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Coastal Dune Vulnerability Assessment: Integrating Adaptation Information into Dune Management System in South Padre Island

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ABSTRACT--A new integrated dune vulnerability assessment model was evaluated in this study to quantify the risk levels of dune vulnerability parameters for development of a dune management system. The methodology used dune exposure criteria such as marine, aeolian and anthropogenic impacts; dune sensitivity criteria such as geomorphological and vegetation conditions; and community adaptation programs to estimate the overall dune vulnerability along a 20 km coastal stretch in South Padre Island (SPI), Texas, USA. Analytical hierarchy process (AHP) was used to prioritize and select site-specific parameters from each criterion. Using remote sensing techniques with high resolution aerial images and digital elevation model, dune vulnerability parameters (including vegetation cover and dune elevation) were estimated. Results showed that dune geomorphology (e.g. low elevation and fragmentation) and vegetation characteristics (e.g. low vegetation cover and lack of root spreading species) were the most significant drivers of dune vulnerability at SPI with high to very high index values. Aeolian vulnerability had 78% correlation with vegetation vulnerability indicating a synergistic benefit for adequate dune vegetation maintenance. Where robust ecological and cultural adaptation programs were implemented at a dune segment, vulnerability index decreased by 20% while a lack of adaptation programs further increased vulnerability index by 11% at other segments. A dune management system was proposed for implementation by County Parks to match a specific dune segment's vulnerability characteristic with appropriate restoration strategy.

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1.0 Introduction

Coastal erosion and its impact on communities and economies has become a global priority. In the United States, more than $100 million has been invested in Delaware for restoration of damaged dunes and beaches (Murray, 2016), while in San Francisco, California, about $650 million in damage cost is expected by 2100 due to explosive waves from the Pacific Ocean (Barringer, 2012). Despite the hazards associated with coastal communities such as sea level rise (SLR), storm surges, erosion and flooding, these areas provide homes, businesses and recreation for millions of people all over the world (Spalding et al., 2014). As of the year 2000, 2.3% of total land area in coastal countries was designated to be within the low elevation coastal zone (LECZ), yet 10.9% of the population in these countries live in LECZ (Neumann et al., 2015) areas. A study of three towns in Massachusetts showed that people would pay a premium for a property closer to the beach (Jin et al., 2015). This trend may be due to lack of availability of quantifiable risk information from the National Flood Insurance Program (NFIP) for the United States Atlantic and Gulf coasts and the highly subsidized beachfront ownership program funded by other tax payers (Leatherman, 2017).

As commercial and infrastructural developments in the coastal areas continue to increase, dunes can consequently suffer damage particularly where beach access is not properly managed (Muñoz-Vallés and Cambrollé 2014). Before Hurricane Sandy, coastal dunes were often regarded as obstruction to beach use and property development (Charbonneau 2015). Consequently, land owners reserved the right to grant easements (Granatell 2013) in many States. In some Texas coasts, dune vegetation have been removed based on ignorance of its ecological value (Pinchback, 2015). Human activities such as driving vehicles on dunes, livestock grazing on dune vegetation, agricultural expansion and excavation for building materials (Scottish Natural Heritage, 2000) can contribute significantly to erosion of beach-dune system. Dunes dissipate near shore wave energy and protect human communities and biodiversity (Spalding et al., 2014), therefore, removal of frontal dunes to create beachfront hotels and recreational facilities can eliminate the buffering capacity of dunes against devastating waves.

In addition to dune vulnerability due to human activities, marine parameters are responsible for wave erosion of the frontal dunes and breaching of barrier islands (Williams et al. 2011; Alexandrakis and Poulos 2014). Depending on the wave energy and storm duration, erosion of dunes and barrier islands due to storm impact can occur in a swash regime, collision regime, overwash regime and breaching regime (Roelvink et al., 2009). The aeolian (wind) influence on dune erosion depends on wind intensity and sediment abundance in the beach area (Sloss et al., 2012).

1.1 Management framework for coastal use and risk reduction

State laws allow free and unrestricted access to public beaches. These laws also prohibit destruction or removal of sand dunes and dune vegetation seaward of dune protection lines and critical dune areas. For instance, the Texas Administrative Code requires the General Land Office (GLO) to implement prohibition of construction activities that weaken dunes or damage vegetation in critical dune areas. Texas consequently established the Coastal Erosion Planning and Response Act (CEPRA) to implement programs that reduce the impact of erosion on beach, natural resources and public infrastructures. Coastal counties are also mandated to have an Erosion Response Plan (ERP) that details potential vulnerabilities and adaptation plans.

Coastal vulnerability assessments provide information to coastal planners and managers to identify areas and species with high vulnerability and determine the level of risks to infrastructures and ecosystems to allow for better planning of adaptation strategies (Denner et al. 2015; Sano et al. 2015). A new concept for vulnerability assessment was framed in the International Panel on Climate Change's (IPCC) fourth assessment report (AR4) as a combination of a system's exposure, sensitivity, and adaptive capacity (IPCC, 2014). Exposure and sensitivity reflect the degree of impacts imposed by a hazard, while adaptive capacity is a measure of a systems' resilience and ability to adjust to potential hazards, (Cabral et al., 2016; Nguyen et al., 2016;

Salik et al., 2015; Sano et al., 2015). The adaptive capacity of a system reflects its intrinsic abilities to adapt to a disruption (Blanco-Canqui and Lal 2010; Corstanje et al. 2015) or can be defined by the management practice, education and awareness and community actions implemented to restore a system after a disturbance (Hosseini and Barker 2016; Nguyen et al. 2016). In addition to climate change parameters, vulnerability assessment addresses socio-economic and non-climatic drivers in order to measure resilience and adaptive capacities of a system prone to coastal hazards.

