure 4. Examples of in-field well sampling methodology. A hose is connected to a spigot and water is routed through tubing attached to a YSI multi-probe low-flow sampling port. The YSI probe continually measures water temperature, specific conductivity, pH, and total dissolved solids. When these parameters stabilize, samples are collected in prepared containers from tubing exiting sample chamber.

Groundwater Geochemistry Interpretation Methods

Maximum chloride concentration data from individual wells were contoured using Surfer (Surfer 11, Golden Software, Inc.). Contours were exported to GIS (ArcGIS 10.6, ESRI, Inc.) and mapped as equal (iso-) chloride concentration contours. Historical groundwater-quality data collected between 1971 and 1999 (Park, 1985 and SCDNR well file records) from similar well locations used in this study were summarized to provide a historical context for the present-day study to identify locations where shifts in the freshwater-saltwater interface may have occurred in the Charleston and Charleston/Gramling aquifers (Appendix, Table A3). Potentiometric maps of the Middendorf and Charleston aquifers (pre-development; 1982; 2004; 2011; and 2019) were examined to evaluate how external factors may have influenced changes in groundwater chemistry and the positions of chloride contours over time.

A linear regression analysis was made for the Charleston aquifer samples to evaluate the relationship between field-measured specific conductance and laboratory-analyzed chloride ion concentration. A strong, positive linear relationship has been documented between these two variables as part of other studies (Hem, 1985; Landmeyer and Belval, 1996). Data collected during the study were evaluated to ascertain if specific conductance measured using a multiparameter probe can be used as a good proxy for chloride in the Charleston aquifer study area.

Chemical analyses were completed to provide information regarding the chemical character of the resource and to provide an approximation of chloride concentration in the Charleston aquifer. The results were converted from mg/L to milliequivalents per liter (meq/L). Trilinear Piper plots were created to illustrate the chemical composition of groundwater and to determine groundwater facies. Stiff diagrams were created to examine differences and similarities in groundwater composition across the study area (from mainland to barrier islands), and among Charleston aquifer wells and those wells assumed to be completed

in the both the Charleston and underlying Gramling aquifer. A cation-anion balance (sum of the positively charged ions compared to the sum of the negatively charged ions) was calculated as a quality-assurance metric to determine the suitability of the laboratory analyses. The cation-anion balance of the lab-analyzed samples ranged between -6% and +8%, with an average of 5%. This range of error was considered acceptable for this study. In most analyses, an error exceeding 5% was due to the absence or near-zero concentration of fluoride or sulfate ions.

Results and Discussion

Summary statistics of physical and chemical parameters for Charleston aquifer samples (n=25) are shown in Table 2. Samples from wells CHN-814 and CHN-604, located on Kiawah Island and Isle of Palms, respectively, had notable differences in groundwater quality relative to the other 15 wells and are believed to be completed in both the Charleston and the underlying Gramling aquifers. Results from these wells were, therefore, excluded from Table 2 but are included in this discussion to provide contrast between samples collected solely from the Charleston aquifer. A summary of all field groundwater-quality and laboratory-analyzed data is provided in the Appendix in the form of tables.

Table 2. Summary statistics of physical and chemical water-quality parameters of groundwater samples from the Charleston aquifer (n=25)

Parameter	Unit	Minimum	Maximum	Mean	Standard Deviation
Temperature	°C	34.4	40.0	37.2	1.5
pH	--	8.10	8.68	8.40	0.14
TDS	mg/L	611	1,807	1,298	280
Specific Conductance	µS/cm	939	2,777	1,997	431
Ca ²⁺	mg/L	0.71	2.47	1.56	0.35
Mg ²⁺	mg/L	0.14	1.53	0.53	0.28
K ⁺	mg/L	1.65	3.98	2.95	0.65
Na ⁺	mg/L	228	620	457	96.2
Si	mg/L	13.8	17.6	15.9	0.9
Hardness	mg/L	2.37	12.5	6.09	1.95
Br ⁻	mg/L	0 (not detectable)	0.98	0.51	0.27
F ⁻	mg/L	0 (not detectable)	6.70	3.38	2.33
Cl ⁻	mg/L	10.4	320	135.4	71.6
SO ₄ ²⁻	mg/L	0 (not detectable)	4.61	0.60	1.03
HCO ₃ ⁻	mg/L	435	970	788	133
CaCO ₃ ²⁻	mg/L	38.2	71.9	47.7	9.17

Groundwater Physiochemistry

The temperature of groundwater samples from the Charleston aquifer ranged from 34.4 to 40.0°C (Celsius) with a mean value of 37.2°C, and the pH ranged from 8.10 to 8.68 with a mean value of 8.40. Charleston aquifer samples from eight sites in various locations of the study area slightly exceeded or met the EPA secondary standard for high pH. The Charleston aquifer samples ranged from freshwater to brackish water. Total dissolved solids concentrations exceeded the EPA secondary standard of 500 mg/L, ranging from 611 to 1,807 mg/L with a mean value of 1,298 mg/L. Measurements of specific conductance yielded similar results, ranging from 939 to 2,777 $\mu\text{S}/\text{cm}$ (microsiemens per centimeter) with a mean value of 1,997 $\mu\text{S}/\text{cm}$.

Groundwater samples collected from the two wells assumed to be completed in both the Charleston and Gramling (Charleston/Gramling) aquifers ranged in temperature from 38.8 to 41.1°C; and the pH ranged from 7.79 to 8.00. The Charleston/Gramling aquifer samples were brackish. Total dissolved solids (3,010 to 3,247 mg/L) and specific conductance values (4,630 to 4,993 $\mu\text{S}/\text{cm}$) were higher than those measured in the Charleston aquifer.

Collectively, the results from all groundwater samples analyzed in this study indicate bicarbonate (HCO_3^-) was the most abundant anion, followed by chloride (Cl^-), fluoride (F^-), and sulfate (SO_4^{2-}). The most abundant cation was sodium (Na^+), followed by potassium (K^+), calcium (Ca^{2+}), and magnesium (Mg^{2+}). Groundwater samples were very soft, with hardness values ranging from 2.37 to 12.50 mg/L in the Charleston aquifer and a slightly higher range in the Charleston/Gramling aquifer wells (16.9 to 21.0 mg/L). The difference in hardness is driven by a higher concentration of cations from the Charleston/Gramling aquifer samples. Chloride ion concentration in the Charleston aquifer generally increased towards the coast and, in most cases, the highest chloride ion concentrations were observed in samples from wells screened deeper in the Charleston aquifer and wells drilled adjacent to the dual-aquifer wells. Chloride concentration was highest in wells completed in the Charleston/Gramling aquifers.

