Temperature and Salinity Estimation in Estuaries of the Northern Gulf of Mexico

Prepared for:

NOAA

Prepared by:

Trent McDonald
Andrew Telander
Peter Marcy
Jacob Oehrig
Amelia Geggel
Henry Roman
Sean Powers

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Abstract

In 2010, in response to the encroaching oil from the Deepwater Horizon oil spill (DWH spill), Louisiana opened its Davis Pond and Caernarvon salinity control structures in an attempt to protect the shore from oil. These structures directed large amounts of river water into Barataria Bay and Black Bay/Breton Sound in the spring and summer months of 2010. In order to determine the impact of this river water influx, we developed a model to estimate changes in salinities before and after the DWH spill. This model incorporates salinity and temperature data collected between 2005 and 2012 by eleven governmental agencies across the northern Gulf of Mexico. Three agencies operated a total of 308 continuous monitoring stations during this period; nine agencies analyzed discrete water samples collected at 3,860 distinct locations (one agency generated both types of data). Using spatio-temporal kriging models applied to all available data, we estimated daily salinity and temperature maps in five adjoining polygon-shaped "estimation areas" that encompassed the estuaries, watersheds, and salinity control structures from Vermilion Bay eastward to Mobile Bay. We validated the model-generated daily salinity maps using two methods. The first compared estimated values to discrete field measurements made within our modeling timeframe but not included in the model. The second consisted of hold-out cross-validations. Validation concluded that estimated and measured salinity values were on average within ±0.5 parts per thousand (ppt) of one another during fall time periods. In spring periods, estimated and measured salinities were on average within ±2.0 ppt. The results of the model show a clear impact of the opening of Davis Pond and Caernarvon salinity control structures in the northern Gulf of Mexico. This kriging model may be used in analyses assessing the impact of changes in salinity and temperature across the northern Gulf of Mexico.

Introduction

Following the Deepwater Horizon oil spill (DWH spill) in April 2010, the state of Louisiana opened two salinity control structures in attempt to minimize the amount of oil reaching the shore (Martinez et al. 2012, Rose et al. 2014). These structures directed large amounts of river water into Barataria Bay (through the Davis Pond structure) and Black Bay/Breton Sound (through the Caernarvon structure). The 2010 opening of these structures was atypical; they remained opened for significantly longer than usual and maintained a maximal flow rate during the spring and summer seasons when they are usually closed. Because substantial river water releases can lead to salinity drops that may harm marine life, we created a model to investigate how these releases may have altered salinity in Barataria Bay and Black Bay/Breton Sound from late April through mid-September following the DWH spill, when compared against historical baseline profiles.

The Davis Pond salinity control structure sits on the southwestern bank of the Mississippi River in St. Charles Parish, approximately 15 miles upstream of New Orleans (US ACE). The Caernarvon structure sits on the east bank of the Mississippi River in Plaquemines Parish, downstream of New Orleans (LCWPPRA Program 2003). The state of Louisiana opens these structures to divert water from the Mississippi River during years of high precipitation and high river levels. The Caernarvon structure was opened on April 23, 2010 and remained open through the first two weeks of August at or near maximum capacity (approximately 8,000 cubic feet per second (cfs)) (Figure 1a). Davis Pond remained open from May 8 through September 10, 2010, with flow ranging from 7,000 to 10,000 cfs (Figure 1b). Normally, these structures are opened only during the cooler winter and early spring months of each year because of potential impacts to oysters and other fisheries from low salinity water exposure during the warm late-spring and summer months (Turner 2006, Rose et al. 2014).

We developed a model to estimate salinity and temperature in the northern Gulf of Mexico using a comprehensive dataset for the years 2005 through 2012. We compiled a large database containing more than 35 million salinity and temperature records originally collected by eleven state and federal agencies. Spatially, the database covered most estuaries from Vermilion Bay, LA (in the west) to Mobile Bay, MS (in the east). The data consisted of two types. First, research teams collected salinity and temperature values as part of other field operations. This report labels these one-time, hand-collected data, as *discrete data* because they were collected at discrete points in time and space, even though the actual measurements were continuous measures in parts per thousand (ppt) or degrees Celsius. While these discrete data are temporally and spatially sporadic, collectively they represent a substantial data set spanning many locations and years. The second form of data came from autonomous water-quality monitoring stations maintained by three governmental agencies. These stations record salinity and temperature at fine temporal scales (e.g., 15 minutes, hourly, or daily), but are fewer in number than the discrete. This report labels data from autonomous stations as *continuous* because they were collected nearly continuously through time.

While the locations of both discrete and continuous salinity data points in the Gulf of Mexico is quite extensive (Figure 2), interpolation of salinity and temperature data between these points is needed to help characterize salinity conditions at locations across a range of resource habitats. Therefore, we interpolated these salinity and temperature values to generate average daily salinity and temperature estimates across a grid of cells covering critical locations within the study area. We performed the interpolation by estimating a spatio-temporal kriging model (Szpiro et al. 2010; Sampson et al. 2011; Lindström et al. 2014) in each estimation area and computed predicted values at a dense grid of points. In essence, this model smoothed and interpolated salinity and temperature values through time and space to estimate values every day each year within cells of a 200-meter X 200-meter grid superimposed on each estimation area. Following estimation, comparison to a separate set of salinity and temperature values collected by the Natural Resource Damage Assessment (NRDA) Fish Technical Working Group (TWG) validated the accuracy of the model output. The model was further validated by hold-out cross-validation procedures, as described below.

The spatial-temporal kriging model facilitated comparison of salinity and temperature between the pre-spill baseline period (2006-2009) and post-spill years (2010, 2011). The model shows a clear impact of the opening of these salinity control structures on large areas of the northern Gulf of Mexico. Large portions of these areas experienced atypically depressed salinities for weeks to months longer than in a typical year. The output from this model can be used to assess damage to natural resources in the Gulf of Mexico resulting from response to the DWH spill.

Methods

Based on availability of data and hydrologic similarity, we identified five estimation areas where salinity and temperature estimation was practical and informative to the injury assessment (Figure 2). We interpolated values in the following areas, moving west to east:

- The Morganza/Vermilion estimation area includes Vermilion Bay, West Cote Blanche Bay, the Atchafalaya Delta, Atchafalaya Bay, Caillou Bay, Terrebonne Bay, and Timbalier Bay. All these bays have the potential to receive river water from the Morganza Spillway when it is open.
- The Davis Pond estimation area includes Barataria Bay, which receives river water from the David Pond salinity control structure when open.
- The Caernarvon estimation area includes areas east of the Mississippi River and west of the Mississippi River Gulf Outlet "(MRGO) canal skirting the western shore of Lake Borgne. This area receives river water from the Caernarvon salinity control structure when open.
- The Bonnet Carré estimation area includes Lake Borgne, Bay St. Louis, Biloxi Bay, and Mississippi Sound to Mobile Bay, all of which have the potential to receive river water from the Bonnet Carré Spillway when open.
- The Mobile Bay estimation area encompassed Mobile Bay.

We compiled data from discrete water samples collected by the following nine agencies (Table 1; see Appendix A for further details):

- Louisiana Department of Environmental Quality (LDEQ)
- Louisiana Department of Health and Hospitals (LDHH)
- Louisiana Department of Wildlife and Fisheries (LDWF)
- Mississippi Department of Environmental Quality (MDEQ)
- Louisiana Office of Coastal and Protection and Restoration (OCPR)
- STORET Data Warehouse
- Alabama Department of Public Health (ADPH)
- Mobile Bay National Estuarine Program (MBNEP)
- NRDA Oyster TWG sampling plans.

We compiled data from continuous recording stations maintained by the following three agencies:

- U.S. Geological Survey (USGS)
- Louisiana Office of Coastal and Protection and Restoration (OCPR)
- National Estuarine Research Reserve System (NERRS).

Analysts checked and verified all data using extensive manual data inspection procedures and automated QA/QC procedures. The temporal period of data spanned January 2005 to

December 2012. Sporadic data gaps existed in both the discrete and continuous data series because studies were discontinued or stations failed or stations were moved

The number of usable salinity and temperature records in each year from each source appears in Table 2. The number of stations providing data appears in Table 3.[1] Appendix A contains more details on data sources, the measurement standardization process, and quality assurance checks.

