Social and Ecological Vulnerability of Beaches, Galapagos Islands, Ecuador

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Introduction

Following the oil spill caused by the grounding of the tanker the *Jessica* in January 2001, a European Union Task Force and the Charles Darwin Foundation called for the creation of a response network in Galapagos for natural resource management and preparation for coastal hazards (Sanderson et al. 2001). One decade later, the arrival of two tsunamis caused property damage and losses in the coastal towns, and altered the shape and configuration of shorelines that are nesting grounds for endemic flightless cormorants, marine turtles, marine iguanas, and more (Lynett et al. 2011). To anticipate the scale and impacts of change due to natural hazards, human use (direct & indirect), economic development, tectonic uplift and subsidence, or sea level rise, novel and transferable vulnerability assessment approaches are required – especially in diverse and fragile island settings. Vegetated (e.g., mangroves & wetlands) and non-vegetated (e.g., sand beaches and rock outcrops) coastal areas are critical transition zones between land, freshwater habitats, lagoons, wetlands, residential communities and tourist services, and the marine near-shore and open ocean that provide essential ecosystem services, including shoreline protection, nutrient cycling, fisheries resources, habitat and food, and regulation of nutrients, water, particles, and organisms (Defeo et al. 2008). This project proposes to create a comprehensive, geographic database for the beach habitats of Galapagos that will be used to investigate the interactive processes that govern their vulnerability and resilience. We define beaches as the coastal regions including water and adjacent shore-lands, from dunes through the littoral zone, including the foreshore and backshore as well as the shore zone (Figure 1). Particular emphasis is placed on erosional and depositional landform units of beaches as well as the near-shore bathymetry and the neighboring vegetated landscape units, including fringing mangroves, wetlands, and primary and secondary dunes.

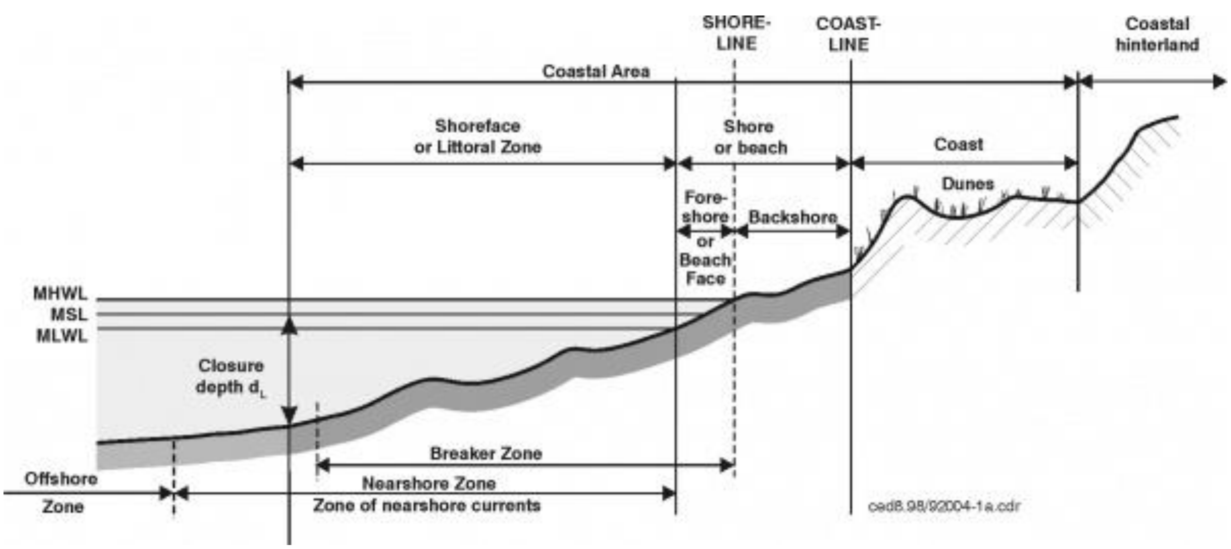

Figure 1. Coastal profile and typical beach geomorphology (Arnott 2010).

Our goals for June/July 2013 are to (1) collect baseline data for a group of intensive study areas, e.g., selected beaches distributed in different geographic, geomorphic, and biogeographic settings to support a preliminary analysis of beach vulnerability by social and ecological forces, with additional field work conducted in the summer of 2014 to expand the number of beaches in the analysis and to calibrate and validate our preliminary analyses of beach vulnerability, and (2) develop an information database on beaches and surrounding coastal areas as the basis of a monitoring network that will facilitate informed, responsive decisions about the sustainable management of Galapagos beach areas, relative to imposed threats to the fragile and sensitive ecosystems of beaches and their interactions with social, terrestrial, and marine sub-systems of the Galapagos Islands.

