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A Coastal Vulnerability Index for Sea Turtle Conservation Management in Tortuguero National Park, Costa Rica

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Abstract

Globally, as a result of the rising sea levels, the erosion, flooding, and retreat of the coastline would affect coastal communities, in particular, the economy of tropical and biodiverse regions. From an ecological point of view, tropical beaches are important nesting habitats for endangered sea turtle species. Therefore, it is crucial to develop tools to estimate the vulnerability to sea level rise of nesting beaches. Tortuguero National Park is located in the Northern Caribbean coast of Costa Rica and is the most important nesting ground for green turtles (Chelonia mydas, L.), in the Western Hemisphere. To assess the vulnerability to sea level rise of this nesting site, this study adapted the widely used Coastal Vulnerability Index (CVI) framework to the socio-economic conditions, and at the same time, to the biological settings of the nesting population of green sea turtles. To calculate the total CVI, first, the Physical Vulnerability sub-index (PVI) which includes six physical parameters (shoreline change rate, mean sea level rise, coastal slope, significant wave height, tidal range, coastal regional elevation) were calculated; then the Anthropogenic Vulnerability sub-Index (AVI) with three parameters (distance to town center, land cover, touristic impact) and the Biological Vulnerability sub-index (BVI) with two parameters (Distribution of nesting, eroded and inundated nests) were calculated thereafter. Different weights were assigned to each of the parameters using the Analytical Hierarchical Process (AHP) approach. The urbanized sectors of Tortuguero National Park were dominated by “High” and “Very High” vulnerability classes while the sectors within the National Park were categorized in “Low” and “Very Low” vulnerability classes. The overall coastal vulnerability map shows a high risk, induced by unregulated urbanization on the beachfront. This type of urbanization reduces not only the sea turtle nesting activity but also the vegetation line, that can serve as a buffer in the case of a potential beach retreat. The lack of regulation by the authorities has allowed the construction of buildings outside the retreat area allowed by the Costa Rican legislation. This study recommends the implementation of a setback line for the town of Tortuguero, to enable an adequate buffer line between the beach and the buildings. It is also suggested to carry out reforestation campaigns of the vegetation on the beachfront in order to maintain the ideal conditions for sea turtle nesting.

Key words: coastal vulnerability index, sea level rise, coastal management, sea turtles, Tortuguero National Park

Resumen

A nivel mundial, la erosión, las inundaciones y el retroceso de la línea costera, como resultado del aumento del nivel del mar, afectarían a las comunidades costeras, en particular, a la economía de las regiones tropicales y a la biodiversidad. Desde un punto de vista ecológico, las playas tropicales son hábitats importantes para la anidación de especies de tortugas marinas en peligro de extinción. Por lo tanto, es crucial desarrollar herramientas para estimar la vulnerabilidad al aumento del nivel del mar de las playas de anidación. El Parque Nacional Tortuguero está ubicado en la costa norte del Caribe de Costa Rica y es considerado como la playa de anidación más importante para las tortugas verdes (Chelonia mydas, L.), en el Hemisferio Occidental. Para evaluar la vulnerabilidad al aumento del nivel del mar de esta playa de anidación, este estudio adaptó la metodología ampliamente utilizada del Índice de Vulnerabilidad Costera (CVI), añadiendo a los cálculos las condiciones socioeconómicas y biológicas de la población de anidación de las tortugas marinas verdes. Para calcular el CVI total, primero se calculó el subíndice de Vulnerabilidad Física (PVI), que incluye seis parámetros físicos (tasa de cambio de la línea costera, elevación media del nivel del mar, pendiente costera, altura de ola significante, rango de mareas, elevación regional costera); luego se calculó el subíndice de Vulnerabilidad Antropogénica (AVI), con tres parámetros (distancia al centro del pueblo, mapa de uso del suelo, impacto turístico), y el subíndice de Vulnerabilidad Biológica (IVB), con dos parámetros (distribución de los nidos de tortuga verde y presencia de nidos erosionados e inundados). Se asignaron diferentes pesos a cada uno de los parámetros utilizando el enfoque del Proceso Analítico Jerárquico (AHP). Los sectores urbanizados del Parque Nacional Tortuguero estaban dominados por las clases de vulnerabilidad "Alta" y "Muy Alta", mientras que los sectores dentro del área protegida del Parque Nacional estaban clasificados con una vulnerabilidad "Baja" y "Muy Baja". El mapa general de vulnerabilidad costera muestra un alto riesgo, inducido por la urbanización no regulada en el frente de playa. Este tipo de urbanización no sólo reduce la actividad de anidación, sino también la línea de vegetación de borde a la playa, que puede servir de amortiguamiento en caso de una posible pérdida de playa. La falta de regulación por parte de las autoridades ha permitido la construcción de edificios fuera del área de retiro permitida por la legislación costarricense. Este estudio recomienda la implementación de una línea de retroceso para el pueblo de Tortuguero, para permitir una adecuada línea de amortiguamiento entre la playa y las edificaciones. También se sugiere realizar campañas de reforestación de la vegetación en el frente de playa para mantener las condiciones ideales para la anidación de tortugas marinas.

Palabras clave: índice de vulnerabilidad costera, aumento del nivel del mar, manejo de áreas costeras, tortugas marinas, Parque Nacional Tortuguero.

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1. Chapter 1: Introduction

Beaches are essential habitats for many marine and terrestrial species since they build the interface where fluvial, marine, and terrestrial habitats interact (Colombini & Chelazzi, 2003; Mahoney & Bishop, 2017). For the endangered group of sea turtles, they are crucial to fulfilling their reproductive cycle (Chacon, Dick, Harrison, Sarti, & Solano, 2008). Sea turtles are long-lived reptiles that spend most of their life inside the water, and only the females come back to shore to lay their eggs (Omar Defeo et al., 2009; Fish, Côté, Gill, Jones, & Watkinson, 2005; Fujisaki, Lamont, & Carthy, 2018; Hamann et al., 2010; Hawkes, Broderick, Godfrey, & Godley, 2007; Mazaris, Matsinos, & Pantis, 2009). Sea turtles have an exceptional reproductive behavior which consists in returning to the same beaches to nest where they were born (Miller, 1997; Mazaris et al., 2009; Spotila, et al. 2017). This behavior may limit their ability to make rapid and significant scale shifts to other suitable nesting areas (Butt, Whiting, & Dethmers, 2016). Therefore, a potential loss of the nesting beaches represents a decrease of incubation success of the nests and a decrease in the survival of hatchlings (Butt et al., 2016). Although, these impacts will depend on the specific nesting requirements of each species and the site-specific capacity to adapt to changes. *Chelonia mydas* (Linnaeus, 1758), or green sea turtles, have a range from 0.2 to 1.2 km from their hatching beach (Archie Carr & Carr, 1972), and thus are highly site-specific.

Sea turtles are pantropically distributed, and their nesting grounds are found on tropical beaches (Archie Carr, 1986; Seminoff & Southwest Fisheries Science Center, 2004). They are areas of high productivity that worldwide represent critical habitats for marine-terrestrial species and host a growing human population with increasing economic activities (Ramesh et al., 2015). The impacts, of this human-induced pressures, have made coastal areas possibly the most transformed and most endangered socio-ecological system on earth (Cummins et al., 2014). They are often characterized by widespread unsuitable practices, that degrade the structure and function of these ecosystems (Wong, 2003).

