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Key Points:

- We compared coastal change forecasts describing the probability of coastal change with observed coastal changes along the Louisiana coast for 2020 Hurricanes Laura, Delta, and Zeta.
- The true positive forecast ratio was 0.93 for overwash and 0.75 for inundation indicating the forecast has skill predicting overwash and inundation.
- High false positive forecast ratios for overwash and inundation are the result of a conservative forecast of extreme water levels.

Abstract:

During hurricane season, the U.S. Geological Survey (USGS) forecasts the probability of coastal change prior to named storm landfall. Forecasts both quantify potential storm effects on the sandy coastlines and test our understanding of the drivers of coastal change. The forecasts can also be used to aid emergency response and management decisions in real-time. This study analyzed the skill of three USGS forecasts of coastal change, defined as the probability of collision, overwash, and inundation (PCOI) along the approximately 250 km of Louisiana coast from Hurricanes Laura, Delta, and Zeta in 2020. To test forecast skill, forecasts were compared with coastal changes identified in post-storm emergency response aerial imagery. Forecasts accurately identified areas where overwash and inundation were likely (true positive forecast ratios >0.75). Forecasts also produced an overly conservative estimation of overwash and inundation (false positive forecast ratios 0.56). High false positive forecast ratios for overwash and inundation may be the result of an overestimate in forecast extreme water levels.

Plain Language Summary

This study tested the accuracy of three U.S. Geological Survey forecasts of coastal change along the Louisiana coast caused by Hurricanes Laura, Delta, and Zeta in 2020. Changes to the coast were determined by comparing photography collected from an airplane before and after the storms. The forecasts were compared to the coastal changes observed in the imagery. Study results suggest that the forecasts correctly identified most locations that experienced dune erosion but also estimated dune erosion at many places where it did not occur. Forecasts provide important information for coastal communities who experience landfalling hurricanes and tropical storms in the United States.

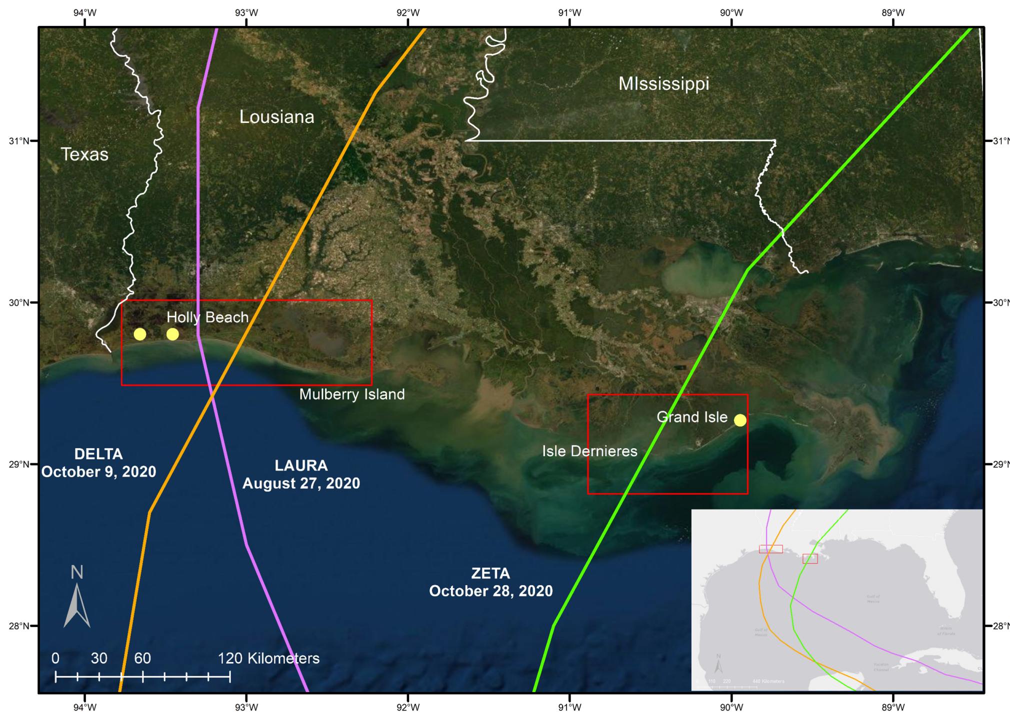
1 Introduction

1.1 Background

During the record breaking 2020 Atlantic Hurricane Season (Blackwell, 2020) the U.S. Geological Survey (USGS) produced forecasts of the probability of coastal change in Louisiana, USA prior to storm landfall to both quantify and test understanding of coastal change during extreme events. Perhaps more importantly, the forecasts can aid emergency response and management decisions by providing actionable information in real-time. The probability of coastal change is forecast by comparing modeled elevations of storm-induced extreme water levels to the elevations of coastal topographic features. Forecasts are disseminated through the USGS Coastal Change Hazards Portal as storms approach landfall (https://marine.usgs.gov/coastalchangehazardsportal/).