1.2 Coastal Dune Vulnerability assessment and indices

Dune vulnerability indices (DVI) have been developed from scientific theories, deduced from observations and statistical inferences or can simply be based on individual or expert opinion (García-Mora et al. 2001; Alexandrakis and Poulos 2014; Satta et al. 2016). The procedure involves selection of relevant vulnerability indicators (Judge et al. 2003; Cabral et al. 2016; García-Mora et al. 2001), their normalization to a common scale and single vulnerability index (Nguyen et al., 2016). Several indices have been developed for beach-dune system vulnerability assessments using indicator parameters which are specified based on the physical relationships between the exposure factors and response of the beach-dune system (Alexandrakis and Poulos 2014) and from many years of data collection (García-Mora et al. 2001). For example, the biophysical vulnerability indices describe physical and biological systems (Cinner et al. 2012; Borges et al. 2014; Bagdanavičiūtė et al. 2015; Denner et al. 2015), social vulnerability indices address demography, economic and educational status (Boruff et al. 2005; Dumenu and Obeng 2016) while the integrated approach combines both biophysical and social aspects of vulnerability (Nguyen et al., 2016). The U.S Geological Survey uses a six physical parameter index to measure coastal vulnerability (Hammar-Klose, 1999), García-Mora et al. (2001) developed a dune vulnerability index based on a checklist of exposure and sensitivity information of dunes, while other studies (Majumdar et al., 2014; Williams et al., 2011, 2001) expressed dune vulnerability as a ratio of protection measures. Recent trends in vulnerability assessments have adopted the systems exposure, sensitivity and adaptive capacity approach (IPCC 2014; Cui et al. 2015; Salik et al. 2015).

The importance of a comprehensive vulnerability dune assessment has been well established (García-Mora et al. 2001; Williams et al. 2011). This study further used an analytical hierarchy process to eliminate non-relevant parameters (such as grazing and agricultural land use impact) in order to have site-specific dune vulnerability characterization for a given coastal segment. The specific objective of this study was to apply site specific dune exposure and sensitivity criteria parameters to determine the major drivers of coastal dune vulnerability and to demonstrate the significance of community adaptations programs toward mitigation of dune vulnerabilities at different coastal segments in South Padre Island, Texas. This approach provides dune vulnerability characterizations and indices which can be used as a knowledge base for a dune management expert system and selection of suitable mitigation strategies

2.0 Methodology

2.1 Study Area

South Padre Island is one of the most popular open beaches and resort destinations in the United States (Gerlach 1989; THK Associates 2005). Inspite of this, Texas' Cameron County and Padre Island are well established (Boruff et al., 2005) as one of United States' most vulnerable coastal communities based on physical and socio-economic variables. The Gulf coast is associated with high intensity hurricanes. In 2008 Hurricane Dolly made landfall at South Padre barrier Island and resulted in an estimated $1 billion damage including the disturbance to the Laguna Madre estuary ecosystem (Pasch and Kimberlain 2009). A recent report showed that South Padre Island currently has 2 ft/year accretion in the southerly end, a fairly stable shoreline at the middle section and a 2 ft/year erosion rate in the northerly end (Ravella et al., 2012). The shoreline change and dune height variation between years 2000 and 2005 have been credited to sediment availability and transport potential (Houser and Mathew 2011). A second access causeway has been proposed to connect the South Texas mainland to South Padre Island near Beach Access 3. The new causeway is expected to stimulate further mobility and economic development on the Island as well as unintended threats to dune existence if not properly managed. Vegetation dynamics studies were previously carried out on the South Padre Island (Lonard et al., 1999), however, there are no recent detailed studies of the dunes that quantifies their vulnerability for implementation of appropriate restoration strategies. Ten coastal segments along a 20 km coastal stretch were selected for the dune vulnerability assessment based on accessibility to private and public lands, historic shoreline change and human impacts (Ravella et al., 2012). The width of each segment was 200 m with variable transect lengths bounded by the beach and Park highway 100 from South to North as shown in Figure 1.