In addition, hazards also come at a global scale, like the sea level rise induced by climate change (Omar Defeo et al., 2009; Mahapatra, Ratheesh, & A.S., 2013). Although, episodic events, like storms, can affect shorelines (Mahabot, Pennober, Suanez, Troadec, & Delacourt, 2017), sea level rise is a long term threat that will increase the risk of coastal flooding and storminess (Cambers, 2009; Omar Defeo et al., 2009; Kim, Park, Woo, Jeong, & Lee, 2017; Union of Concerned Scientists, 2012; Xie, Zou, Mignone, & MacRae, 2019). The global mean sea levels are under the prediction of a rise of 0.3 to 1.0 m by 2100, following the low to high greenhouse scenarios (IPCC, 2014a; Xie et al., 2019). This rise can create significant changes in the shoreline dimensions like the process known as shoreline retreat or coastal squeeze. This process represents the long term landward retreat of the shoreline and coastal habitats (J. P. Doody, 2013). That is the reason why predicting shoreline retreat is critical for planning coastal management strategies and assessing habitat destruction and its biological impacts (E. Doukakis., 2005).

Sea turtles have evolved in high-energy and wave-dominated environments with continuous alterations over a period of millions of years (seasonal erosion and accretion, high tide flooding, etc.), but the rate of this extensive coastal development might not give them the time required to adapt (Butt et al., 2016; Dewidar & Frihy, 2010; Fish et al., 2005; Mazaris et al., 2009). This study will address the coastal vulnerability to sea level rise on second sea turtle nesting rookery in the world. The study site is located in Tortuguero National Park, on the Caribbean coast of Costa Rica and will be carried out for the nesting period of the green sea turtle season species (July to November). Tortuguero National Park has the particularity of having a tourist town directly next to it, which increases human influence.

Tortuguero National Park has a long biodiversity conservation history, set as an example in the region (STC, 2019b). Its conservation strategies have been successful in minimizing the impacts of humans on the sea turtle populations (Troëng & Rankin, 2005). These strategies have also helped to protect a highly important rainforest ecosystem for the Caribbean of Costa Rica. It is considered to be the largest rookery for the endangered green sea turtle (*C. mydas*) in the western hemisphere, which has made it one of the most touristic places in Costa Rica (IUCN, 2019a; STC, 2019a). But despite having successful conservation trajectory (Troëng & Rankin, 2005), the Caribbean beaches are particularly vulnerable to changes caused by rising sea levels (Cambers, 2009). Tortuguero is a thin strip of land, intersected by two river mouths that define the area as an elongated island (COOPRENA R. L., 2007). As well, as many biodiversity protected areas around the region, the conservation efforts in

Tortuguero have been focused on halting the illegal poaching and extraction of nests, but there is a lack of efforts towards the potential loss of coastline. In recent years sea turtle population and tourist activity have both grown, which has led to the urbanization of the coast as well as deforestation on the edge of the beach.

It is necessary to adopt long- term measures to cope with the vulnerability of habitats towards sea level rise and human-induced environmental degradation, to protect biodiversity. Approaching biodiversity at a habitat level promotes in situ conservation and demands more complex solutions for conservation-development conflicts (Keith, 2015). The IPCC & CZMS (1992) describe the term 'vulnerability of coastal zones' in the context of climate change as the incapability of the system to cope with the resulting impacts of the accelerated sea level rise (Mahapatra et al., 2013). In other words, vulnerability assessments include the susceptibility of the coastal zone to physical changes, possible impacts on socio-economic and ecological systems and adaptation options (Harvey, Clouston, & Carvalho, 1999; Mahapatra et al., 2013). Internationally, there have been several attempts of vulnerability assessments of coastlines towards climate change and sea level rise (Mahapatra et al., 2013), the 'Coastal Vulnerability Index' (CVI) being a broadly used method. This CVI assessment can be used to highlight the coastal segments or sectors where the impacts of sea level rise might be the greatest, and where there is a higher probability of physical changes on the beach as sea level rise (Mahapatra et al., 2013).

Nevertheless, the coastal vulnerability assessments using the CVI method have not been applied to sea turtle nesting beaches. There is a gap in the CVI's anthropogenic pressures and biological vulnerability parameters specific for the species considered. This gap makes the application of the CVI to underestimate the actual vulnerability of a coast as a habitat.

The present study seeks to calculate the sandy coast's natural vulnerability to sea level rise and the subsequent habitat loss for a sea turtle nesting in Tortuguero National Park. This research will adapt the existing Coastal Vulnerability Index method by adding anthropogenic and biological (species-specific) parameters. Tortuguero has the advantage of having multi-temporal data available for anthropogenic and specific parameters of green turtles. The result of this approach will be the characterization of Tortuguero's beach at a local scale, through mapping and ranking of the different parameters. The overall CVI map will serve to compare vulnerability classes across different beach sectors and will be used to derives recommendations for coastal management planning.

1.1. Justification

Sea turtles are marine reptiles that are closely linked to tropical beaches. Coastal tropical areas are sites of high economic and population growth (Archie Carr, 1986; Ramesh et al., 2015; Seminoff & Southwest Fisheries Science Center, 2004). They are continually impacted by human activities and could be severely affected by changes in climate regimes (Omar Defeo et al., 2009; Mahabot et al., 2017). Climate change's subsequent sea level rise could affect the coasts of Costa Rica (Carranza M., 2013) which are biodiversity hotspots and crucial nesting habitats of endangered sea turtle species (Drews & Fonseca, 2009a; Troëng & Rankin, 2005).

Tortuguero National Park is one of the most important nesting beaches for green sea turtles in the world (Troëng & Rankin, 2005) and in recent years, has experienced rapid growth in tourism activity. This touristic increase has been influencing the rising number of constructions in the beachfront (houses, hotels, airport, etc.) (COOPRENA R. L., 2007). Due to the lack of regulation of the authorities in the area (COOPRENA R. L., 2007), some of these constructions that are beyond the permitted distances in the legislation of Costa Rica have deforested the vegetation in front of the beach. This can create a perturbation the recovery of the beach after a storm event and can also affect the nesting activity.

In order to maintain the capacity of Tortuguero National Park to adjust to the physical changes, without losing its ecological conditions, it is important to estimate the vulnerability of the area to sea level rise. This study applied the widely used Coastal Vulnerability Index (CVI) (Mahapatra et al., 2013) to assess the vulnerability of Tortuguero nesting beach. But this tool has not been specifically applied to the context of a sea turtle nesting beach yet. Overall in some vulnerability assessments, there is still a gap in the understanding of coastal areas as habitats, carrying out calculations that not include relevant ecological factors.

This study will adapt the classical CVI approach, by adding socio-economic and biological parameters, relevant to the study area and to green sea turtle species. This approach can contribute to creating a more holistic vulnerability assessment that can be applied to other nesting habitats for other sea turtle species.

1.2. Background

1.2.1. Species of Sea Turtles present in Tortuguero

Like many other beaches on this central America region, Tortuguero represents a nesting habitat for different species of sea turtles. Tortuguero has the largest green turtle (*Chelonia mydas*) rookery in the Western Hemisphere and also has nesting populations of leatherback (*Dermochelys coriacea*) and hawksbill turtles (*Eretmochelys imbricata*) (STC, 2019a).

Scientists recognize seven species of sea turtles in the world (STC, 2019a), and all of them are listed in the IUCN Red List of Threatened Species (IUCN, 2019b). Depending on the species, sea turtles reach sexual maturity between 10 to 50 years (Chacon et al., 2008; Mortimer & Donnelly, 2008; Seminoff & Southwest Fisheries Science Center, 2004; Wallace, Tiwari, & Girondot, 2013). It has been suggested for the Caribbean green sea turtle that sexual maturity may take 26+ years (Frazer & Ladner, 1986; Troëng & Rankin, 2005). Additionally, evidence suggests that all sea turtles show one of the most remarkable behaviors, they return to nest to the same region where they were born (Mortimer & Donnelly, 2008; Seminoff & Southwest Fisheries Science Center, 2004; Wallace, Tiwari, & Girondot, 2013; Miller, 1997); being Tortuguero one of the first sites where this behavior was ever studied for green sea turtles (Archie Carr & Carr, 1972).