We built a spatio-temporal statistical model (Szpiro *et al.* 2010; Sampson *et al.* 2011; Lindström *et al.* 2014) for salinity and temperature using all available discrete and continuous data. We evaluated the model at a (1000-meter x 1000-meter) lattice of non-sampled locations overlaid upon the areas of interest. We then refined the predictions to a 200-meter x 200-meter grid using bicubic polynomial interpolation.

The spatio-temporal model had the form:

$$y(s,t) = \mu(s,t) + \varepsilon(s,t),$$

where $\mu(s,t)$ = the mean of temperature or salinity at location s on day t ($y(s,t)$) (the spatio-temporal mean field, and $\varepsilon(s,t)$ = the residual or difference between $\mu(s,t)$ and $y(s,t)$. (the spatio-temporal residual field),

The spatio-temporal model estimated the mean field as the sum of two linear functions, one containing spatially and temporally varying covariates, the other containing a set of smooth temporal basis functions where coefficients of this model had a universal kriging structure. The set of temporal bases accounted for temporal correlation among observations taken at the same station during different time periods, and under this assumption, the residual space-time field was assumed independent in time with stationary spatial covariance. The spatial covariance of residuals contained a correlation component to account for spatial dependencies, as well as an uncorrelated component to account for small-scale variability and measurement error. The smooth temporal basis functions were constructed using the procedure of Fuentes *et al.* (2007). Predictions of $y(s,t)$ were then standard kriging estimates.

We used the `SpatioTemporal` (Lindström *et al.*, 2013) package in R to carry out estimation of the spatio-temporal model. The method implemented in `SpatioTemporal` utilized the block structure of the overall variance-covariance matrix to compute generalized least squares estimates for the parameters. Profile or restricted maximum likelihood (REML) was used to estimate the correlation parameters. We used the bi-cubic interpolation procedure of Akima (1996) to refine estimates from the 1000-meter grid to the 200-meter using the `bicubic.grid` function contained in the `akima` R package (Akima *et al.*, 2013).

[1] Note that a small portion of eastern Caernarvon estimation area overlaps the western portion of the Bonnet Carre area. Due to this overlap, a few stations were located within both areas, their data contributed to models in both estimation areas, and counts in Table 2 and Table 3 for Bonnet Carre and Caernarvon are not mutually exclusive.

Validation Procedure

A series of validation exercises investigated the accuracy and reliability of predictions following model estimation. First, salinity values in the Davis Pond estimation area were compared to those in a separate data set collected by the NRDA Fish Technical Working Group (TWG). Comparisons were facilitated by extracting model predictions for the specific locations and times reported in the NRDA Fish TWG field data. The NRDA Fish TWG collected samples in David Pond, Caernarvon, and Bonnet Carre estimation areas; however, data sparseness east of the Mississippi delta (i.e. Caernarvon and Bonnet Carre) and long distances between the continuous monitoring stations and Fish TWG sites made reliable validation in those areas problematic. Thus, validation took place in the Davis Pond estimation area only.

Following the above comparison to an independent data set, two sets of hold-out cross validations were performed. During the first, all salinity data collected at discrete stations associated with investigated oyster sites within Davis Pond, Caernarvon, Morganza-Vermillion and Bonnet Carré during 2010 through 2012 were temporarily removed. The remaining data were used to re-estimate the spatio-temporal model at the locations and dates of the held-out data. Model predictions were then compared to their respective held-out discrete data values.

During the second hold-out cross-validation exercise, salinity data collected during 2010 at 20% of the continuous stations in the vicinity of oyster sites in Davis Pond and Caernarvon were temporarily removed. The particular set of stations removed was selected using the spatially balanced random sampling procedure provided by ESRI's *Geostatistical Analyst Sampling Network Design Toolset*. The remaining data in Davis Pond and Caernarvon were used to re-estimate the spatio-temporal model at the locations and dates of the held-out data. Model predictions were then compared to their respective held-out data values.

Development of Area of Freshwater Influence Polygons

To investigate the impact of fresh water in the northern Gulf of Mexico following the opening of the Davis Pond and Caernarvon salinity control structures, we used the salinity model to identify areas that experienced higher than normal levels of river water exposure. Our analysis focused on the period April 27 to September 15 because river water from the open structures in 2010 flowed into Barataria Bay and Black Bay/Breton Sound during this time.

For each 200 square meter (m^2) gridcell, we calculated the number of consecutive days of salinity below 5 ppt during April 27 to September 15 in 2010 and 2011. We developed a baseline estimate for the number of days below 5 ppt by calculating the historical average of consecutive days below 5 ppt during April 27 to September 15from 2006 through 2009. Because a few days of higher salinities do not counteract the damaging effects of longer periods of low salinity, we considered days to be "consecutive" even if interspersed by up to three days of salinity above 5 ppt.

To yield a conservative estimate of the potential impacts of these structure openings on salinity, we identified areas in 2010 that deviated substantially below their historic averages. For that purpose, the number of consecutive days with salinity below 5 ppt in 2010 was compared to historical averages of the same number computed for each grid cell. If the difference between the 2010 condition and the historical average was more than 30 days, the grid cell was considered to be substantially below its historic average, and the cell was included in a river water release impact polygon. The difference of 30 days[2] was selected to maximize the difference between average salinities inside and outside the affected areas in 2010, thereby representing the greatest low salinity impact.

We conducted several sensitivity analyses, as follows:

- We repeated the above calculations using salinity threshold of 3 ppt. The number of days below 3 ppt that maximized the salinity difference between inside and outside the affected area in 2010 occurred at 19 days in Barataria Bay.
- We reran the calculations using the additional number of total days (regardless if those days occurred consecutively or not) of low salinity in 2010 versus the baseline years of 2006-2009. We ran this calculation using salinity thresholds of 3 and 5 ppt.

Additionally, based on expert opinion, more than 30 days total below 8 ppt during the critical time period would affect the recruitment of oysters (Davis,1958). To determine the areas that would experience this recruitment impact, all grid cells with more than 30 total days below 8 ppt from April 27 to September 15, 2010 were included in the impact polygon.

Results

Model Predictions

Model estimation resulted in one estimated map per day per estimation area (365 days × 5 estimation areas × 8 years = 14,600 maps, discounting leap years). The full set of maps cannot be presented here, but are available on DIVER (Data Integration, Visualization, Exploration and Reporting 2015). Typical salinity maps estimated for May 1, August 1, and November 1 in three years for each of the five estimation areas are shown in Figures 3 through 7.

Validation Results

The rainy season of the northern Gulf of Mexico generally consists of the months of May through August. Seasonal differences between model predicted salinities and discrete measurements appear in Table 4. In general, most differences were positive, indicating over prediction of measured salinity. Mean monthly differences ranged from 1.31 ppt to 2.16 ppt and averaged 1.77 ppt from June to August 2011. During the drier season, mean differences ranged from 0.40 ppt to -0.67 ppt and averaged -0.13 ppt during September and October of 2011. The RMSE of differences (Table 4) were generally greater than the mean leading to an average coefficient of variation of 163%. RMSE represents the root mean squared error for the salinity predictions. Because most values were small, relative differences averaged 26% during June through August and 7% during September and October.

[2] In Barataria Bay, this maximum occurs at 30 additional consecutive days whereas in Black Bay/Breton Sound the maximum occurs slightly earlier. However, to be conservative, we decided to use the same 30 days threshold for both areas.

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Individual predictions for the 2011 NRDA sample locationsand corresponding NRDA salinity measurements appear in Figure 9. Figure 9 shows a tendency for the model to over-predict salinity (by approximately 2 ppt) for values of salinity between 0 and approximately 15 ppt in the areas in which the 2011 NRDA samples were collected When measured salinities increased above approximately 15 ppt, model predictions tended to be highly accurate or slight underestimates. The greatest over-prediction observed was approximately 10 ppt. Overall, correlation between predicted and measured salinity was 0.93 in the area where the 2011 NRDA samples were collected.

The more geographically representative hold-out cross validations also indicated strong correlations between modeled and measured values with elevated match rates across each basin and year (Tables 5 and 6). Results from the first cross-validation exercise indicated that modeled salinity had strong statistical correlation with held-out values, particularly in 2010 and 2011 (Table 5). Match rates for the 5 ppt and 10 ppt thresholds were >80% and often perfect. Results of the second cross-validation again indicated strong correlation between held-out and modeled values, with elevated match rates (Table 6). These strong match rates based on the more geographically diverse hold-out exercise suggests that any overestimation bias in the salinity model does not significantly impact determinations of whether daily salinity values are above or below our threshold value of 5 ppt.