Chloride concentration was slightly variable between the sampling efforts and, generally, samples collected during the summer contained a higher concentration of chloride ions. This difference could be from increased pumping during the summer months, although it was not explored. Fluoride concentration in all samples was below detectable limits during the first round of sampling in February (Appendix, Table 2A), but all samples analyzed during the second round in June had fluoride concentrations exceeding the EPA limit of 2.0 mg/L, with several wells exceeding 5.0 mg/L. A laboratory analysis error from the February samples was identified as the source of the discrepancy.

A Piper trilinear plot (Figure 5) shows the groundwater hydro-chemical facies grouped by TDS range: Group 1, TDS < 1,000 mg/L; Group 2, TDS between 1,000 and 1,500 mg/L; and Group 3, TDS > 1,500 mg/L. The subdivisions on the diamond plot correspond to the relative concentration of dissolved cations and anions plotted in the triangle plots (Piper, 1944). Wells in Berkeley and Dorchester Counties had the lowest TDS (TDS Group 1). TDS was higher in Charleston County (TDS Groups 2 and 3), indicating that groundwater in the Charleston aquifer is more mineralized owing to its proximity to the coast. In all groundwater samples, regardless of source, alkalis ($\text{Na}+\text{K}$) exceeded alkaline earths ($\text{Ca}+\text{Mg}$). Samples from the 15 wells completed solely in the Charleston aquifer were NaHCO_3 (sodium bicarbonate) type water. Samples from the 2 wells (circled in Figure 5) suspected to be receiving groundwater from both the Charleston and Gramling aquifers were NaCl (sodium chloride) type water.

Stiff diagrams are shown in Figure 6 to summarize the groundwater composition collected from selected well locations in the study area. The diagrams represent the meq/L percentage of cations to anions; therefore, similar shapes equate to similar groundwater composition. Samples from the Charleston aquifer all have a similar shape indicating NaHCO_3 -type water is predominant, and chloride generally increases towards to the coast. NaHCO_3 -type water is characteristic in areas where calcium bicarbonate rich freshwater has been transported to an area where it encounters saline water and marine sediments, resulting in ion exchange between calcium and sodium (Foster, 1950).

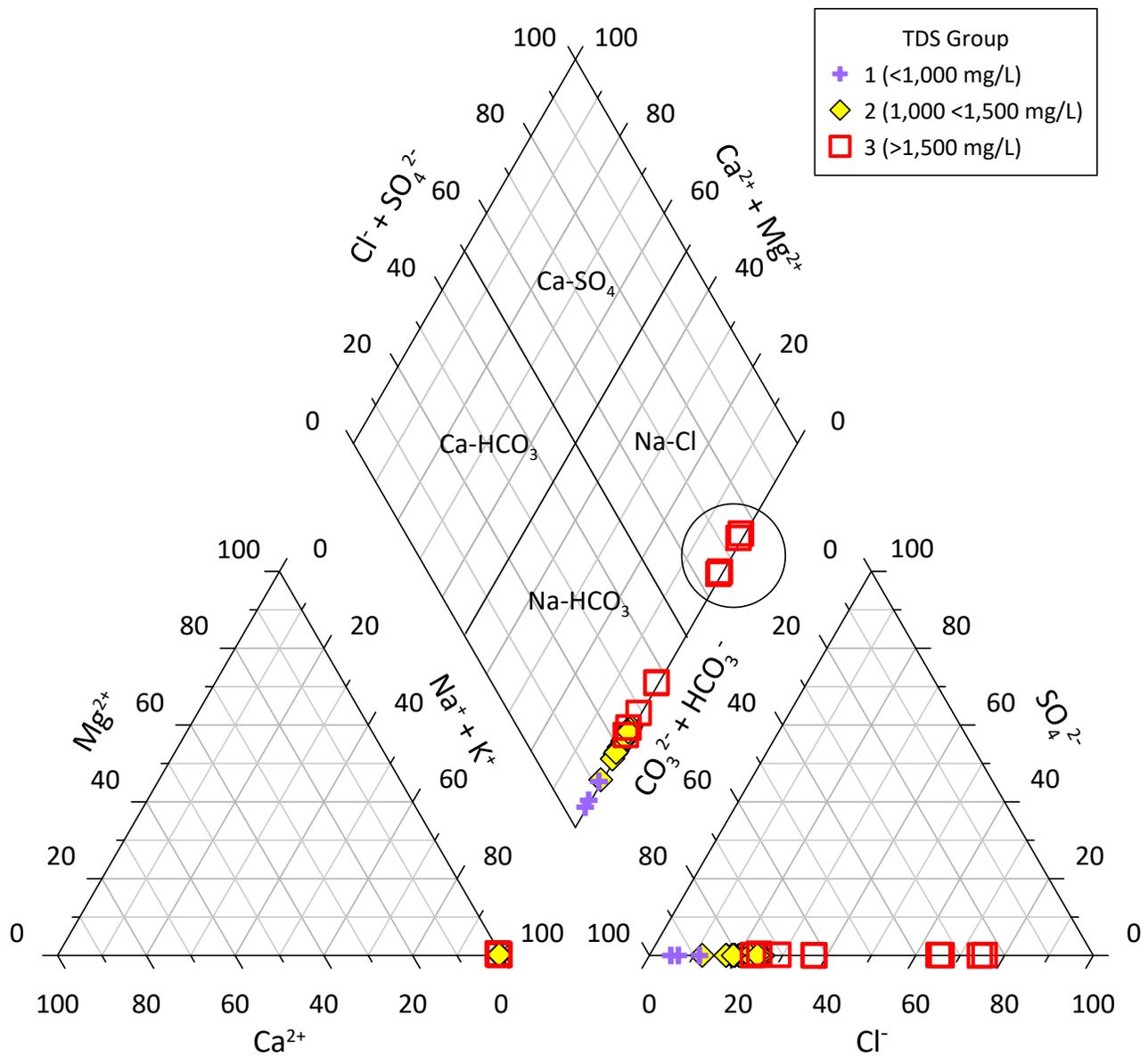


Figure 5. Piper trilinear plot showing major hydro-chemical facies classed by total dissolved solids in the groundwater samples. The circled points represent wells that are completed in both the Charleston and Gramling aquifers.

