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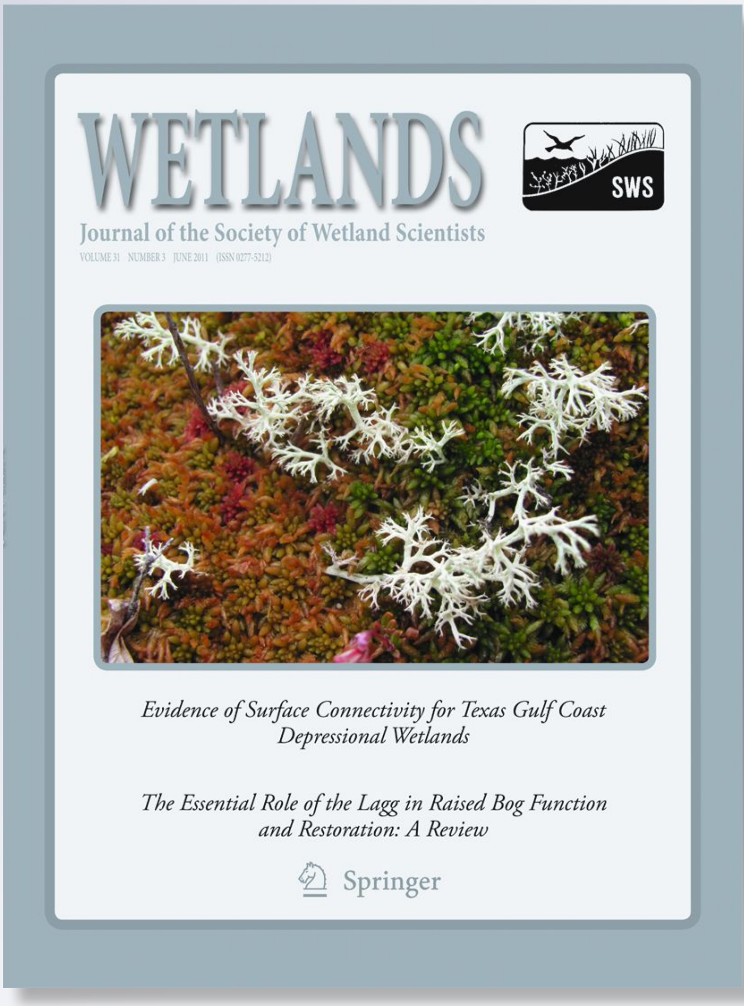

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ARTICLE

Acute Physicochemical Effects in a Large River-Floodplain System Associated with the Passage of Hurricane Gustav

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Abstract On 1 September 2008, Hurricane Gustav passed over the Atchafalaya River Basin (ARB) in south-central Louisiana. Anticipating physicochemical shifts due to concentrated precipitation and wind stress generated by this strong category 2 storm, we deployed a continuous recording multiparameter water quality sonde in a southern ARB bayou 3 days prior to storm arrival to document conditions before, during, and after hurricane landfall. Quarter-hourly physicochemical measurements taken over a 2-week period indicated that dissolved oxygen (DO), pH, and specific conductance all reached annual lows immediately following storm passage. The most pronounced post-storm fluctuation involved DO. Daily mean DO concentration dropped to hypoxic level (DO≤2 mg/L) within 3 days of landfall, followed by near anoxic conditions within 5 days that resulted in extensive system-wide fish kills. Within 6 weeks, however, DO returned to, and pH was near pre-storm levels. To evaluate the impact of Hurricane Gustav on ARB physicochemistry, we contrasted data on DO, pH, temperature, and specific conductance collected from 16 lower ARB sampling sites over a 54-day interval prior to storm landfall with data collected during a 45-day post-storm period. Results indicated that water quality was highly dissimilar ($P<0.0001$) between the two periods.

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Keywords Atchafalaya River Basin · Dissolved oxygen · Hypoxia · Louisiana · Water quality

Introduction

Hurricane Gustav made landfall near Cocodrie, Louisiana on 1 September 2008, as a strong category 2 hurricane on the Saffir-Simpson scale with measured wind speeds in excess of 166 km/h and tropical storm force winds extending approximately 321 km from the eye wall (Beven and Kimberlain 2009). As the hurricane passed over the lower Atchafalaya River Basin (ARB) in south-central Louisiana (Fig. 1), it deposited up to 250 mm of rainfall (Grumm 2008) and produced extensive defoliation. Within 2 weeks of Hurricane Gustav, Hurricane Ike made landfall on 13 September 2008 approximately 483 km west of the ARB in Galveston, Texas as a category 2 storm with 175 km/h winds (Berg 2009). Although the ARB was not in Hurricane Ike's direct path, the immense size and intensity of the storm generated significant precipitation and hurricane force winds throughout southern Louisiana (Berg 2009).