Areas of River water release Influence

Barataria Bay and Black Bay/Breton Sound experienced much lower salinities for a longer period in 2010 compared to both pre-spill baseline (average of 2006-2009) and 2011. Substantial portions of both basins were affected in 2010 (483 km^2 of Barataria Bay and 362 km^2 of Black Bay/Breton Sound). Figure 8 show the regions experiencing more days of low salinity (below 5 ppt and 3 ppt) in 2010 compared to the historical baseline (2006-2009).

Discussion

We compiled over 35 million salinity and temperature records from stations in the northern Gulf of Mexico from 2005 to 2012. In five estimation areas, we applied spatio-temporal kriging models to smooth time and space. Results of these models were daily predictions of salinity and temperature at all locations in a 200-meter x 200-meter grid contained in the estimation areas. Comparison of model predictions to a separate set of field measurements showed model predictions in Davis Pond basin in 2010 generally over-predicted salinity by approximately 2 ppt. With one exception, cross validation correlations between modeled and held-out values of salinity was generally very high, with match rates often exceeding 90% in various investigated basins and years.

Due to high correlation with measured values, the modeled predictions of salinity are adequate for use in other studies as explanatory covariates. Based on maps of prediction standard errors, regions within 400 meters to 600 meters of a measurement station that has provided concurrent observations should be <1 ppt from the actual salinity value.

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Output from the spatiotemporal kriging model confirms salinity in 2010 was atypically low in Barataria Bay, Breton Sound, and Black Bay. The most likely and plausible cause of these lowered salinities was the opening of salinity control structures during response actions following the DWH. These response actions exposed large estuarine areas of the northern Gulf of Mexico to low salinity levels for a much longer period than usual. It is well established that continually low salinity has detrimental effects to a wide variety of aquatic life (Chatry 1983, Melancon et al. 1998, Turner 2006, La Peyre et al. 2009, Soniat et al. 2013).

The river water release impact area analysis conducted using a cut-off of 3 ppt led to polygons that were smaller but generally covered similar areas to the 5 ppt threshold polygons. This analysis reinforces the finding that 2010 was highly atypical and that significant portions of these bays were exposed to very low salinities for extended periods compared to historical averages.

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Tables

Table 1. Data sources contributing salinity and temperature information delineated by type of data supplied and contact method.

Data Source	Data Type	Website/Contact Method
NERRS	Continuous	http://www.nerrs.noaa.gov/
OCPR-Continuous	Continuous	http://coastal.louisiana.gov/
USGS	Continuous	http://waterdata.usgs.gov/nwis
ADPH	Discrete	Contact agency personnel
LDEQ	Discrete	Contact agency personnel
LDHH	Discrete	Contact agency personnel
LDWF	Discrete	Contact agency personnel
MDEQ	Discrete	Contact agency personnel
MBNEP	Discrete	http://www.mobilebaynep.com/
NRDA Oyster TWG	Discrete	https://dwhdiver.orr.noaa.gov/
OCPR-Discrete	Discrete	Contact agency personnel
STORET	Discrete	http://www.epa.gov/storet/

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Table 2. Number of daily salinity and temperature records contributed by each of the eleven agencies, by year. Numbers reflect observations which fell in one of the five estimation areas considered in this report. Additional records exist pre-2005, post-2012, and outside the five estimation areas that were not used in this study (See Appendix A).

	Continuous Data			Discrete Data								
Year	NERRS	OCPR-Continuous	USGS	ADPH	LDEQ	LDHH	LDWF	MDEQ	MBNEP	NRDA Oyster	OCPR-Discrete	STORET
2005	0	18995	5937	0	266	5814	1268	279	0	0	580	0
2006	0	34050	6400	0	182	6778	1529	272	0	0	1938	0
2007	0	56710	6682	0	0	7288	1540	275	0	0	4535	0
2008	0	78579	6220	0	108	6962	1560	265	0	0	5650	0
2009	2084	81614	7332	0	171	7412	1743	0	1405	0	6893	172
2010	1911	83848	7718	69	109	7257	1622	15	1398	243	6683	77
2011	1980	83939	8096	43	119	6405	1486	277	1425	948	6784	523
2012	1980	69154	7891	31	0	0	1431	0	1464	496	823	254
Total	7955	506889	56276	143	955	47916	12179	1383	5692	1687	33886	1026

Note: ADPH = Alabama Department of Public Health; LDEQ = Louisiana Department of Environmental Quality; LDHH = Louisiana Department of Health and Hospitals; LDWF = Louisiana Department of Wildlife and Fisheries; MDEQ = Mississippi Department of Environmental Quality; MBNEP = Mobile Bay National Estuarine Program; NERRS = National Estuarine Research Reserve System; NRDA Oyster = Natural Resource Damage Assessment Oyster Technical Working Group; OCPR = Office of Coastal and Protection and Restoration; STORET = U.S. EPA STOrage and RETrieval Data Warehouse; USGS = U.S. Geological Survey.

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Table 3. Number of stations providing continuous and discrete data within each of the five estimation areas.

		Number of Stations within estimation area					
Year	Data Type	Morganza/ Vermilion	Davis Pond	Caernarvon	Bonnet Carre	Mobile	Total
2005	Continuous	24	42	23	6	NA	95
	Discrete	230	218	160	152	NA	760
2006	Continuous	87	59	22	6	NA	174
	Discrete	376	290	139	152	NA	957
2007	Continuous	116	75	33	16	NA	240
	Discrete	1038	572	276	242	NA	2128
2008	Continuous	140	84	35	19	NA	278
	Discrete	1087	601	263	253	NA	2204
2009	Continuous	140	84	34	21	NA	279
	Discrete	1674	868	393	287	NA	3222
2010	Continuous	140	83	32	22	4	281
	Discrete	1692	842	409	345	27	3315
2011	Continuous	140	83	32	22	4	281
	Discrete	1707	931	450	507	65	3660
2012	Continuous	139	74	26	20	4	263
	Discrete	276	163	85	140	39	703

Table 4. Results of the salinity model validation in the Davis Pond area using NRDA Fish TWG data as a reference and the predicted values from the spatio-temporal kriging models aggregated by month. RMSE in the table represents the root mean squared error for the salinity predictions. MRPE represents the mean relative absolute prediction error for the salinity predictions.

Month	Year	Mean Prediction-Observed (P_{avg})	RMSE	MRPE	n
June	2011	1.845358	2.313245	0.228927	205
July	2011	1.312724	1.705225	0.282058	53
August	2011	2.160987	3.138116	0.269274	53
September	2011	0.405799	0.670206	0.061779	6
October	2011	-0.67232	1.697888	0.07921	17

Table 5. Results of hold-out cross validation of the spatio-temporal model for salinity whereby discrete samples were temporarily removed, by basin and year. Match rates provide the percentage of cases where the hold-out measurement and its interpolated values were both above or below the given salinity threshold (either 5 ppt or 10 ppt).

Basin	Year	Hold-out Data		Measured vs Modeled			
		Station Counts	Measurement Counts	R^2	R^2 sig. (p value)	Match Rate (5ppt)	Match Rate (10 ppt)
Morganza-Vermillion	2010	13	59	0.75	< 0.001	100.0%	91.5%
	2011	16	70	0.68	< 0.001	90.0%	87.1%
	2012	18	59	0.16	0.002	100.0%	79.7%
Davis Pond	2010	11	53	0.90	< 0.001	94.4%	100.0%
	2011	33	72	0.77	< 0.001	100.0%	100.0%
	2012	44	114	0.80	< 0.001	97.4%	86.0%
Caernarvon	2010	8	33	0.63	< 0.001	81.8%	81.8%
	2011	22	135	0.68	< 0.001	97.8%	91.9%
	2012	22	92	0.01	0.433	90.2%	82.6%
Bonnet Carré	2010	34	91	0.57	< 0.001	100.0%	100.0%
	2011	79	269	0.58	< 0.001	99.6%	94.4%
	2012	77	254	0.51	< 0.001	98.8%	88.6%

Table 6. Results of hold-out cross validation of the spatio-temporal model resulting from removal of a spatially balanced random sample of 20% of the continuous monitoring stations in the vicinity of oyster sites in Davis Pond and Caernarvon. Match rates provide the percentage of cases where the hold-out measurement and its interpolated values were both above or below the given salinity threshold (either 5 ppt or 10 ppt).

