

# Impact of hurricanes storm surges on the groundwater resources

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**Abstract** Ocean surges onto coastal lowlands caused by tropical and extra tropical storms, tsunamis, and sea level rise affect all coastal lowlands and present a threat to drinking water resources of many coastal residents. In 2005, two such storms, Hurricanes Katrina and Rita struck the Gulf Coast of the US. Since September 2005, water samples have been collected from water wells impacted by the hurricanes' storm surges along the north shore of Lake Pontchartrain in southeastern Louisiana. The private and public water wells tested were submerged by 0.6–4.5 m of surging saltwater for several hours. The wells' casing and/or the associated plumbing were severely damaged. Water samples were collected to determine if storm surge water inundated the well casing and, if so, its effect on water quality within the shallow aquifers of the Southern Hills Aquifer System. In addition, the samples were used to determine if the impact on water quality may have long-term implication for public health. Laboratory testing for several indicator parameters (Ca/Mg, Cl/Si, chloride, boron, specific conductance and bacteria) indicates that surge water entered water wells' casing and the screened aquifer. Analysis of the groundwater shows a decrease in the Ca/Mg ratio right after the storm and then a return toward pre-Katrina values. Chloride concentrations were elevated right after Katrina and Rita, and then decreased downward toward pre-Katrina values. From September 2005 to June 2006, the wells showed improvement in all the saltwater intrusion indicators.

**Keywords** US Gulf Coast · Aquifer · Saltwater intrusion · Hurricanes · Water quality

## Introduction

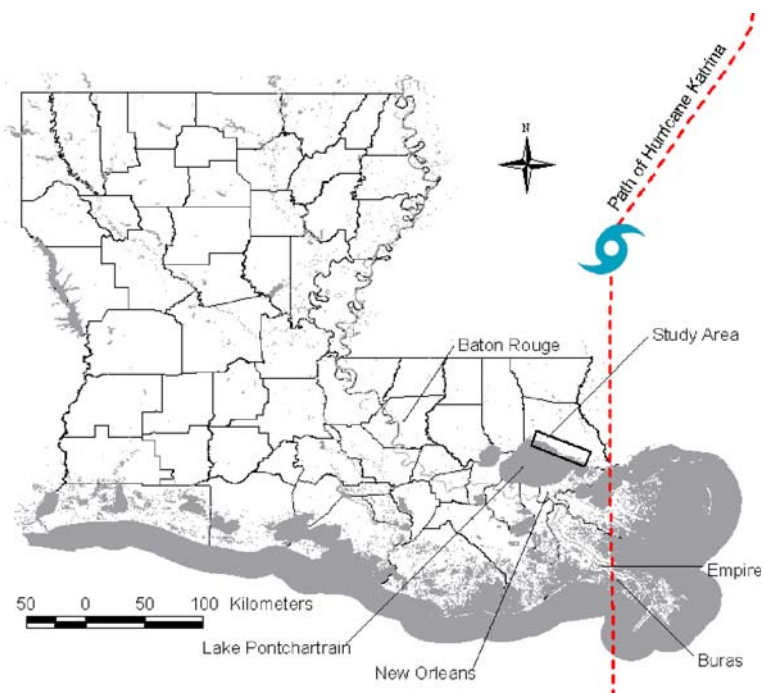
Coastal regions of the world are subject to saltwater flooding due to storm surges and tsunamis, as well as subsidence and sea level rise. In December 2004, the coastal areas of many countries surrounding the Indian Ocean (approximately 55,440 km<sup>2</sup>) were affected by a large tsunami generated by the Sumatra-Andaman Island earthquake (Anderson and Brakenridge 2004). In 2005, hurricanes Katrina and Rita affected the low-lying coastal areas of the United States (US) Gulf Coast states (Alabama, Florida, Louisiana, Mississippi and Texas), with Louisiana being affected the most. These coastal areas, aside from being threatened by storm surges, are also affected by sea level rise, and naturally and anthropogenically-driven subsidence. An estimate of the impact of climate-induced sea level fluctuation for the US suggests that a 1 m rise would flood approximately an area of 44,500 km<sup>2</sup> of the coastal United States (Titus 1989). Of the 44,500 km<sup>2</sup>, 22,500 km<sup>2</sup> represent submerging coastal wetlands, with approximately 16% of these being in coastal Louisiana (Titus 1989).

This study encompasses the north shoreline of Lake Pontchartrain in southern St. Tammany Parish, Louisiana (Fig. 1). The parish was Louisiana's fastest growing parish in terms of population between 1990 and 2000 (Calhoun and McGovern 2002). More recently, an estimated 30% increase, temporary or permanent, in population has been attributed to New Orleans' displaced residents moving to higher ground across Lake Pontchartrain (Donze F, The Times-Picayune, November 14

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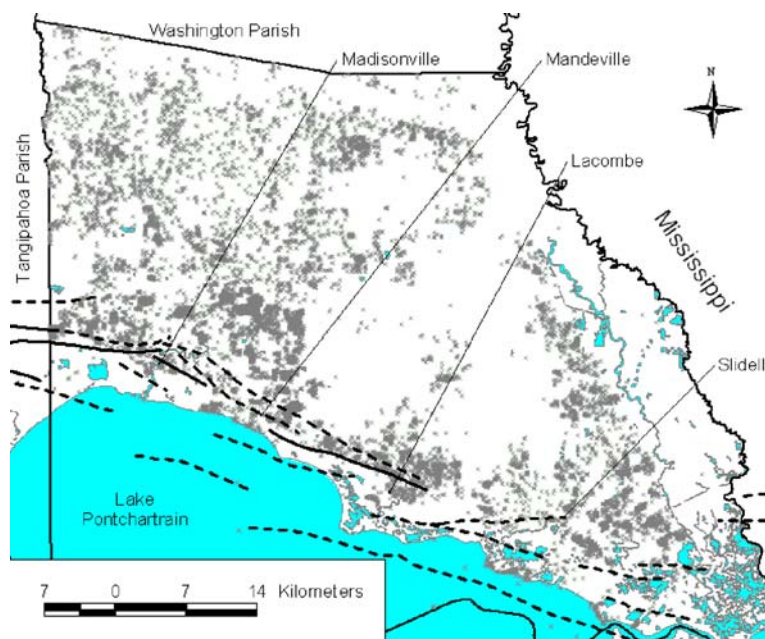
**Fig. 1** Study area location map (Office of the Governor 1999) and path of Hurricane Katrina [National Oceanic and Atmospheric Administration (NOAA) 2005]



2005). Groundwater is the dominant source for domestic and public water supplies, and, in 1988, the US Environmental Agency (USEPA) designated the Southern Hill Aquifer System as the sole-source aquifer system (USEPA 1988). A vast number of domestic and public water wells have been drilled and are in operation in St Tammany Parish (Fig. 2). The Louisiana Department of Transportation and Development (LDOTD) database indicates that approximately 7,970 domestic and 418

public water supply wells were installed in the parish between 1990 and 2003. Approximately 98% of these domestic wells are screened across three sand aquifers: the Upland Terrace, the Upper Ponchatoula, and the Lower Ponchatoula. Due to the relocation of New Orleans residents to the parish as a result of hurricanes Katrina and Rita, the drilling and development activity has greatly increased from previous years (Hanson B, LDOTD, unpublished data, 2006).