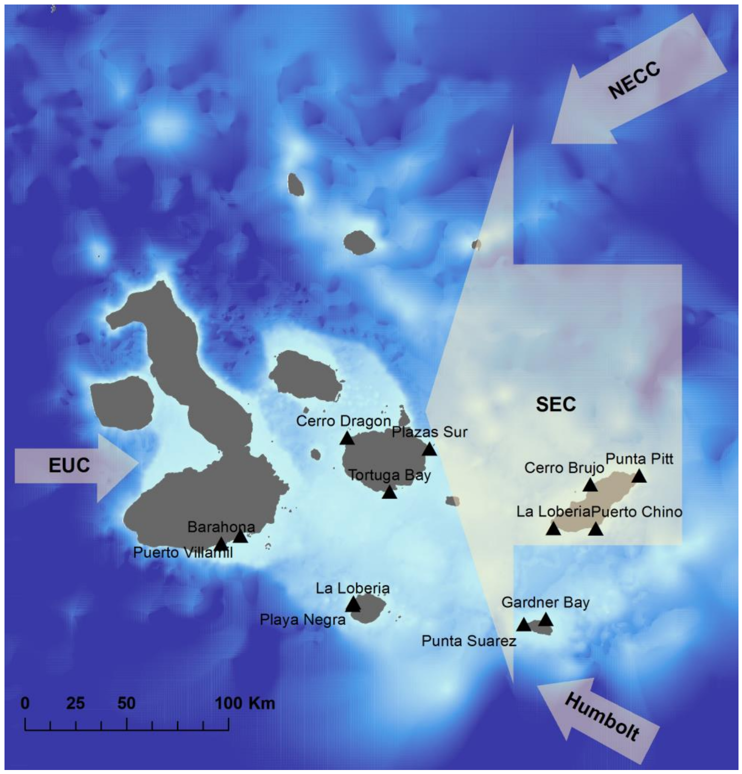

Figure 2. Target beaches for 2013 fieldwork, prevailing current directions, and bathymetry.

Because the islands and individual beaches within the Galapagos archipelago are not homogenous, we have identified 34 singular beaches that represent a range of environmental conditions and human impacts: we have selected 13 of these beaches for this analysis during the summer of 2013, with the remained examined during the spring and summer of 2014 (Figure 2). The selected beaches are within the boundaries of our current holdings of fine-resolution, multi-spectral satellite imagery and aerial photographs that provide contemporary and historical information about land and marine features, with a focus on beaches. Coastal Vulnerability Indices (CVI) have been developed for shoreline areas at varying scales around the world, using geologic, geographic, geomorphic, and biophysical process variables, such as, near-shore bathymetry, regional elevation, geologic uplift, slope angle and aspect, landscape shape and configuration, wave heights, tidal ranges, and sea level change (Thieler and Hammar-Klose 1999; UNEP 2005; Kumar and Kunte 2012). The majority of these studies, however, do not incorporate a human component (Omo-Irabor et al. 2011; Farhan and Lim 2012). Our study will create a database of linked spatial, social, and environmental indicators of vulnerability for the Galapagos coastline, the first of its kind. This project will proceed in two phases: (1) Preliminary data collection will be carried out on target beaches during June/July 2013. Because of their high accessibility, we will first consider six beaches near the populated areas; namely, La Loberia and Puerto Chino (San Cristobal), La Loberia and Playa Negra (Floreana), Puerto Villamil (Isabela), and Tortuga Bay (Santa Cruz). If possible, we will visit several beaches that are restricted for scientific or tourism purposes, including Cerro Brujo and Punta Pit (San Cristobal), Gardner Bay and Punta Suarez (Española), Barahona (Isabela), La Loberia and Playa Negra (Floreana), and Cerro Dragon and Plazas Sur (Santa Cruz). Expert knowledge through key informant interviews will be used to validate vulnerability categories. Satellite imagery will be used to extract additional biophysical and geographic shoreline characteristics of target beaches; (2) after summer 2013 fieldwork is complete, we will calculate a CVI for each target beach, and assemble digital data for all candidate beaches in the study. During late 2013 and 2014, we will expand the scope of the study to more remote beaches, and using satellite imagery for the entire archipelago, we will extrapolate vulnerability criteria associated with target beaches to all shoreline areas.