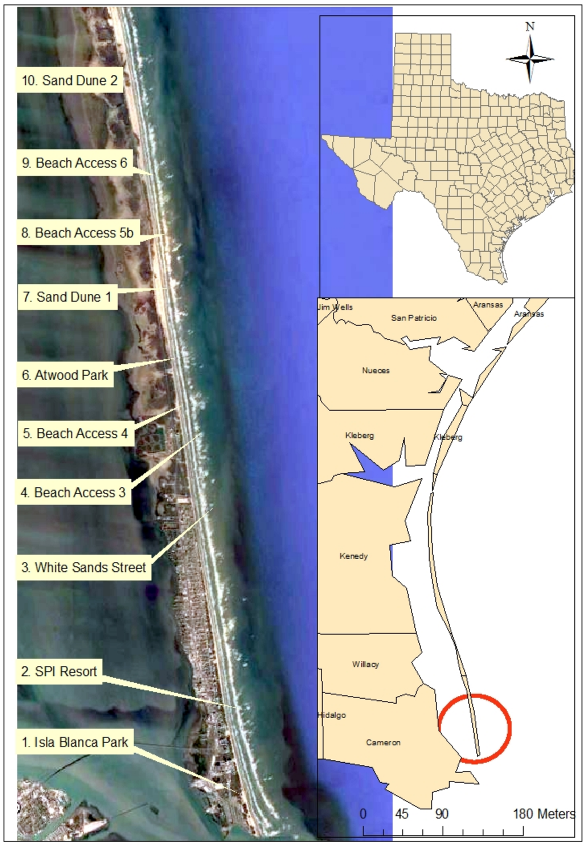

Figure 1. Location of selected coastal segments for dune vulnerability study in South Padre Island (SPI) in Cameron County, Texas, along the Gulf of Mexico.

2.2 Structure for dune vulnerability indices

Subsequent to a preliminary field investigation of the South Padre Island and public records, vulnerability parameters (García-Mora et al. 2001; Majumdar et al. 2014) were categorized into exposure, sensitivity and adaptation criteria (Nguyen and Woodroffe 2015; Nguyen et al. 2016) as shown in Figure 2.

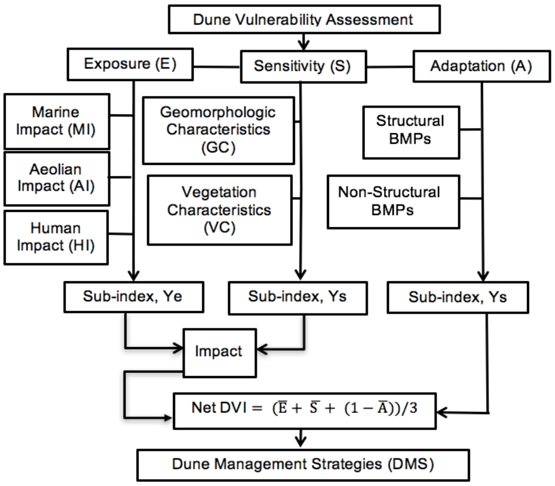

Figure 2. Integration of vulnerability criteria and parameters for a dune vulnerability assessment and dune management system for South Padre Island, Texas

The vulnerability parameters were coalesced and prioritized with an Analytical Hierarchy Process (AHP) (Saaty 1990; Camare and Lane 2015; Boateng et al. 2015) approach as shown in Figure 3. Coastal managers, Parks Supervisors, County Engineers, public records and site surveys provided data and informatory guide for an AHP pairwise comparison of vulnerability parameters to select 41 final site-specific vulnerability parameters based on their relative importance. By excluding non-relevant vulnerability parameters, the AHP procedure eliminates possible underestimation of the overall vulnerability index at any dune segment compared to using a reference total of 64 (Majumdar et al. 2014) or 65 (Williams et al. 2001) vulnerability parameters previously used.

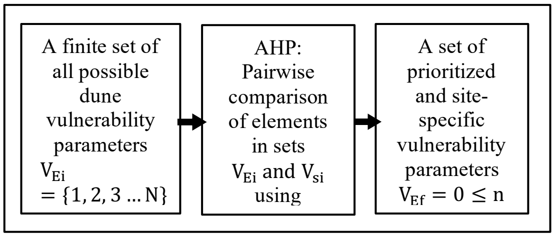

Figure 3. An AHP approach for selection of site specific dune vulnerability parameters for South Padre Island. The subscripts i and f represent before and after AHP respectively.

The net Dune Vulnerability Index (DVI) was calculated for each coastal segment using normalized partial vulnerability indices (Nguyen et al., 2016; Salik et al., 2015; Sano et al., 2015)

$$\text{Net DVI} = \frac{\overline{E}+\overline{S}+(1-\overline{A})}{3} \qquad (1)$$

where $\overline{E}$ is the sum of sub-indices from exposure criteria partial vulnerabilities (MI + AI + HI), $\overline{S}$ is sum of sub-indices from sensitivity criteria partial vulnerabilities (GC + VC) and $\overline{A}$, is a sum of adaptive capacity sub-indices. The sub-index y_n for each criterion (MI, AI, HI, GC and VC) was calculated using equation 2 for each dune segment.

$$y_n = \frac{\sum_{i=1}^{n} R_i}{\sum_{i=1}^{n} R_{i,max}} \qquad (2)$$

where R_i is the risk value of ith parameter of a criterion defined as 0 to 4 in Table 1, $R_{i,max}$ is the maximum possible risk value of a parameter. The dune vulnerability of each coastal segment was designated as low, moderate, high and very high (Table 2) based on a risk scoring scale, partial and total vulnerability indices of each criterion. An analysis of variance was used to test a null hypothesis that there is no significant difference in the impact of dune vulnerability parameters at the ten locations studied (Figure 1).

Table 1. Site specific and relevant dune vulnerability parameters used for South Padre Island, Texas.