**Fig. 2** Location of registered water wells (grey Xs), and known and suspected shallow faults in St Tammany Parish (modified from Van Biersel 2006)



Very little currently available research assesses the effect of storm surge on groundwater systems. Most of the recent research that followed the catastrophic storm surge and flooding caused by Hurricane Katrina focused on surface water quality, predominantly that of Lake Pontchartrain, and the flooding waters in New Orleans (Pardue et al. 2005). Very little attention has been given to the impact on the Southern Hills Aquifer System, and the water supply to residents and businesses along the north shore of the lake in St Tammany Parish. Much of the lack of research of this type can be attributed to the difficulties in logistics and access associated with a research project directly after a major catastrophe. Similar information was collected by researchers (Violette et al. 2005) during the December 2004 Indian Ocean tsunami although not directly associated with the consumption of water. In North Carolina, Anderson (2001, 2002) looked at the effects of Hurricane Emily on the aquifer of Cape Hatteras. In this case, the unconfined groundwater aquifer was directly recharged by seawater, resulting in elevated chloride concentrations in the aquifer for over a 4-year period.

In the 1990s, several publications were generated by US Geological Survey (USGS) scientists, which examined storm surge, their effects on coastal regions and the social and ecological consequences (Schuck-Kolben and Kaufman 1991; Bales et al. 2000). The water quality data presented by the USGS generally looks at stream and coastal wetlands (Bales and Oblinger-Childress 1996; Weaver and Zembrzusi 1998). Weaver and Zembrzusi (1998) did report on a public water supply system on Cape Hatteras, which was impacted by chloride during Hurricane Emily. These researchers indicated that no private well was sampled during their study of the unconfined coastal aquifers. Information was gathered on water level and salinity. It should be noted that these aquifers were not heavily used for water supply along the shoreline.

This study differs with previous studies, in that it examines the short- and long-term impacts of the storm surge on the ability of residents and businesses to continue to use the sole-source aquifer system. In addition, this study further examines the public health issues associated with waterborne pathogens. After Katrina's landfall, the Louisiana Department of Health and Hospital (LDHH) reported that 246 public water systems had been affected by the storm (e.g. lost power or rendered inoperable) in St Tammany Parish. Of those, 222 were still under a boil order 3 months later. LDHH, in collaboration with local agencies and the USEPA, monitored public water wells and provided testing services to private residences in the affected parishes (USEPA 2006). The private residence data obtained (Taylor B, LDHH, unpublished data, 2006) indicates that, of 263 samples tested after Katrina, 2.3% were positive for fecal coliforms and 28.9% for total coliforms.

After Rita, 8.2% of the 882 samples analyzed tested positive for fecal coliforms and 39.2% for total coliforms. However, it should be noted that this database did not identify if these wells had been submerged or impacted by storm water, or if the tested wells had been previously rehabilitated (e.g. chlorinated).

### Sea level rise, land loss and faulting

Southeastern Louisiana is vulnerable to hurricanes. During the last century, 44 hurricanes and 55 tropical storms have reported landfall on the Louisiana coastline, an average of approximately one storm per year (Penland et al. 2002). Of these, 7 hurricanes and 20 tropical storms passed within 160 km of Lake Pontchartrain. One hurricane and nine tropical storms passed directly over Lake Pontchartrain; approximately one storm every decade (Penland et al. 2002).

There are three geohydrologic factors that exacerbate the vulnerability of this and many other coastal regions to storms and their associated surges: relative sea level rise, land loss, and regional faulting and associated land subsidence. The first factor is a general trend of rising relative mean sea level. Sea level rise along the Louisiana coastline, when not compounded with natural and human-induced subsidence, is believed to range between 2 and 10 mm/year (Thieler and Hammar-Klose 2000; Gonzalez and Tornqvist 2006). All five Lake Pontchartrain gaging stations indicate mean sea level is rising between 0.36 and 1.09 cm/year for different time intervals that fall within 1931 to 1988. The greatest rate of rise is for two stations nearest to the study region, but on the opposite side of Lake Pontchartrain. Both these stations have a rate of rise over 1 cm/year (Penland et al. 2002). This rise is probably a result of both general sea level rise (Ramsey and Penland 1989) and local subsidence (Kazmann and Heath 1968; Gagliano et al. 2003a).

The second factor is the loss of wetlands. Based upon digital models, ~25,000 km<sup>2</sup> of coastal Louisiana has an elevation below 1.5 m, and ~30,000 km<sup>2</sup> below 3.5 m (Titus and Richman 2001). South of Lake Pontchartrain, the wetland can act as a buffer to surging Gulf of Mexico and Lake Pontchartrain water (Stumpf 2006). Between 1932 and 1990, approximately 650 km<sup>2</sup> of wetlands were lost in the Lake Pontchartrain Basin. The projected loss of wetlands between 1990 and 2050 is estimated to be another 440 km<sup>2</sup> (Penland et al. 2002). In addition to the loss of wetlands south of Lake Pontchartrain, the shoreline of the lake has advanced inland at an average rate of 1.25 m/year over the past 150 years (Penland et al. 2002). These events result in bringing open water and storm surges closer to the center of communities such as Slidell, Lacombe and Mandeville, Louisiana (Fig. 2).

The third and last factor that affects southern Louisiana and Lake Pontchartrain is driven by tectonism and natural and anthropogenic-driven subsidence. Active tectonism within the Gulf Coast region of the US has resulted in the presence of a complex fault system throughout southern Louisiana. The location of the north shore Lake Pontchartrain has been attributed to modern fault activity (Sabate and Wiltenmuth 2003). The fault system encompasses many *en échelon* growth faults, including the Tepestate, Denham Springs-Scotlandville, and Baton Rouge faults. Together with others, these faults became known as the “Tepestate-Baton Rouge Fault System” (McCulloh 1991). The fault system delimits the edge of the lower Cretaceous shelf (Meloy and Zimmerman 1997; Pope 1998; Gagliano 1999), which is the margin of the South Louisiana Tertiary Basin (Penland et al. 2002; Lopez et al. 1997). This margin separates the subsiding buried reef to the south from the structurally uplifting area to the north (Zimmerman 1997; Gagliano et al. 2003b). The resulting growth-fault systems, based on Hamblin (1965), Adams (1997), Gagliano et al. (2003a, b, c), appears to be a reflection of the basement topography. Saucier (1963) and Durham et al. (1967) make the first mention of faulting, separating the Holocene marshes along the north shore of Lake Pontchartrain from the Pleistocene Epoch terraces. The association of the formation of Lake Pontchartrain with faulting was first suggested by Saucier (1963). Saucier (1963, 1994), Autin and Mossa (1986), and Lopez (1991) suggested that downwarping of the Pleistocene terraces, and ensuing subsidence, resulted in the formation and enlargement of the current lake. Van Biersel (2006) assigned surface displacement values to the escarpment of the fault system of up to 6 m in the vicinity of Madisonville, approximately 5 m near Mandeville, just under 3 m near Lacombe and approximately 1–2 m near Slidell (Fig. 2). In addition to the on-going tectonic activity, subsidence rates of up to 10.6 mm/year (Penland and Ramsey 1990; Shinkle and