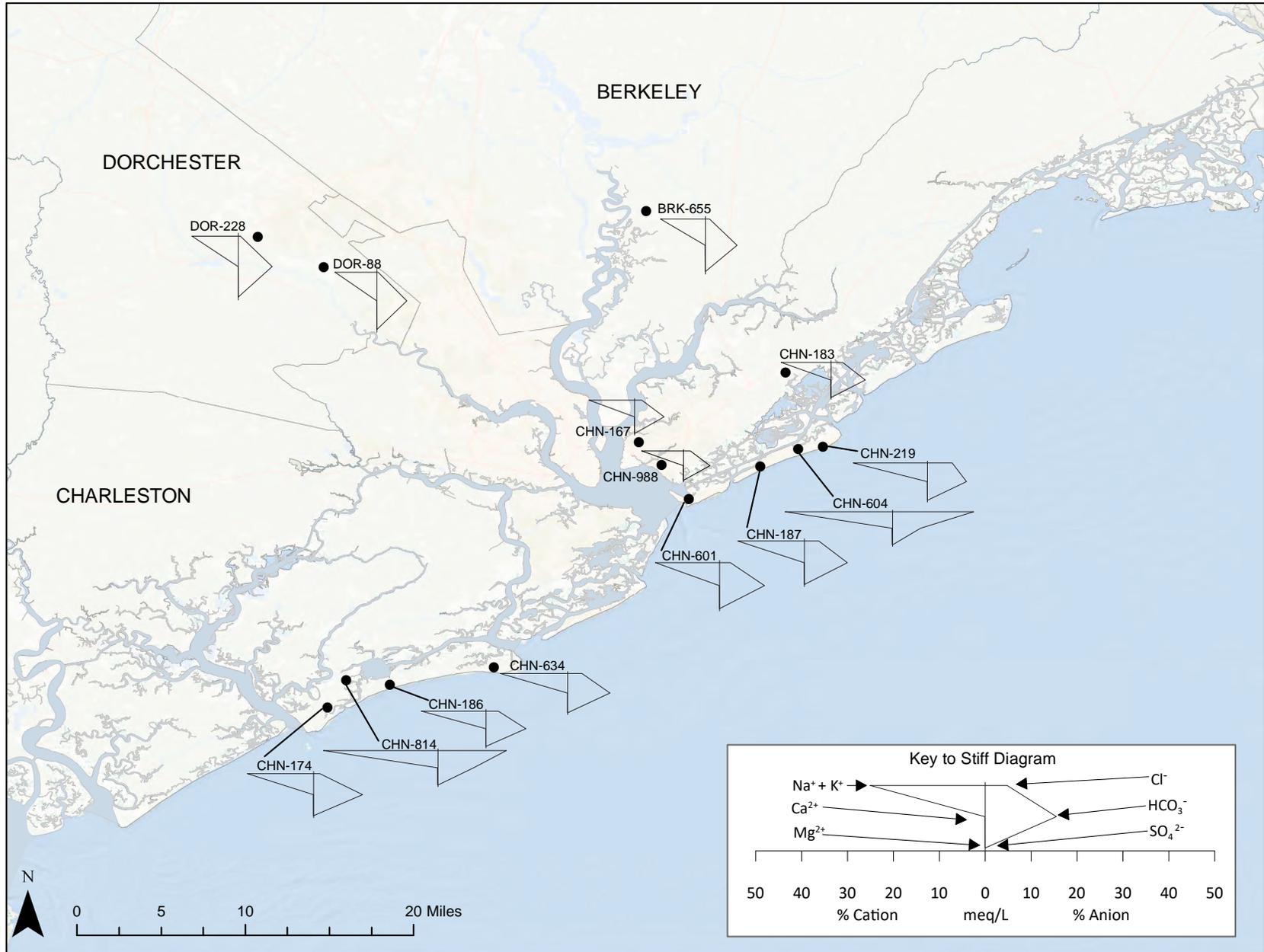


Figure 6. Stiff diagrams of selected wells showing groundwater composition in the Charleston and Charleston/Gramling aquifers.

The Stiff diagrams from the Charleston/Gramling wells (CHN-814 and CHN-604) are shaped similarly and represent a NaCl-type water. NaCl-type water, characteristic of ocean environments and brines (Piper, 1944), suggests that groundwater from the Gramling aquifer is saline and its presence may have contributed to the increased chloride concentration. The common occurrence of potassium feldspar (KAlSi_3O_8) in the Gramling aquifer, identified from core hole lithology, could account for the increased potassium concentration when compared to the Charleston aquifer.

A comparison of Stiff diagrams from wells completed in the Charleston aquifer that were drilled near wells completed in the Charleston/Gramling aquifers suggests inter-aquifer transfer (groundwater from both aquifers contributes to the well) is occurring at these locations during pumping. Well pairs located on the Isle of Palms: CHN-604 (screened 1,850–2,190 ft) and CHN-219 (screened 1,773–1,985 ft); and on Kiawah Island: CHN-814 (2,498 ft; screened 2,014–2,488 ft) and CHN-186 (screened 2,018–2,210 ft) have overlapping screened intervals. Upconing from the Gramling aquifer during pumping may be contributing to the higher concentration of sodium and chloride ions relative to other Charleston aquifer samples collected during this study. The same trend was not identified at CHN-174. A future analysis of groundwater samples from CHN-219 and CHN-186 collected while the deeper wells are not actively pumping could provide more information at these locations.

Changes in Chloride Concentration over Space and Time

Iso-chloride concentration contours drawn for the Charleston aquifer using data from the current (2020) study (Figure 7) indicate that 92 percent of the sampled wells in Charleston County exceed 100 mg/L of chloride, and chloride concentration in the Charleston aquifer is highest in wells located at Kiawah Island and at the northern portion of the Isle of Palms. Historical measurements indicate many sites in the study area have experienced only minor shifts in chloride concentration between present day and historical measurements. While the historical measurements provide a context for changes that have or have not occurred, they come with a degree of uncertainty. The historical measurements were not collected as part of a regional effort, and they were collected sporadically under different aquifer conditions and pumping scenarios over several decades. Further, the methodologies for collection and preservation are generally unknown and analyses were completed by various laboratories.

The present-day location of the freshwater-saltwater interface, as defined by the 250 mg/L iso-contour, is at the northern end of the Isle of Palms and was determined largely by the 320 mg/L chloride concentration in CHN-219. Unfortunately, historical chemistry information, which might indicate the rate of movement of the freshwater-saltwater interface, is not available for CHN-219. The most notable increases from historical data identified in this study occurred at Kiawah Island, in CHN-186 (227 mg/L in 2020 vs. 151 mg/L in 1977) and CHN-634 (175 mg/L in 2020 vs. 137 mg/L in 1990). This increase is presumably the result of brackish or saline water encroaching laterally or upconing from deeper portions of the Charleston aquifer due to prolonged potentiometric pressure loss from pumping. Other wells on the Isle of Palms and Sullivan's Island had lower chloride concentrations in 2020 compared to historical data, most notably CHN-187 (159 mg/L in 2020 vs. 172 mg/L in 1982) and CHN-635 (139 mg/L in 2020 vs. 182 mg/L in 1992). These differences could be attributed to groundwater development; the 1992 result from CHN-635 was collected at the completion of a 24-hour pump test.