Phase 1: Vulnerability measures and 2013 fieldwork

During the first phase of this project, we will assign values from 1 (very low) to 5 (very high) to a set of eight vulnerability criteria for each beach (Table 1). We have chosen four local factors (i.e., land use, land cover, remoteness, human use intensity) and four external factors (i.e., orientation, connectivity, slope, geomorphology – landform type and landscape shape and configuration, i.e., localized topographic convexity and concavity). A final CVI value will be computed for each target beach. In the following sections, we describe the vulnerability factors, their context in Galapagos, and how we propose to assign or collect the relevant metrics.

Table 1. Vulnerability factors and classifications

	Category				
Variable	**Very low (1)**	**Low (2)**	**Moderate (3)**	**High (4)**	**Very high (5)**
GNPS land use	Restricted	Natural intensive	Managed intensive	Nearby intensive	Recreational
Land cover	Extensive presence of invasive plant species, habitat loss, low habitat use	Partly invaded, or altered state (e.g. reduced wetland)	Shoreline areas with some non-native vegetative cover, low disturbance	Seasonal use by iconic species, few to no invasive species	Critical habitat that hosts iconic species (e.g. mangroves, sea lion colonies)
Remoteness	75-100 km	50-75 km	25-50 km	10-25 km	<10 km
Human use intensity	Low		Moderate		High
Orientation	North	Northwest	West	East	South
Connectivity, diversity, endemism	High		Moderate		Low
Topographic curvature: concavity & convexity	>12%	9-12%	6-9%	3-6%	<3%
Geomorphic types	Rocky coasts/cliffs	Pocket beaches (<200 m long) among cliffs	Small beaches (200-1000 m) separated by rocky outcrops	Large beaches (>1000 m) with coarse sediment, lagoons	Large beaches (>1000 m) with fine sediment

GNPS land use

The Galapagos National Park Service has classified visitor sites within the protected areas of the archipelago according to their use and level of access. We adopt their classification scheme as a measure of vulnerability associated with land use, per the categories described below:

- Restricted: These are sites that have well-preserved ecosystems, with unique landscape, biological, or geographic features. Because of fragility or vulnerability, severe restrictions are imposed on tourist visitation.
- Natural intensive: Excellent state of conservation, with endemic or unique species of flora and fauna and particular geological formations.
- Managed intensive: Excellent landscapes and natural and biological attractions, with tourist infrastructure due to its fragility or erosion.
- Nearby intensive: Close to populated areas, with marine or land access, outstanding natural features, but some evidence of human alteration.
- Recreational: Sites within the Galapagos National Park for the recreation and enjoyment of the local community and visitors in a natural setting near urban limits, easily accessed.

Land cover

Beach ecosystems and intertidal areas provide habitat for a myriad of species in Galapagos. We will use coastal land cover as a measure of habitat suitability, by documenting the presence or absence of native and introduced species, state changes in land use/land cover, levels of productivity and disturbance regimes, and beaches that have historically supported turtle nesting areas and other key flora and fauna characteristic of native and endemic species as well as iconic and emblematic species in the Galapagos. Using a hand-held spectro-radiometer (325-1100 nm) and a plant canopy analyzer, we will collect spectral and productivity measurements of selected specimens that represent differences of age, density, species, and Leaf Area Index, an indicator of productivity. GPS technology will be used to reference field measurements to Worldview-2 satellite imagery, aerial photographs, and multi-thematic coverages organized in a GIS for classifying landscape conditions and spatial pattern of beach features and components.

Remoteness

Similar to land use/land cover, remoteness is calculated as the distance from an urban center or tour boat embarkation points in Galapagos (Baltra, Puerto Ayora, Puerto Baquerizo Moreno, and Puerto Villamil). For the 34 beaches identified in this study, the average distance to the nearest embarkation point is 29 km, with a standard deviation of 24.6 km and a min/max of 0.9 and 90 km, respectively. We define the highly vulnerable beaches as those within 25 km of an access point, a distance that can be reasonably traveled by small boats or fishing vessels, with vulnerability levels decreasing by one standard deviation for the remaining categories. Remoteness differs from land use in that a “Restricted” beach may be quite close to a town or embarkation point. The well-known sea turtle nesting sites, Barahona and Quinta Playa near Puerto Villamil on Isabela Island, are two examples.