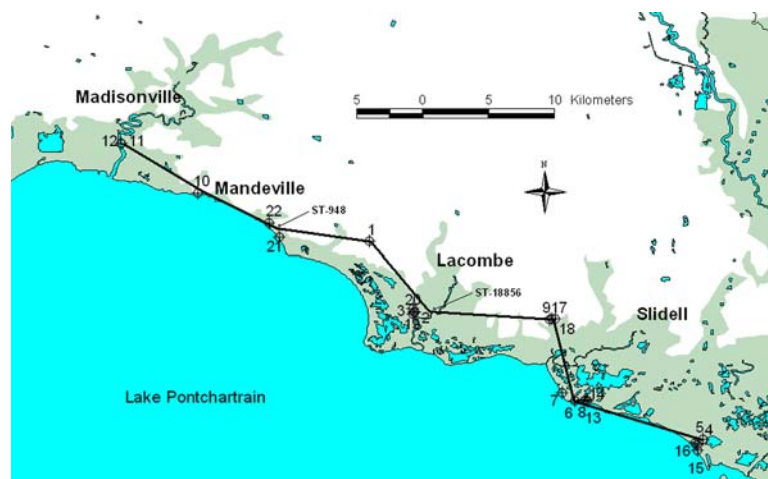
Dokka 2004) have been suggested for the Mississippi Delta and a larger portion of coastal Louisiana. These estimated subsidence values are the result of both natural (Tornqvist et al 2006; Dokka 2006) and anthropogenic (Morton and Purcell 2001; Morton et al 2002; Miller 2006) origin.

### Hurricane Katrina and storm surge water

Hurricane Katrina (Katrina) made landfall near the Southeastern Louisiana towns of Empire and Buras, on 29 August 2005 (Fig. 1). Katrina’s wind surged water into Lake Pontchartrain, affecting all the shoreline communities (Fig. 2). The communities along the north shore of the lake suffered greatly from flooding and hurricane-spawned tornadoes. The storm surge was observed in the field and ranged from 2.4 m to 3 m near Eden Isle, Louisiana (which is south of Slidell) to 1.5 m in Madisonville and Mandeville, Louisiana (Fig. 3). Storm surge in Slidell (6.4 km inland) and Lacombe (8 km inland) was approximately 1.5 m. On 21 September 2005, Hurricane Rita (Rita) struck the coast of southwestern Louisiana, sending another, but smaller, storm surge into Lake Pontchartrain. Areas previously devastated were again affected by flooding. Rita struck too quickly after Katrina to allow for the repair of wells, hence resulting in another period of flooding, and some additional intrusion of saline lake water.

Soon after Katrina’s landfall, the water chemistry of Lake Pontchartrain included elevated specific conductance, and the water samples exhibited the presence of bacteria (Stoeckel et al. 2005; Pardue et al. 2005; Hou et al. 2006). Specific conductance values ranged from 7,460 to 13,100 microSiemens ( $\mu\text{S}$ )/cm, and there was a presence of fecal coliforms and *Enterococcus*. However, there was no presence of *Escherichia coli* (*E. coli*) bacteria for samples collected in the middle of Lake Pontchartrain along the Causeway Bridge (Stoeckel et al. 2005).

**Fig. 3** Study wells and cross section location map (Office of the Governor 1999). The grey shading represents the areas flooded by Hurricane Katrina’s storm surge (modified from Federal Emergency Management Agency (FEMA) 2006; Anderson and Brakenridge 2005; and Carroll et al. 2005)



### Hydrogeological setting

Along the north shore of Lake Pontchartrain, water wells are predominantly completed in three shallow aquifers of the Southern Hills Aquifer System (Fig. 4). The three aquifers at risk within the study area include the Upland Terrace, Upper Ponchatoula, and Lower Ponchatoula. The Upland Terrace Aquifer (Lovelace and Lovelace 1995) is also known as the “shallow aquifer” and as the Gonzales-New Orleans Aquifer (Nyman and Fayard 1978; Boswell 1979; Buono 1983; Griffith 2003). This shallow aquifer is separated from the surface by a thin layer of clay, which is absent in the vicinity of Mandeville (Griffith 2003) and Lacombe. Inspection of drillers’ logs for wells sampled, and nearby wells (LDOTD water well records), indicates that the surficial clay thickness generally ranged from about 18 to 30 m. Another complication, as discussed earlier in this paper, is the presence of faulting along the north shore of the lake, resulting in a not yet quantified displacement (approximately 1 to 6 m, based on Light Detection and Ranging (LIDAR) imagery of the surface escarpment displacement) of the units (Van Biersel 2006). The deeper sands of the aquifer system are also confined throughout the study area, and subject to a limited amount of surficial recharge locally (Boniol 1988). Domestic wells in St Tammany Parish are mainly screened in the Upland Terrace (approximately 64% of domestic wells) and Upper

Ponchatoula (approximately 23% of domestic wells). Lower Ponchatoula accounts for about 11% of all domestic wells in St Tammany Parish, while deeper aquifers account for only 2% of domestic wells in St Tammany Parish. These deeper aquifers are mainly used for public supply.

The three upper sand units have maintained relatively constant heads over the past 25 years (Fig. 5). This is probably a result of the comparatively light demand on these units within St Tammany Parish (approximately  $19\text{--}23 \times 10^3 \text{ m}^3/\text{day}$ ) from rural domestic demand (Lovelace 1991; Lovelace and Johnson 1996; Sargent 2002). In addition, the area is underlain by highly conductive sands with approximate geometric mean hydraulic conductivity values as follows: Upland Terrace 7 m/day; Upper Ponchatoula 10 m/day; and Lower Ponchatoula 7 m/day (Carlson 2004).