Dune Exposure Criteria (E)					
Marine Influence (MI)	0	1	2	3	4
Orthogonal fetch (km)	< 25	< 100	<250	< 500	> 1000
Berm Slope (degrees)	< 5		5 to 10		> 10
Tidal Range (m)	< 2		2 to 4		> 4
Coastal orientation to wave direction (degrees)	> 45	30-35	15 - 30	5 - 15	< 5
Width of the zone between HWSM and dune face (m)	> 75	< 50	< 25	< 15	< 5
Breaches in the frontal dune due to wash over, relative total area	0%	< 5%	< 25%	< 50%	> 50%
Trend in sea level rise	Decreasing		stable		Increasing
Particle size of the beach: Phi size	1	2	3	4	5
Aeolian Impact (AI)	0	1	2	3	4
Sand supply input (as width of beach, m)	High, > 15		Moderate > 10		Low < 10
% cover of embryo dunes along the seaward edge	> 50	> 25	> 5	< 5	none
Blowouts and Aeolian breaches in the seaward face not induced by trampling as % of system	< 5	< 10	< 25	< 50	> 50
% of primary dune not vegetated	< 10	> 10	> 20	> 40	> 75
If recent sand deposition, assess colonization by *Ipomoea*	High		Moderate		Low
Human Impact (HI)	0	1	2	3	4
Visitor pressure	Low		Moderate		High
Visitor frequency	Low		Moderate		High
On dune driving	None		Some		Much
Horse riding	None		Some		Much
Path network as percent of frontal dune	0%	< 5%	> 5%	> 25%	> 50%
Summer beach cleaning frequency (high is twice a day, medium is daily) mechanical cleaning	Low		Moderate		High
% permanent infrastructures replacing active dunes (road, house)	< 5	< 25	< 50	< 75	> 75
% ephemeral infrastructures replacing active dunes (outdoor facilities, camping)	< 5	< 25	< 50	< 75	> 75
Dune Sensitivity Criteria (S)					
Geomorphologic Characteristics (GC)	0	1	2	3	4
Length of homogenous active dune system (km)	> 20	> 10	> 5	> 1	> 0.1
Width of dynamic dune system (km)	> 2	> 1	> 0.5	> 0.1	< 0.1
Average height of primary dunes (m)	> 10	> 7.5	> 5	> 2.5	< 2.5
Average height of secondary dunes (m)	> 10	> 7.5	> 5	> 2.5	< 2.5
Slope steepness of frontal dune	< 15		15 - 30		> 30
Degree of dune fragmentation	Low		Moderate		High
Particle size of primary dune (mm)	2	1	0.5	0.25	0.125
Relative area of wet slacks measured from map (%)	Low		Medium		High
Historical shoreline erosion/accretion rate (ft/yr)	> 2.0		stable		> - 2.0

Vegetation Characteristics (VC)	0	1	2	3	4
Percent of plants species that withstand salt spray and sand burial in the primary dune	< 25		> 50		> 75
Percent of plants species with extensive root system in the primary dune for stabilization	> 15		> 5		0
Percent of dune segment vegetated	> 75	> 50	> 25	> 10	< 10
% cover of exotic species in the seaside of the frontal dune	0	< 1	< 5	< 15	> 15
% cover of vigorous or normal vitality in the seaside of the frontal dune	> 75	> 50	> 25	> 10	< 10
Dune Adaptation Criteria (A)					
Adaptation programs (Benefits score)	0	1	2	3	4
Surveillance and signage	None		Some		Much
Controlled access, dune driving and parking	None		Some		All
Erosion control BMPs implemented	Negligible		Some		Elaborate
Coastal vegetation and re-vegetation frequency	Low		some		High
Dune nourishment and re-construction	None		some		High
Rolling Easement allowed (offset from dune vegetation) ft.	none		100		>200

Table 2. Recommended segment's dune vulnerability designation based on its overall vulnerability parameters indices (Palmer et al., 2011).

	Low	Moderate	High	Very High
DVI score	0.00 – 0.25	0.25 – 0.50	0.50 – 0.75	0.75 – 1.00

2.3 Description of Dune Vulnerability and Adaptation parameters

A set of dune vulnerability indices criteria and parameters considered for site assessment are listed and described below:

Marine Impacts (MI): These impacts include wave action parameters like fetch (which determines the magnitude of offshore wave height and dominant wave period), berm slope (which determines if a wave is dissipative or reflective near shore), tidal range, coastal orientation to the wave (which determines the intensity of wave power component transporting sediments alongshore) and beach sand particle size.

Aeolian Impacts (AI): The parameters considered were sand supply budget, the percentage of embryonic dunes and blowout areas, and percentage of vegetated and unvegetated dunes (which relates to the intensity of wind erosion).

Human Impacts (HI): These parameters include visitors' frequency, horse riding, paths, dune driving and percentage of permanent structures (roads, houses, parking) on dunes.

Geomorphological Characteristics (GC): The resilience and susceptibility of coastal dunes depends on the ability of the geomorphology to absorb wave, wind and human impacts. These parameters include length, width and height of dunes, slope steepness, homogeneity and degree of fragmentations.

Vegetation Characteristics (VC): Vegetation was classified into two categories from the standpoint of building diverse dune topography through sand trapping with shoot system and structural stability against erosion with root structure: (1) species that are highly tolerant to saltwater spray and capable of withstanding sand burial such as Sesuvium portulacastrum (sea purslane), and (2) species that have below-ground roots spreading and leaves that are adapted to coastal stress such as Uniola paniculata (sea oats).