The two wells assumed to be completed across the Charleston and Gramling aquifers were omitted from the map because the chloride concentrations were notably higher than the surrounding wells, resulting in steep concentration gradients. Large increases in chloride ion concentration were observed between historical and current data. Historical data indicate chloride ion concentration at CHN-814 has increased from 340 mg/L (1999) to 961 mg/L over a 21-year period, and CHN-604 has increased from 162 mg/L (1985) to 1,260 mg/L over a 35-year period. These wells account for only a fraction of the total groundwater use in the TCUA, so it is unclear why increases have occurred at these locations. It is possible that lateral encroachment of seawater is driving the increase, and this assumption is supported by the NaCl-dominant ion pair and slightly higher hardness from increased calcium relative to other samples collected during this

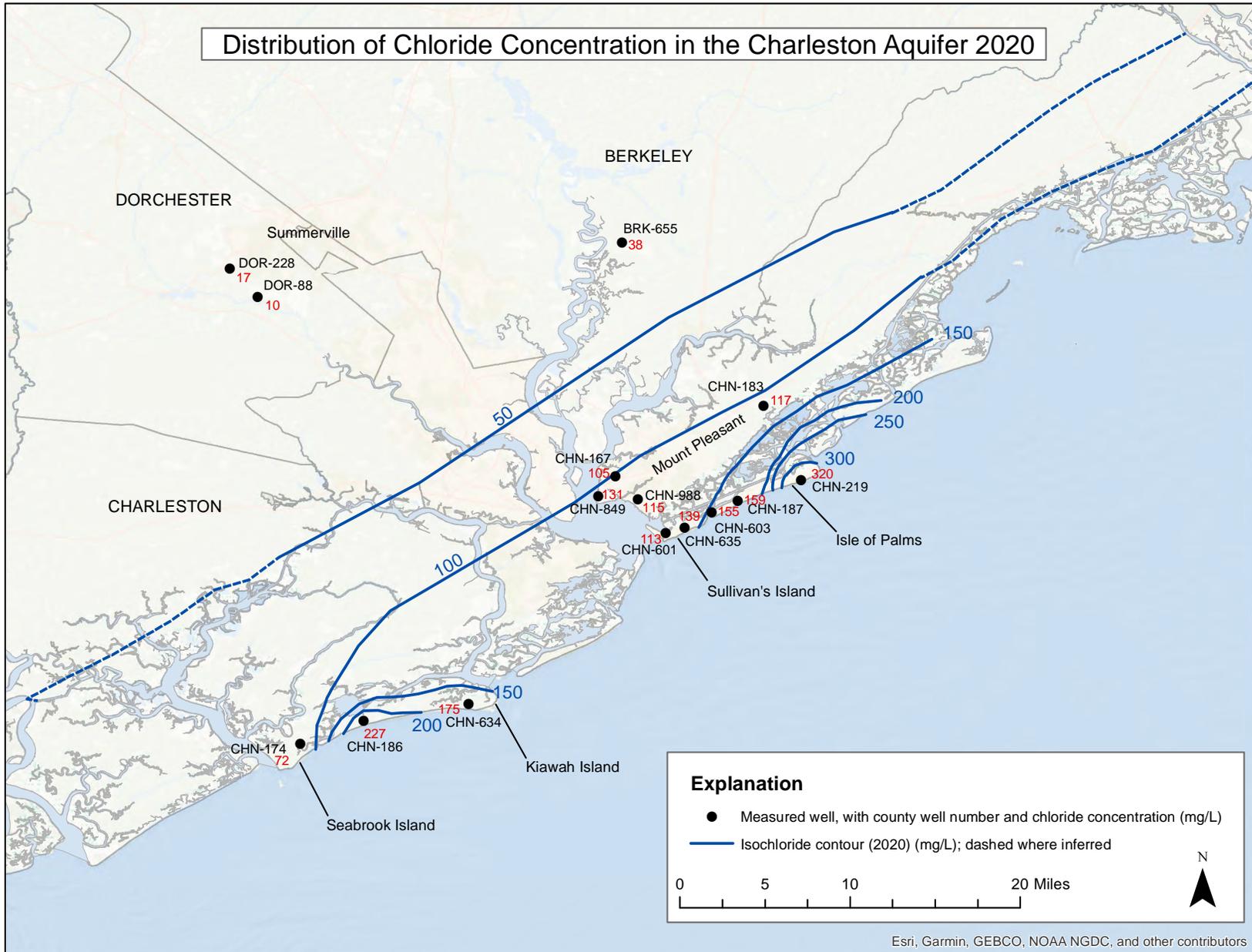


Figure 7. Contour map of maximum chloride ion concentration in the Charleston aquifer from samples collected between June and September 2020. CHN-183 (117 mg/L) is the median concentration of three samples (Appendix, Table A2).

study. The location of the Gramling aquifer's offshore outcrop area is unknown, so interaction with modern seawater cannot be assessed. Upconing of connate seawater from the Gramling aquifer may be more probable, due to incomplete flushing of the aquifer. There are no wells in the study area completed solely in the Gramling aquifer, which is known to have a lower transmissivity and is, consequently, less productive than the Charleston aquifer. Repeated, periodic measurements at these well locations would provide more information.

Water Use and Changes in the Potentiometric Surface over Time

Figure 8 shows potentiometric surface maps of the Charleston aquifer (former Middendorf aquifer) for 1982, 2004, 2011, and the McQueen Branch-Charleston-Gramling aquifers in 2019 (Aucott and Speiran, 1985; Hockensmith, 2008 and 2013; Czwartacki and Wachob, 2020). In 1982 (A), wells in the study area were flowing, with potentiometric levels of +75 to +100 ft above mean sea level. Groundwater development between 1982 and 1996 caused a decline in water levels resulting in the development of a cone depression centered over Mount Pleasant. When water use peaked between 2002 and 2004 (Figure 1), water levels were more than 200 feet below pre-development levels at Mount Pleasant and Kiawah Island. A multi-year period of significant drought between 1998–2002 also likely contributed the low levels shown on the 2004 map (B). In the years following, groundwater use declined to a low in 2010 owing to reduced pumping and increased reliance on surface water supplies or supplementation with surface water. On the 2011 map (C), the cones of depression have rebounded an average of 50 ft, but an area of low potentiometric pressure also appears in southern Berkeley County and the zero-elevation contour line has moved inland. Although groundwater use has been increasing since 2015, data collected in 2019 (D) shows that recovery in the aquifer has occurred and most of the groundwater levels have rebounded again by at least 25 ft since the last decade. The 2019 map also indicates region-wide lower potentiometric pressure compared to 30 years ago, as the zero-elevation contour line has moved farther inland. Historical water-quality measurements were not collected during the same time periods when water-levels were mapped, so it is unclear if the resultant changes in water chemistry are due to lowered potentiometric head and regional gradient changes. However, chloride concentration is increasing at specific well locations where water-level changes have been documented. Regular, periodic monitoring could provide more insight on how these factors are related.