Regarding the species nesting at Tortuguero, the green sea turtle is cataloged as endangered of extinction, indicating an extensive subpopulation decline in all major ocean basins over the last three generations (Seminoff & Southwest Fisheries Science Center, 2004). According to Seminoff (2004), this species has suffered a decline of 37% to 61 % on its population over the last 141 years. This decline is a result of overexploitation of eggs and adult females at nesting beaches, juveniles and adults in foraging areas, and incidental mortality involving to marine fisheries, and degradation of marine and nesting habitats (Seminoff & Southwest Fisheries Science Center, 2004). The habitats for this species are marine intertidal, marine neritic, marine oceanic, marine coastal/supratidal (Seminoff & Southwest Fisheries Science Center, 2004).

The second most important sea turtles in Tortuguero are the Leatherback turtles (*D. coriacea*). It grows the largest, dives the deepest, and travels the farthest of all sea turtles (STC, 2019a). This species was previously classified as critically endangered, but recently, it has been cataloged as vulnerable (Wallace et al., 2013). Its habitats are classified as marine intertidal, marine oceanic, marine coastal/supratidal (Wallace et al., 2013).

Tortuguero has occasionally, hawksbill turtles (*E. imbricata*) nesting on its beach. Among all sea turtle species, this is the most highly endangered (Mortimer & Donnelly, 2008). It is classified in the Red List as Critically Endangered, which means that the species is an extremely high risk of extinction in the wild in the immediate future (Mortimer & Donnelly, 2008). Like the rest of sea turtle species, their habitats are classified as marine intertidal, marine oceanic, marine coastal/supratidal (Mortimer & Donnelly, 2008).

All of the sea turtles are sensitive to similar threats. The anthropogenic threats are harvesting of eggs and adults, fishing & harvesting of aquatic resources, residential and commercial development around the coast, and pollution (Wallace et al., 2013). In addition, sea turtles are experiencing threats derived from climate change like the increase in sand temperatures on nesting beaches affecting hatchling sex ratios, the sea level rise, and the storm frequency and intensity affecting nesting habitats (Wallace et al., 2013). This study focuses on the impacts of sea level rise on a green sea turtle nesting habitat.

Each species has a different vulnerability to the changes in nesting habitats due to specific nesting behaviors. At a general level, sea turtle species share broad nesting requirements, like selecting a nest site on exposed marine beaches with loose sand above the high-tide line (Fish et al., 2005; J. R. Hendrickson, 1995). Overall, the nesting trend for leatherbacks is in the open area of the beach, between the high tide line and the edge of the vegetation (Chacon et al., 2008). In the case of green and hawksbill turtles, they generally tend to nest at the edge of the vegetation or within the vegetation (Chacon et al., 2008). This study will focus specifically on the population of green turtles that nest in Tortuguero.

The green sea turtles individuals that nest in Tortuguero are highly migratory animals (Seminoff & Southwest Fisheries Science Center, 2004). Their nesting, feeding, and mating grounds are located in Costa Rica, Nicaragua, and Panamá (Carr, Carr, & Meylan, 1978; Troëng & Rankin, 2005). Therefore the policy-making in these countries has contributed to the population recovery (Troëng & Rankin, 2005).

1.2.2. Green sea turtle nesting in Tortuguero's beach.

In the case of green sea turtles, the IUCN had analyzed the species' sub-populations and classified it as globally endangered. Although in Tortuguero, the estimations are different. Tortuguero has been carrying out decades of conservation actions that helped to protect reproductive females and nests (Troëng & Rankin, 2005). Now, Tortuguero has the second largest nesting population of green sea turtles in the world (Sea Turtle Conservancy, 2017). With an estimated rookery size of 17,402 to 37,290 nesting females per year (Troëng & Rankin, 2005). It is an example of successful conservation efforts that, after the last 50 years of conservation efforts, the green sea turtle population has experienced an increase of 471 % (STC, 2019b; Troëng & Rankin, 2005). The trend of green sea turtle nesting and rookery size at Totuguero, have implications on the global status of the species, as well as in the conservation management at a national and international scale (Troëng & Rankin, 2005).

Overall, the nesting populations of green sea turtles in Tortuguero have adapted to nest in a high-energy beach. They display a substantial interannual variation (Troëng & Rankin, 2005), which makes it essential to develop long-term data sets. Long-term data will make it possible to compare nesting trends with changes in the shoreline.

Because of the location of the Costa Rican Caribbean region, the climatic regime is partially formed by the recurrent impact of cold breaks and tropical cyclones (Alfaro M., Quesada R., & Solano C., 2010; Campos D. & Quesada R., 2017; Quesada R. & Pérez B., 2019). These climatic events are the cause of the strong waves on the Costa Rican Caribbean coast (Lizano

R., 2007). Overall Tortuguero has a high-energy intermediate beach. The average wave height is 1.37 m, and the maximum height reported is 3.87 m (Lizano R., 2007). Regarding the tidal behavior, the Caribbean coast has, on average, an intertidal range of 21 cm (Lizano R., 2009).

1.2.3. Description of Tortuguero

Tortuguero National Park is one of the 158 natural protected areas in the National System of Conservation Areas (SINAC) of Costa Rica (SINAC-Programa de Turismo en Áreas Silvestres Protegidas, 2017). It is located in the northeast of Costa Rica, and its beach has a total length of 32 km. It has a total area of 76,937 hectares, of which 50,284 is maritime, and 26,653 is terrestrial protected area.

The national park is divided into zones that serve for the management of its natural resources (Figure 1). The terrestrial sector is divided into the following zones (SINAC-Programa de Turismo en Áreas Silvestres Protegidas, 2017):

- Zone of absolute protection: with an area of 20,331 ha, it is the 76% of the total terrestrial protected area. The presence of tourists is forbidden in this zone (MINAE, ACTo, & SINAC, 2004).
- Zone of restricted use: with 5,120 ha, it is the 19% of the terrestrial protected area. The visit is limited to research. It is a buffer for the zone of absolute protection (MINAE et al., 2004).
- Zone of special use: with 975 ha, it is 4% of the terrestrial protected area. The four operational centers of the national park are in this zone (MINAE et al., 2004).
- Zone of public use: with 227 ha, it is 1 % of the terrestrial protected area. This zone includes trails, rivers, and the beach (MINAE et al., 2004). Urbanized areas, or the town center, are not included in this section.
- The maritime sector of the National Park is divided in the following zone (SINAC-Programa de Turismo en Áreas Silvestres Protegidas, 2017):

- Zone of absolute protection: with an area of 50,284 ha, it is the 100% of the total maritime protected area. All fishing activities are forbidden in this zone (MINAE et al., 2004).