Adaptive Capacity (AC): Structural and cultural adaptation parameters considered to increase coastal dune resilience were education and awareness, surveillance and signage, erosion control BMPs, regulatory and response plans, re-vegetation, controlled parking and setbacks and easement allowed.

2.4 Data and Data Sources

Marine data were accessed from the National Oceanic and Atmospheric Administration (NOAA) and through aerial images and field surveys. Blowouts and dune vegetation percentage cover were determined by digitizing and classifying a 2016, 1m resolution Worldview 3 satellite image acquired from Digital Globe Foundation. In addition, ground truthing of each segment's aeolian vulnerability features were carried out. The human impact information with respect to tourists' footprints, proposed development projects, and general ownership rights on the Island was accessed from a survey of County administrators and public records. Aerial image visualization with Google Earth and field reconnaissance were also used to complement public records. Distances, elevations and slopes were measured using the 2013 digital elevation model from the national elevation dataset (NED), Google Earth elevation profile and levelling surveying method. Land cover was evaluated with a 2016 1m-resolution classified image while the location of different vegetation species along a dune transect were randomly recorded in a field survey with a hand-held Trimble GPS. The vigorousness and vitality of dune vegetation was determined with the normalized difference vegetation index (NDVI) as shown in equation 3. Due to the high chlorophyll content, healthy vegetation reflects more radiation in the near-infrared (NIR) and green wavelengths of the electromagnetic spectrum than any other wavelengths. Vegetation absorbs radiation in the Red and Blue wavelength.

$$\text{NDVI} = \frac{\text{NIR}-\text{Red}}{\text{NIR}+\text{Red}} \qquad (3)$$

The number and types of adaptation programs around each coastal segment was physically documented.

3.0 Results

Tables 3 and 4 show the partial vulnerability indices for exposure, sensitivity and adaptation criteria parameters at the selected ten coastal dune segments. For each vulnerability criterion, the boxplot (Figure 4) shows the degree of variability of impacts from one dune segment to another. Aeolian and vegetation criteria had the highest variance while marine exposure criteria impact had the lowest variance. The impacts of the various dune vulnerability criteria (MI, AI, HI, GC and VC) significantly varied from one coastal segment to another, therefore the null hypothesis was rejected at $P < 0.05$. Also, dune sensitivity criteria (geomorphology and vegetation condition) had the overall highest partial vulnerability indices at all dune locations. Dune vulnerability impact due to the sensitivity criteria was significantly greater than the combined exposure criteria (marine, aeolian and human impacts) at $P < 0.05$ student t-test.

Figure 4. Distribution of partial dune vulnerability indices at the ten dune segments due to Marine Impact (MI), Aeolian Impact (AI), Human Impact (HI), Geomorphological Characteristics (GC) and Vegetation Characteristics (VC) at South Padre Island, Texas in 2017.

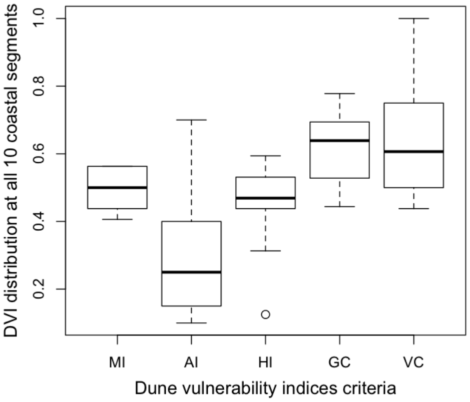

Table 3. Partial dune vulnerabilities indices estimated from the respective vulnerability criteria for the ten selected dune segments at South Padre Island in 2017.

∗WSS – White Sand Street

Table 2. Dune Exposure, Sensitivity, Adaptation and Total Vulnerability indices for the selected ten dune segments at South Padre Island in 2017.

The calculation procedure for net dune vulnerability index is demonstrated below using geomorphologic characteristics parameters for at the Isla Blanca dune segment.

$$y_{\text{GC, Isla Blanca}} = \frac{\sum_{i=1}^{n} R_{iGC}}{\sum_{i=1}^{n} R_{iGC,max}}$$

$$= \frac{(4+4+3+4+1+0+3+0+0)}{36}$$

$$= 0.528$$

Calculation was repeated for aeolian, human, vegetation, marine and adaptation parameters at the Isla Blanca dune location.

$$\text{Net DVI} = \frac{\overline{E} + \overline{S} + (1 - \overline{A})}{3}$$

$$= \frac{(\text{MI} + \text{AI} + \text{HI}) + (\text{GC} + \text{VC}) + (1 - \text{A})}{3}$$

$$\overline{E} = \frac{(0.406 + 0.150 + 0.438)}{3} = 0.331$$

$$\overline{S} = \frac{(0.528 + 0.450)}{2} = 0.489$$

$$\text{Net DVI} = \frac{(0.331 + 0.489 + (1 - 0.833\ )}{3}$$
$$= 0.329$$

The procedure was then repeated for the other nine (9) dune locations.