Ocean driven storm impacts on sandy beaches can be described in terms of three regimes, (a) collision, where wave runup interacts with the dune, (b) overwash, where wave runup overtops the dune crest, and (c) inundation, where the mean water level exceeds the dune crest (Sallenger, 2000). These regimes may result in coastal changes (Stockdon et al., 2007). For example, during collision, the seaward side of the dune may erode. Overwash and inundation may result in washover deposits, defined as the net landward movement of dune sediment, and inundation may result in island breaching (Sallenger, 2000). Natural processes of overwash and breaching contribute to the regional and long-term morphologic development of a barrier island (Donnelly et al., 2006). However, collision, overwash, and inundation, and accompanying erosion represent a coastal hazard risk when buildings or infrastructure are present on a barrier island (McNamara & Lazarus, 2018).

In this study we test the skill of forecasts of the probability of collision, overwash, and inundation (PCOI) along sandy sections of the Louisiana coast from Hurricane Laura, Hurricane Delta, and Hurricane Zeta (Figure 1). Post-storm emergency response aerial imagery was used to identify areas where coastal change occurred and to assess the skill of coastal change forecasts.



94°W
93°W
92°W
91°W
90°W
89°W
31°N
30°N
29°N
28°N
MIssissippi
Lousiana
Texas
Holly Beach
Mulberry Island
Grand Isle
Isle Dernieres
DELTA
October 9, 2020
LAURA
August 27, 2020
ZETA
October 28, 2020
N
0
30
60
120 Kilometers

Figure 1. Tracks of the three hurricanes included in this study, Laura (purple), Delta (orange), and Zeta (green). Names and dates denote each storm and date of landfall in Louisiana. Red boxes indicate study areas; yellow symbols mark locations of water level sensors used in this study. Inset map indicates the regional study area along the Gulf of Mexico coast.

1.2 Study Site Morphology

The Louisiana Chenier Plain extends from the Texas border to Vermilion Bay and comprises the Hurricane Laura and Delta study area (Figure 1, left red box). The area is characterized by a series of long, narrow beach ridges (cheniers) composed of shell and sand that lie parallel to the modern shoreline (Sallenger, 2009). These cheniers extend inland over tens of kilometers, with marshes that lie near sea level in between each ridge. Approximately 57% of the coast within the study area is backed by a low berm with elevations ranging from 1 to 2 meters, rather than a dune. Because of the low elevation topography, communities along the Chenier Plain have long been identified as an area of high coastal vulnerability (Kelley et al., 1984; Sallenger, 2000; Sallenger et al., 2009; Louisiana's Comprehensive Master Plan for a Sustainable Coast, 2017).

Grand Isle, located just northwest of the Mississippi River delta complex, comprises the Hurricane Zeta study area (Figure 1, right red box). Grand Isle is the only inhabited barrier island on the Louisiana coast, and its coastline has been shaped by both natural and anthropogenic influences. Grand Isle is considered a morphologically stable island when compared to other Louisiana barrier islands, which has allowed for its residential and commercial development (Himmelstoss et al., 2017; Penland et al., 2003). With the exception of a 3.8 m NAVD88 dune built in 2008 (*Grand Isle and Vicinity, Louisiana*, 2008), ~75% of the island's beaches are backed by low-elevation dune ridges ranging from 0.1 to 1.0 m. These areas are susceptible to erosion from high winds associated with hurricanes, storm surge, and sea level rise (Torresa et al., 2020).

1.3 Storms of the 2020 Season

This work focuses on three storms that made landfall in Louisiana during 2020 and were forecast by the USGS to cause coastal change (Table 1). Hurricane Laura was the strongest storm to hit the Louisiana (LA) coast since Hurricane Camile in 1969 (Pasch et al., 2021) and caused catastrophic wind damage and record-breaking storm surge (6.1 m at Creole, LA). Hurricane Delta made landfall ~17 km east of the site of Laura's landfall less than 2 months later with a maximum observed storm surge of 3.1 m at Freshwater Canal Locks, LA. The Louisiana coast was also impacted by Hurricane Zeta with a maximum observed storm surge of 2.7 m at Waveland, MS. The combination of low elevations throughout the study area and storm surge resulted in standing water and visible coastal changes (Figure 2).

Storm	**Landfall date, time (UTC)**	**Landfall location**	**Landfall strength**	**Landf**
(m, NAVD88)				
Laura[a]	27 August 2020, 0600	Cameron, Louisiana	Category 4	240
Delta[b]	9 October 2020, 2300	Vermillion Parish, Louisiana	Category 2	155
Zeta[c]	28 October 2020, 2100	Caillou Bay, Louisiana	Category 3	185

Table 1 Storm statistics for Hurricanes Laura, Delta, and Zeta including landfall date, time in Coordinated Universal Time (UTC), location, category, wind speed in kilometers per hour (km/h) and observed storm surge in meters (m) North American Vertical Datum of 1988 (NAVD88). Maximum observed storm surge values for Laura and Delta were high water marks. Maximum observed storm surge value for Zeta was at a U.S. Geological Survey stream gage. [a]Pasch et al., (2021). [b]Cangialosi and Berg (2021). [c]Blake et al., (2021).