Researchers have documented various environmental characteristics of the ARB (e.g., rainfall and runoff patterns, Denes and Bayley 1983; circulation, thermal, and chemical cycles, Sabo et al. 1999a; seasonal hypoxia, Sabo et al. 1999b; and nitrogen budgets, Xu 2006), but there is limited information about the physicochemical changes associated with storms such as Hurricane Gustav that are not infrequent phenomena along the Gulf coast. Because of the difficulty in predicting the landfall of a hurricane, researchers often rely on variations in long-term organismal monitoring programs (Stevens et al. 2006) or inter-annual changes in biogeochemical cycles (Paerl et al. 2001) to assess both temporary and

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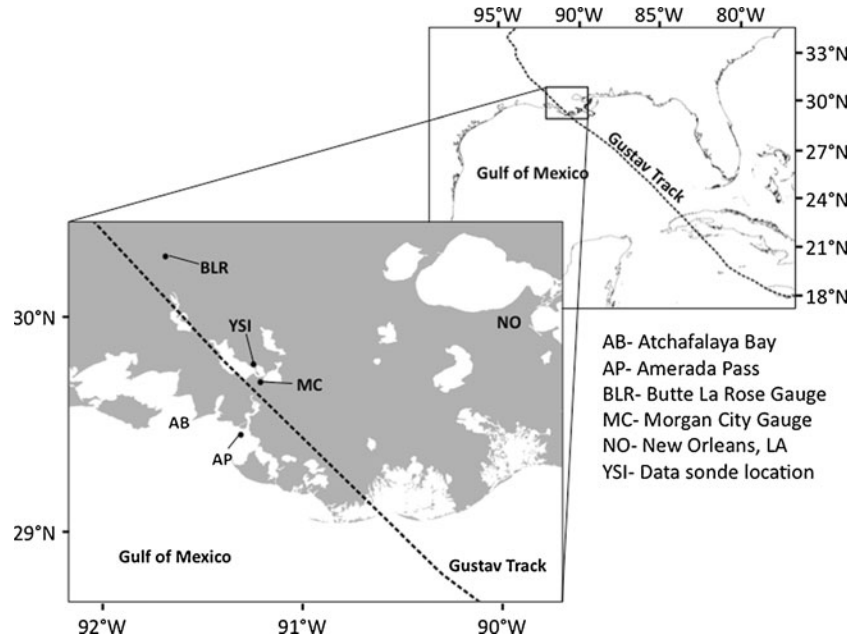
Fig. 1 Hurricane Gustav's track across south-central Louisiana and the lower Atchafalaya River Basin on 1 September 2008



longer-term impacts associated with large-scale storms. Although multiple studies have documented storm-related shifts in the density, distribution, and composition of various aquatic biota, such as benthic macrofauna (Balthis et al. 2006; Poirrier et al. 2008), decapods (Knott and Martore 1991), fishes (Greenwood et al. 2006; Paperno et al. 2006; Stevens et al. 2006; Van Vrancken and O'Connell 2010), and aquatic plants (Havens et al. 2001; James et al. 2008; Jin et al. 2011), most studies do not have real-time environmental data directly associated with passage of the storm. Further, although considerable research has addressed storm-related impacts on ecosystem-level physical processes such as deleterious nutrient cascades (Paerl et al. 2001) and episodic hypoxia events (Stevens et al. 2006), most hurricane related studies have chronicled conditions in brackish systems. As a result, post-hurricane conditions in freshwater ecosystems remain largely unknown and to our knowledge, no study has collected continuous water quality data or examined short-term physicochemical variability following storm landfall. In this paper, we present quarter-hourly physicochemical data in the days before, during, and for over a week after the passage of Hurricane Gustav, examine water quality fluctuations over a 3 month period prior to and following the storm from periodic water quality assessments, and characterize changes in river stage in the aftermath of sequential hurricanes in this large river-floodplain ecosystem.

Study Area

The ARB in south-central Louisiana is the largest remaining bottomland hardwood river-floodplain system in North America (Lambou 1990) and is comprised of shallow headwater and backwater lakes, numerous bayous and excavated petrochemical canals, and seasonally flooded swamps (Rutherford et al. 2001). The Atchafalaya River, the dominant feature of the ARB and a major distributary of the Mississippi River, receives 30% of the combined volumes of the Mississippi and Red Rivers. The U. S. Army Corps of Engineers regulates the amount of water entering the system through the Atchafalaya River with various water control structures. Although the annual timing, magnitude, and duration of the flood pulse varies, typically, the ARB is inundated in the spring followed by a pronounced drawdown period lasting from late summer to early fall (Denes and Bayley 1983; Lambou 1990; Fontenot et al. 2001; Bonvillain et al. 2008). During periods of inundation, the ARB forms a nearly continuous water body. However, anthropogenic modifications (levee and canal construction and flood control structures) have altered the historic river-floodplain connectivity resulting in increased sedimentation (Hupp et al. 2008) and reduced water circulation and flow patterns that often prompts the formation of hypoxic conditions (dissolved oxygen [DO]≤2 mg/L; Sabo et al. 1999b).