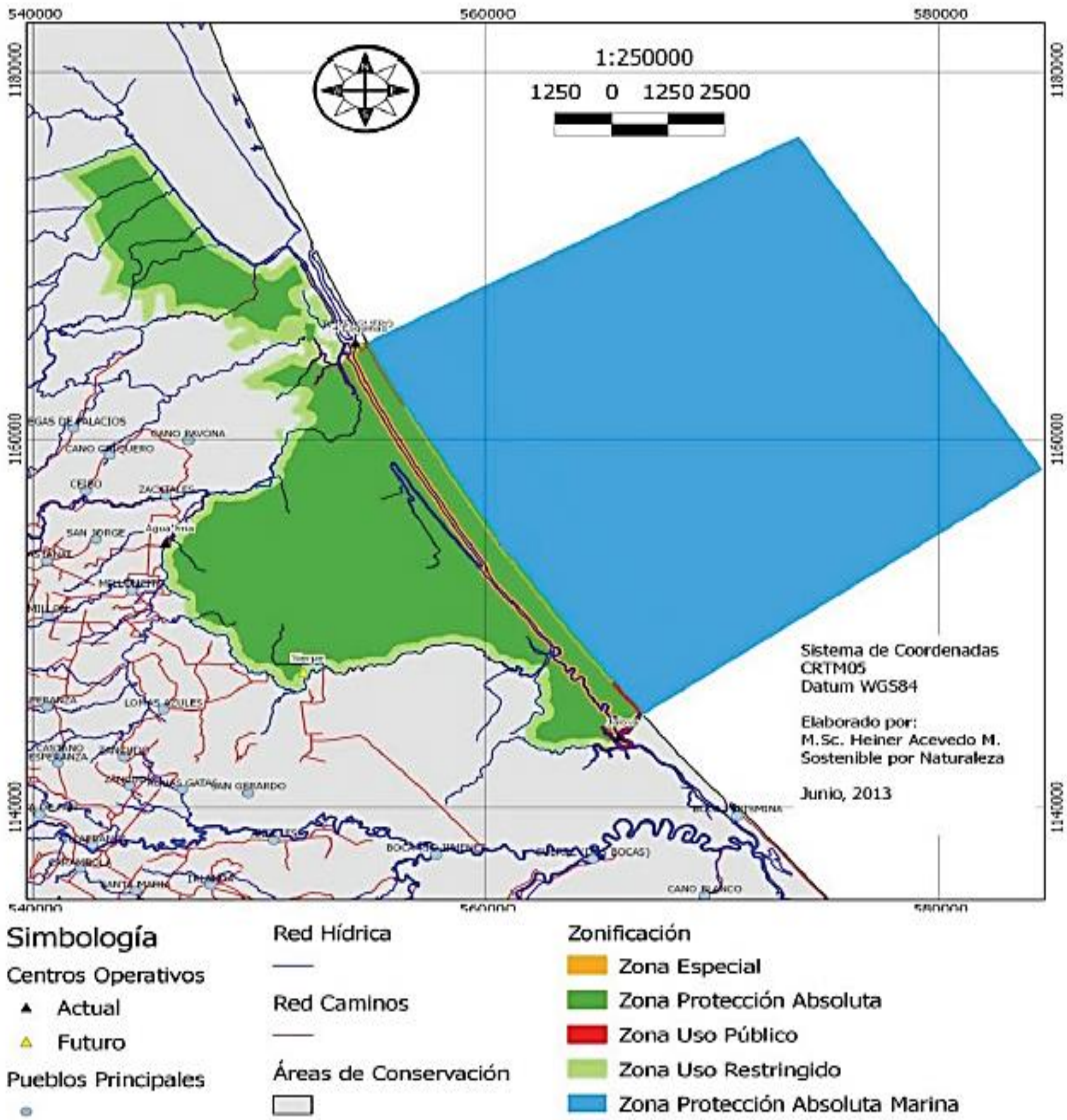


Figure 1: Zones of Tortuguero National, 2013. Source: SINAC Programa de Turismo en Áreas Silvestres Protegidas, 2017.

1.2.3.1. History of sea turtle conservation in Tortuguero

In Tortuguero, the relationship of humans with sea turtles goes back to pre-colonial times. Green sea turtles were hunted in Tortuguero, by indigenous groups before the arrival of Europeans (Lefevre, 1992; Troëng & Rankin, 2005). The first time that the area was described as an important nesting area was in 1596 (Troëng & Rankin, 2005; van Linschoten, 1934). In the 18th century, Tortuguero was identified as "place of turtles" in the Spanish maps (San Martin-Suarez, 1787; Troëng & Rankin, 2005). Jackson (1997) estimated that the number of green sea turtle adults could have been 33 to 39 million in pre-Columbian times (Troëng & Rankin, 2005).

In a global context, the history of sea turtle conservation starts in the town of Tortuguero. In the early '50s, Tortuguero was a very isolated settlement with few inhabitants and was the place where Archie Fairly Carr first started an assessment of sea turtle populations (Carr, 1956; STC, 2019a). The town was inhabited by few families who lived off the logging and harvest of sea turtles. He concluded that the green sea turtle population was decreasing due to the extensive harvesting of adults and eggs; some of the products were exported to the Cayman Islands (Anon., 1959). After Carr's findings, Tortuguero National Park was created in 1970, with the purpose to protect and conserve the biodiversity in the area (SINAC, 2017).

For more than 40 years, the non- profit organization that derived from Carr's work, the Sea Turtle Conservancy-Tortuguero (STC) has been monitoring and giving valuable information on the biology of sea turtles, and continue its work to date (Sea Turtle Conservancy, 2017). This research will work in collaboration with the STC. These long-term conservation efforts on reproductive females and nests at Tortuguero, have shown to be successful. National policies (like the regulation of harvesting turtles and eggs in 1963) have also contributed to the recovery of sea turtle populations (Government of Costa Rica, 1963). Although, in the Caribbean region, there has been an increase in green sea turtle harvesting since the mid-1990s (Troëng & Rankin, 2005).

At an international scale, there has been intensive endeavors to protect, restore and manage biodiversity, like the Convention on Biological Diversity (CBD) of Río 1992, in which was recognized that biodiversity is composed of ecological, organismal, genetic and cultural diversity (Heywood, 1997; Watson, et al. 1995), setting the conceptual basis and agreements that are still used in conservation planning. Subsequently, many of the conservation efforts have been focused at the level of species, being the “IUCN Red List of Threatened Species” one of the most significant attempts to categorized the current conditions of the world’s species (IUCN, 2016). In addition to this categorization, other classifications were stablished, like CITES that focus on the economic trade of threatened species (CITES, 2019). At a national level, the sea turtle conservation management and planning were stablished by the Law of Protection, Conservation, and Recovery of sea turtle populations N° 8325 (La Gaceta Nº 230, 2002).

1.2.3.2. Geography and Geomorphology

Tortuguero national park is located in the north-Caribbean zone of Costa Rica. This area is a vast basin of subsidence, called “Nicaraguan depression” (MINAE et al., 2004). This basin starts in the Fonseca Gulf (in the pacific of El Salvador, Honduras, and Nicaragua) and finishes in the Caribbean of Costa Rica (MINAE et al., 2004). This depression was formed in the early Tertiary as a consequence of the subduction of the Cocos plate under the Caribbean plate (MINAE et al., 2004). Since then, the basin was filled with several thousand meters of sedimentary rocks; most of them of marine origin (Figure 2) (MINAE et al., 2004; Quesada Román & Pérez B., 2019). However, the surface of the depression was covered mainly by terrestrial sediments (in the Quaternary), derived from the Central Volcanic Mountain Range and dragged by the rivers that cross the zone (MINAE et al., 2004; Quesada Román & Pérez B., 2019).

In geomorphological terms, Tortuguero National Park is composed by alluvial plains, coastal plains, and ancient volcanic cones (MINAE et al., 2004). The alluvial plains are formed by the dragging of sediments by rivers, with variable drainage and texture (MINAE et al., 2004). The coastal plains are sandy marine deposits, formed around 5,000 years ago (MINAE et al., 2004) that in combination with volcanic material, shape the sandy beach that serves as nesting habitat. This is the area that goes parallel to the sea, approximately 500 to 300 m wide, with an altitude not exceeding the 4 m above the sea level (MINAE et al., 2004).

The study area is located in a coastal plain, parallel to the sea and the river. This area is also known as intertidal sub-system (SINAC, 2017). This sub-system is exposed to the tides (SINAC, 2017).