Use of Field-Measured Specific Conductance as a Proxy for Laboratory Analysis of Chloride

Repeated measurements of chloride in the laboratory are recommended to monitor Charleston aquifer wells for changes in chloride ion concentrations, but the possibility exists that field measurements of specific conductance could serve as a relatively rapid and inexpensive proxy. Figure 9 shows the relationship between field-measured specific conductance and laboratory measured chloride concentration for 25 Charleston aquifer groundwater samples collected from 15 of the 17 wells. A linear regression was calculated using the least squares method. Samples from the dual-aquifer wells were omitted from the analysis since the focus of this study was to examine changes occurring in the Charleston aquifer. The coefficient of variation ($R^2 = 0.82$) indicates that the field-measured specific conductance is highly correlated with chloride concentration and can be used to approximate chloride concentrations in the Charleston aquifer using the equation:

$$y = 0.15x - 165$$

where x is specific conductance ($\mu\text{S}/\text{cm}$) from field-measurement and y is chloride concentration (mg/L) from laboratory analysis. Continued measurement and comparison of chloride and specific conductance at these sites would likely improve the correlation between these two parameters. Specific conductance measurements could be made at the surface from grab samples like the ones collected for this study or could be made downhole in the well casing using a handheld conductivity probe suspended from a cable. The later method may not produce similar results due to the stratification of fresh and saltwater within the well casing but could provide more information on the vertical location of the freshwater-saltwater interface in a particular well.

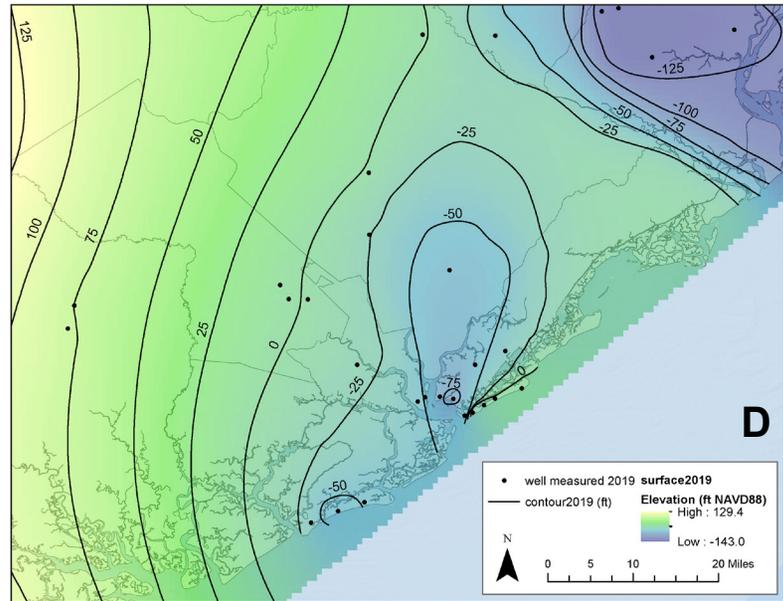
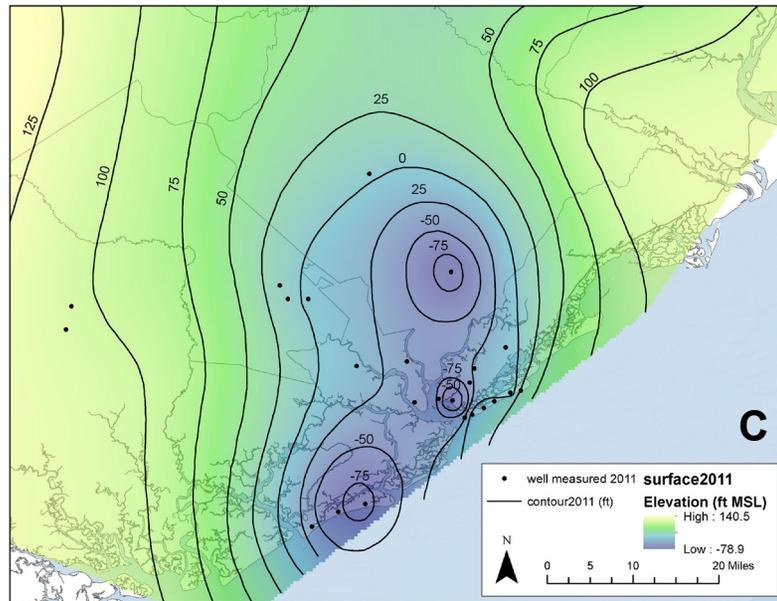
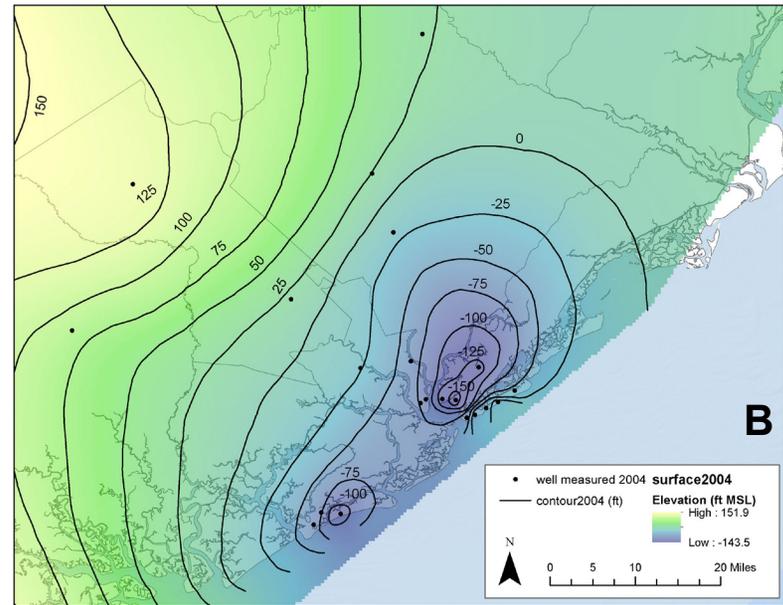
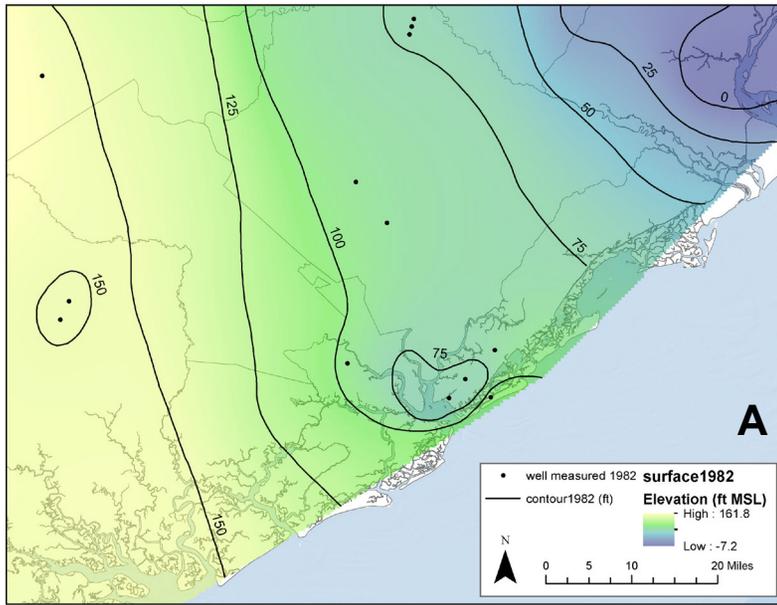