Methods

On 29 August 2008, 3 days prior to Hurricane Gustav's landfall, a continuous recording multiparameter water quality sonde (YSI model 6600, Yellow Springs, Ohio) was secured to the base of a tree approximately 0.75 m below the surface in Little Bayou Jessie (29°46' N, 91°14' W), a bayou located in the southeastern ARB (Fig. 1). Because Little Bayou Jessie consistently had the highest DO concentrations in our study area and hypoxia was not recorded during 2008 sampling prior to the passage of Hurricane Gustav, we selected this location for sonde deployment to observe hurricane associated physicochemical fluctuations. DO (mg/L), temperature (°C), specific conductance (mS/cm), pH, turbidity (NTU), and relative depth (m; the change in water level relative to the deployment depth of the sonde) were recorded at 15 min intervals (n=96 observations per day) until sonde retrieval on 10 September 2008. Because of OBS sensor malfunction, turbidity measurements were only obtained through 5 September 2008. Wind velocity (m s^{-1}) and barometric pressure (mbar) observations were obtained from the nearby Amerada Pass Meteorological Station (Fig. 1; National Oceanic and Atmospheric Administration, gauge 876422).

From 7 March 2008 to 2 March 2009 we collected surface DO, temperature, specific conductance, and pH every 2 to 4 weeks with a handheld multiparameter water quality sonde (YSI model 6820, Yellow Springs, Ohio) at 16 sample locations located in a 40 km^2 area of the southeastern ARB. Sample locations included habitats that are typically found throughout the lower ARB (e.g., bayous and canals) and exhibit variable morphological characteristics, flow velocities, river-floodplain connectivity, and macrophyte density and composition. Daily stage of the Atchafalaya River was obtained from the U. S. Army Corps of Engineers recording gauges located at Morgan City (gauge 03780, 29°41’47” N, 91°12’39” W) and Butte La Rose (gauge 03120, 30°16’57” N, 91°41’17” W), Louisiana (Fig. 1).

To assess the physicochemical effects of Hurricane Gustav, we grouped and then contrasted water quality observations at the 16 sampling locations for three consecutive sampling dates preceding (pre-Gustav, 54-day period prior to the arrival of the hurricane) and following (post-Gustav, 45-day period after hurricane landfall) storm passage. Pre-Gustav sample dates included 9 July, 28 July, and 12 August, whereas post-Gustav sample dates included 9 September, 24 September, and 16 October. The temporal periods selected for analysis include both the seasonal low DO concentration and DO recovery after storm passage. Principal components analysis (PCA) with a varimax rotation was used to examine pre- and post-Gustav physicochemical differences in DO, temperature, specific conductance, and pH from each period, and we retained principal components (PC) with eigenvalues greater than 1 (PC1 and PC2) and physicochemical variables with correlations greater than 0.4 for subsequent analysis (Hardle and Simar 2007). Pre- and post-Gustav PC scores were plotted on PC1 and PC2 to graphically examine hurricane-related differences among sites. Multivariate analysis of variance (MANOVA) with a Tukey-Kramer *post hoc* adjustment was used to examine statistically significant physicochemical differences between pre- and post-Gustav groups and between individual sample dates (SAS 9.1.3 2003). Physicochemical univariate results from MANOVA analysis were interpreted when models were significant. Significance for all statistical tests was determined at an α= 0.05 level.

Results

During the 2 days prior to the arrival of Hurricane Gustav, Little Bayou Jessie daily water quality from sonde observations were relatively predictable (Fig. 2). Once the hurricane made landfall, however, daily mean water temperature dropped over 2°C and considerable variation was measured in both DO and water level (Fig. 2). The large water level oscillations observed in Little Bayou Jessie as well as at Amerada Pass coincide with increased wind velocities and a pronounced drop in barometric pressure associated with the passage of the hurricane (Fig. 3). Barometric pressure lows recorded at Amerada Pass during Hurricane Gustav have the potential to introduce relative depth error up to 0.29 m in Little Bayou Jessie sonde measurements. Although DO concentration degraded substantially 48 h after hurricane passage, the daily mean DO level (3.91±0.10 mg/L) did not become hypoxic until 4 September, 3 days post-Gustav landfall (1.43±0.05 mg/L, daily maximum=2.04 mg/L; Fig. 2). By 7 September, 6 days post-Gustav landfall, daily mean DO concentration was near anoxia (0.17±0.00 mg/L; Fig. 2), where it remained until sonde retrieval on 10 September. DO declined at a rate of 0.18 mg/L/h until it reached hypoxia where the declination rate then slowed to 0.02 mg/L/h as levels approached anoxia (0.16 mg/L). The decline in post-storm DO was accompanied by a steady drop in pH (Fig. 2). Additionally, peak turbidity measurements were recorded during hurricane passage (Fig. 2). Hurricane Gustav effects were also evident with an Atchafalaya River stage increase at Morgan City and perceptible declines in mean DO, pH, and specific conductance levels, each reaching an annual low immediately following storm passage at the 16 sample locations (Fig. 4).