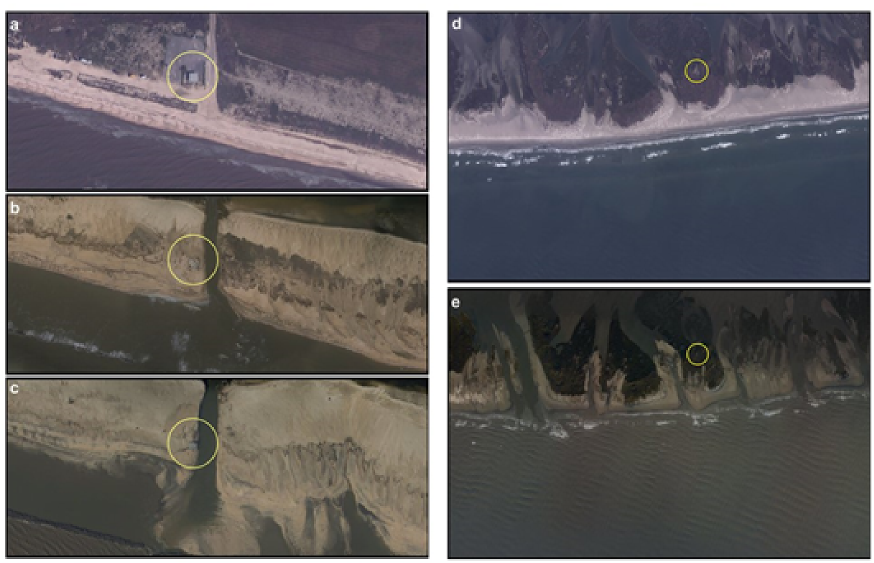


Figure 2. Pre- and post-storm imagery of 2020 storm impacts in coastal Louisiana. Pre-storm imagery at a) Rutherford Beach (29.759, -93.124) and d) Breton National Wildlife Refuge (29.935, -88.825). Post-storm imagery for Hurricanes b) Laura, c) Delta and e) Zeta. Yellow circles denote identical features within each image group.

2 Methods

of the three storms in this study making landfall along the Louisiana coast, the probabilities of coastal change were forecast for the sandy portion of the coastline. The decision to produce a forecast for a named storm depends on whether the expected storm event has a high likelihood of causing coastal change, whether significant societal or ecosystem effects are expected, and whether the forecast area overlaps with ongoing research or applied efforts (Birchler et al., 2019). Forecasts may be produced starting several days in advance of landfall and updated when new advisories for storm surge are issued. The results reported here are for forecasts produced 15 hours prior to landfall for Laura, 8 hours for Delta, and 7 hours for Zeta (Doran et al., 2022).

Forecasts depend on recent estimates of the elevations of beach morphologic features in comparison to the elevations of extreme water levels. Beach morphologic features include the dune crest elevation, dune toe (seaward base of the dune) elevation, and beach slope (defined as the endpoint slope between mean high water shoreline and dune toe). The dune feature extraction methodology follows Stockdon et al. (2012), which incorporates lidar point clouds which are rotated and then gridded at 10 m alongshore and 2.5 m cross shore spacing. Areas of slope change and maximum curvature determine the automated delineation of the dune crest and toe for each transect (or grid row). This results in a cross-shore position and elevation for the dune crest and toe, as well as the position of the mean high water level shoreline every 10 m alongshore. Automated estimates also go through an extensive human-guided QA/QC process.

Elevations of extreme water levels are based on offshore oceanographic forcing and local beach slope. Peak combined tide and storm surge water levels were obtained from the NOAA NWS Probabilistic Tropical Storm Surge (P-Surge) model 120-hour forecast (Taylor et al., 2014). To extract storm surge levels from the probabilistic model, the 10 % exceedance surge level was chosen to represent a reasonable worst-case scenario. Maximum significant wave heights and associated peak wave periods at the 20-m isobath were obtained from the NOAA Environmental Modeling Center WaveWatch III model 7-day forecast (WW3DG, 2019). Wave runup elevations at the shoreline are composed of the mean water level at the shoreline due to waves, called setup, and an extreme-value statistic for the time-varying shoreline due to waves. Wave runup elevations were computed using the 7-day maximum wave heights and peak periods along the 20-m isobath and the Stockdon parameterization with the most recent estimate of local beach slope (Stockdon et al., 2012; Stockdon et al., 2006). The extreme water level (EWL) is then computed using the maximum storm surge and wave runup, which may not be coincident in time. Mean water level (MWL), or still water level, is the sum of the maximum storm surge and the maximum wave setup, which may also not be coincident in time (Birchler et al., 2019).

To compute the probabilistic forecast, the elevations of morphologic features were compared with forecast extreme water levels due to storm surge and wave runup. The extreme water level and morphologic feature comparisons were interpolated to a 500 m alongshore resolution using a Hanning window with a full width of 1 km. Each interpolated value was assigned a root mean square difference (RMSD) calculated from the scatter of the data in the smoothing window. The mean and RMSD are used to describe normal distribution for each morphologic and hydrodynamic variable. Using the statistical distribution of the input values at each alongshore location, the probability that the extreme water level exceeds the dune crest or dune toe elevation threshold for a particular storm regime is calculated from the normal cumulative distribution function of elevation minus water level (Stockdon et al., 2012). The forecast extents are summarized in Table 2. The coastal change forecast used the best lidar-based elevation data available at the time for Louisiana, which were collected between 2012 and 2017 (Doran et al., 2020). Forecasts of potential coastal change are categorized as very likely to occur when the probability exceeds 90% for a particular regime. This definition is used in the forecast skill assessment when comparing with observed changes in post-storm imagery.