Figure 8. Potentiometric maps of the Middendorff aquifer for (A) 1982; (B) 2004; and (C) 2011; and (D) the McQueen Branch-Charleston-Gramling aquifers in 2019, illustrating water-level change over the past several decades.

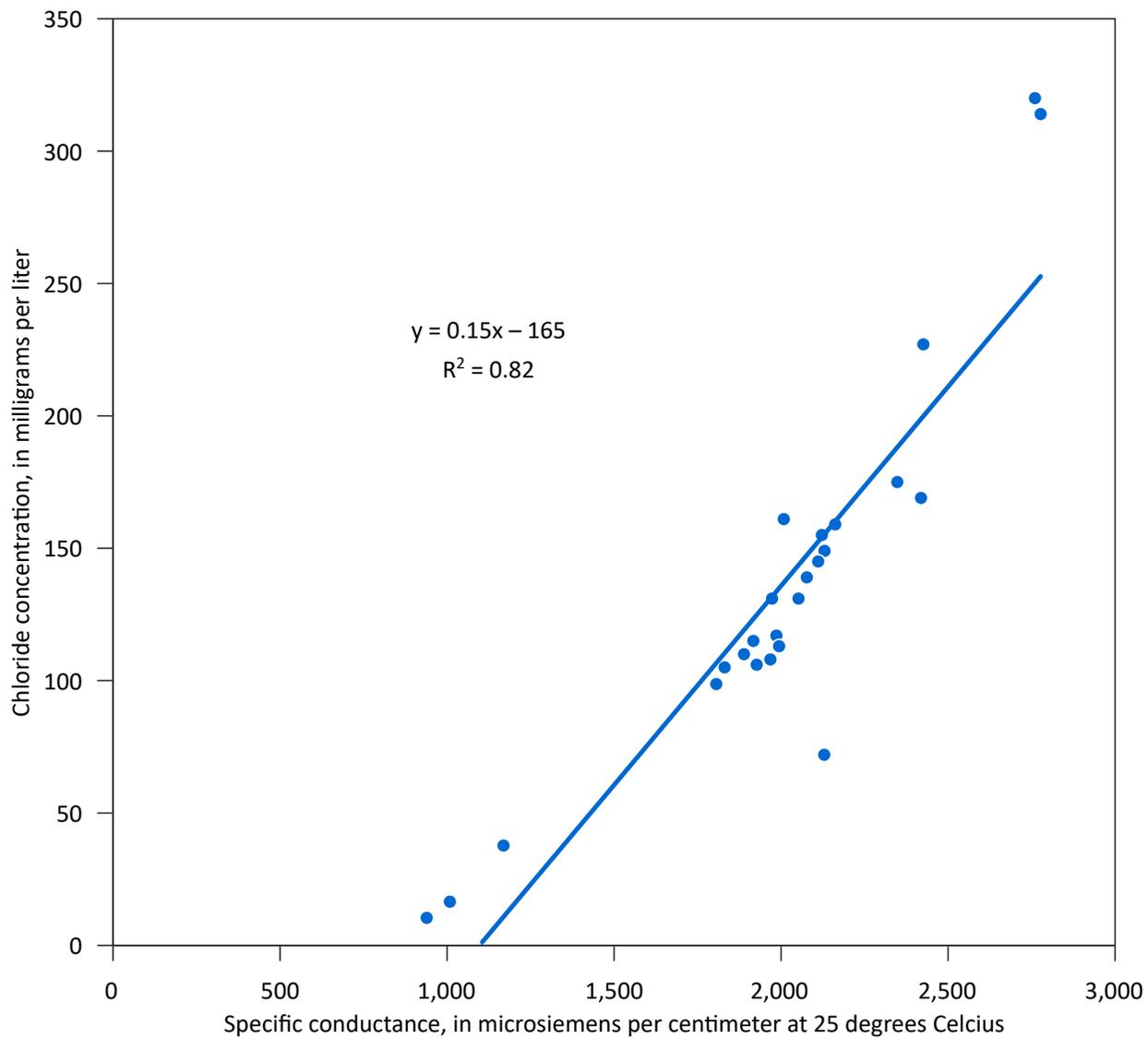


Figure 9. Regression of specific conductance and chloride concentration from Charleston aquifer samples collected during this study (n=25).

Conclusions and Recommendations

This study presents the current (2020) distribution of chloride concentration in the Charleston aquifer in the Trident Capacity Use Area. Data collected for this study update previously collected groundwater quality data of the Charleston/Gramling aquifers. The identification of shifts in groundwater chemistry within the aquifer are based on changes observed between data collected at wells between 1971 and 1999 and sampling conducted in 2020 for this study. The results suggest, based on the location of current-day 250 mg/L iso-chloride contour line, the freshwater-saltwater interface in the Charleston aquifer is located at the northern tip of the Isle of Palms. Chloride concentration has also increased in Charleston aquifer wells located on Kiawah Island. Notable increases in chloride were also identified wells completed in both the Charleston aquifer and the underlying Gramling aquifer, suggesting these sites are particularly susceptible to saltwater intrusion because the wells are screened across multiple hydrostratigraphic units. Brackish or saline water from the deeper Gramling aquifer is apparently mixing with fresher water in the Charleston aquifer.