The PCA yielded two PCs (PC1 and PC2) with eigenvalues greater than 1.0 that explained 76% of the physicochemical variation between pre- and post-Hurricane Gustav observations. Temperature and specific conductance were positively correlated with PC1 (0.95 and 0.93, respectively), whereas DO and pH were positively correlated with PC2 (0.97 and 0.44). Plots of site scores on PC1 and PC2 revealed a pre-Gustav (9 July, 28 July, and 12 August) group overlapping across sample dates (Fig. 5), with most sites characterized by higher water temperatures and elevated specific conductance. Substantial variation occurs on 12 August as sites were recovering from seasonal

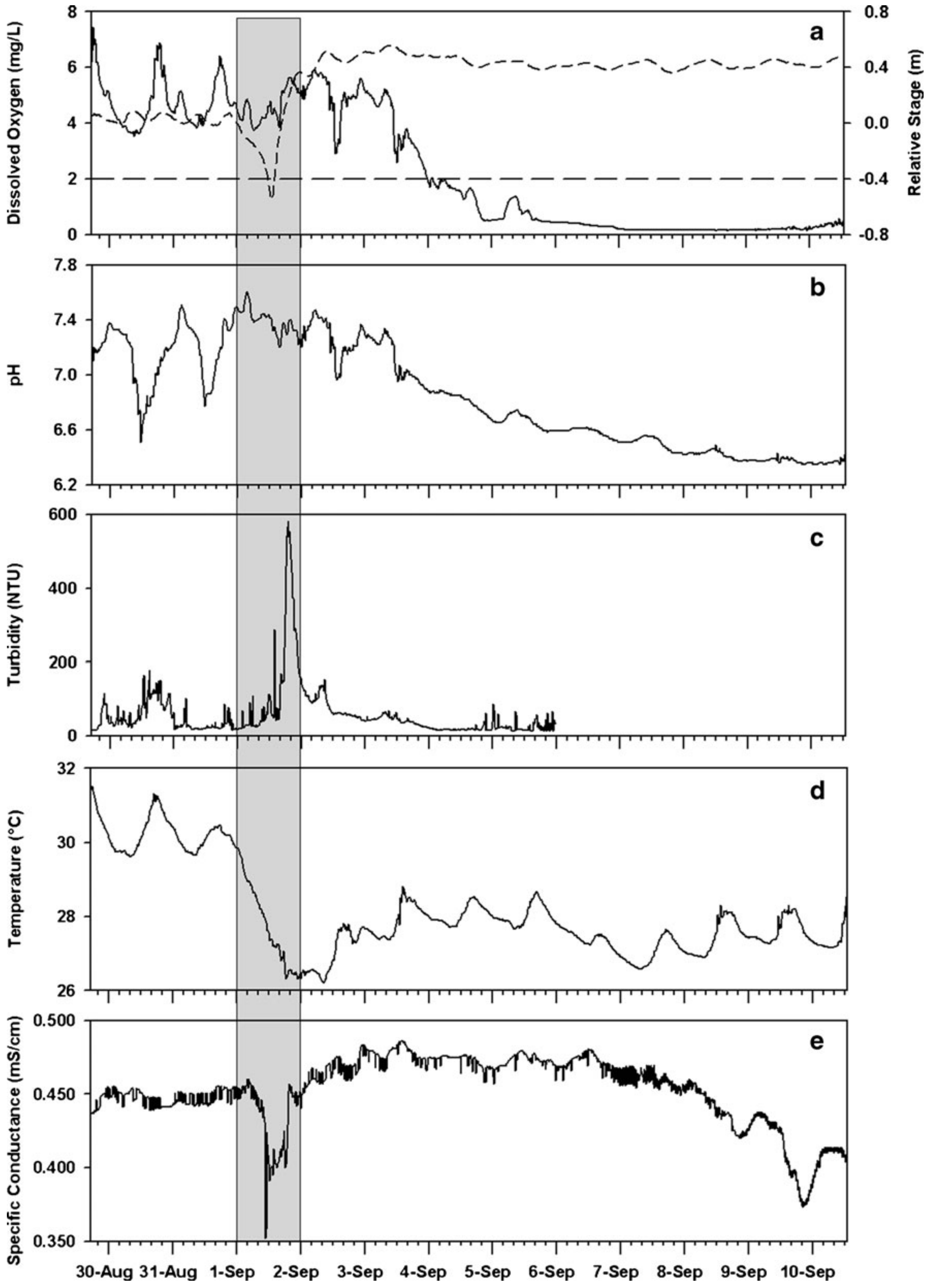


Fig. 2 Quarter-hourly sonde physicochemical measurements from 29 August to 10 September 2008 in Little Bayou Jessie located in the lower Atchafalaya River Basin. Hurricane Gustav made landfall on 1 September 2008. (**a**) Dissolved oxygen (*solid line*) and relative stage (*short broken line*), (**b**) pH, (**c**) turbidity, (**d**) temperature, and (**e**) specific conductance. The dashed horizontal reference line on the dissolved oxygen graph (**a**) indicates hypoxic level (dissolved oxygen≤2 mg/L). The grey box is a representative 24 h temporal domain that captures hurricane passage over the sample area