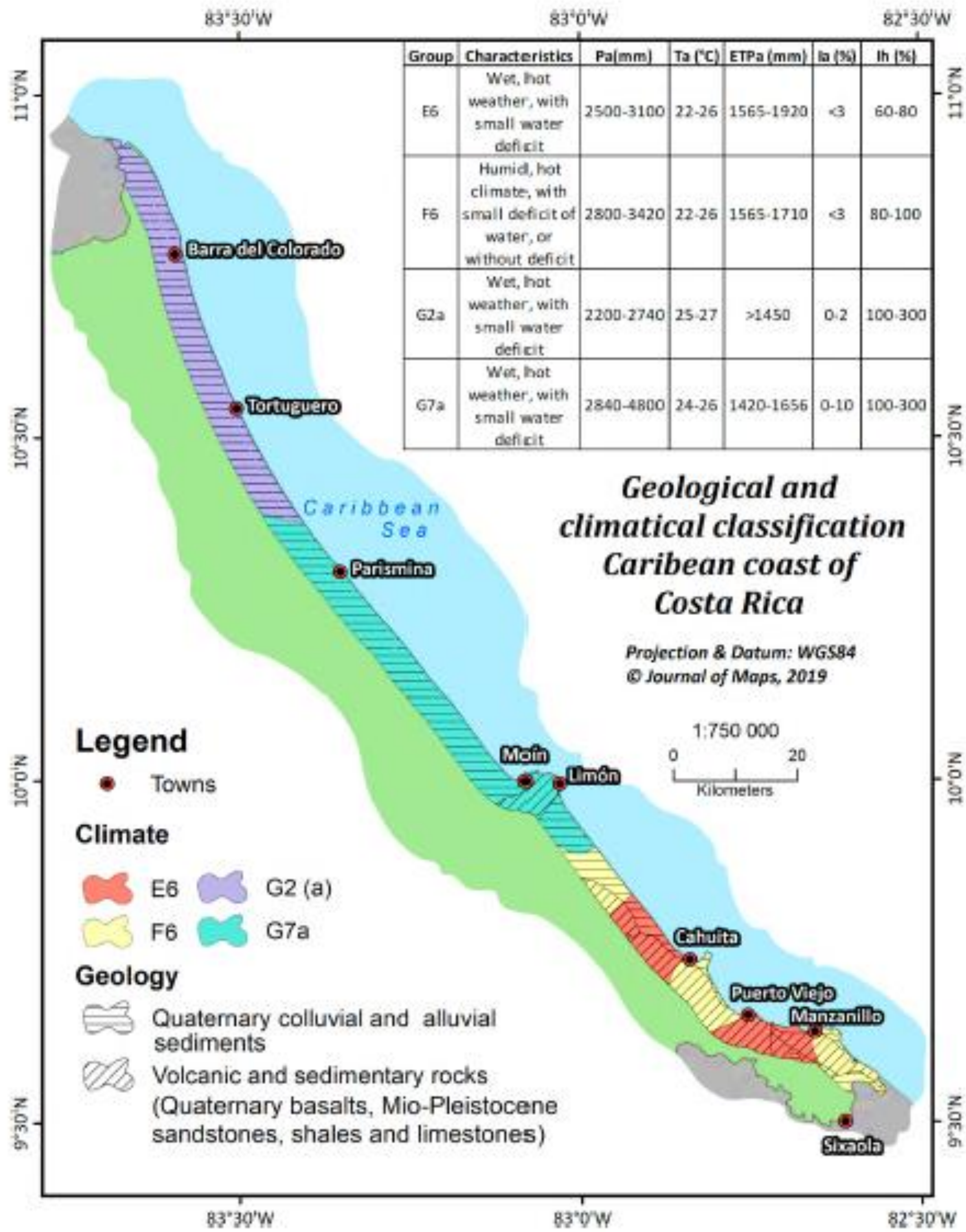


Figure 2: Geological characteristics and coastal climatic groups of the Caribbean of Costa Rica. Pa: Mean annual rainfall; Ta: Mean annual temperature; ETPa: Annual potential evapotranspiration; Ia: Drought index; Ih: Hydric index. Source: Quesada Román & Pérez B., 2019.

1.2.3.3. Climate

In the Caribbean of Costa Rica (also in Tortuguero National Park), a humid and very humid tropical climate predominates (MINAE et al., 2004). According to the Köppen-Geiger climate classification, it is classified as Af (Tropical Humid Climate) (Naranjo, Glantz, Temirbekov, & Ramírez, 2018). This regional climate is caused by very humid trade winds from the north and northeast, called “alisios” (MINAE et al., 2004). In the national park, specifically, the mean annual precipitation goes up to 6,000 mm (MINAE et al., 2004). Being July and December the most humid months, which means that most of the green sea turtle season (July-November) does not experience extremes in precipitation. The hours of light are less in the rainy month (2-3 hours per day) than in the dry months (6 hours per day).

The average temperature is between 25 to 30 °C. Two wind systems characterized the area: the “alisios” trade winds coming from the north and northeast and the sea breeze coming from southeast to west direction (MINAE et al., 2004).

1.2.3.4. Demography

During the last years, it has been a challenge to determine the actual population number in the town of Tortuguero. This can be caused by increasing tourism; the lack of land tenure permits and the illegal immigration flux coming from Nicaragua. Tortuguero is part of Colorado district, of the Pococí county in the province of Limón. According to the National Institute of Statistics and Census of Costa Rica (INEC, 2011), the majority of the towns in the district are classified as rural areas. The district of Colorado had a population of 4,681 by 2016 (INEC, 2011).

But this refers only to the static population of Tortuguero. As a touristic destination, the town also counts with a mobile population. According to the Costa Rican Institute of Tourism, Tortuguero has an average of 104,401 visitors per year (Instituto Costarricense de Turismo, 2017).

1.2.3.5. Economy

Tortuguero National Park is one of the main touristic destinations of Costa Rica. It is located in a coastal plain with sandy soils, with low fertility for agriculture (SINAC, 2017). Since the mid-1980s, there has been a development of ecotourism activities in Tortuguero (Troëng & Rankin, 2005). This new ecotourist market has provided alternative livelihoods for the community and has lessened the extractive use of the rookery (Troëng & Rankin, 2005). As a result, the people from the community have ventured into tourism as their main livelihood (SINAC, 2017).

The surrounding towns are small human settlements founded by agricultural companies (of banana and palm oil plantations) (SINAC, 2017). Unlike the Tortuguero community, the residents of these communities have mainly one agricultural livelihood: banana plantations (SINAC, 2017). According to INEC (2011), Colorado district has unemployment of 2.1%, which is related to the touristic development in the area (COOPRENA R. L., 2007).

It is essential to mention that unemployment is not a synonym of poverty, since Colorado district has low rates of unemployment, but a high level of poverty (52.95%) (COOPRENA R. L., 2007). The presence or absence of employment is not the cause of poverty in these communities (COOPRENA R. L., 2007). In some areas of this remote community, there is a deficiency of basic services, like access to potable water (COOPRENA R. L., 2007). There is no sufficient support from the state, and the land tenure is informal (COOPRENA R. L., 2007). All this limits the access of all the population to services necessary to satisfy basic needs (COOPRENA R. L., 2007).