All selected dune locations had similar marine vulnerability parameters with an overall average marine criteria vulnerability index of 0.491±0.059. The mean sea level rise was 3.48 mm/year based on monthly mean sea level data from 1958 to 2006 (NOAA 2017) and the maximum tidal range previously recorded was 2.93 m. The coastal orientation was 15o-30o(SE), the fetch was approximately 1000 km while the Google Earth elevation profile for all dune segments on the 20 km coastal stretch showed an average berm slope of less than 5o. As expected, aeolian impact had a high vulnerability index (0.700) at Sand Dune 1 which had no vegetation and other sites including WSS (0.400) and Sand Dune 2 (0.400) where frontal dunes had little vegetation. Sand Dune 2 also had significant blowouts and aeolian breaches in the primary and secondary dunes. Human activity impact had a high vulnerability index (0.594) at WSS within the city limit resulting from a combination of high visitors' frequency, pressure and removal of dunes for outdoor leisure such as beach volley ball and building of sand castles. Locations with less frequent visitors (Access 5b and Sand Dune 2) had low human impact vulnerability indices.

The average geomorphological vulnerability index at all segments was 0.626±0.109, high vulnerability indices were estimated at Sand Dune 2 (0.694), WSS (0.722) and Sand Dune 1 (0.778) respectively. A 20 km longitudinal cross section of the study area digital elevation model showed a 0-10 m dune elevation profile and high degree of fragmentation (Figure 5), the cumulative average height was estimated as 2.28 m with ArcGIS classification tool. The height of primary dunes at the Sand Dune 1 and WSS were barely above the high-water mark but also reach up to 7 m at Access 3 and 4, and Atwood Park. Typical dune widths were as low as 15 m at WSS within the city limit and up to 250m at the Access 3 and 4, and Atwood Park.

The average vulnerability index of vegetation condition at all locations was 0.639±0.191. The classified image (Figure 6a) had 53% dune vegetated area and 47% bare (sand dune, pavilion roof and paved road) area. The unvegetated Sand Dune 1 and 2 were extremely vulnerable with very high vulnerability indices of 1.000 and 0.938 respectively. Figure 6b shows the NDVI map for the entire area. According to a previous classification (Gandhi et al., 2015), the bare area and dead vegetation had NDVI values less than 0.1, the brush and grassland had about 0.2 – 0.3 while the most healthy and vigorous vegetation were in the 0.5 – 1.0 range. Overall, dunes at the southern end had higher NDVI values and more vigorous and healthy vegetation than those in the northern end of the Island.

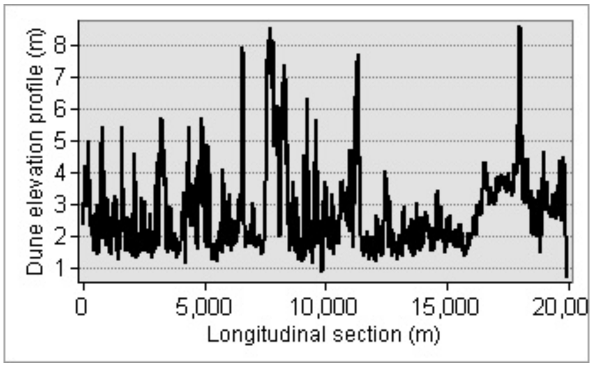

Figure 5. Dune elevation profile along a 20km longitudinal section from Isla Blanca Park to Sand Dune 2 location.

Figure 6. (a) Classified image of Land cover showing 53% dune vegetation and 47% bare area (b) NDVI shows dune vegetation health classification, Bare area and dry vegetation: < 0.25, grassland and brush: 0.25 – 0.50, healthy vegetation 0.5 – 1.0. South Padre Island satellite image, Texas, 2016.

4.0 Discussion

4.1 Dune Exposure Criteria Vulnerability

Marine criteria parameters have a moderate to high vulnerability impact on South Padre Island dunes. Marine criteria parameters are the same at every dune segment within the 20 Km coastal stretch because of the relatively small scale of the study area relative to the fetch and the coastal orientation to dynamic wave energy. The orientation angle (α) of SPI to incoming ocean waves suggests a strong dissipation at the shoreline and alongshore erosion vulnerability due to potential increases in horizontal component of wave power (Pcos α) as α tends to zero (Komar, 1998). Sea shells and Sargassum found at the toe of foredunes as well as breached and fragmented foredunes are evidence of the tidal energy strength. Gentle slopes have dissipative effects and can provide some surge attenuation (USACE, 1984), although the coastal fetch at South Padre Island (1000 km) is long enough to generate catastrophic storm surges such as seen in Hurricane - 5 (Beulah), Hurricane – 3 (Allen), Hurricane – 4 (Bret) and Hurricane – 1 (Dolly) (Roth, 2010).

Aeolian vulnerability impact on South Padre Island dunes is greater at unvegetated dune segments than areas with established vegetation. Formation of barchan dune landforms and regular sand burial of Park Highway 100 (Figure 7), which often presents a high maintenance cost for the Texas Department of Transportation (Judd et al., 2008), are evidence of dominant aeolian transport at the unvegetated dune locations. Dunes at the public parks (Atwood and Access 3) have well stabilized railroad vine on the seaside of the primary dune and potentially contribute to wind speed reduction, sand trapping and consequently low aeolian vulnerability indices (0.100). Moreover, a strong correlation (78%) between dune vegetation vulnerability and aeolian vulnerability suggests a potential mitigation of aeolian vulnerability impacts through dune re-vegetation and maintaining appropriate cover density.