The potentiometric surface for each of these three aquifers dips toward Lake Pontchartrain. It should be noted that the aquifers have potentiometric levels less than 6 m near the shoreline and often less than sea level (Fig. 6). This potentiometric level differential suggests that the wells damaged by storm surge and inundated with lake water for an extended period of time (several hours to days) are likely to have allowed significant quantities of water to intrude into the broken well casing and/or the associated plumbing (e.g. pressure tank, pump, etc). An exception is the Lower Ponchatoula near the shoreline of Lake

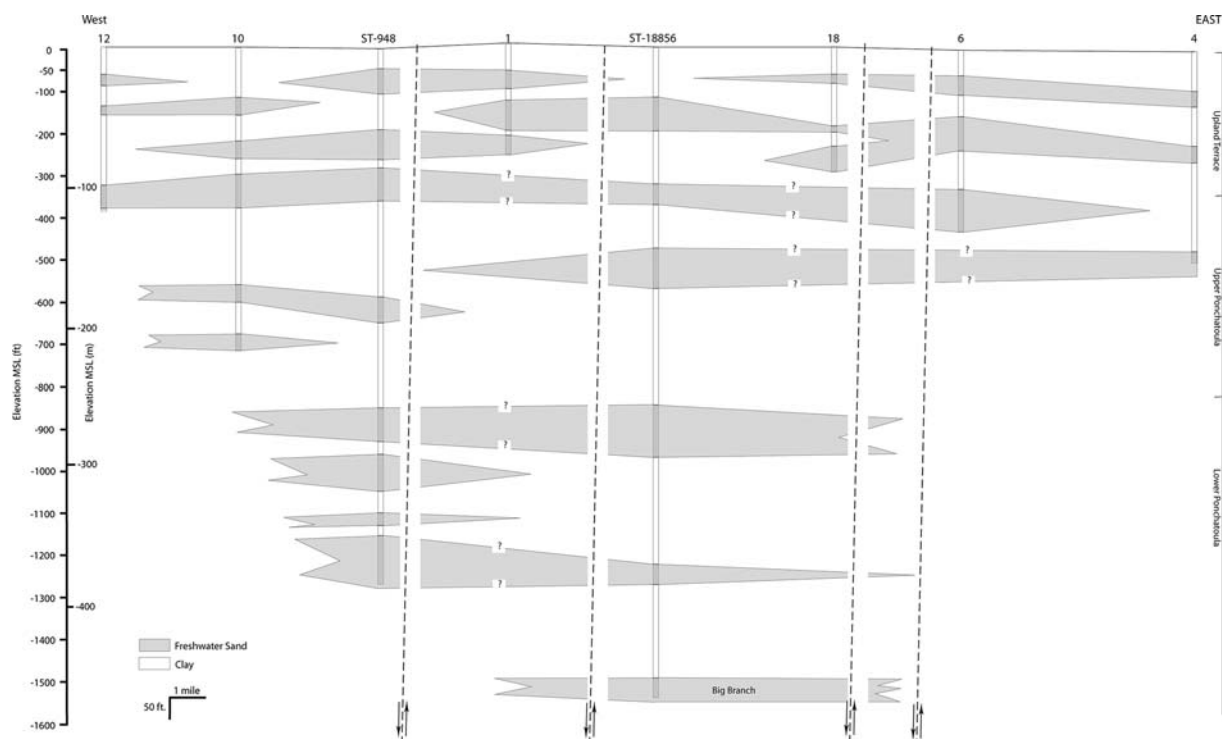
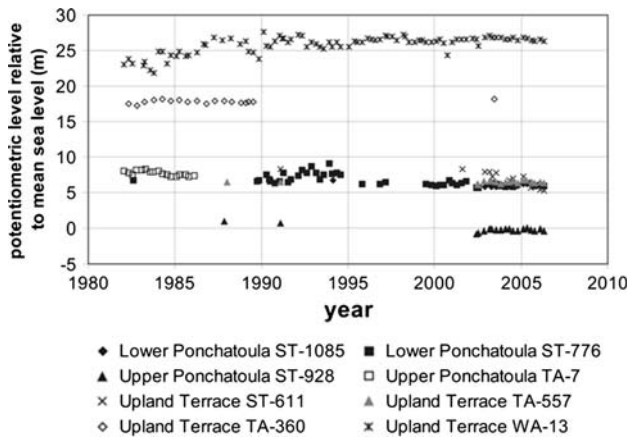


Fig. 4 Geologic cross section across the study area. The location of the cross section is included in Fig. 3)



**Fig. 5** Change in hydraulic head in the upper aquifers of the Southern Hills Aquifer System (source of data: USGS 2006)

Pontchartrain, which has higher head than the other two aquifers, and is less likely to have a hydraulic head below the storm surge level.

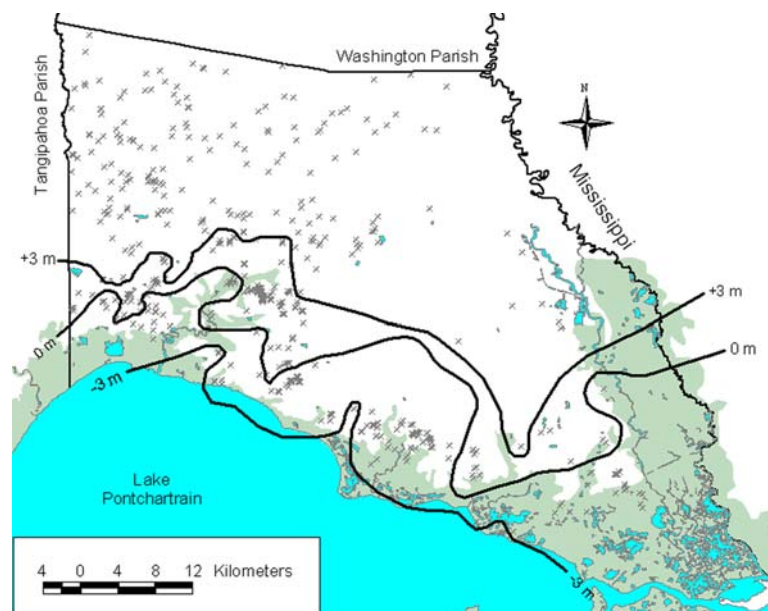
The storm surge was a problem for the few deeper wells in the shoreline area. These wells, although historically under flowing artesian conditions, now exhibit a depressed piezometric surface due to local and regional pumping. For example, the heads within deeper aquifers and associated wells are even lower than for the top three aquifers, Upland Terrace, Upper Ponchatoula and Lower Ponchatoula (Table 1). The data in Table 1 includes the arithmetic mean ( $X$ ), the standard deviation ( $\sigma$ ) and the size of the data set ( $n$ ). Hence, if any of these larger-deeper public supply or industrial wells were damaged by surge, they were likely to be impacted as well.

## Materials and methods

During September and October, 2005, samples were collected from 14 different water wells (numbered #1 through #14) over six sampling events (Fig. 3). Later, in May and June, 2006, additional samples were collected from eight of the same wells (#3, #4, #5, #6, #7, #9, #13 and #14) sampled in 2005, and eight new wells (numbered #15 through #22) where access permission was granted. The public and domestic water wells sampled were selected based upon access, functionality, safety, and location within the surge zone (Fig. 3). Wells were selected by identifying areas where multiple wells were present, and visiting those areas. The wells sampled were all operational, and permission for access was obtained. In some cases, the wells had been rehabilitated by water well drillers, including chlorination. Well construction documentation was obtained from the LDOTD, when available.