Basin	Year	Hold-out Data		Measured vs Modeled			
		Station Counts	Measurement Counts	R^2	R^2 sig. (p value)	Match Rate (5ppt)	Match Rate (10 ppt)
Davis Pond	2010	16	485	0.86	< 0.001	93.8%	90.3%
Caernarvon	2010	5	558	0.76	< 0.001	87.6%	88.2%

Figures

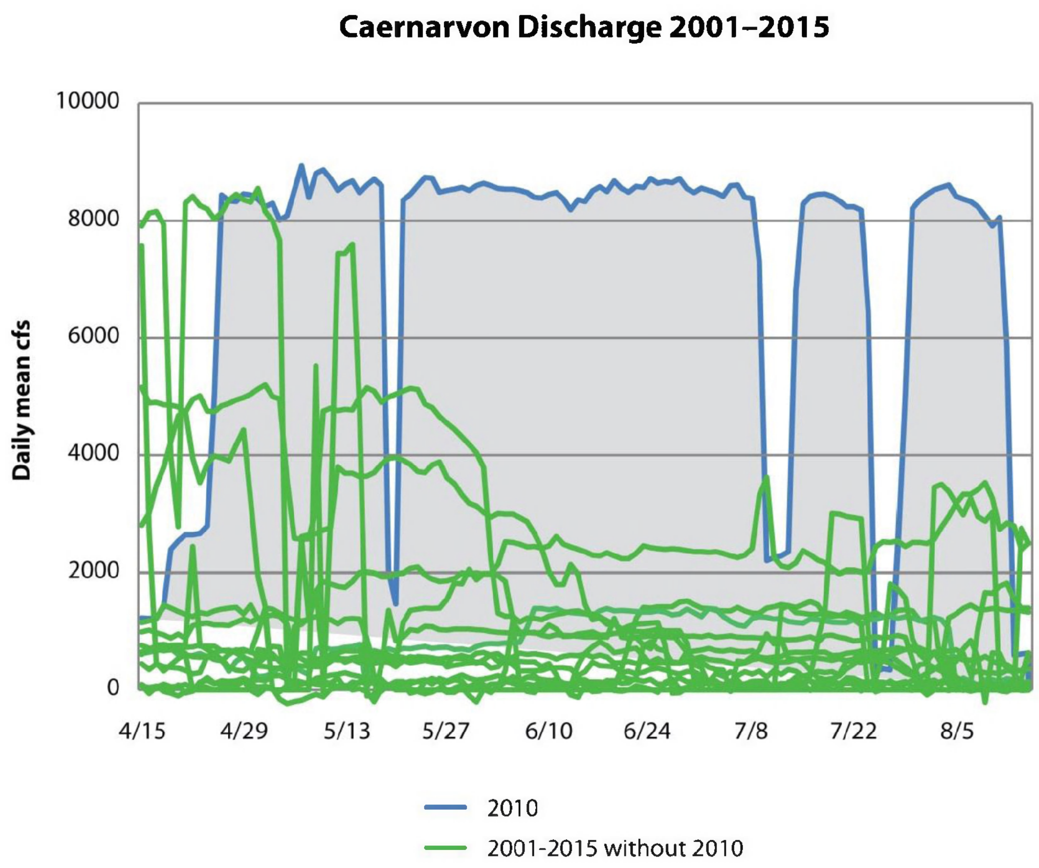


Figure 1a. River water discharge rate (daily mean feet^3 second^{-1}) through Caernarvon salinity control structure across April 15-August 15 2001-2015.

DWH-AR0270952

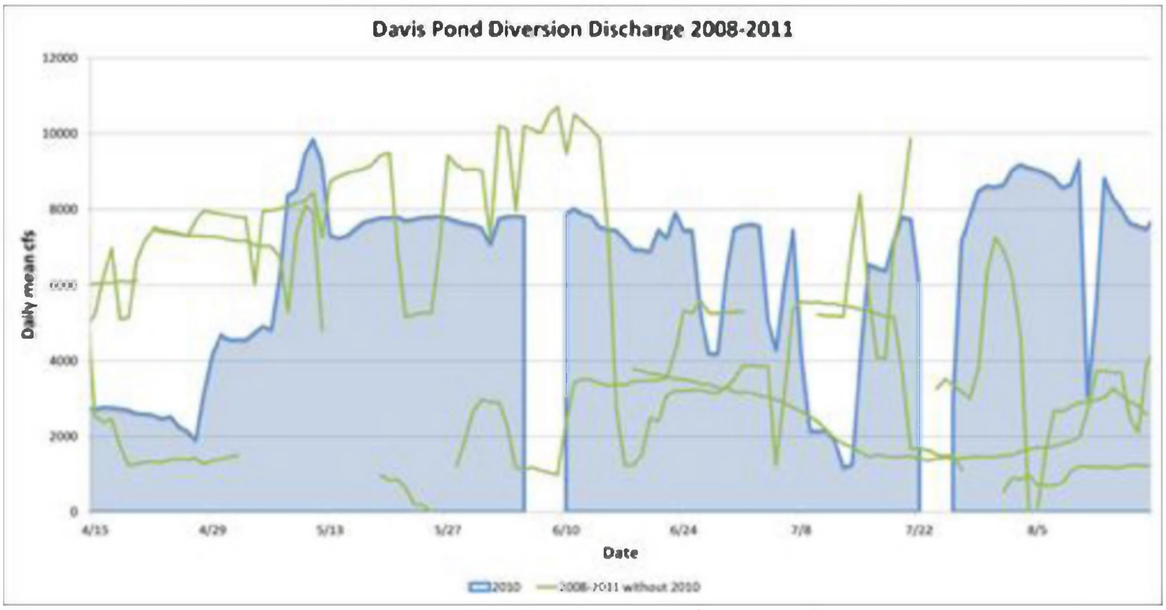


Figure 1b. River water discharge rate (daily mean feet^3 second^{-1}) through Davis Pond salinity control structure across 2008-2011.

DWH-AR0270953

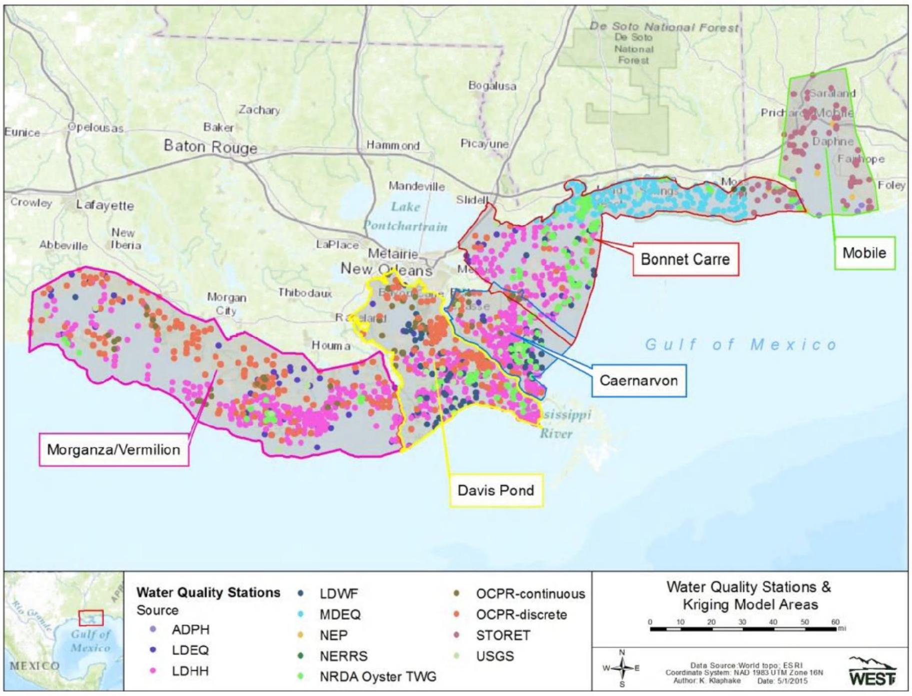


Figure 2. Estimation areas, station locations, and data source used to model salinity and temperature during 2005 to 2012. Most stations were discrete and provided only a few raw data values.