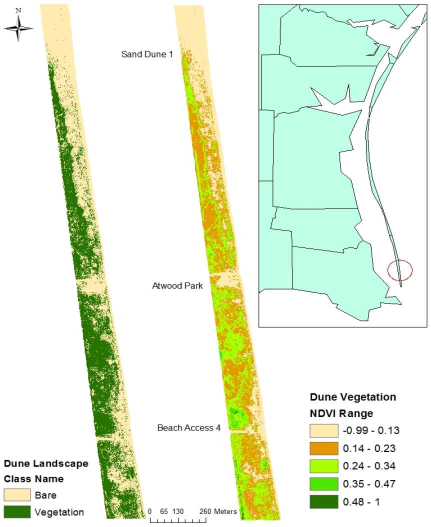

Figure 7. Barchan dune landform and sand deposition on Park Highway 100 at South Padre Island, Texas, 2017

Human impacts on dune vulnerability are higher where the intensity and frequency of beach usage is high. At the public parks and beach access points, high human impact vulnerabilities were due to removal of significant portions of secondary dunes for essential services like construction of parking and pavilions which inadvertently reduced the width of dunes. An unintended consequence of routine mechanical cleaning of the upper beach is compaction of sand which inhibits aeolian transport and growth of embryo dunes as previously reported (Kelly, 2014). Since the human impact on dune vulnerability depends on size of recreational activities, land use and installation of public facilities, proper planning, dune protection awareness and enforcement of ordinances can be effective ways to reduce impact. Human impact on dune vulnerability is dynamic and can improve or deteriorate depending on dune education or the lack of it. Potential economic projects should implement construction strategies that cause minimal impact to nearby dunes (Wagner et al. 2016; Wang and Xiang 2016).

4.2 Dune Sensitivity Criteria Vulnerability

Dune sensitivity criteria consisting of geomorphology and vegetation parameters are the major drivers of dune vulnerability on South Padre Island. Exposure criteria pose moderate to high vulnerability to dunes while sensitivity criteria constitute high to very high vulnerability to dunes. Hence, Coastal managers should channel their resources into reinforcing the sensitivity parameters in order to build a resilient dune system against external disturbances. Dunes on the South Padre Barrier Island are particularly vulnerable since the widths of the island is bounded on both sides by dynamic Gulf waves and the Laguna Madre bay in addition to Park Highway 100 which runs through the middle of the dunes from south to north. Parameters contributing to high geomorphologic vulnerability include low elevation of dunes below 2.5 m, small dune width, absence of secondary dunes at many locations and high dune fragmentation. Secondary dunes within the city limits have generally been removed for construction of hotels and beach fronts facilities and are therefore more vulnerable than other dune fields. A design height of primary dune maybe recommended based on wave run-up height (Cheon and Suh 2016; Larson et al. 2004; Tsoukala et al. 2016) using storms and hurricanes wave data, however the checklist method (García-Mora et al. 2001) provides a safe and conservative estimation range for dune height although with considerable overestimations at times.

A high dune vegetation vulnerability index is associated with sites that have little vegetation or a few clusters of soft leaf species (sea purslane). Transects with moderate vulnerability also had dicotyledons (sea purslane, railroad vine and gulf croton) in the foredunes. Although these species have saltwater spray tolerance, aboveground sand trapping and dune building functionality, they lack a robust root system for sand dune enmeshment and stabilization (Gyssels et al. 2005; Preston and Crozier 1999). Previous studies classified dune vegetation vulnerability (García-Mora et al. 2001) based on native dune vegetation in Europe and their adaptation to stress and location along a transect landward of tidal influence. The approach used in this study further classified dune vegetation by the resilience it impacts to dunes through reinforcement and stability from roots enmeshment, thereby reducing particle translational displacement during erosion events. Coastal dune segments where secondary dunes exist, clusters of root spreading species like saltmeadow cordgrass, bitter oats and sea oats flourished. These species once dominated the windward and leeward sides of the primary dunes (Lonard et al., 1999) but have been mostly replaced by railroad vine, gulf croton and camphorweed possibly due to their susceptibility to water logging (Shadow, 2007). These trends suggest that South Padre Island dunes maybe potentially less resistant to storm erosion since there are fewer species in the foredune with root enmeshment functionality for dune stabilization and resilience against hydrodynamic impacts (Machado et al., 2015; Silva et al., 2016).

4.3 Dune Adaptation Criteria

Figure 8 shows about 20% reduction of total vulnerability indices at Isla Blanca Park, Access 3 and Access 4 due to implementation of adaptation programs whereas non-implementation of adaptation programs further increased total vulnerability index by 11% at Sand Dune 2. Dunes at Sand Dunes 1 and 2 have low adaptation indices (below 0.250) due to non-implementation of surveillance, re-vegetation, set-backs, dune walkovers and dune re-shaping programs. WSS, SPI Resorts and Access 5b segments have low to moderate adaptation indices (0.250 – 0.500) due to unrestored beaches and insufficient land easement for shoreline change and sea level rise. Beach Accesses 3, 4 and 6, Atwood Park and Isla Blanca Park, all have adaptation indices above 0.500 attributable to several structural and non-structural management practices such as surveillance, dune protection information boards, designated parking area, dune walkovers and dune conservation areas intended to minimize the impacts of exposure parameters. A resulting $P<0.05$ suggests that implementation of adaptation programs at South Padre Island can significantly decreased the overall dune vulnerability index.