Groundwater samples were collected in accordance with standard sampling protocol of the Louisiana Geological Survey (LGS), the Louisiana Department of Environmental Quality (LDEQ) and the US Geological Survey (USGS). Water level measurements were collected, where possible, using a water level probe. The water wells were purged for approximately 20 min (approximately three well/casing volumes), prior to collecting the groundwater samples. During the purging period, pH (Hanna Instrument model HI 9811), specific conductance (Hanna Instrument model HI 9033), and temperature measurements were recorded. After purging, the groundwater samples were collected at a faucet located closest to the wellhead. The sampling faucet

**Fig. 6** Contoured hydraulic head in the Upper Terrace Aquifer (note: Only the  $-3$ ,  $0$  and  $+3$  m contours are shown). The grey shading represents the areas flooded by Hurricane Katrina's storm surge (modified from FEMA 2006; Anderson and Brakenridge 2005; and Carroll et al 2005) and the grey Xs represent water wells used to compile the data



was cleaned with methanol, prior to collection of the bacteriological samples (last sample collected).

The samples were field-preserved, acidified (if necessary) and stored in an iced cooler, in accordance with standard methods. Upon arrival at the laboratory, the samples were stored in a refrigerator, unless processed for analyses immediately. Samples were brought back to the laboratory within the 6-h time span specified by the USEPA for bacteriological analyses, unless they had been processed in the field. Samples deviating from this protocol (holding time not met) were identified as such.

Laboratory analyses performed during the fall of 2005, for organic and inorganic parameters were performed in accordance with standard testing methods by several laboratories, including the LDEQ’s laboratory in Baton Rouge, the USGS’s National Water Quality Laboratory in Denver, Colorado, and LGS’s wet chemistry lab at Louisiana State University (LSU). The samples collected in 2006 were tested by LGS only. The water samples were tested for chloride, nitrate, sulfate, orthophosphate, hardness and fluoride, using a Hach® spectrophotometer DR/2500, and using methodology adapted by Hach® from standard methodology for the examination of water and wastewater (Hach 2004). The water samples were tested for aluminum, arsenic, boron, calcium, cadmium, chromium, copper, iron, potassium, magnesium, manganese, sodium, nickel, phosphorus, lead, silica, and zinc were analyzed in Professor Robert Gambrell’s laboratory in the Wetland Biogeochemistry Institute at LSU, using a Varian ICP-OES model MPX. The bacteriological analyses for total coliform, fecal coliform, *Enterococcus* and *Escherichia coli* (*E-coli*) performed on the fall 2005 samples were completed by the USGS’s field Ohio Water Microbiology Laboratory, and by Prof. Aixin Hou’s microbiology laboratory at LSU. Starting in 2006, the analysis for total coliform and *E-coli* were performed in the field by LGS using a Millipore™ Water Test Kit. In addition, total colonies were tested on 6 June, 2005 samples using Becton,

Dickinson and Company Difco™ Hycheck™ contact slides. The field analysis was selected in order to meet the 6-h method holding time.

The 22 wells that were sampled are labeled on Fig. 3. The results from the fall 2005 analyses indicate that there were no volatile organic compounds (VOCs) present above the detection limit in any of the samples (Van Biersel et al. 2006). Although additional water quality parameters were run on the samples, this study focuses on five indicators of saltwater intrusion: specific conductance (SC); boron (B); the calcium (Ca) to magnesium (Mg) ratio; chloride (Cl); and the chloride to silica (Si) ratio (Table 2). It should be noted that well #1 was outside the area flooded, and represents a background well.

The parameters selected were identified based on their distinctive signature between fresh and seawaters. The Ca concentration of seawater is lower than that of freshwater, and the opposite is true for Mg (Hem 1985). The Ca/Mg ratio is greater (>) than one for freshwater and less than (<) one for seawater. Similarly, Cl concentration is higher in seawater than freshwater and the opposite is true for Si (Hem 1985). Therefore, a high Cl/Si ratio is characteristic of seawater. Finally, the boron concentration and specific conductance measurement is higher in seawater than freshwater.

**Results**

In this study, the post-Katrina groundwater values (Tables 2, 3) are also compared with regional pre-Katrina groundwater (Table 3) and Lake Pontchartrain surface water values (Table 3). The pre-Katrina data set consists of available (USGS 2006; Tomaszewski D, USGS, unpublished data, 2006) groundwater quality data for water wells in St Tammany Parish, and screened in the Gonzales-New Orleans (112GZNO) and Upper Ponchatoula aquifers (112PNCLU). Ground-water quality data for wells in

**Table 1** Potentiometric levels for local aquifers

Aquifer	Depth of hole (m)			Depth to water (m)			Potentiometric level relative to mean sea level (m)		
	<i>n</i>	<i>X</i>	$\sigma$	<i>n</i>	<i>X</i>	$\sigma$	<i>n</i>	<i>X</i>	$\sigma$
Upland Terrace	165	87	36	167	3.3	1.9	158	-1.2	2.2
Upper Ponchatoula	232	178	40	232	3.0	1.9	226	0.2	2.4
Lower Ponchatoula	54	278	43	54	4.5	4.4	49	-1.6	5.2
Abita/Big Branch	2	541	46	2	14.0	4.8	1	-16.4	
Covington	3	621	40	3	21.3	12.9	3	-17.5	13.7
Slidell	12	713	19	12	25.2	8.0	12	-22.3	8.5
Tchefuncte	2	802	11	2	19.0	5.4	2	-18.7	5.0

Note: These values are for aquifers in the vicinity of Slidell, LA (within Township 9 South-Range 14 East). The values were determined from initial record of water level for a well near the time of well construction