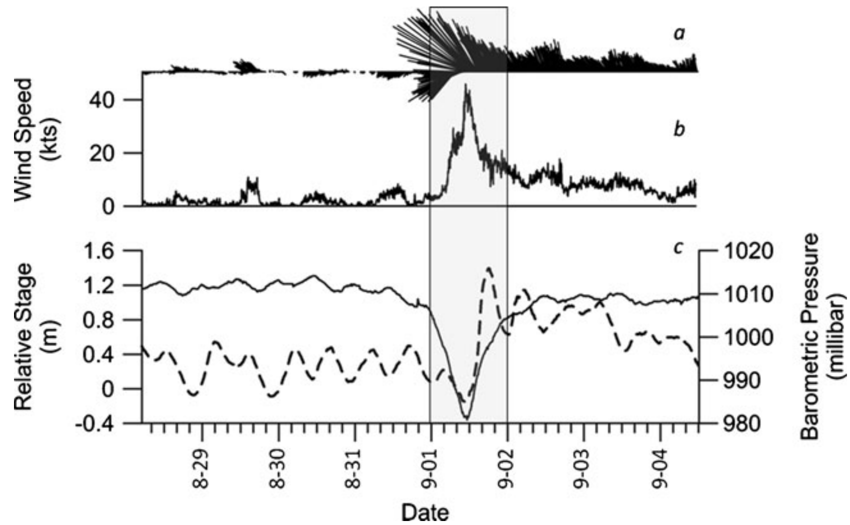


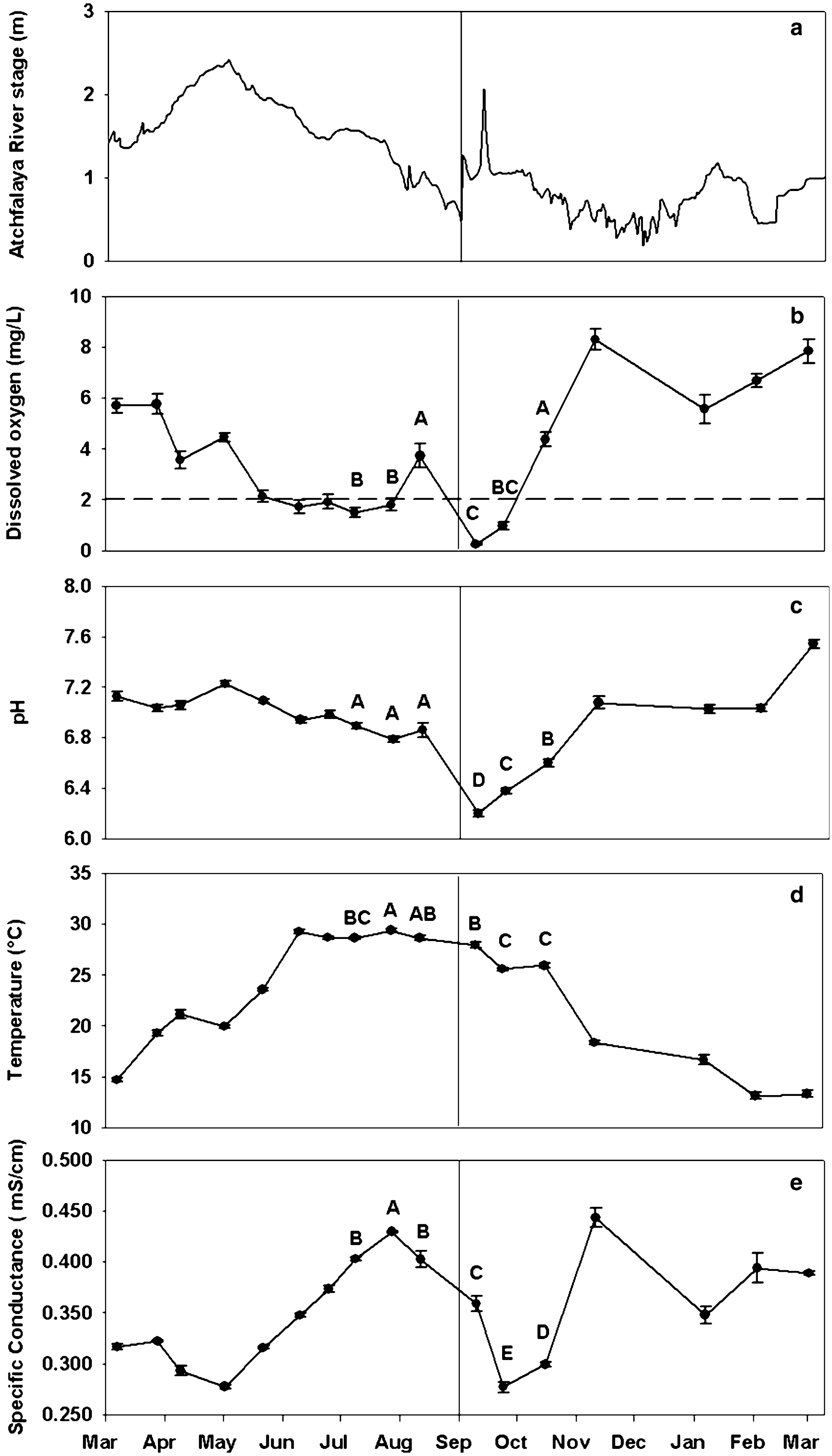
Fig. 3 Meteorological and water data obtained from Amerada Pass (National Oceanic and Atmospheric Administration, gauge 876422) associated with passage of Hurricane Gustav. (**a**) Wind velocity vectors (vectors point in the direction of the wind and indicate wind magnitude), (**b**) wind speed measurements, and (**c**) relative stage (*broken line*) and barometric pressure (*solid line*) from 28 August to 4 September 2008. The grey box is a representative 24 h temporal domain that captures hurricane passage over the sample area