While it is difficult to assign the exact processes that are driving the increase in chloride concentration at these wells, it is likely caused by regional groundwater-level declines from long-term groundwater development, and attendant replacement by more saline groundwater from unknown sources. The observed increases in chloride concentration in the Charleston and Charleston/Gramling aquifers are likely due, in part, to upconing, whereby higher saline groundwater from the base of the aquifer is reaching pump intakes, and from inter-aquifer transfer, whereby the deeper, more saline water from the Gramling aquifer is mixing with the fresher groundwater in the overlying Charleston aquifer. To protect the Charleston aquifer from inter-aquifer transfer, it is recommended that dual aquifer screened wells be decommissioned or backfilled so that only the Charleston aquifer is screened.

The Charleston aquifer will remain an important source of groundwater for Berkeley, Charleston, and Dorchester Counties. The population in these coastal counties is expected to increase and more groundwater will be needed. To protect the Charleston aquifer from saltwater intrusion, water-quality criteria need to be developed. Repeated sampling and monitoring at the wells discussed in this report is recommended every three to five years to look for changes that may occur from water-level changes in the Charleston aquifer. These future analyses can determine the rate of movement of the saltwater interface and may provide more insight regarding the source of chloride in the Charleston aquifer.

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APPENDIX

In-field and laboratory analyses of water-quality data for samples collected from wells completed in the Charleston and Charleston/Gramling aquifers

Table A1. Field-analyzed water-quality data from wells completed in the Charleston and Charleston/Gramling (shaded) aquifers

SCDNR Well ID	Well Owner Identification Name	Sample Date	Temp °C	Specific Conductance μS/cm	Total Dissolved Solids (mg/L)	pH
BRK-655	Huger Industrial Well 2	7/23/2020	35.2	1,169	761	8.68
CHN-167	MPW Deep Well 2	2/11/2020	37.7	1,806	1,173	8.52
CHN-167	MPW Deep Well 2	6/24/2020	37.8	1,831	1,190	8.42
CHN-174	Seabrook Island Fire	6/18/2020	38.9	2,129	1,385	8.27
CHN-183	MPW Deep Well 6	2/11/2020	35.2	1,986	1,294	8.49
CHN-183	MPW Deep Well 6	6/24/2020	35.5	2,008	1,307	8.38
CHN-183	MPW Deep Well 6	9/18/2020	35.5	1,927	1,255	8.34
CHN-186	KIU Plant Well	6/8/2020	40.0	2,426	1,580	8.16
CHN-186	KIU Plant Well	10/30/2020	39.9	2,419	1,573	8.31
CHN-187	IOPWSC Well 1	2/12/2020	37.5	2,130	1,385	8.48
CHN-187	IOPWSC Well 1	6/26/2020	37.6	2,162	1,404	8.25
CHN-219	IOPWSC Well 3	6/26/2020	38.4	2,777	1,807	8.21
CHN-219	IOPWSC Well 3	9/18/2020	37.9	2,760	1,794	8.10
CHN-601*	SIWSD Well 1-A	2/12/2020	36.8	1,968	1,281	8.51
CHN-601*	SIWSD Well 1-A	6/25/2020	36.6	1,994	1,294	8.35
CHN-603	IOPWSC Well 2	2/12/2020	37.9	2,111	1,372	8.45
CHN-603	IOPWSC Well 2	6/26/2020	37.9	2,122	1,378	8.34
CHN-604	IOPWSC Well 4	6/26/2020	38.8	4,993	3,247	7.96
CHN-604	IOPWSC Well 4	9/18/2020	38.8	4,939	3,211	8.00
CHN-634**	Ocean Golf Course Well 2	7/24/2020	38.7	2,348	1,528	8.50
CHN-635*	SIWSD Well 2	2/12/2020	36.4	2,052	1,333	8.50
CHN-635*	SIWSD Well 2	6/25/2020	36.7	2,077	1,352	8.31
CHN-814	KIU Cassique Golf Course	6/8/2020	41.2	4,654	3,023	7.79
CHN-814	KIU Cassique Golf Course	10/30/2020	41.1	4,630	3,010	7.95
CHN-849**	Patriot's Point Golf Course	6/24/2020	38.0	1,973	1,281	8.39
CHN-988	MPW Deep Well 1	2/11/2020	36.7	1,889	1,229	8.54
CHN-988	MPW Deep Well 1	6/24/2020	37.0	1,917	1,248	8.36
DOR-88	SCPW Well 3	6/1/2020	34.4	939	611	8.57
DOR-228	SCPW Well 5	6/1/2020	34.7	1,009	657	8.53

* Only one well volume removed.

** Samples collected in a 5-gallon bucket.

See Table 1 for Well Owner Identification abbreviations.

Table A2. Laboratory-analyzed water-quality data from wells completed in the Charleston and Charleston/Gramling (shaded) aquifers