The territory of Tortuguero shows two irregularities: the informality of land tenure and the urban development outside the legal boundaries of marine-terrestrial zones (building to close to the beach). Regarding the land tenure, Tortuguero is officially an area bellowing to JAPDEVA (Administrative Committee on Ports and Economic Development of the Atlantic

Slope). In the town area, there is not an official land tenure for the community members, hotel industry, restaurants, etc. This irregularity causes the local businesses not to be legally recognized by the national government (COOPRENA R. L., 2007). The second irregularity are the constructions in prohibited spaces. Due to the lack of legal land tenure, many of the buildings are done without the municipality and health ministry permits (COOPRENA R. L., 2007). This together with the lack of monitoring by the municipality, allow high urban development in front of the beach (beyond the distance permitted by the Costa Rican environmental legislation) (COOPRENA R. L., 2007). In the context of climate change, the retreat of the coast has both economic and ecological consequences in Tortuguero. The sea turtle nesting is the main touristic attraction; therefore the shoreline retreat will affect the sector indirectly, by loss of revenue, and directly, through loss of infrastructure (Fish et al., 2005).

1.2.3.6. Relevant stakeholders in Tortuguero

The main touristic stake-holders in Tortuguero are:

- ASOPROTUR: the association of local touristic guides (SINAC, 2017).
- Trackers: People of the community in charge of patrol the beach searching for nesting sea turtles. Their main task is to spot nesting turtles and notify the location to the tourist guides to minimize the presence of people on the beach (SINAC, 2017).
- Development association: is a social organization that refers directly to the municipality of Pococí (SINAC, 2017). It is an open communal organization that carries out projects to implement development strategies in the town (due to the isolation of Tortuguero, the municipality has a low impact) (SINAC, 2017).
- Sea Turtle Conservancy (STC): It is the organization in charge of the sea turtle monitoring program. It is the first organization carrying out research in the area, and it is involved with the development strategies in the community (SINAC, 2017).
- CATUTOR: Is the local organization formed by hotel entrepreneurs, restaurants, local stores, and ASOPROTUR (SINAC, 2017).

- ASVO: or Association of Volunteers for the Service in the Protected Areas of Costa Rica (ASVO, 2019) is one of the organizations that works for the conservation of the natural resources and wildlife in the area.
- GVI Jalova: is one of the organizations that works for the conservation of the natural resources and wildlife in the area and is located in the southern border of the National Park (Global Vision International (GVI), 2019).

1.3. Habitat loss induced by sea level rise

1.3.1. Shoreline retreat

According to Sorensen & McCreary (1990), a coastal zone, or shoreline, is a transition zone or "part of the land affected by its proximity to the sea and part of the ocean affected by its proximity to the land. It is an area in which processes depending on the interaction between the land and the sea are most intense". The extension of the shoreline varies due to daily tides, seasonal and astronomic forces, and events like sea storms and river floods (Mahapatra et al., 2013). "The coastal zone is a physiographic unit" -highly dynamic and fragile (Mahapatra et al., 2013).

The low-lying coasts, built on unconsolidated sediments, are some of the most threatened coastal environments (Allenbach et al., 2015). Their erosion can be driven by factors like the sea level rise, extreme storms events, low sediment supply caused by highly managed rivers, coastal development and sediment (sand) mining (Allenbach et al., 2015; Maktav, Erbek, & Kabdasli, 2002; Shuisky, 2000; Stanica, Dan, & Ungureanu, 2007; Trifonova, Valchev, Andreeva, & Eftimova, 2012). This erosion has mainly two types: a shorth-term erosion, caused by storm surges and waves, and a long term, irreversible landward migration or shoreline retreat (Allenbach et al., 2015).

Sea level rise threatens beaches with short and long-term retreats (Allenbach et al., 2015). The process of beach retreat is the tendency of the shoreline to advance inland due to the sea level rise (E. Doukakis., 2005). An estimation called "the Bruun Rule" tries to describe the relationship between sea level rise and shoreline retreat. This Brunn Rule establishes that for every 1 cm of sea level rise, there is a beach retreat inland of 1 m (Cambers, 2009). Nevertheless, this is a generalization of a complex process (unique to each site underwater topography, specific heating, and beach morphodynamics). The shoreline retreat is a dynamic process that has already happened in the past, but currently, the urban development and infrastructure in front of the beach, will not let the shore to retreat inland. In these cases, it is very likely that the beaches will get narrower (Cambers, 2009).

1.3.2. Threats of sea level rise in sea turtle nesting areas

Around 70% of the world's sandy beaches are eroding, resulting in gradual and continuous shoreline retreat (Bird, 1985; Jongejan et al., 2016). It is driven by sea level rise and episodic storm erosion (Cazenave & Llovel, 2010; Jongejan et al., 2016). Sea level rise is defined as "the height of the sea measured relative to a mark on the nearby land, called the Tide Gauge Benchmark. It is usually described as tidal data that is the arithmetic mean of hourly water elevations observed over a specific 19-year cycle" (Mahapatra et al., 2013).

It is a process driven by the warming of the world's seas and oceans, together with the freshwater melting input from ice-sheet melting (Butt et al., 2016; IPCC, 2007b, 2014a; Mahapatra et al., 2013; Union of Concerned Scientists, 2012). The combination of these factors has made the sea level to rise 3.2 ± 0.4 mm per year, since 1993 (Church & White, 2011; Parris et al., 2012). This projection of Church & White (2011) is the result of an extensive gathering of a global data set for the period 1993 to 2009, and it is near the upper end of IPCC Climate Change's Third and Fourth assessment reports (for 1901-2010), and Copernicus predictions (for 1991 to 2017) (Figure 3) (Church & White, 2011; Copernicus Climate Change Service (C3S) & Copernicus Marine Environment Monitoring Service (CMEMS), 2018; IPCC, 2001, 2007a, 2014b).