DWH-AR0270954

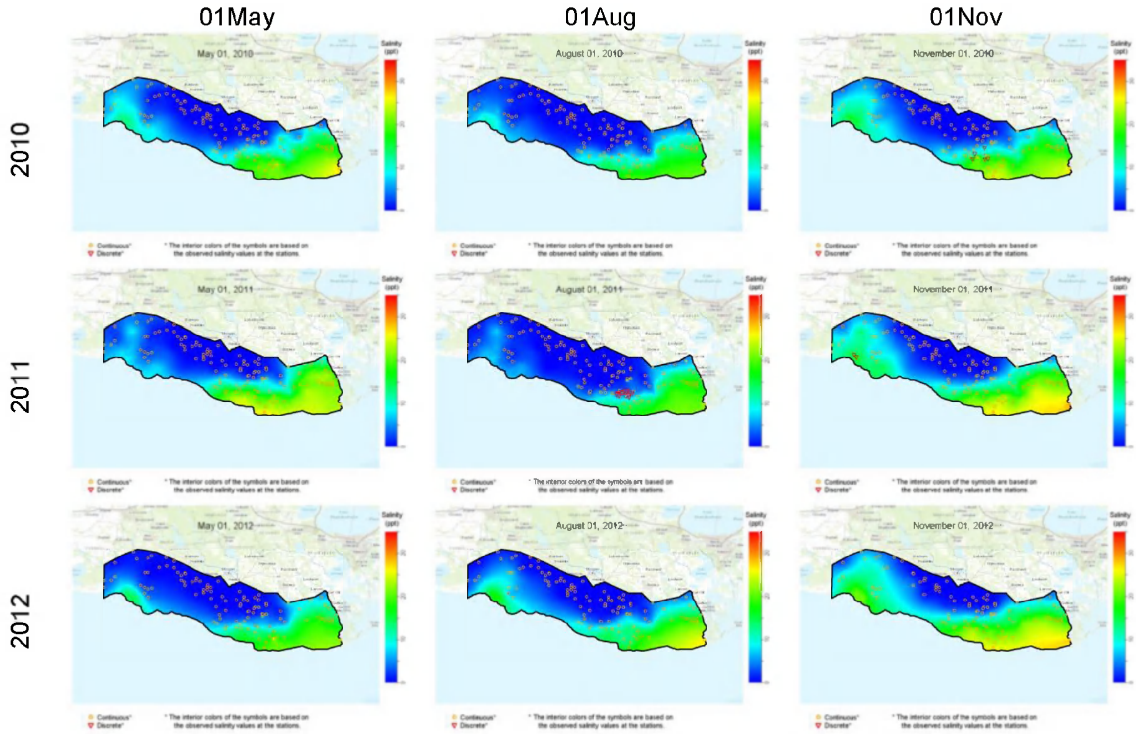


Figure 3. Estimated salinity in Morganza/Vermilion (MV) estimation area on three representative days in 2010, 2011, and 2012.

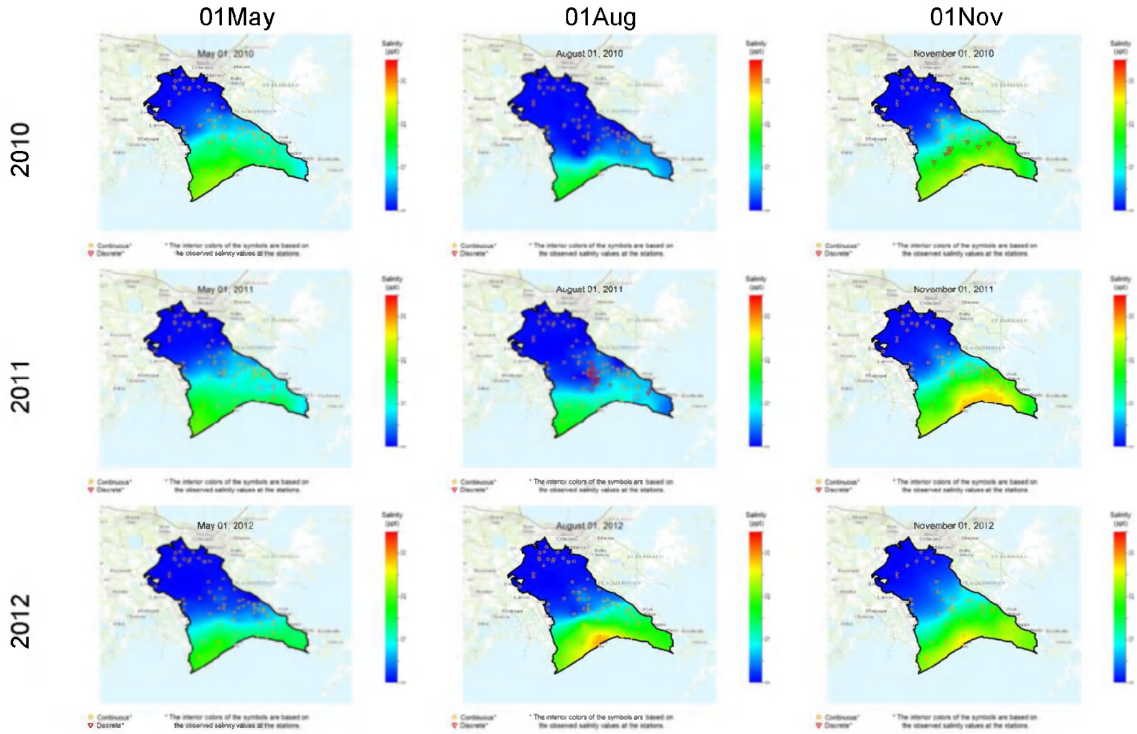


Figure 4. Estimated salinity in Davis Pond (DP) estimation area on three representative days in 2010, 2011, and 2012.

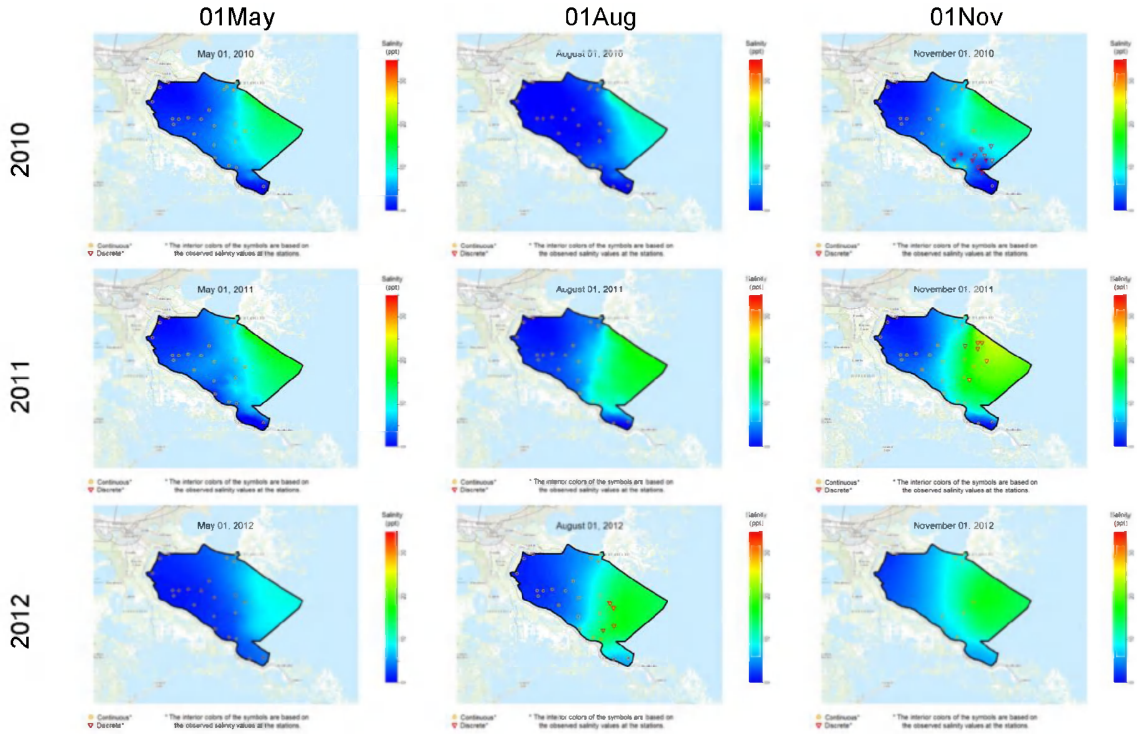


Figure 5. Estimated salinity in Caernarvon (CN) estimation area on three representative days in 2010, 2011, and 2012.