**Table 2** Post-Katrina (2005 and 2006) laboratory results for key saltwater intrusion parameters

Well #	SC ( $\mu\text{S}/\text{cm}$ )	B (mg/L)	Ca (mg/L)	Mg (mg/L)	Ca/Mg	Cl (mg/L)	Si (mg/L)	Cl/Si
1	283–292	0.5	2.88–2.96	1.39	2.1	7.4–7.76	7.6	1.0
2	597–612	<0.2	7.86–8.08	4.01–4.16	1.9–2.0	10.7–10.8	11.9	0.9
3	308–352	<0.2–0.3	0.58–0.59	0.12–0.13	4.6–4.9	3.6–4.9	15.5–17.3	0.2–0.3
4	531–24500	0.40–1.5	2.33–157	495–1.10	0.3–2.1	19.8–6730	5.5–13.5	1.6–772
5	554–723	0.49–0.73	2.11–2.22	0.86–1.02	2.2–2.6	17.5–28.0	12.6–14.6	1.4–1.8
6	625–834	<0.2–0.38	0.67–0.76	0.13–0.14	5.0–5.6	18.0–28.5	15.7–17.5	1.2–1.6
7	501–588	<0.2–0.4	1.98–2.60	1.16–1.85	1.1–2.2	16.3–26.9	6.8–8.0	2.4–3.2
8	513–1088	0.3–0.5	1.96–2.07	1.78–1.80	1.1–1.2	31.4–207	9.2–13.7	3.8–15.1
9	369–439	<0.2–0.6	1.53–1.67	0.53–0.57	2.8–3.1	7.6–10.1	8.2–9.4	0.9–1.0
10	251–271	0.4	1.04–1.19	0.46	2.6	5.3–5.9	10.7	0.5
11	247	<0.2	3.29	0.86	3.8	3.2	33.2	0.1
12	187–207	0.3	2.28–3.38	0.42–0.90	3.7–5.4	2.9–3.0	22–29.6	0.1
13	473–619	0.3–0.4	2.05–2.14	1.06–1.13	1.8–2.0	7.9–22.4	8.3–8.8	1.0–2.5
14	656–3500	0.3–0.7	16.6–41.0	1.19–48.63	0.8–1.5	18.1–318	12.3–22.1	1.5–23.8
15	537–611	0.47–0.69	1.22–1.27	0.77–0.83	1.5–1.7	17.2–17.5	12.8–12.9	1.3–1.4
16	642–652	0.49–0.90	1.65–1.66	0.67–0.76	2.2–2.5	17.6–18.4	13.0–13.1	1.3–1.4
17	398–436	0.4–0.6	2.50–2.74	0.92–0.96	2.6–3.0	6.8–6.9	7.9	0.9
18	416–433	0.4–0.6	2.00	0.78–0.84	2.4–2.6	7.2	7.6–8.0	0.9–1.0
19	276–391	0.2–0.5	0.57	0.11–0.12	4.8–5.4	4.6–6.4	15.2–15.4	0.3–0.4
20	340–354	0.2–0.5	0.35–0.36	0.06	5.7–6.0	3.6–4.2	14.7	0.2–0.3
21	279–322	0.2	3.34–3.44	1.45–1.67	2.1–2.3	6.1–8.6	7.4–7.6	0.8–1.1
22	546–567	0.2–0.3	0.90–0.94	0.07	12.9–13.6	3.0–3.7	8.9	0.3–0.4

southern St Tammany Parish [approximately bounded by Interstate 12 (north), and Lake Pontchartrain (south)] was included in the pre-Katrina data set (Table 3). In this case, the database did not specify an aquifer determination (but included other values); wells 183 m or less in depth were included among those evaluated. This set of data was used because the depths of wells sampled during this investigation, which had available well construction logs, ranged from 80 to 150 m below land surface. In case the database contained more than one pre-Katrina record for a well, the most recent and most complete record was used. The second data set (Lake Pontchartrain) included surface water chemistry from studies performed on the Lake by the USGS during 1994–1996 (USGS 2006). The data was used to obtain an arithmetic mean ( $X$ ) and the standard deviation ( $\sigma$ ). The  $n$  value represents the number of values in the dataset.

The pre-Katrina data set indicates that background chloride concentrations range between 2.2 and 39.2 mg/L ( $X = 12.8 \pm 11.4$  mg/L). This range covers a span large enough to include all but three (#4, #8 and #14) of the samples collected (Table 2). If mean is used, seven wells sampled exceed that value. Specific conductance has a smaller range for pre-Katrina values (172–688  $\mu\text{S}/\text{cm}$ ), which is exceeded in four cases (wells #4, #5, #6 and

#14). Possible changes in the chloride concentrations for the two sets of groundwater data are inconclusive, as indicated by  $t$  test statistical analysis, which yields a confidence of difference between pre-Katrina and the 2005 post-Katrina groundwater that is over 70% (Table 4). Confidence of difference is a statistical parameter used to assess whether two datasets are the same or significantly different. Confidences of difference that are below 95% are considered to be insignificant (Kirk 1990). This observation is also valid if the non-parametric Mann-Whitney rank test (Table 5) was used, which also quantifies the confidence of difference for a small not normally distributed dataset, which is the case for most of our parameters.

Two of the water wells tested (#4 and #14) were sampled relatively soon after they became operational, and prior to being chlorinated. These wells showed that, with increased purging, specific conductance (Fig. 7) and chloride concentration decreases, and the Ca/Mg increases (Fig. 8). During a ~1-h (#14) and ~4-h (#4) pump test, a reduction of up to a 34% in the chloride concentration was measured, as well as a 4.5 m (#4) and 4 m (#14) drop in the hydraulic head. Continued pumping of the well is expected to flush the saltwater stored in the well casing, and probably any saltwater that may have entered the aquifer. Based

**Table 3** Pre-Katrina and Lake Pontchartrain values for saltwater intrusion parameters

Parameter	SC (μS/cm)	B (mg/L)	Ca (mg/L)	Mg (mg/L)	Ca/Mg	Cl (mg/L)	Si (mg/L)	Cl/Si
Pre-Katrina	315 ± 178 (10)	0.46 ± 0.40 (2)	2.8 ± 1.3 (8)	1.4 ± 1.9 (9)	5.4 ± 4.7 (8)	12.8 ± 11.4 (18)	27.3 ± 13.5 (4)	0.39 ± 0.32 (4)
Lake Pontchartrain	5007 ± 2262 (52)		33.8 ± 12.6 (53)	98.1 ± 42.7 (53)	0.44 ± 0.50 (53)	1494 ± 771 (53)	4.2 ± 0.99 (53)	391 ± 203 (53)
Post-Katrina 2005	1350 ± 2884 (13)	0.56 ± 0.35 (7)	9.4 ± 20.0 (13)	19.8 ± 61.2 (13)	2.6 ± 1.6 (13)	290 ± 904 (13)	14.8 ± 7.4 (13)	27.5 ± 88.6 (13)
Post-Katrina 2006	517 ± 160 (16)	0.42 ± 0.14 (16)	1.66 ± 0.87 (16)	0.66 ± 0.50 (16)	4.7 ± 4.7 (16)	11.8 ± 6.7 (16)	11.3 ± 3.2 (16)	1.1 ± 0.6 (16)

Note: the data present is  $X \pm \sigma$  ( $n$ ); table modified from Van Biersel et al (2006)

on the specific conductance data, this decrease is not linear (Fig. 7), and may indicate that complete flushing will require some time.