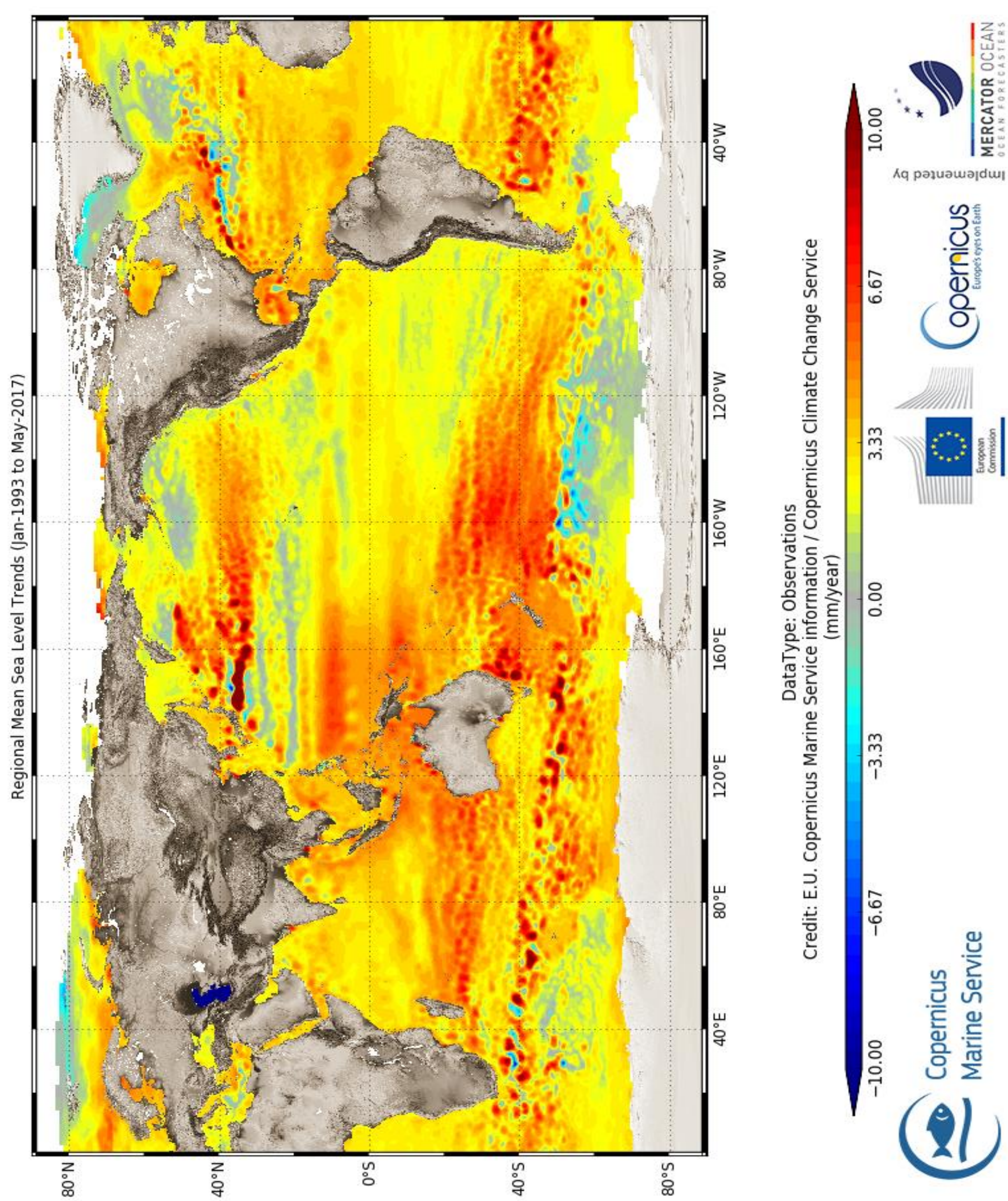


Figure 3: Global trends of regional mean sea levels, for the period of January 1993 to May 2017. Source: Copernicus - Marine service information et al., 2019.

Nonetheless, sea level rise is not a process spatially uniform, and its impacts on coastal areas will vary geographically (Butt et al., 2016). Local factors, like land subsidence, cause additional displacement to the local effect of sea level rise (Losada et al., 2013). The relative sea level rise combines land subsidence with the mean sea levels (Losada et al., 2013). During the 20th century, the Caribbean region has experienced an increase in the average of mean relative sea levels of 1 mm per year, with extensive local variation (Cambers, 2009; IPCC, 2007b).

The majority of Costa Rica's shoreline will be impacted by sea level rise (Carranza M., 2013; United Nations et al., 2012). In the region, the increase in sea levels can reach 1 m by 2100 (Carranza M., 2013; World Bank Group, 2011). Under this scenario, Costa Rica's shoreline is under threat of increasing the areas exposed to tidal floods (Carranza M., 2013; World Bank Group, 2011).

From an ecological point of view, habitats that are climatically unsuitable increase the risk of extinction if populations do not move or adapt (Butt et al., 2016; Parmesan, 2006). Sea turtles can respond to climate change by shifting their biogeographical range (Butt et al., 2016; Fuentes, Limpus, Hamann, & Dawson, 2009). But for some species that show high site fidelity, the shifting of the nesting range might be restricted (Butt et al., 2016; Miller, 1997).

A negative impact that shoreline retreat (or habitat loss) may have oversea turtles is the increase in density of nests on a particular beach. The reduction in the nest available area increases the risk of nest destruction by other nesting females (Fowler, 1979), and by predators or microbes as well (Mazaris et al., 2009). Also, the location of a sea turtle nest has a significant effect on hatching success (Mazaris et al., 2009). Areas close to the high tide line may affect embryonic development, fitness, sex determination, and increase risk of inundation (Fowler, 1979; Mazaris et al., 2009).

The study of Drews & Fonseca (2009) predicted the impacts that the rising of 1 m in sea levels will have on a sea turtle nesting beach, on the Pacific coast of Costa Rica. This study predicted 50 meters of the inland retreat of the shoreline, that can bring adverse effects on the sea turtle nesting population (Drews & Fonseca, 2009b). They proposed that no constructions should be allowed on the beachfront, to leave enough area for the beach to retreat (Drews & Fonseca, 2009b).

It is difficult to predict the scale and the speed of range shifts of nesting beaches, because it will depend on the current nesting range, species behavior and on the magnitude and scale of shoreline changes (Butt et al., 2016). It is a challenge for Costa Rica to develop planning that addresses the impacts of climate change in coastal areas (Carranza M., 2013).

1.4. Coastal Vulnerability Index

1.4.1. Vulnerability assessment

The concept of vulnerability is defined by IPCC (2007), as the "degree to which a system is susceptible to, or unable to cope with, the adverse effects of climate change, including climate variability and extremes. Vulnerability is a function of the character, magnitude and rate of climate variation to which a system is exposed, its sensitivity and adaptive capacity" (Gitay, Suárez, Watson, & Dokken, 2002). The IPCC defines three crucial factors to assess vulnerability: "The climate hazard (exposure), sensitivity to the hazard, and the capacity to adapt or cope with the potential impacts" (Bezuijen, Charlotte, & Mather, 2011; Gitay et al., 2002). Blaikie et al. (1994) define vulnerability as "the characteristics of a group and context that influence their capacity to anticipate, cope with, resist, and recover the impact of a natural hazard."

Particularly for coastal zones, the (IPCC & CZMS, 1992) defines vulnerability as the degree of a coastal system to cope with the impacts of climate change and the derived sea level rise. There are four main categories in the definition of vulnerability to sea level rise: a) the susceptibility of the coastal area to physical and ecological changes, b) the potential impacts on the socioeconomic system, c) the inherent state of the system before the event happens, and d) the capacity of the system to cope with this impacts, including the adaptive capacity (Allen, 2003; R. Klein & Nicholls, 1999; Lim, Spanger S., Burton, Malone, & Huq, 2004; Murali, Misra, & Vethamony, 2013). Another essential definition, in vulnerability assessments, is the adaptive capacity. It is understood as the ability of a system to adjust to climate change /sea level rise, to moderate potential damages or to cope with the consequences (IPCC, 2007b).

1.4.2. Previous Vulnerability Assessments

There has been intensive research over the last two decades for coastal vulnerability assessment regarding the methods and tools (Mahapatra et al., 2013). The primary focus of these approaches is the impacts and adaptations of coastal zones to climate change, specifically to sea level rise (Abuodha & Woodroffe, 2006; Mahapatra et al., 2013). The approaches that have been developed for these assessments are: IPCC Common Methodology (CM), Global Vulnerability Assessment (GVA), Bruun rule, The Synthesis and Upscaling of Sea-level Rise Vulnerability Assessment (SURVAS), Land and wetland loss assessment, Dynamic Interactive Vulnerability Assessment (DIVA), Simulator of Climate Change Risks and Adaptation Initiatives (SimCLIM), Community Vulnerability Assessment Tool (CVAT), Coastal Zone Simulation Model (COSMO), South Pacific Island Methodology (SPIM), Shoreline Management Planning (SMP) (Mahapatra et al., 2013), and the Coastal Vulnerability Index (CVI) that is the method this study is based on.

The study of Gornitz & Kanciruk (1989) was the first one to define and validate a CVI for sea level rise and set the base for future studies (Murali et al., 2013). The CVI has been a widely used method to assess coastal vulnerability and usually was composed just by physical parameters (Physical Vulnerability Index PVI) (Gornitz & Kanciruk, 1989; Mahapatra et al., 2013). These physical parameters are: Significant wave height, sea level rise rate, beach slope, regional elevation, rate of shoreline change and tidal range (E. Doukakis., 2005; Fish et al., 2005; Gornitz & Kanciruk, 1989; Kumar, Mahendra, Nayak, Radhakrishnan, & Sahu, 2010; Mahapatra et al., 2013). But there are new approaches that recognize that the complexity of the vulnerability to climate change includes more than just physical factors. Murali, Misra, & Vethamony (2013), adapt the CVI with physical factors and add four socio-economic factors in the analysis (population, Land-use/Land-cover (LU/LC), roads and location of touristic places).