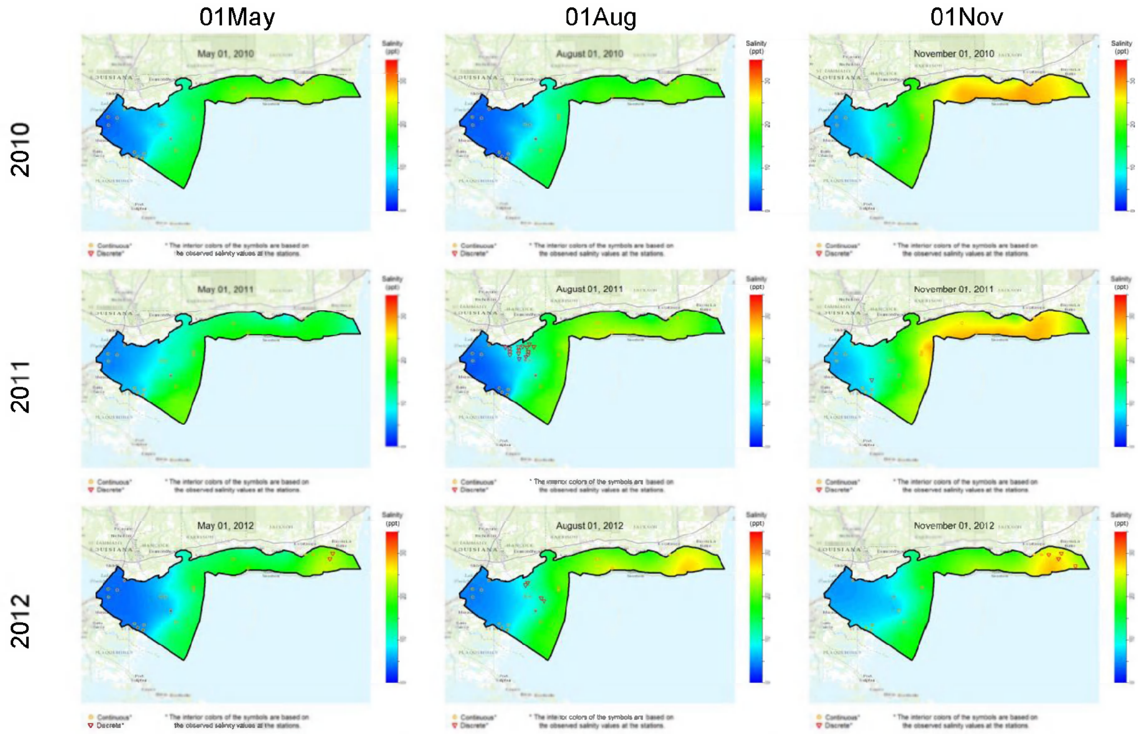


Figure 6. Estimated salinity in Bonnet Carre (BC) estimation area on three representative days in 2010, 2011, and 2012.

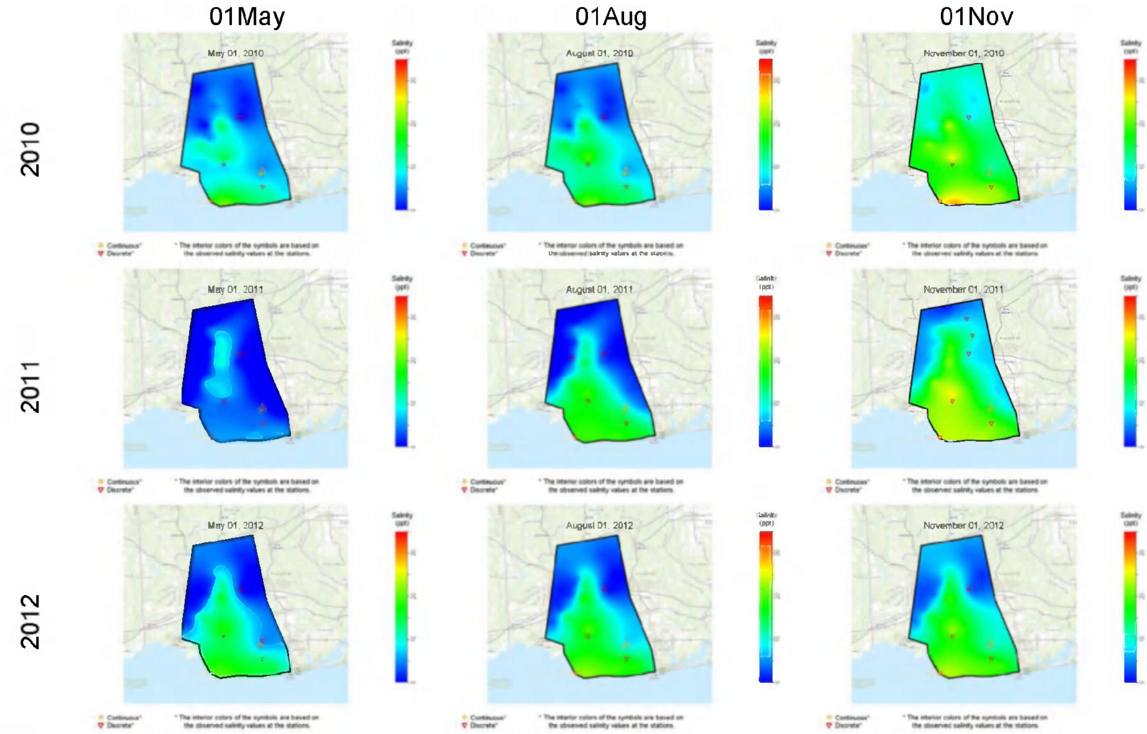
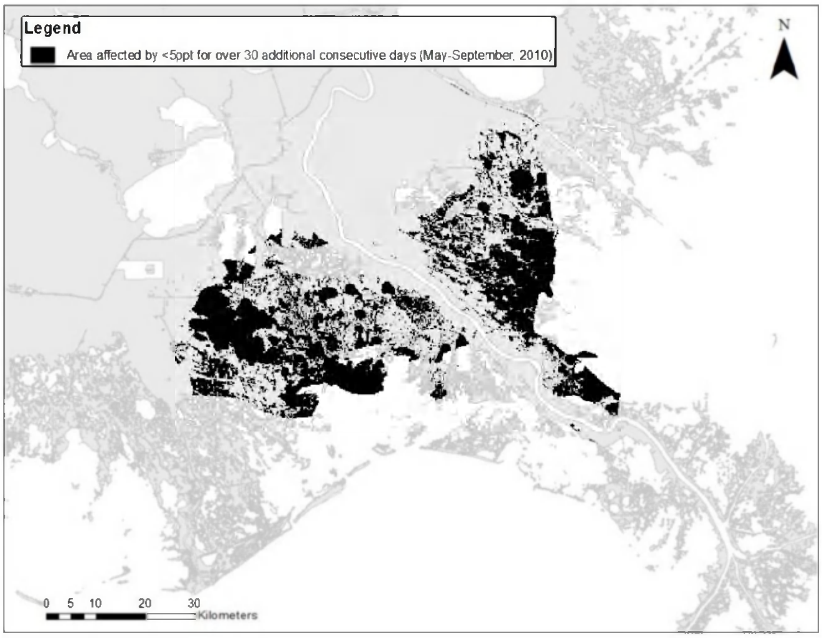


Figure 7. Estimated salinity in Mobile Bay (MB) estimation area on three representative days in 2010, 2011, and 2012.