The boron concentration is generally higher in seawater (~4.6 mg/L; Hem 1985) than in Louisiana groundwater [ $0.29 \pm 25$  mg/L,  $n = 1302$  (USGS 2006)]. The pre-Katrina boron (USGS 2006) value (0.18–0.74 mg/L) is limited by the fact that there are only two available data points for the shoreline dataset. If the data (USGS 2006) from the whole parish is used, the range changes to 0.009–0.74 mg/L ( $X = 0.19 \pm 0.32$  mg/L,  $n = 5$ ). If the range for the shoreline is used, only one well (#4) exceeds the upper range (0.74 mg/L). Using the mean concentration for the whole parish, all the wells except for one (#11), exceed the mean

concentration. This observation would indicate that the pre-Katrina dataset is too small. Also, the detection limit of the testing done during the fall of 2005 was higher (<2 mg/L) than the calculated mean. Furthermore, changes in the boron concentrations for the pre- and post-Katrina sets are inconclusive, as indicated by  $t$  test statistical analysis. This analysis yields a confidence of difference between pre-Katrina, and the 2005 and 2006 post-Katrina groundwater that is under 50% (Table 4). This is also consistent with the Mann-Whitney rank test (Table 5).

The Ca/Mg and Cl/Si ratios were used to assess the presence of saltwater in a freshwater system. The Ca/Mg ratio in freshwater is the inverse of the ratio in saltwater. The background calcium concentrations range between 1.2

**Table 4** Statistical comparison of averages using the  $t$ -test

Parameter	Post Katrina 2005 versus Pre-Katrina		Post-Katrina 2005 versus Lake Pontchartrain	
	$t$ test value	Confidence of difference (%)	$t$ test value	Confidence of difference (%)
SC	1.08	>70	4.84	>99.9
B	0.30	<50		
Ca	0.89	>60	5.40	>99.9
Mg	0.86	>60	5.31	>99.9
Ca/Mg	1.87	>90	8.21	>99.9
Cl	1.26	>70	5.08	>99.9
Si	2.23	>95	9.95	>99.9
Cl/Si	0.57	<50	6.21	>99.9

Parameter	Post-Katrina 2006 versus Pre Katrina		Post-Katrina 2006 versus Lake Pontchartrain	
	$t$ test value	Confidence of difference (%)	$t$ test value	Confidence of difference (%)
SC	2.88	>99	7.82	>99.9
B	0.27	<50		
Ca	2.43	>95	10.05	>99.9%
Mg	1.42	>80	9.00	>99.9
Ca/Mg	0.34	<50	6.32	>99.9
Cl	0.29	<50	8.21	>99.9
Si	4.06	>99.9	13.76	>99.9
Cl/Si	2.16	>95	7.57	>99.9

Note: Table modified from Van Biersel et al (2006)

**Table 5** Statistical Comparison of data sets using the Mann-Whitney ranks test

Parameter	Post Katrina 2005 versus Pre Katrina		Post Katrina 2005 versus Lake Pontchartrain	
	Z value	Confidence of difference (%)	Z value	Confidence of difference (%)
SC	2.11	96.4	4.30	>99.9
B	0.26	11.1		
Ca	0.47	35.5	4.52	>99.9
Mg	0.50	35.3	4.64	>99.9
Ca/Mg	1.74	91.1	4.91	>99.9
Cl	0.96	65.9	4.55	>99.9
Si	2.15	96.8	5.55	>99.9
Cl/Si	1.70	89.8	5.20	>99.9
Parameter	Post Katrina 2006 versus Pre Katrina		Post Katrina 2006 versus Lake Pontchartrain	
	Z value	Confidence of difference (%)	Z value	Confidence of difference (%)
SC	2.90	99.7	5.45	>99.9
B	0.14	5.9		
Ca	1.83	93.0	6.03	>99.9
Mg	1.08	69.9	6.03	>99.9
Ca/Mg	0.43	30.3	5.81	>99.9
Cl	0.59	42.5	6.03	>99.9
Si	3.02	>99.9	6.03	>99.9
Cl/Si	2.46	98.9	6.03	>99.9

and 5.2 mg/L ( $X = 2.8 \pm 1.3$  mg/L). Background magnesium concentrations ranged between <0.1 and 6.4 mg/L ( $X = 1.4 \pm 1.9$  mg/L). The mean background Ca/Mg ratio was  $5.4 \pm 4.7$  (Table 3). The Ca/Mg ratios for the pre-Katrina and 2005 post-Katrina data are possibly different, as confirmed by a *t* test which yielded a confidence of difference between pre-Katrina and 2005 post-Katrina groundwater that is over 90%. However, that with the 2006 post-Katrina data is <50% (Table 4). These values are consistent with the Mann-Whitney test (Table 5). The 2006 post-Katrina Ca/Mg ratio shows that, as a group, the water wells have returned to background values. The statistical test results indicate that the confidence of differences between the two post-Katrina datasets and the Lake Pontchartrain dataset is significant (Tables 4, 5).

The second ratio, Cl/Si, is a combination of two conservative environmental tracers: chloride, which has a very high concentration in saltwater but not in groundwater; and silica, which is elevated in groundwater systems, but not in meteoric and seawater (Hem 1985). The pre-Katrina water samples exhibit a Cl/Si ratio of  $0.39 \pm 0.32$ . This value is exceeded by 11 of the 14 (78%) wells tested in 2005, and in 12 of the 16 (75%) wells tested in 2006. Differences between the Cl/Si ratios for the pre-Katrina and 2005 post-Katrina data are statistically insignificant. This was indicated by the *t* test and Mann-Whitney rank test results that

yielded a confidence of difference under 95% (Tables 4, 5). This observation may be the result of the very small size of the pre-Katrina data set (only four values). In comparison, the two tests yield a statistically significant difference (>95%) between the pre-Katrina and the 2006 post-Katrina, and between the two post-Katrina datasets and the Lake Pontchartrain dataset is significant (Tables 4, 5).

As previously stated, confidence of difference is a statistical parameter used to assess whether two data sets are the same or significantly different. Confidences of difference that are below 95% are considered to be insignificant (Kirk 1990). The calculated confidences of difference between pre-Katrina and the 2005 post-Katrina mean parameters (Table 4) are insignificant, with the exception of that for Si. This may be related to the fact that the 2005 post-Katrina data set has a very large standard deviation. For the 2006 post-Katrina data set, the confidences of difference indicate that all the parameters, with the exception of boron, magnesium, Ca/Mg ratio and chloride, are significant. The confidence of differences between the two post-Katrina and Lake Pontchartrain mean parameters are greater than 99.9% for all chemical parameters tested. This can also be seen in the *t* test values, which are typically three–nine times those for the same chemical parameter between pre-Katrina, and the 2005 and 2006 post-Katrina groundwater data. The *t* test statistical analyses appear to be inconclusive for differences