DO and pH lows at various rates. Conversely, post-Gustav observations (10 September, 24 September, and 16 October) tended to separate by individual sample date and displayed a trend of increasing DO and pH and decreasing temperature as date increased. Although decreased temperatures and specific conductance largely influence separation of post-Gustav sample dates, all sample sites display similar temporal physicochemical recovery following Hurricane Gustav. Overall differences in physicochemistry between pre- and post-Gustav sample dates were evident (MANOVA, Wilks' Lambda=0.10, $F_{4,91}$=209.29, $P<0.0001$), which were also reflected by each of the physicochemical parameters between the two periods ($P<0.0001$). Additionally, physicochemical comparisons among sample dates (n=6) revealed that pH and specific conductivity for post-Gustav sample dates were dissimilar from each other and from all pre-Gustav dates (Fig. 4). Initially, post-Gustav DO concentrations were lower than pre-Gustav DO observations in the weeks prior to the storm, but concentrations had already surpassed 12 August levels by 16 October (Fig. 4). Although there was a clear physicochemical shift following the passage of both storms, water quality observations suggested that conditions were returning to 12 August pre-storm levels throughout the sample area within 6 weeks of the passage of hurricanes Gustav and Ike (Fig. 4). Water quality changes were accompanied by a substantial increase in discharge from the Atchafalaya River (Fig. 6).

Discussion

As Hurricane Gustav made landfall on the morning of 1 September, water depth in Little Bayou Jessie fell 0.54 m (Fig. 2) as northwest winds (Fig. 3) transported water south and out of the bayou. Following eyewall passage, winds shifted to the southeast (Fig. 3), pushing water northward, which resulted in a Little Bayou Jessie depth increase greater than 1 m (Fig. 2). The relatively consistent specific conductance measurements as the storm passed over the system suggest that the storm surge in Little Bayou Jessie was not coastal or estuarine in origin (Fig. 2). Given that Little Bayou Jessie drains into the northwest portion of Flat Lake, a shallow, freshwater lake (~ 3 m deep) in the southern portion of the study area and ARB, the observed depth oscillations were probably produced by a combination of Flat Lake surge coupled with variable flows and intermittent connectivity across much of the floodplain (Fig. 2). As the high-intensity, unidirectional winds generated by Hurricane Gustav subsided, Little Bayou Jessie depth began to return to pre-storm levels, coincident with a rapid turbidity spike (Fig. 2). This phenomenon is likely attributable to the mixing of different water masses as well as an increased suspended sediment load entering Little Bayou Jessie as the system drained.