Many beaches within the study areas have only a beach berm with no sand dune backing the beach. Locations without a sand dune do not have a dune toe, which is required for our definition of collision. If a location without a sand dune is forecast to undergo overwash, collision in that location is assumed to occur. Note that the percentage of coastline forecast to experience change sums to more than 100 %, as the three regimes are calculated independently, and impacts from multiple regimes may be forecast at the same location (Table 2).

Storm	Total length of forecast area (km)	Fraction of area with collision forecast	Fraction o
Laura	160	0.43	1.00
Delta	154	0.43	0.97
Zeta	91	0.64	0.84

Table 2. Fraction of coast forecast (probability > 90%) and observed to experience coastal change for each storm.

2.2 Imagery and Water Level Observations

Locations where forecasts of overwash and inundation were produced were compared with post-storm observations. Post-storm observations of overwash and inundation were determined from visual observations of washover deposits and breaching manually delineated in georectified post-storm imagery. Coastal change was assessed using NOAA aerial imagery collected following Hurricane Laura on August 27-31, 2020 (NGS, 2021a), Delta on October 10-11, 2020 (NGS, 2021b), and Zeta on October 29-30, 2020 (NGS, 2021c) (Figure 2). After NOAA aerial imagery was collected and made publicly available (https://storms.ngs.noaa.gov/), imagery was accessed via a Web Map Tile Service connection to the NOAA server and viewed in geographic information system (GIS) software. A dual data frame was used for side-by-side comparison of pre-and post-storm imagery in GIS map view. A frame of reference that allows for both attention to detail along the coast and a large enough field of view to be efficient is used (2000 m stretch of coastline). The pre- and post-storm imagery was analyzed for occurrence of overwash or breaching via a gradual scan within the spatially linked data frames. When overwash or breaching were observed, the alongshore extent of the feature was manually digitized to denote the length and position of the coastal impact. It was noted if overwash was confined to the sandy portion of coast or extended inland over a road or marsh. Digitization of coastal change impacts were identified along the full coastline within the study area (Figures 1 and 2). The alongshore extent of washover deposits and breaches were defined as line feature classes (Doran et al., 2021). The number and length of 500-m segments of observed overwash was used to determine total instances and alongshore length of overwash for each storm. Each observed segment was coincident with a 500-m forecast segment.

Observations of water levels during Hurricanes Laura and Delta were collected by the USGS Short Term Network (USGS, 2020) of water level sensors in the northern Gulf of Mexico. Higher than normal water levels were observed at sensors exposed to storm impacts located just inland of the beach. The sensors had a recording interval of 60 seconds, and pressure data were low-pass filtered to obtain an estimate of mean water level due to tides and storm surge. The peak water level, as reported by the USGS (2020), is defined as the maximum of the low-pass filtered water level. Sensors along Parish Road 532 in Cameron Parish (LACAM04361) and in Holly Beach (LACAM27066) recorded maximum mean water levels for both Hurricanes Laura and Delta (Table 3). The sensors were deployed on the same pre-installed brackets on power poles for both storms. The center of both storms passed to the east of both sensors; the sensors at Holly Beach were closer to the storm center and shoreline and the observed water levels were higher at this location for both storms. For Hurricane Zeta, there were no sensors deployed within the study area, but USGS streamgages were operating during the storm and recording at 15-minute intervals. The data from the deployments are accessible through the USGS Flood Event Viewer (https://stn.wim.usgs.gov/FEV/).

Storm	**Forecast EWL (m, NAVD88)**	**Forecast MWL (m, NAVD88)**	**Peak measurement (m, NAVD88)**
Laura			[a]
			[b]
Delta			[c]
			[d]
Zeta			[e]

Table 3. Maximum water levels measured and forecast in meters (m) at discrete sensor locations along the sandy coast. Forecast Extreme Water Level

(EWL) and Mean Water Level (MWL) obtained from the U.S. Geological Survey (USGS) Coastal Change Hazards Portal (https://marine.usgs.gov/coastalchangehazardsportal/). Peak measured water levels were obtained from USGS Flood Event Viewer (https://stn.wim.usgs.gov/FEV) a) USGS Water Level Sensor, site LACAM04361, Parish Rd. 532, Cameron Parish, LA, 27 Aug, 2020, 0819UTC; b) USGS Water Level Sensor, site LACAM27066, Holly Beach, Cameron Parish, LA, 27 Aug, 2020, 0558UTC; c) USGS Water Level Sensor, site LACAM04361, Parish Rd. 532, Cameron Parish, LA, 09 Oct, 2020, 2011UTC; d) USGS Water Level Sensor, site LACAM27066, Holly Beach, Cameron Parish, LA, 09 Oct, 2020, 2038UTC; e) USGS Streamgage, Barataria Pass at Grand Isle, LA, October 28, 2020 06:15 PM CDT.