SCDNR Well ID	Well Owner Identification Name	Sample Date	Calcium (mg/L)	Magnesium (mg/L)	Potassium (mg/L)	Sodium (mg/L)	Silica (mg/L)	Hardness	Bromide (mg/L)	Fluoride (mg/L)	Chloride (mg/L)	Sulfate (mg/L)	Bicarbonate alkalinity (mg/L)	Carbonate alkalinity (mg/L)
BRK-655	Huger Industrial Well 2	7/23/2020	1.22	0.23	1.85	264	14	4	0.20	2.76	38	ND	497	68
CHN-167	MPW Deep Well 2	2/11/2020	1.42	0.44	2.56	418	17	5	0.52	ND	99	0.48	753	46
CHN-167	MPW Deep Well 2	6/24/2020	1.55	0.45	2.82	425	16	6	0.53	3.71	105	0.59	739	60
CHN-174	Seabrook Island Fire	6/18/2020	1.35	0.5	3.86	491	16	5	ND	5.58	72	0.28	970	66
CHN-183	MPW Deep Well 6	2/11/2020	1.63	0.59	3.51	472	16	6	0.56	ND	117	ND	827	46
CHN-183	MPW Deep Well 6	6/24/2020	1.73	0.57	3.88	476	16	7	0.85	6.70	161	ND	813	46
CHN-183	MPW Deep Well 6	9/18/2020	1.62	0.49	2.97	444	15	6	0.16	4.94	106	ND	787	52
CHN-186	KIU Plant Well	6/8/2020	1.81	0.96	3.88	565	14	8	0.57	5.53	227	2.08	914	70
CHN-186	KIU Plant Well	10/30/2020	1.86	1.01	3.87	574	16	9	0.27	5.32	169	2.61	946	56
CHN-187	IOPWSC Well 1	2/12/2020	1.33	0.48	2.88	514	18	5	0.79	ND	149	0.26	855	46
CHN-187	IOPWSC Well 1	6/26/2020	1.37	0.46	2.54	479	16	5	0.42	5.68	159	0.33	823	42
CHN-219	IOPWSC Well 3	6/26/2020	2.08	0.70	3.25	610	16	8	0.98	4.91	314	0.95	889	48
CHN-219	IOPWSC Well 3	9/18/2020	2.02	0.67	3.64	620	16	8	0.88	4.99	320	0.90	870	72
CHN-601*	SIWSD Well 1-A	2/12/2020	1.69	0.45	2.95	462	18	6	0.55	ND	108	0.19	829	52
CHN-601*	SIWSD Well 1-A	6/25/2020	1.57	0.42	2.59	434	16	6	0.70	5.06	113	0.27	810	60
CHN-603	IOPWSC Well 2	2/12/2020	1.35	0.45	2.72	489	17	5	0.78	ND	145	0.30	846	38
CHN-603	IOPWSC Well 2	6/26/2020	1.46	0.44	2.43	456	15	5	0.44	5.29	155	0.39	814	56
CHN-604	IOPWSC Well 4	6/26/2020	4.89	1.97	4.77	957	16	20	6.52	3.79	1,260	2.66	707	ND
CHN-604	IOPWSC Well 4	9/18/2020	5.09	1.99	5.09	1,010	16	21	6.84	3.62	1,180	2.57	701	ND
CHN-634**	Ocean Golf Course Well 2	7/24/2020	2.47	1.53	3.98	535	16	13	0.72	5.43	175	4.61	895	66
CHN-635*	SIWSD Well 2	2/12/2020	1.61	0.44	2.71	477	18	6	0.69	ND	131	0.22	839	44
CHN-635*	SIWSD Well 2	6/25/2020	1.49	0.42	2.56	450	16	5	0.38	5.48	139	0.25	821	52
CHN-814	KIU Cassique Golf Course	6/8/2020	4.09	1.77	5.37	983	15	18	8.25	3.79	922	2.70	837	14
CHN-814	KIU Cassique Golf Course	10/30/2020	3.95	1.72	5.39	1,040	16	17	2.45	3.49	961	2.60	864	ND
CHN-849**	Patriot's Point Golf Course	6/24/2020	1.63	0.42	2.62	441	17	6	0.68	4.04	131	0.15	778	64
CHN-988	MPW Deep Well 1	2/11/2020	1.5	0.46	2.97	430	16	6	0.52	ND	110	0.15	756	52
CHN-988	MPW Deep Well 1	6/24/2020	1.64	0.47	3.19	441	16	6	0.54	4.26	115	ND	748	62
DOR-88	SCPW Well 3	6/1/2020	0.71	0.14	1.65	228	16	2	ND	2.30	10	ND	435	51
DOR-228	SCPW Well 5	6/1/2020	0.85	0.17	1.81	236	15	3	ND	2.57	17	ND	461	53

* Only one well volume removed; ** Samples collected in a 5-gallon bucket; See Table 1 for Well Owner Identification abbreviations; ND indicates not detectable.

Table A3. Historical laboratory water-quality analyses from wells completed in the Charleston and Charleston/Gramling (shaded) aquifers

SCDNR Well ID	Well Owner Identification Name	Sample Date	Calcium (mg/L)	Magnesium (mg/L)	Potassium (mg/L)	Sodium (mg/L)	Silica (mg/L)	Hardness	Fluoride (mg/L)	Chloride (mg/L)	Sulfate (mg/L)	Bicarbonate alkalinity (mg/L)	Carbonate alkalinity (mg/L)	Laboratory*
CHN-163	MPW Old Deep Well 1	3/5/1981	2.20	0.70	5.00	380	20	16	4.40	135	ND	841	ND	SCWRC
CHN-167	MPW Deep Well 2	12/3/1971	ND	ND	ND	ND	20	30	ND	120	ND	602	8	COM
CHN-167	MPW Deep Well 2	3/9/1981	2.06	0.76	4.10	37	11	14	4.00	104	ND	767	ND	SCWRC
CHN-174	Seabrook Island Fire	2/20/1973	1.60	ND	ND	536	9	4	5.00	87	1.00	950	90	COM
CHN-183	MPW Deep Well 6	7/23/1979	1.70	0.40	3.80	530	14	6	5.20	130	5.80	880	ND	USGS
CHN-186	KIU Plant Well	3/7/1977	1.60	0.50	ND	557	ND	6	6.00	151	1.00	920	80	COM
CHN-187	IOPWSC Well 1	9/5/1975	2.80	0.50	ND	539	16	9	5.00	170	ND	860	68	COM
CHN-187	IOPWSC Well 1	2/1/1982	2.00	0.57	4.78	450	9	8	6.30	172	ND	884	ND	SCWRC
CHN-601	SIWSD Well 1-A	8/4/1987	1.30	0.43	ND	ND	ND	5	3.70	120	ND	ND	ND	SCDHEC
CHN-601	SIWSD Well 1-A	6/4/1986	1.60	0.50	ND	450	20	6	3.40	130	2.00	798	32	COM
CHN-603	IOPWSC Well 2	10/13/1986	1.20	0.05	ND	482	18	5	4.60	136	2.00	825	35	COM
CHN-603	IOPWSC Well 2	2/18/1987	2.50	0.41	5.88	523	9	ND	4.74	142	ND	862	ND	SCDHEC
CHN-604	IOPWSC Well 4	5/29/1985	4.70	1.87	4.80	1024	6	24	4.50	162	3.00	704	<1	COM
CHN-634	Ocean Golf Course Well 2	3/28/1990	2.22	1.20	4.04	588	ND	ND	5.00	137	<5	963	84	COM
CHN-635	SIWSD Well 2	1/21/1992	ND	ND	ND	ND	ND	5	5.35	182	<5	804	70	COM
CHN-814	KIU Cassique Golf Course	2/18/1999	2.80	0.97	4.20	500	ND	11	3.30	340	<5	830	20	COM
CHN-849	Patriot's Point Golf Course	11/20/1997	1.91	0.49	3.60	481	30	10	4.20	118	<5	710	0	COM
DOR-88	SCPW Well 3	7/9/1979	1.00	0.20	1.70	210	ND	3	2.70	11	2.60	460	ND	USGS
DOR-228	SCPW Well 5	7/17/1987	0.86	0.14	1.89	252	ND	ND	2.91	20	<0.2	482	32	COM

See Table 1 for Well Owner Identification abbreviations; ND indicates not detectable.

* Laboratory abbreviations: SCWRC: South Carolina Water Resources Commission; COM: Commercial laboratory; USGS: U.S. Geological Survey Lab; SCDHEC: South Carolina Department of Health and Environmental Control.