5 ppt



3 ppt

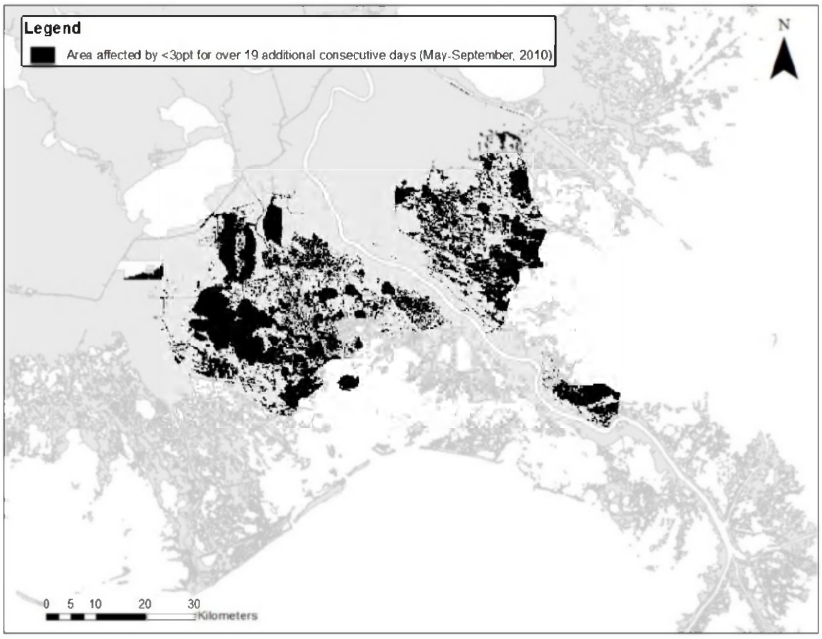


Figure 8. Areas of River water release influence in 2010 showing areas with at least 30 additional consecutive days of salinity below 3 ppt and 5 ppt relative to their historic averages.

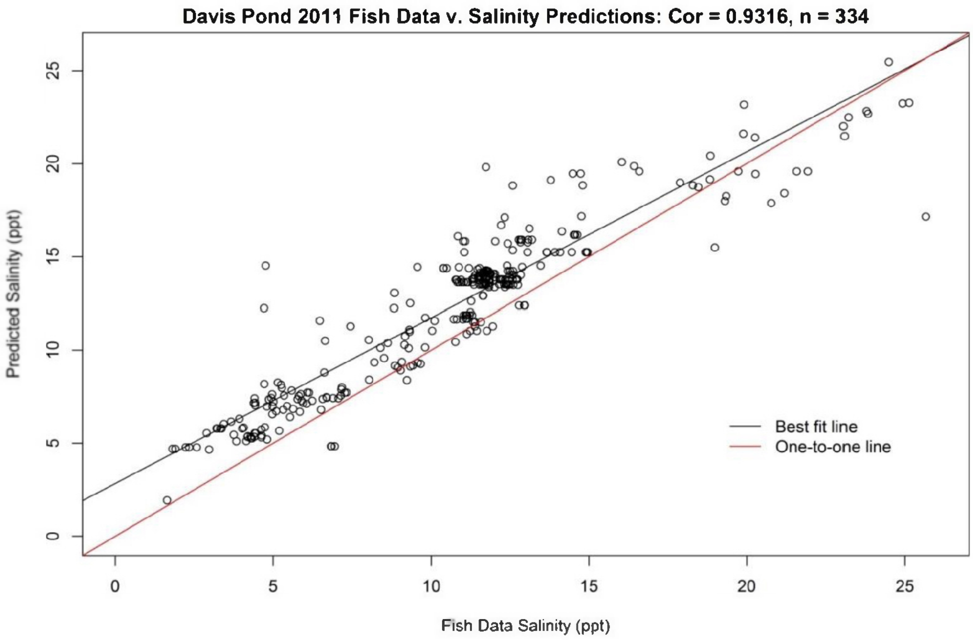


Figure 9. Scatter plot validating predictions of salinity in the Davis Pond area when compared to discrete measurements at the same place and time. Overall, correlation between predicted and measured salinity was 0.93 in the area where the NRDA samples were collected. These strong match rates based on the more geographically diverse hold-out exercise suggests that any overestimation bias in the salinity model does not significantly impact determinations of whether daily salinity values are above or below our threshold value of 5 ppt. All measurements taken in 2011.

Appendix A: Data Sources

U.S. Geological Survey (USGS)

The USGS data contain water quality data collected daily by the United States Geological Survey between 1980 and 2013 following the *Guidelines and Standard Procedures for Continuous Water-Quality Monitors: Station Operation, Record Computation, and Data Reporting* (Wagner et al. 2006). A total of 181 (of 1,055,223) relevant records were determined to be unreliable by QAQC procedures. See Table A1 for specific collection parameters.

Table A1. *USGS Frequency and location of collection parameters*

Parameter and Reporting Units	Location and Frequency	Method/Reference
Temperature (°C)	All Sites - Daily	Thermistor
Salinity (parts per thousand or mg/mL)	All Sites - Daily	Calculated (derived from conductivity)
Specific Conductance (µS/cm at 25°C)	All Sites - Daily	Contact sensors, both with and without electrodes

Louisiana's Office of Coastal and Protection and Restoration (OCPR) – continuous

The OCPR continuous data contain water quality data collected hourly at pre-determined stations by the Louisiana Office of Coastal Protection and Restoration between 1992 and 2012 following *A Standard Operating Procedures Manual for the Coast-Wide Reference Monitoring System-Wetlands: Methods for Site Establishment, Data Collection, and Quality Assurance/Quality Control* (Folse et al. 2008). A total of 594,486 (of 90,301,848) relevant were determined to be unreliable by QAQC procedures. See Table A2 for specific collection parameters.

Table A22. *OCPR-continuous frequency and location of collection parameters*

Parameter and Reporting Units	Location and Frequency	Method/Reference
Temperature (°C)	703 Sites - Hourly	YSI 600LS or Hydrolab MS5 continuous recorder
Salinity (ppt)	666 Sites - Hourly	YSI 600LS or Hydrolab MS5 continuous recorder (derived from conductivity)
Dissolved Oxygen (mg/L)	1 Site - Hourly	YSI 600LS or Hydrolab MS5 continuous recorder
Wind Speed (mph)	6 Sites - Hourly	Anemometer
Wind Direction (radian degrees)	6 Sites - Hourly	Anemometer
Water Velocity (ft/s)	5 Sites - Hourly	YSI 600LS or Hydrolab MS5 continuous recorder
Precipitation (in/hr)	6 Sites - Hourly	Cumulative number of tips of "tipping bucket" type rain gauge

Depth (ft)	709 Sites - Hourly	YSI 600LS or Hydrolab MS5 continuous recorder

National Estuarine Research System (NERRS)

The NERRS data contain water quality data collected sub-hourly as part of a collaboration between NOAA and coastal states. All NERRS data are housed in the NERRS Centralized Data Management Office (CMDO). The CMDO applies QAQC standards that improve data quality and result in data standardization. Further information pertaining to NERRS data and CMDO data management practices can be found at < http://www.nerrs.noaa.gov/>.

Alabama Department of Public Health (ADPH)

The ADPH data contain water quality data collected at discrete points in time. There are two sub-data sources within the ADPH dataset. These sub-data include Harmful Algal Bloom (HAB) data and seafood monitoring data. The HAB dataset included water salinity, temperature, turbidity, tidal stage, and wind characteristics. The seafood monitoring data contain water salinity and temperature data.

Louisiana Department of Environmental Quality (LDEQ)

The LDEQ data contain water quality data collected monthly at approximately 1-meter depth by the Louisiana Department of Environmental Quality between 1986 and 2011 following the Quality Assurance Project Plan (QAPP) protocol. A total of 1192 (of 28,942) relevant records were determined to be unreliable by QAQC procedures. The data have no specific limitations. The full Quality Assurance Project Plan (QAPP) for the ambient water quality monitoring network can be found at <*http://www.deq.louisiana.gov/portal/Portals/0/planning/QAPP_1004_r05%202011%20FINAL%208-29-2011.pdf*>. See Table A3 for specific collection parameters.