2.3 Forecast Skill Assessment

We use the water level observations and imagery to assess forecast skill and determine possible sources of error. Water level observations are limited to those along ocean-facing shorelines where waves are expected to contribute to MWL and EWL. Washover deposits observed in the imagery are assumed to be representative of areas where overwash occurred and are compared with prestorm forecasts of overwash. It may be difficult for the analyst to differentiate between overwash and inundation. We use breaching in aerial photography as the best available proxy for observed inundation; however, coasts may not breach but could still be inundated if the MWL exceeds the beach berm or dune crest. The same 500 m alongshore segments used in the coastal change forecast were used to categorize the observations; observed overwash and inundation were determined to be present or absent within each alongshore section.

The coastal change forecast skill is examined using observed overwash and inundation via the following commonly used statistics (NOAA Forecast Verification Glossary https://www.swpc.noaa.gov/sites/default/files/images/u30/Forecast%20Verification%20Glossary.pdf The false positive ratio (FPR) compares the missed forecasted events to the total events forecasted,

$$FPR = \frac{b}{(a+b)} \quad \textit{(Equation 1)}$$

where a represents events that were both forecasted and observed (true positive) and b represents those events that were forecasted but were not observed (false positive).

The true positive ratio (TPR), or probability of detection, compares the number of correctly forecasted events (true positives) to the total number of events observed,

$$TPR = \frac{a}{(a+c)} \quad \textit{(Equation 2)}$$

where c is events that were not forecasted but were observed (false negatives). The Brier Score, B, is represented by the following equation,

$$B = \frac{1}{N}\sum_{t=1}^{N}(F_t - O_t)^2 \quad \textit{(Equation 3)}$$

where N is the total number of forecast segments in the calculation, F_t is the full range of forecast probabilities (ranging from 0 to 1), and O_t are the observations where a value of 1 represents observed and 0 represents not observed (Birchler et al., 2019). The Brier Score assigns a value from 0 to 1, where 0 denotes a perfect forecast and 1 denotes a completely imperfect forecast.

The calculation of the frequency bias is used for categorical forecasts and compares the number of segments forecast to experience coastal change, f, to the number of segments that were observed to experience coastal change, o,

$$bias = \frac{f}{o} \quad \textit{(Equation 4)}$$

A bias of 1 indicates a perfect score for the categorical forecast.

3 Results

3.1 Forecast EWL, MWL and Observations

EWL and MWL in the PCOI forecasts exceeded observations and were dominated by the contribution from storm surge. During Hurricane Laura, the two sensors recorded peak water level elevations of 1.9 and 2.8 m NAVD88, while the forecast mean water levels were 3 and 2.4 m greater than the observations, respectively at those locations (Table 3). Surge represented 90% of the forecast MWL, with wave setup contributing the remaining 10%. Forecast MWLs during Hurricane Delta were also overestimated for the same study area and sensor locations, though not as severely as Hurricane Laura. Observed peak water levels of 1.6 and 2.0 m NAVD88 were overestimated in the forecast by 0.4 and 0.3 m respectively (see Figure 3 for more information). Storm surge represented 80% of the forecast MWL for Delta. A USGS real-time streamgage in Barataria Pass, near Grand Isle, LA measured a peak water level of 2.8 m, which was 0.8 m higher than forecast MWL (2.0 m) and 0.6 m lower than the forecast EWL (3.4 m). No USGS water level sensors were deployed during Hurricane Zeta, limiting our ability to assess the contribution of waves and storm surge to EWL and MWL.

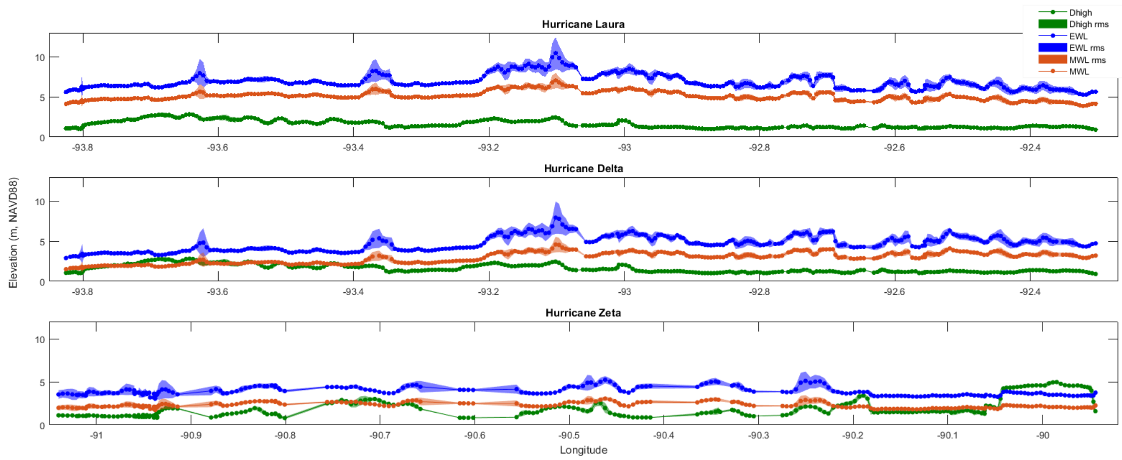


Figure 3. Dune crest elevations and root mean square difference (RMSD) (green), predicted extreme water level and rms difference (blue), and mean water level (red) for Hurricanes Laura (a), Delta (b), and Zeta (c).