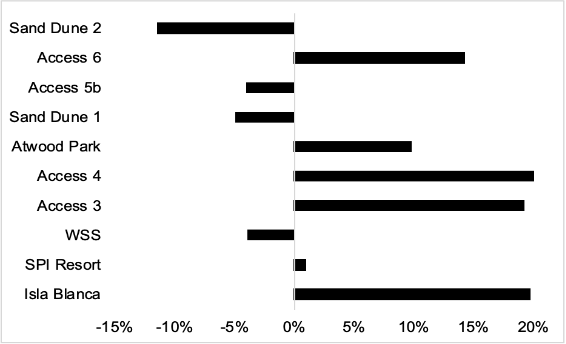

Figure 8. The impact of implementation and non-implementation dune adaptation programs on the overall dune vulnerability indices at different locations on South Padre Island, Texas.

Figure 8 does not only demonstrate the capacity of adaptation programs to reduce dune vulnerability but also encourages more cooperation and investments from coastal managers and other stakeholders (Cheong, 2014; Sarzynski, 2015). The practice and success of dune adaptation programs shown in this study for South Padre Island (Figure 9) is consistent with the overall application of adaptation strategies in coastal communities for mitigation of climate change impacts (Cheong, 2014; Sano et al., 2015; Wong et al., 2014). However, dune adaptation project should be based on resilient designs and anthropologic data to avoid recurring failures (Figure 10). An argument has been made that coastal natural resource restoration programs including dunes should receive lower spending budgets relative to the socio-economic gains they provide (Alves et al., 2017). It is however important to consider that the capacity of dunes to protect the very same coastal communities and socio-economic activities is central to their continued conservation and restoration. Collective actions among coastal communities, research centers and media have been successfully reported to be more effective than individual efforts towards mitigating erosion impacts (Karlsson and Hovelsrud 2015), and just like in Hurricane Sandy (Clay et al., 2016), social capital is needed among interest groups and conservationists as a force for sustaining dune ecological resilience. While results obtained in this study for ten dune segments are promising, more coastal segments and transects study is needed for a generalization of the dune vulnerability characterization and impact of adaptation programs in South Padre Island.

Figure 9. Recent integrated dune conservation program at Atwood Park, South Padre Island Texas, 2017: Revegetation, dune walkover, sand fences, designated parking and signage

Figure 10. A failed section of restored dune few weeks after construction due to lack of toe protection at South Padre Island, Texas, 2017

4.4 Proposed Dune Management Support System (DMSS) for South Padre Island

Dune vulnerability information is needed to build a resilient dune system and potential management of socio-economic and exposure criteria parameters. A dune management system guideline (Figure 11) is proposed to help coastal managers use dune vulnerability characterization and indices as knowledge base for a dune management support system. The proposed dune management support system prioritizes and provides a multi-layer assignment for ecological dune management strategies (DMS) for dune sites based on their individual vulnerability criteria parameters, partial vulnerability indices and total vulnerability index. The list of DMS include but not limited to (1) Dune re-shaping and reconstruction (2) Dune re-vegetation (3) installation of sand fences (4) Installation of geotextiles for toe protection (5) Installation of dune walkovers (6) Construction setbacks and rolling easements (7) Warning signs and surveillance (8) Designated parking areas (9) Dune protection education.

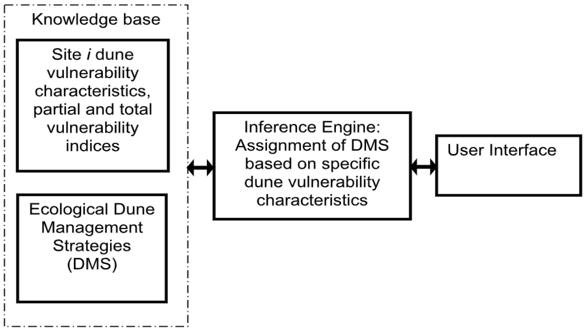

Figure 11. Decision support system architecture matches a suitable ecological dune protection approach with a given dune site based on the dune vulnerability indices and characterization

5.0 Conclusions

Coastal dunes provide valuable ecosystem services notably the protection of coastal communities from tropical storms and habitat for wildlife. This study developed a unique dune vulnerability assessment method for South Padre Island by using the analytical hierarchy process for pre-selection of relevant and site-specific dune exposure, sensitivity and adaptation criteria parameters.

Results from this work show that combined sensitivity criteria (geomorphology and vegetation condition) has significantly greater impacts on South Padre Island dune vulnerability at all evaluated coastal segments than the combined exposure criteria (marine, aeolian and human impacts) parameters. A positive correlation between vegetation and aeolian vulnerability, suggests that re-vegetating dunes can lead to reduction of aeolian vulnerability impacts.

Remote sensing techniques with digital elevation models and high-resolution satellite imagery provide a quick and accurate assessment of coastal dune geomorphologic (dune height, slope, width, length, fragmentations) and vegetation condition (vegetation density and health) for adaptation decision making.

Structural and cultural adaptation programs like dune walkovers, dune protection awareness and other dune management strategies can contribute up to 20% reduction of the overall impacts of human and natural vulnerabilities at some dunes sites while their absence further exacerbated vulnerability up to 11%. This study highlights the power of adaptation programs to discount the overall dune vulnerability and encourages greater participation and funding from coastal community leaders and private partners.

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