Pervasive hypoxia is a common result following hurricane passage in coastal and near-coastal ecosystems (Tilmant et al. 1994; Mallin et al. 1999; Paerl et al. 2001; Mallin et al. 2002; Burkholder et al. 2004; Balthis et al. 2006; Stevens et al. 2006; Tomasko et al. 2006; Poirrier et al. 2008). In Little Bayou Jessie, DO concentrations became hypoxic less than 72 h after Hurricane Gustav made landfall, and reached near anoxic levels 5 days post-storm (Fig. 2). Prior to the passage of Hurricane Gustav, DO concentrations in Little Bayou Jessie never reached hypoxic levels during 2008 daytime sampling. Potential mechanisms for hurricane associated DO declines can be attributed to increased allochthonous inputs and subsequent decomposition (Van Dolah and Anderson 1991; Balthis et al. 2006), elevated biochemical oxygen demand levels (Mallin et al. 1999; Mallin et al. 2002; Tomasko et al. 2006), and wind-driven resuspension of benthic sediments (Jin et al. 2011) that can increase sediment oxygen demand rates and reduce water column DO concen-



Atchfalaya River stage (m)
3
2
1
0
a
Dissolved oxygen (mg/L)
10
8
6
4
2
0
b
A
B
B
C
BC
A
pH
8.0
7.6
7.2
6.8
6.4
6.0
c
A
A
A
D
C
B
Temperature (°C)
35
30
25
20
15
10
d
BC
A
AB
B
C
C
Specific Conductance (mS/cm)
0.500
0.450
0.400
0.350
0.300
0.250
e
B
A
B
C
E
D
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Jan
Feb
Mar

Fig. 4 Mean (±SE) physicochemical measurements from sample locations ($n=16$) in the lower Atchafalaya River Basin from 7 March 2008 to 2 March 2009. The vertical line on each graph represents Hurricane Gustav landfall on 1 September 2008. Results of the *post hoc* (Tukey-Kramer) comparisons of physicochemical variables between sample dates are given; different letters within a physicochemical parameter indicate a significant difference by date ($P<0.05$). (**a**) Daily Atchafalaya River stage at Morgan City, Louisiana (U. S. Army Corps of Engineers gauge 03780), (**b**) dissolved oxygen, (**c**) pH, (**d**) temperature, and (**e**) specific conductance. The dashed horizontal line on the dissolved oxygen graph (**b**) indicates hypoxic level (dissolved oxygen≤2 mg/L)

trations (Wainright and Hopkinson 1997; Hickey 1998; Matlock et al. 2003; Waterman et al. 2011). Additionally, elevated riverine discharge (Fig. 6) and increased turbidity likely reduced the euphotic zone, leading to decreased phytoplankton production (Tilmant et al. 1994; Mallin et al. 1999; Mallin et al. 2002; Burkholder et al. 2004; James et al. 2008), temporally shifting the productivity of the system towards heterotrophy. Daily sonde pH measurements in Little Bayou Jessie began to decline on 4 September and coincide with DO decreases that suggest the presence of elevated carbon dioxide and hydrogen ions associated with the onset of anaerobic conditions throughout the water column (see Makkaveev 2009). Interestingly, DO returned to, and pH was near 12 August pre-Gustav levels within 6 weeks (Fig. 4) despite the passage of Hurricane Ike on 13 September. Although Ike made landfall almost 500 km west of the ARB, strong winds and rain associated with the storm triggered rapid, sustained fluctuations in the Atchafalaya River. These fluctuations lasted for 3 weeks (Fig. 6) and are likely the reason for the delayed return of specific conductance to pre-Gustav level (Fig. 4). While it is unclear if Hurricane Ike prolonged post-Gustav DO and pH recovery in the ARB, it does not appear to have significantly hindered improvement.

In the ARB, hypoxic conditions generated by the arrival of the flood pulse tend to occur gradually, allowing aquatic organisms the opportunity to acclimate to reduced oxygen levels or relocate to more favorable environments (Rutherford et al. 2001). Mean rate of oxygen decline in the lower ARB during a typical flood pulse is approximately 0.06 mg/L/day (C. P. Bonvillain unpublished data). Consequently, large non-storm related fish kills are typically not experienced during the ARB flood pulse. Conversely, acute hurricane-associated reductions in DO can result in extensive fish mortality (Tabb and Jones 1962; Knott and Martore 1991; Tilmant et al. 1994; Mallin et al. 1999; Mallin et al. 2002; Burkholder et al. 2004) and lead to observed changes in fish community abundance and composition (Greenwood et al. 2006; Paperno et al. 2006; Stevens et al. 2006; Van Vrancken and O'Connell 2010). Because of rapid oxygen decline rates (4.32 mg/L/day to hypoxia then 0.48 mg/L/day to near anoxia), we observed near anoxic conditions at all 16 sample stations less than a week (0.23 mg/L mean DO concentration, Fig. 4) after Hurricane Gustav. Fishes probably had limited opportunity to find suitable oxygen refugia which resulted in an extensive fish kill estimated at 128 million individuals throughout the ARB (LDWF 2008).