3.2 Forecast Probability and Observations of Collision, Overwash, and Inundation

The forecast area for Hurricanes Laura and Delta extended from the Texas/Louisiana border to Mulberry Island, LA, comprising the Chenier Plain coast of Louisiana (Figure 1, left box). The forecast area for Hurricane Zeta extended from Isle Dernieres, LA to Grand Isle, LA (Figure 1, right box), comprising the western delta barrier islands. Nearly all of the study area was forecast to be very likely (probability > 90 %) to experience coastal change during all three storms (Figure 4, Table 2).

For Hurricane Laura, 38 % of the alongshore segments were observed to have overwash present, and 27 % of segments were observed to have breaching present. For Hurricane Delta, 62% of the coast was observed to have overwashed and 64 % of the coast was observed to have breached. For Hurricane Zeta, 15 % of the study area was observed to have overwashed and 0 % of the coast was observed to have breached (Doran et al. 2021).

Comparisons of forecast and observed PCOI were reported as true positives (forecast and observed), false positives (forecast and not observed), false negatives (observed and not forecast) and true negatives (not observed and not forecast) (Table 4). Laura and Delta had false positive ratios for overwash of

0.55 and 0.20, respectively. Laura and Delta had true positive ratios for overwash of 1.0 and 0.97 respectively. There were low numbers of false negatives for overwash across all three storms, with 0 for Laura, 7 for Delta, and 21 for Zeta. True negatives for overwash during Laura and Delta were also low (0 and 1 respectively) because nearly the entire coast was forecast to overwash during Laura and Delta (Fig 4). Inundation predictions were less reliable, as no observed breaches during Zeta yielded high numbers of false positives (61). However, the number of true negatives (121) indicates skill in identifying areas not susceptible to inundation.

Brier Score (3) and frequency bias (4) were used to compare the forecasts and observations (Table 4). For this study, forecasts made for Hurricane Delta were the most skillful in terms of Brier Score, with a value of 0.19 for overwash and 0.36 for inundation. Hurricanes Laura and Zeta had higher Brier Scores, suggesting the forecast was not very skillful. The frequency bias for all three storms indicates an over-estimate for the occurrence of forecast overwash and inundation events. The frequency bias for Hurricane Delta was 1.21 for overwash and 1.09 for inundation, suggesting a more accurate forecast than that of Hurricane Laura (2.24 for overwash and 3.68 for inundation) or Hurricane Zeta (0.87 for overwash; no bias calculated for inundation due to zero observed occurrences of inundation) (Equations 3, 4).