Human use intensity

Pollution from point sources is the primary factor affecting water quality at Galapagos beaches. Although runoff from uplands to lowlands is low (Adelinet et al. 2008; d'Ozouville 2008), nutrients and large and small organic debris are transported from the upper highlands to the coasts during extreme rainfall from El Niño events and along the coast through longhsore current and persistence swell directions, and wave features, and to a lesser extent during the hot, rainy season from January to April. Coastal lagoons and public beaches can be contaminated by the mixing of untreated sewage and wastewater from towns. On Isabela Island, Walsh et al. (2010) identified point contaminants of groundwater from Puerto Villamil’s public water system that can infiltrate coastal lagoons and impact water quality, both near and distant to the town. Wheeler et al. (2012) found that wildlife near public use beaches on San Cristobal carried antibiotic-resistant bacteria of human origin, while sampling at more distant sites revealed none, indicating human waste contamination of coastal waters. Cargo and passenger vessels also adversely impact water quality in the bays of the populated islands through exchange of oil and ballast water. We will use DEMs created by Ecuador's Instituto Geografico Militar from 2007 aerial photographs to extract hydrologic features at an archipelago-wide scale and identify coastal areas of high probability pollution and freshwater/saltwater mixing. During fieldwork 2013, we will collect secondary data on offshore pollutant loads and anthropogenic waste from the Charles Darwin Research Station and the Galapagos National Park. We will also seek information from the Galapagos National Park and tourism operators on tourist visitation load at sites with restricted access. We will also use 3-D terrain laser scanner to construct high resolution digital terrain models to characterize geomorphic settings, such as curvature and convexity for hydrologic routing of water and associated pollutants. We will also develop canopy models of coastal vegetation, particularly, fringing mangroves that are important for terrestrial and marine studies.

Orientation

In addition to prevailing surface and sub-surface current directions, Schaeffer et al. (2008) found that islands in the eastern part of the archipelago are the first to experience the impacts of El Niño events and suppressed upwelling, with eastern coastal areas of Santiago, Santa Cruz, and Floreana experiencing the greatest decrease in phytoplankton biomass during these events. Individual site vulnerability to changes in upwelling and current intensity may vary, however, according to barrier features such as coral reefs, marine topography, and cliffs and related lava flows and outcrops. In this study, beach orientation will be used as a proxy for wave energy, which in the archipelago is driven by the South Equatorial Current and the Equatorial Undercurrent, in combination with seasonal shifts in the trade winds. During visits to each target beach, we will observe wave breaker type, long-shore current direction, and ongoing beach erosion and deposition. To quantify seasonal shifts in marine heterogeneity, level 3 satellite data products from SeaWiFS, MODIS, and AVHRR sensors will be acquired to establish oceanographic environmental profiles for target beaches and their surrounding areas over a 3-year period (chlorophyll concentration, sea surface temperature, and water turbidity). We will also interview local fishermen, divers, and other informed sources about seasonal shifts in beach-swell interactions, historical changes, and recent changes associated with the recent tsunami event in the Galapagos Islands.

Connectivity, Diversity, Endemism

Shoreline connectivity and oceanographic forces have a strong impact on biological dispersal and genetic diversity (Collins et al. 2010). The scale of connectivity in marine systems is typically greater than in terrestrial systems, due to high levels of mixing and mobility. Shapefiles and satellite imagery will be used to identify the nearest neighborhood beaches by geodesic distance, as a measure of habitat connectivity. For the purposes of this evaluation, we will consider large, isolated beach environments to be less vulnerable to regional phenomena such as El Niño/La Niña, as well as local hazards like colonization by invasive species.

We are also mindful of the importance of species diversity and endemism in the Galapagos Islands and the possible social and ecological threats to beach communities that support or could support future colonization. Using existing data on Galapagos flora and fauna, we will associate such data with our selected study beaches and adjacent terrestrial and marine neighborhoods. Using satellite derived land use/land cover information we will generate spatial diversity measures, descriptions of biodiversity of each intensive study area, and characterize each beach environment relative to the presence/absence of native and endemic species.

Terrain Configuration

Coastal landforms are shaped by erosional factors (e.g., wave-cut platform, sea caves and wave cut notches, and sea stacks and arches) and depositional features (beaches, barrier bars, beach ridges, spits, bay-mouth bar, tombolo, and intertidal mud flats, marshes, and mangroves) that are often influenced by local to regional controls on wave energy (e.g., seafloor geometry, storm surges, seismic waves, tides, and local currents). Further, coastal geomorphology is influenced by sediment supply, dominant wind velocity and direction, moisture and vegetation patterns, landform units, depositional or erosional forces, and historical contexts, including, dune morphology. We will measure the convexity and concavity of each sampled beach, and note differences in seafloor makeup and bottom type. We will employ a FARO 3-D Laser Scanner for constructing high resolution digital elevation models of entire beaches and/or selected beach segments that represent different landform settings and topographic transitions. At sites where fine resolution, Worldview-2 satellite imagery is available, we will integrate the FARO measurements of beach curvature with near-shore bathymetry observations and coastal vegetation patterns derived from the satellite images. Elsewhere in the archipelago, we will use bathymetric data compiled by Ecuadorian Naval Hydrographic Charts from the 1990s and early 2000s and medium resolution satellite data from Landsat and Aster programs and multispectral systems.