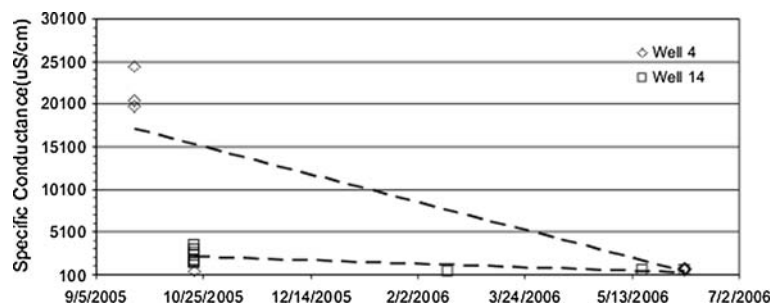
between the 2005 post-Katrina and pre-Katrina groundwater, as differences between one set of parameters are significant, but are not significantly different for seven other sets. The *t* test statistical analyses are also inconclusive between the 2006 post-Katrina and pre-Katrina water, as only four out of the eight tests show significant difference. However, post-Katrina groundwater datasets are significantly different than Lake Pontchartrain water. For all seven parameters considered, the 2005 post-Katrina groundwater has concentrations intermediate between the values for pre-Katrina groundwater and for Lake Pontchartrain water. In fact, the average values for specific conductivity, calcium, magnesium, chloride and silica indicate that 2005 post-Katrina groundwater consists of approximately 60% pre-Katrina groundwater and 40% Lake Pontchartrain surface water. The 2006 post-Katrina groundwater has concentrations substantially closer to the values for pre-Katrina groundwater and farther from the values for Lake Pontchartrain water. The average values for specific conductance, calcium, magnesium, chloride and silica indicate that the 2006 post-Katrina groundwater consist of approximately 86% pre-Katrina groundwater and 14% Lake Pontchartrain surface water. The statistical analysis of the four different types of water (pre-Katrina groundwater, the 2005 and 2006 post-Katrina groundwater, and Lake Pontchartrain surface water) indicate that the storm surge has impacted some of the groundwater wells that were sampled, which were within the storm surge zone (Fig. 3). However, the measured ion concentrations for those wells also indicate that they are returning to pre-Katrina values.

Microbiological analyses indicate that bacteria were detected in all but three (#1, #5 and #12) of the 14 wells sampled directly after the storm surge. Total and fecal coliforms were found in two and six out of the ten samples tested, respectively. *E. coli* and *Enterococcus* were found in one and three samples out of ten samples tested, respectively. It should be noted that only two wells (#4 and #14) out of the 14 sampled had not been previously chlorinated by a well contractor. Well #4 also showed that, over the time period of the study, the bacterial count dropped to <1, although it had not yet been chlorinated. In the June, 2006, sampling round, none of the samples collected tested positive for total coliform and *E. coli*, however, tests for total colonies indicate the presence of a large amount of unidentified bacteria in 10 of the 15 wells sampled. It should be noted that out of the 15 wells sampled in 2006, 4 are not in continuous use.

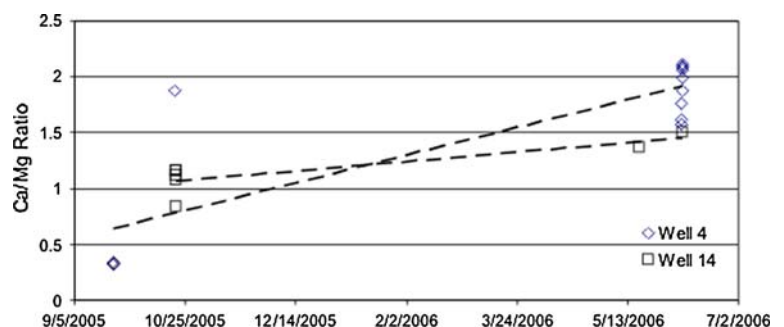
**Discussion**

Eight indicator parameters were used to evaluate whether the surge water from hurricane Katrina and Rita entered shallow aquifers. The surge water intruded into the aquifers through storm-damaged water wells inundated by the storm surge. The study used the concentrations of boron, calcium, chloride, magnesium and silica, as well as the Ca/Mg and Cl/Si ratios, and specific conductance, to determine whether saltwater intrusion occurred in the aquifers. Analyses of the post-Katrina groundwater samples exhibit a rapid

**Fig. 7** Specific Conductivity changes over time at wells #4 and #14



**Fig. 8** Specific Conductivity and Ca/Mg ratio changes over time at wells #4 and #14



increase in chloride, boron, calcium, magnesium, and specific conductance. In addition, the samples exhibit an increase in the Cl/Si ratios, and a decrease in Ca/Mg. The low Ca/Mg and high Cl/Si ratios, in combination with elevated specific conductance and elevated chloride and boron concentrations are indicative of saltwater intrusion in the 2005 samples. Statistical comparison reveals that the difference between pre-Katrina and 2005 post-Katrina groundwater is significant for silica concentration and, possibly the Ca/Mg ratio (Table 4), which have confidences over 95 and 90%, respectively. By comparison, all parameters measured for post-Katrina groundwater and Lake Pontchartrain water have confidence of differences over 99%.

Based on the results of groundwater testing, using the eight saltwater intrusion tracers (calcium, magnesium, boron, chloride, silica, Ca/Mg ratio, Cl/Si ratio and specific conductance), it can be established that wells #4, #5, #6, #7, #8, #13 and #14 exhibit a significant deviation from the expected pre-Katrina values. In addition, wells #2, #9, #15 and #16 exhibit a smaller deviation from pre-Katrina values. Of the remaining wells, four were relatively well protected (#11, #12, #17 and #18), and one is under a strong artesian flowing condition (#22). Wells #2 and #3, near Lacombe, had been severely flooded during the storm surge, but did not exhibit changes in the tracer concentrations. However, visual inspection at the time of sampling indicated that the water had been contaminated, at least by particulate matter. The variability in the 2005 post-Katrina samples is also relative to the fact that some of the wells had been rehabilitated, and pumped more than other wells by the time they were sampled. Only one well (#4) had not been rehabilitated and/or purged prior to this study. All other wells are, or can be, used by the property owners and have been rehabilitated by a water well contractor.

All but three water wells had measurable bacterial counts. Coliform bacteria (total and/or fecal) were found in 67% of the 2005 samples. Similarly, the 2005 samples detected *Enterococcus* in 33% of the samples, and *E coli* in more than 10% of the samples tested. All but two of the samples tested in 2005 grew bacteria on the medium. In 2006, all but four samples grew bacteria, and only one grew total coliform colonies.

It was observed during this study that the water wells (#4 and #14) equipped with submersible pumps, and with larger casings (10 cm in diameter), appear to have been impacted the most. Because the wells with submersible pumps are usually vented to the atmosphere, some of the openings provided an avenue for the surging floodwater to enter the casing during the inundation. However, most of the water wells were equipped with an aboveground centrifugal pump and had smaller casings (5 cm in diameter). The smaller casing and the foot valve associated with the

aboveground pump plumbing appeared to give those wells some protection against the intruding floodwater.

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