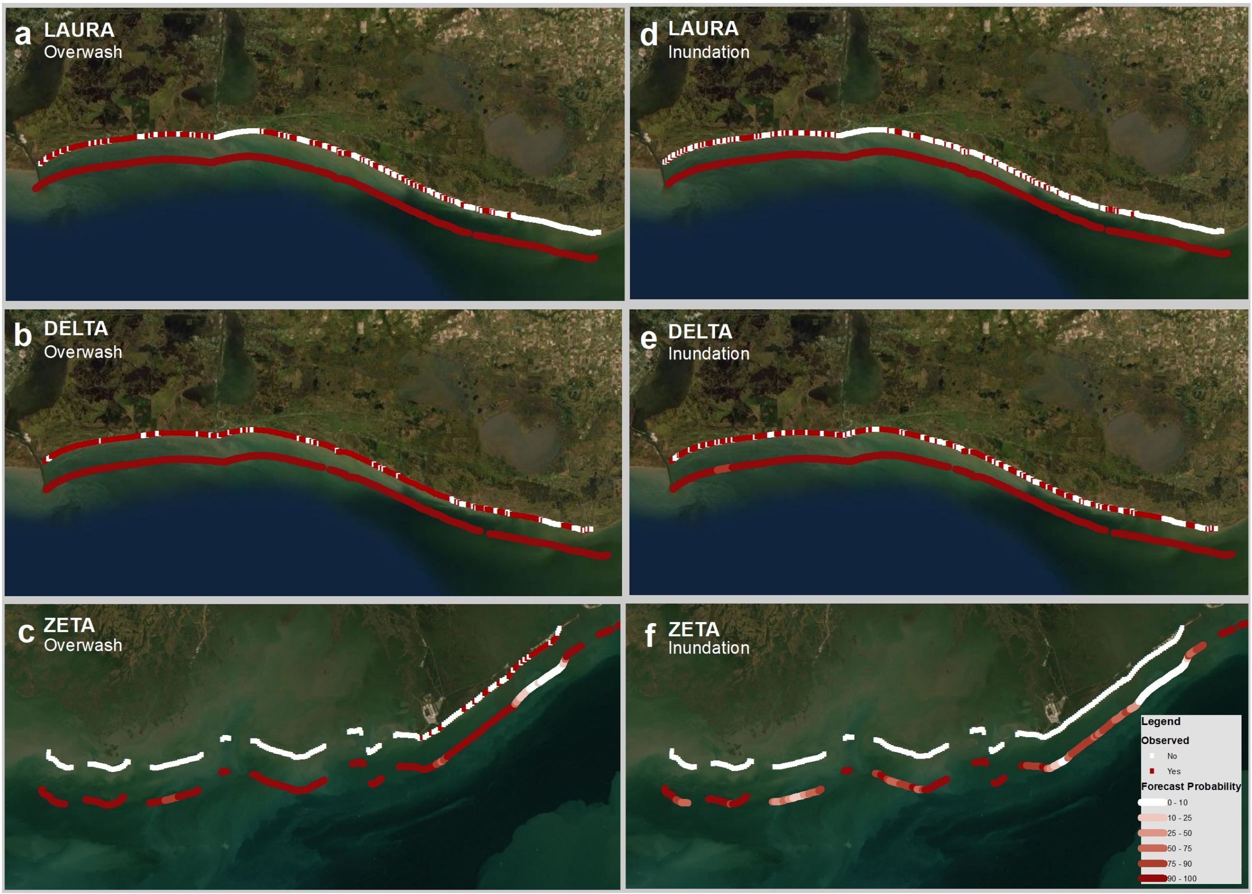

a LAURA
Overwash
d LAURA
Inundation
b DELTA
Overwash
e DELTA
Inundation
c ZETA
Overwash
f ZETA
Inundation
Legend
Observed
No
Yes
Forecast Probability
0 - 10
10 - 25
25 - 50
50 - 75
75 - 90
90 - 100

Figure 4. Comparison of forecast probabilities of overwash and inundation and observations of washover deposits and breaching for Hurricane Laura (a, d), Hurricane Delta (b, e), and Hurricane Zeta (c, f). The seaward line represents the forecast probabilities of impacts for each storm for overwash (a-c) and inundation (d-f). Darker shades of red indicate higher forecast probability of impacts. The landward line indicates observed washover deposits (a-c) and (d-f) breaching (red), and where not observed (white) in post-storm imagery.

a Hurricane Laura	**Observed**	**Not Observed**	**b Hurricane Delta**	**Observed**	**Not Observed**	**c Hurricane Zeta**	**Observed**	**Not Observed**
Forecast Overwash			Forecast Overwash			Forecast Overwash		
Forecast No Overwash			Forecast No Overwash			Forecast No Overwash		
Forecast Inundation			Forecast Inundation			Forecast Inundation		
Forecast No Inundation			Forecast No Inundation			Forecast No Inundation		

d Storm	Brier score	Frequency bias
Overwash		
Laura		
Delta		
Zeta		
Inundation		
Laura		
Delta		
Zeta		N/A

Table 4 Contingency tables of predicted and observed overwash and inundation for a) Laura, b) Delta, c) Zeta and d) Brier Score and frequency bias for overwash and inundation for each storm.

4 Discussion

4.1 Conservative Estimates of EWL May Lead to More False Positives

The high number of false positives for both overwash and inundation and high bias (Table 1) suggests an overly conservative forecast that may be the result of overestimated storm surge, choice of exceedance value, or neglected timing in the estimates of EWL. Here we define a conservative forecast in terms of public safety, where erring on the side of over-forecasting would be conservative, rather than tending towards zero or average conditions. The overestimate of EWLs caused for Hurricane Laura were largely driven by storm surge, with forecast MWLs in Cameron Parish and Holly Beach surpassing measured peak values at the coast (Table 3). A source of the overestimate may be variation between the actual storm track and probable forecast tracks (Pasch et al., 2021). The actual track passed east of Holly Beach and the USGS storm sensors, limiting the volume of water forced upon the sensors by the storm, and as a result the sensor observations did not reach forecast levels. To the east of landfall, USGS high water marks indicate that storm surge exceeded 6 m (Table 1), more consistent with forecasts. MWLs for Hurricane Delta were also overestimated, though only exceeding measured peak values by 10s of cm (Table 3). A conservative estimate of storm surge is important for emergency management considerations, particularly when the track is uncertain and storm surge is highly sensitive to variations in track position. In this case, the conservative storm surge forecast appears to have resulted in a biased coastal change forecast with a high false positive ratio (Table 1).

The 10% exceedance value from the probabilistic storm surge simulations (P-Surge) was used to forecast storm surge at the coast. P-Surge overestimated the true storm surge in many areas, especially those far from the center of Laura (Pasch et al., 2021). The overestimate in MWL likely contributed to an overall false positive ratio of 0.56 for both overwash and inundation when averaged for all 3 storms. Lowering the surge exceedance threshold as forecasts for the location of hurricane landfall become more certain and considering the probability distribution from P-Surge could lead to more accurate predictions of extreme water levels, and therefore coastal change (Van der Westhuysen et al., 2013).

The EWL forecast neglects timing of tidal fluctuations, although the magnitude of tidal fluctuations is included as part of the P-Surge water levels, the independent timing of the highest wave impacts, and peak storm surge. These factors are not necessarily coincident in time, and may result in an overestimate of EWL, even if the independent quantities were accurately forecast. Timing and duration of the highest storm surge and waves are accounted for in the NOAA/USGS Total Water Level and Coastal Change Forecast (http://coastal.er.usgs.gov/hurricanes/research/twlviewer) for much of the Gulf and Atlantic sandy coasts but were not available for the study area during the 2020 storm season.