Geomorphology

The vulnerability of beaches is related to their configuration and their dynamism that is influenced by local and regional factors and its geographic site and situation. For instance, beaches comprised of volcanic boulders and rock outcrops provide a relatively stable substrate that may offer beach protection depending upon their geographic and geomorphic positions on the landscape, and whether the beach is favored by the occurrence of erosional or depositional processes. Conversely, beaches comprised of erodible substrates such as fine sand, unprotected by volcanic outcrops and not anchored by local fringing mangroves could offer a higher level of vulnerability through increased dynamics and geomorphic and ecological fragility. The FARO 3-D Terrain Scanner will be used to assess terrain configurations and landscape units, indicative of geomorphic types, sediment size, and beach texture, particularly, where coral, shells, and large and small organic debris from coastal vegetation, for anchor beaches by colonized mangrove sites. Interviews with key informants will solicit information on short and long-term geological and geomorphic processes, like dune formation and tectonic uplift and subsidence, possibly, altering terrain configurations, erosion and/or deposition patterns for various beach segments, and changing use patterns of iconic species for nesting, foraging, and breeding.

During 2013 fieldwork, we will solicit information from key informants in marine science, conservation, and tourism in Galapagos. We anticipate conducting a maximum of 30 semi-structured interviews on Santa Cruz and San Cristobal to address gaps in available data and to obtain historical information on the vulnerability criteria described above. Because a comprehensive CVI has never been developed for the Galapagos Islands, our observations and interviews may yield alternative values to the vulnerability criteria described in Table 1. All measurements will be made on site, and no samples will be removed from the study areas.

Phase 2: Spatial analysis and shoreline vulnerability classification

When values for all eight vulnerability indicators have been collected for the target beaches, we will calculate a simple CVI for each. The CVI formula employed here was developed by Theiler and Hammar-Klose (1999), and will allow us to relate vulnerability criteria in a quantifiable manner to highlight areas of Galapagos shorelines where the effects of anthropogenic and biophysical factors may be the greatest. Once each target beach is assigned a vulnerability value for a specific data variable, the CVI is calculated as the square root of the sum of the ranked variables, divided by the total number of variables:

$$\mathrm{CVI} = \sqrt{\frac{x_1 + x_2 + \cdots + x_{n-1} + x_n}{\mathrm{n}}}$$

Where x_i is a vulnerability criteria value of 1 to 5.

Vulnerability criteria will also be entered into a GIS to develop virtual beach models that can be compared among sites for common characteristics. Using satellite data holdings for the target beaches, we will apply a set of exploratory procedures commonly used in remote sensing to classify their spectral and spatial characteristics into meaningful categories that may be associated with vulnerability. First, we will conduct a Principle Component Analysis (PCA) to transform spectral values into a set of linearly uncorrelated variables. The first principle component, or spectral band, will account for as much of the variability in the data as possible, and so on, with the goal to reduce redundancy in the imagery. This is especially important in areas where multi-band, fine-resolution satellite imagery, such as Quickbird, IKONOS, and Worldview-2 is available (Al-Khudhairy et al. 2005). Once principle components have been identified, the composition and spatial structure of target beaches will be mapped using Object-Based Image Analysis (OBIA) classification approaches. For comparison, we will also use a classification and regression tree (CART) method to discriminate between land cover types, by recursively partitioning the available spectral signatures and any ancillary data into increasingly homogenous subsets (Lawrence and Wright 2001). An advantage to tree-based classification is its ability to incorporate categorical variables or missing data with continuous numerical data, and the classifier does not need to be trained (Hansen et al. 1996).

Expected Outcomes

Once we have an understanding of the general makeup of each beach, we will apply landscape pattern metrics at the patch, class, and landscape levels to characterize the spatial character and context of beach components. Composition and spatial configuration will be evaluated using both structural (pattern) and functional (process) metrics. Finally, we will integrate established characteristics of each type of beach habitat and associated vulnerability with pre-existing satellite imagery to create a comprehensive vulnerability profile of all beaches in the Galapagos, for use in marine and terrestrial spatial planning and mitigation of environmental hazards.

The data to be collected and derived through mixed methods approaches and the analyses to be conducted will be the basis of a beach monitoring program, an assessment of social and ecological vulnerability of beaches, and the baseline of a study of changes in beach environments over space and through time.

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