Table A3. *LDEQ frequency and location of collection parameters*

Parameter and Reporting Units	Location and Frequency	Method/Reference
Temperature (°C)	All Sites - Monthly	Portable Meter or Thermometer EPA, Method 170.1, SM 2550 B
Dissolved Oxygen (mg/L) - Grab	All Sites - Monthly	Portable Meter EPA, Method 360.1, SM 4500-O G; Manufacturer's Operation Manual
[††]Dissolved Oxygen (mg/L) Continuous Monitoring	After AWQMN DO readings found to be below criteria	Portable Meter EPA, Method 360.1, SM 4500-O G; Manufacturer's Operation Manual
Dissolved Oxygen Saturation (%)	All Sites - Monthly	Portable Meter EPA, Method 360.1, SM 4500-O G; Manufacturer's Operation Manual

ΦSalinity (parts per thousand)	All Sites - Monthly	Portable Meter EPA, Method 120.1 or ASTM Standard Methods D1125-91(A)

ᵀᵀ Follow-up dissolved oxygen continuous monitoring sampling is conducted as needed and as resources allow when AWQMN grab sample results for DO are below the applicable criterion for a water body. The data collection should be initiated within two weeks under similar conditions. This data may be used to override any initial assessment of impairment if supported, otherwise the grab data points will provide the bases for water quality assessments (QAPP-pp.27).

Φ The sample is considered a surface sample (collected at 1-meter depth or less).

Louisiana Department of Health and Hospitals (LDHH)

The LDHH data contain water quality data collected 1-2 times monthly at pre-determined stations by the Louisiana Department of Health and Hospitals between 1998 and 2011. A total of 139 (of 211,143) relevant records were determined to be unreliable by QAQC procedures.

Louisiana Department of Wildlife and Fisheries (LDWF)

The LDWF data contain water quality data collected several times monthly at pre-determined stations by the Louisiana Department of Wildlife and Fisheries between 1992 and 2013. A total of 44 (of 99,956) relevant records were determined to be unreliable by QAQC procedures.

Mississippi Department of Environmental Quality (MDEQ)

The MDEQ data contain water quality data collected at varying time intervals at pre-determined stations by the Mississippi Department of Environmental Quality between 2001 and 2011. A total of 15 (of 53,550) relevant records were determined to be unreliable by QAQC procedures. Data collection followed the *Quality Assurance Project Plan for the §106 Monitoring Network in the State Surface Water Monitoring and Assessment Program* (MDEQ, 2012). For each given day and time, there are multiple observations recorded at various depths throughout the water column. See Table A4 for specific collection parameters.

Table A4. *MDEQ frequency and location of collection parameters*

Parameter and Reporting Units	Location and Frequency	Method/Reference
Conductivity	Generally Yearly	SM 2510-B/MDEQ Master SOP Compendium for Field Services (MDEQ, 2009)
Dissolved Oxygen (%)	Generally Yearly	SM 4500-0C/MDEQ Master SOP Compendium for Field Services (MDEQ, 2009)
Dissolved Oxygen (mg/L)	Generally Yearly	SM 4500-0C/MDEQ Master SOP Compendium for Field Services (MDEQ, 2009)
Salinity (PPT)	Generally Yearly	SM 2520/MDEQ Master SOP Compendium for Field Services (MDEQ, 2009)
Water Temperature (°C)	Generally Yearly	SM 2550 B/MDEQ Master SOP Compendium for Field Services (MDEQ, 2009)

Louisiana's Office of Coastal and Protection and Restoration (OCPR) – Discrete

The OCPR discrete data contain water quality data collected monthly by the Louisiana Office of Coastal Protection and Restoration between 1992 and 2012 following *A Standard Operating Procedures Manual for the Coast-Wide Reference Monitoring System-Wetlands: Methods for Site Establishment, Data Collection, and Quality Assurance/Quality Control* (Folse et al. 2008). A total of 745 (of 222,960) relevant records were determined to be unreliable by QAQC procedures. See Table A5 for specific collection parameters.

Table A5. *OCPR-Discrete frequency and location of collection parameters.*

Parameter and Reporting Units	Location and Frequency	Method/Reference
Temperature (°C)	All sites - monthly	YSI-30 (or equivalent) handheld water instrument
Salinity (ppt)	All sites - monthly	YSI-30 (or equivalent) handheld water instrument
Specific Conductance	All sites - monthly	YSI-30 (or equivalent) handheld water instrument

Mobile Bay National Estuarine Program (MBNEP)

The MBNEP data contain water quality data collected sub-hourly as part a Comprehensive Conservation Management Plan (CCMP). The MBNEP CCMP is administered through the United States Environmental Protection Agency (EPA) under the Clean Water Act (CWA). Data collected through this program include, but are not limited to water salinity, temperature, and dissolved oxygen. Further information including a full copy of the CCMP can be found at the following address: <*http://www.mobilebaynep.com/*>.

NRDA Oyster Technical Working Group (TWG)

The NRDA Oyster Technical Working Group data used in this analysis were collected between 2010 and 2012 across the northern Gulf of Mexico. Data were collected to determine how, if at all, the 2010 Deepwater Horizon Oil Spill injured the oyster resources of the northern Gulf of Mexico. Water quality data collected under the NRDA Oyster TWG included water salinity, temperature, and dissolved oxygen.

STORET

The STORET data were retrieved using the EPA's STORET data warehouse. Many datatypes for various temporal periods can be retrieved using STORET. Data for water salinity, temperature, and dissolved oxygen from early 2009 through 2014 were retrieved.

Data Quality Assurance

The same QAQC procedures were applied to most of the data sources. Some of the data sources required specific QAQC, but general practices were applied to all of the data. Many of the datasets also had QAQC procedures applied prior to download. For all of the data, any negative salinity values or zeroes were considered suspicious and checked for potential errors. The same logic was applied to temperature measurements. Observations outside provided expected value ranges (c/o Sean Powers, personal communications) were also checked for salinity (salinity expected range: 0-40 ppt) and temperature (temperature expected range: 0-35°C). Any suspect value was examined for consistency with surrounding values, considered with time of year (if relevant), and checked against measurements for other fields taken at the same time to ensure the monitor was working properly.

Salinity and temperature outliers were removed from the data. Outliers were determined for the data in aggregate and by site. Data were classified as outliers if they were greater than 1.5 times the inner quartile range of the data. These outliers were checked to determine whether they were extreme but plausible values or erroneous data. Another outlier check was performed on the continuous datasets. A time series analysis was used to identify observations greater than two standard deviations different from a 4-day rolling mean, which indicated any unusual values including zeroes. These unusual values were flagged and checked.
Some specific QAQC was performed on the various datasets. The LDEQ provided validation qualifiers and comments and lab qualifiers for certain observations. These qualifiers and comments were taken into consideration and any value flagged by LDEQ was removed from the LDEQ data.

The OCPR discrete data did not contain salinity data. In its place, specific conductance data was available. The specific conductance data contained no negatives or zeroes, but had several observations outside the expected value range (≥ 50,000) that were determined to be erroneous. All zeroes and values outside the expected value range (> 40 ppt; provided c/o Sean Powers, personal communications) were checked for errors.

Salinity is computed (for conductance records processed correctly for temperature and atmospheric pressure) as

$$S = K_1 + \left(K_2 \times R^{1/2}\right) + (K_3 \times R) + \left(K_4 \times R^{3/2}\right) + (K_5 \times R^2) + \left(K_6 \times R^{5/2}\right),$$

where $K_1 = 0.0120, K_2 = -0.2174, K_3 = 25.3283, K_4 = 13.7714, K_5 = -6.4788, K_6 = 2.5842,$ and R is the ratio of specific conductance to seawater (Wagner et al. 2006).

Literature Cited

Folse, T.M.; West, J.L.; Hymel, M.K.; Sharp, L.A.; Weifenbach, D.; McGinnis, T.; and Rodrigue, L.B. 2008. A standard operating procedures manual for the Coast-Wide Reference Monitoring System-Wetlands: Methods for site establishment, data collection, and quality assurance/quality control. Louisiana Coastal Protection and Restoration Authority, Office of Coastal Protection and Restoration. Baton Rouge, LA. 191 pp.

Mississippi Department of Environmental Quality, Office of Pollution Control. 2012. Quality assurance project plan for the §106 Monitoring Network in the State Surface Water Monitoring and Assessment Program. Jackson, MS. 94 pp.

Wagner, R.J,; Boulger, R.W., Jr.; Oblinger, C.J.; and Smith, B.A. 2006. Guidelines and standard procedures for continuous water-quality monitors – Station operation, record computation, and data reporting: Techniques and methods 1-D3. U.S. Geological Survey: Reston, VA. 51 pp. + 8 attachments.