4.2 Manual Delineation of Collision, Overwash, and Inundation Observations

Differentiating between overwash and inundation regimes in near-nadir imagery is difficult for even experienced analysts and may contribute to uncertainty in observed coastal change and influence forecast skill assessment. Often, a washover deposit in the form of a visible fan of sediment extending landward will allow an analyst to identify an overwash event. Similarly, a visible channel in the beach will identify inundation. The presence of new morphological changes to the coastline from storm-to-storm proved difficult to distinguish given the lack of clear overwash fans in many locations. The Louisiana Chenier Plain is a sediment-starved coastline backed by ridges alternating with low-lying wetlands (Sallenger, 2009). When limited sand is available on the beach to overwash, it may not be clearly visible in the aerial imagery, especially if high water conditions persist. The presence of standing water in areas of low elevation may indicate total inundation but may lack a visual breach or channel. Additionally, the presence of a channel may be ocean-driven or occur when back-barrier lagoon water levels exceed the dune crest (Over et al., 2021). As a result, visual coastal change signals may not be fully representative of overwash or inundation regimes occurring during a storm.

During the analysis of Hurricane Zeta aerial imagery, underexposure and cloud cover, coupled with vast areas of standing water, made detecting visual signals of overwash and inundation difficult. The area affected by Zeta includes areas of low elevation and marsh; rising water levels from both the ocean and back-barrier lagoon may have covered potential visual cues usually associated with overwash or inundation. Without the ability to definitively distinguish the occurrence of overwash or inundation, these areas were not identified as having either event occur during the manual delineation process. These areas were forecast to undergo overwash or inundation, which possibly affected the false negative estimate (Table 1).

4.3 Data and modeling needs

The results of this study highlight the importance of forecasting coastal change hazards and improvements needed to enhance the accuracy of future forecasts. Coastal change hazard forecasts are available on potentially affected sandy beaches within hours of National Hurricane Center forecasts when named storms approach the U.S. coastline. This real-time information is available due to comprehensive analysis of topographic elevation data on sandy open-ocean coasts, application of basic research, (Stockdon et al., 2006; Stockdon et al., 2007), and a well-developed modeling framework that allows post-processing of peak water level and wave forecasts to estimate coastal change. Despite forecast availability, improved methods and capacity for estimating storm-related coastal change are needed to increase forecast accuracy. Increasing the frequency of lidar and structure-from-motion surveys used to assess dune height in coastal areas prone to severe storms, as well as developing methods to rapidly process feature extraction from elevation datasets via machine learning rather than manual delineation, will not only improve forecast accuracy as data is more frequently updated but will reduce sources of uncertainty related to subjectivity and human error during data processing. Already, time dependence of EWL components is being accounted for in next-generation forecasts (e.g., http://coastal.er.usgs.gov/hurricanes/research/twlviewer), and rapid assimilation of total water levels from real-time sensors will improve forecasts in the future. Moving away from forecasts based on conceptual models of coastal change towards real-time estimates of quantitative volumetric and morphologic change may improve skill and add value to forecasts.

5 Conclusions

The probability of coastal change associated with extreme water levels, collision, overwash, and inundation along sandy shorelines of the Louisiana coast were forecast for Hurricanes Laura, Delta, and Zeta. Post-storm aerial imagery was analyzed to assess the accuracy of USGS coastal change forecasts. Forecasts accurately identified locations where coastal change was observed. However, the analysis also demonstrated over-estimation of overwash and inundation for Laura, Delta, and Zeta. The overestimate was most likely due to a conservative storm surge forecast far from the actual location of storm landfall for Laura and Delta. Due to the lack of water level observations for Zeta, and the quality of the post-storm imagery, we are unable to clearly identify the contributing factors to errors in the forecast. The 10% exceedance surge value chosen for forecasting, coupled with neglecting timing elements of the EWL and the manual process of confirming areas of changing beach morphology via observations from aerial photographs may contribute to forecast uncertainties as well. Rapid assimilation of data such as structure-from-motion-derived coastal change, near-real-time total water level observations from coastal cameras, and advances in numerical modeling of coastal change can be explored to enhance the accuracy of these forecasts in the future.

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Open Research

The lidar-derived dune morphology data used for predicting storm impacts in the study are available as a USGS data release via https://doi.org/10.5066/F7GF0S0Z. The probabilities of coastal change for Laura, Delta and Zeta along with the hydrodynamic forcing (surge and waves) are available as a USGS data release via https://doi.org/10.5066/P9Z362BC. The NOAA emergency response imagery used for delineating overwash extents are available from a NOAA web page with links to each individual storm imagery data set via https://storms.ngs.noaa.gov/. The shapefiles of overwash delineation for each storm are available as a USGS data release via https://doi.org/10.5066/P9BW6CG6. The storm tide sensors used to validate modeled water levels are available as a USGS data portal via http://water.usgs.gov/floods/FEV/.

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