It is difficult to predict how environmental conditions in coastal ecosystems (both freshwater and brackish) oscillate in response to the passage of a hurricane because of variability in storm severity and point of landfall. In the ARB, spatially extensive and temporally persistent hypoxia (Sabo et al. 1999b; Rutherford et al. 2001) is associated with widespread overbank flooding and rising water temperatures in late

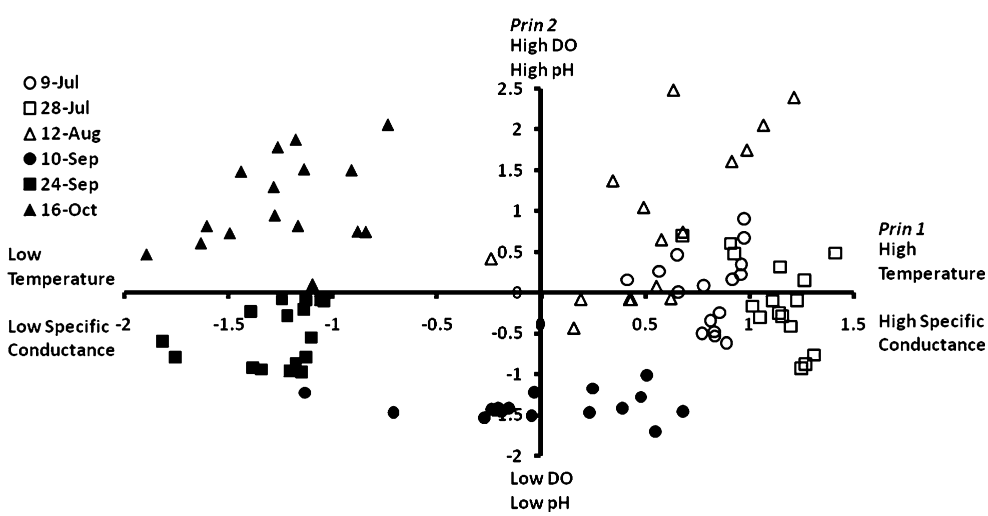


Fig. 5 A bi-plot of principal components analysis of pre- and post-Gustav physicochemical parameters (dissolved oxygen, pH, temperature, and specific conductance) collected at multiple sample locations ($n=16$) in the lower Atchafalaya River Basin during 2008. Open shapes are pre-Gustav sample dates (9 July, 28 July, and 12 August) and filled shapes are post-Gustav sample dates (10 September, 24 September, and 16 October). Multivariate analysis of variance detected a significant difference between pre- and post-Gustav physicochemistry (Wilks' Lambda=0.10, $F_{4,91}=209.29$, $P<0.0001$)

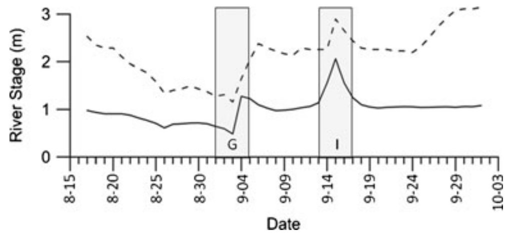


Fig. 6 Atchafalaya River stage at Butte La Rose (broken line) and Morgan City (solid line; U. S. Army Corps of Engineers gauges 03120 and 03780 respectively), Louisiana from 15 August to 3 October 2008. Hurricane Gustav (G) made landfall on 1 September and Hurricane Ike (I) made landfall on 13 September during 2008. The grey box represents a 96 h period that includes the passage of each storm

spring (Kaller et al. 2011). At the end of the flood pulse, hypoxic water on the inundated floodplain moves to canals, bayous, and lakes as Atchafalaya River stages decline (Sabo et al. 1999b; Fontenot et al. 2001), with DO recovery typically occurring after floodplain disconnection when water levels stabilize and primary production increases (Rutherford et al. 2001), often over a period of months. Our observations indicate that DO concentrations were already past seasonal lows by late summer in 2008, so the recovery time for ARB water quality after Hurricane Gustav was rapid relative to recovery from the flood pulse (Fig. 4). An earlier strike might have overlapped with floodplain dewatering and could have prolonged sub-optimal oxygen conditions at the end of the flood pulse, whereas arrival of a storm later in the year would usually coincide with higher DO concentrations and lower water temperatures, perhaps weakening the severity and duration of post-storm hypoxia.

The increased understanding from this study of physicochemical changes following hurricane passage has implications for water management decisions in the ARB prior to and after storm landfall. We suggest that flood management practices in the ARB be evaluated regarding water releases and flooding potential after major storms, because if releases are feasible, an opportunity may exist to reduce storm-related impacts to the ARB, a situation that is not common among northern Gulf coast ecosystems. Because flows into the Atchafalaya River can be controlled, increased releases of oxygenated Mississippi River water into the ARB following a hurricane could help mitigate declines in physicochemical conditions, shorten recovery times, and perhaps reduce the probability of storm-related fish kills. However, sustained post-storm discharge in the Atchafalaya River could compromise levees damaged in the initial strike of a powerful storm and exacerbate flooding threats to Morgan City and other coastal areas.

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