Many of the coastal vulnerability assessment studies work with physical, social, and economic factors, but very few take into account the ecological vulnerability of a habitat. Also, none of the CVI studies, have been used yet to estimate the vulnerability of coastal habitats for endangered species of sea turtles.

The approach of Mazaris et al., (2009) showed the impacts coastal squeeze (as a result of current sea level rise) on sea turtle nesting habitats. Here, it is addressed the nesting habitat loss under different scenarios in the future (Fish et al., 2008; Jensen, Abreu-Grobois, Frydenberg, & Loeschcke, 2006; Mazaris et al., 2009). These studies consider ecological and species-specific parameters (like the presence of the vegetation border on the beaches and the distribution of nesting over the years). Species-specific parameters can be added to a CVI assessment.

1.4.3. Parameters of the CVI for sea turtle conservation management

This study will assess the vulnerability to sea level rise of a particular sea turtle nesting habitat. In other to do so, it is necessary to define some fundamental concepts. First, the physical and the ecological characteristics of the sandy beaches will be described.

Sandy beaches are defined by their sediment transport, wave and tidal regimes, and they go from narrow and steep conditions (reflective beaches) to broad and flat (dissipative); but more beaches are classified in an intermediate stage between these two extremes (Omar Defeo et al., 2009; Finkl, 2004). They are a type of coastal ecosystems inhabited by specialized biota that is structured mainly by physical forces (O Defeo & McLachlan, 2005). Adapted from the ecosystem-based risk assessment conceptual framework of Hobbs et al., (2006), a beach suitable for sea turtle nesting would be a "healthy habitat that maintains its compositional, structural and functional features." In order to facilitate the yearly monitoring, the STC has divided the beach of Tortuguero into units of 200 m that were called "sectors." Each sector will be the basic unit on which all the parameters of the CVI will be calculated.

This study will carry out a vulnerability assessment using the specific approach of the Coastal Vulnerability Index (CVI). The CVI is a vulnerability assessment tool used to map the relative vulnerability of the different sectors of the coastline due to sea level rise (Mahapatra et al., 2013). In other words, a CVI mapping, on a particular coastline, highlights the sectors where there is the greatest probability to experience physical changes if sea level rises (Mahapatra et al., 2013). This CVI assessment will be composed by the combination of a Physical Vulnerability Index (PVI), an Anthropogenic Vulnerability Index (AVI), and a Biological Vulnerability Index (BVI).

According to Klein, Nicholls, & Thomalla (2003), the PVI is an approach that combines the susceptibility of the coastal system to change, together with its natural inherent capacity to adjust changing environmental conditions, and represents an estimation of the system's vulnerability to hazardous events (Murali et al., 2013). The physical vulnerability parameters that have been widely used in PVI are:

1. *Shoreline change rate*

The shoreline is traditionally defined as the interface between land and water (Dolan, Hayden, & May, 1980). But in reality, is more complex than that. The position of the shoreline continually changes through time, due to cross-shore and alongshore sediment movement in the littoral zone and also to the highly dynamic water levels at the coastal boundary (Boak & Turner, 2005). The shoreline must be considered on a temporal scale (Boak & Turner, 2005). Particularly, the changes in shoreline are the result of coastal processes, which depend on wave characteristics, near-shore circulation, sediment characteristics and beach forms (Boak & Turner, 2005; Murali et al., 2013). Likewise, the shoreline is the result of a process called littoral transport, that consists in the transportation of shoreline sediments by the breaking waves and currents in the near-shore (Boak & Turner, 2005; Murali et al., 2013). For this study, the main negative impact of shoreline change is "Coastal squeeze." The coastal squeeze is a process known as the landward retreat of the shoreline and coastal habitats, caused by rising sea levels and factors that increase storminess (J. Patrick Doody, 2013). The final consequence of coastal squeeze for sea turtles will be a habitat loss.

2. Sea Level change rate

The changes in the sea levels are the result of simultaneous contributions from isostatic (at a local level; changes in the land with respect with the sea surface), eustatic (global. Changes in the volume of water in the sea, i.e. glacier melting), tectonic, and local specific factors, over different timescales (Engelhart, et al., 2015; Rovere, Stocchi, & Vacchi, 2016). The change in sea level is considered one of the most important consequences of climate change (Murali et al., 2013). Sea levels are rising and are expected to continue ascending for centuries (Church & White, 2011), leaving the small insular countries, and the Caribbean region, at a high risk of flooding (Cambers, 2009). This risk is the main hazard on which this study will be focused.

3. Coastal Slope

The coastal slope is the ratio of the altitude change to the horizontal distance between two points on the beach (the steepness or flatness) (Kumar et al., 2010). It is a measure that can be linked to the susceptibility of a beach to inundation by flooding (Thieler, 2000). This parameter does not show the topographic variation of the beach profile. Nonetheless, the reason for including the slope value in the calculations was that this parameter had been considered by other studies, which makes possible the comparison of results.

4. Significant Wave Height

Measured from the trough to crest, the Significant Wave Height (SWH) is the average of the highest one-third of waves (NOAA's National Weather Service, 2018). The SWH is a suitable alternative to the wave energy measurement and is highly important for assessing the vulnerability of shorelines (Murali et al., 2013). In summary, an increase in wave height is an increase in the wave energy, what results in a higher erosion and inundation of the shoreline, causing loss of land (Murali et al., 2013). A coastline with high wave heights is more vulnerable than those with low wave heights (Murali et al., 2013).

5. *Tidal range*

The Tidal Range is a measure of the vertical difference between the highest high tide and the lowest low tide, is related to permanent and episodic inundation (Kumar et al., 2010). The tides are defined as the rise and fall of sea levels caused by the effects of the gravitational forces of the moon and the sun, plus the rotation of the Earth (Murali et al., 2013). A high tidal range is often linked to stronger tidal currents, with more erosive capacity and transport of sediments (Murali et al., 2013). For a smaller region, in most of the cases, the tidal range does not change much within a year (Murali et al., 2013).

6. *Coastal Regional Elevation*

The Regional Elevation is the elevation of a specific area above the mean sea level (Kumar et al., 2010). It helps to identify if an era is threatened by future sea level rise (Kumar et al., 2010). Coastal areas with low elevation are particularly vulnerable to sea level rise, while coastal areas with high elevation are more resistant to the impacts of sea level (Murali et al., 2013).

This study will include, in the Anthropogenic Vulnerability Index (AVI), one parameter proposed in the CVI assessment of Murali et al. (2013). The parameters are the following:

1. *Distance to the town center*

Tortuguero has the particularity of having a touristic town inside the national park. Historically, the urbanization of Tortuguero was allowed through "land concessions" to the local families inhabiting the area, before the national park was founded. Now Tortuguero town has become an important touristic destination in Costa Rica, where most of the constructions are poorly regulated. Besides, the impacts that this touristic development has over the beach are stronger in areas where the urbanization is in the border of the beach (like vegetation removing in front of the beach, and the highest concentration of people on the beach closer to the urbanized areas). That is why this study proposes the "distance to the town center" as a parameter that affects the beach physical conditions. Since it has the highest concentration of buildings, deforestation of the beach vegetations and the higher concentration of people (locals and tourist).

2. *Land cover*

It's a map that classifies the anthropogenic activities and natural vegetation in a region (Murali et al., 2013). The urban areas along the shoreline are more vulnerable to a natural disaster than forest land or areas that still conserve a vegetation border in front of the beach.

3. *Touristic impact*

Due to the interactions of people with the shoreline, this study will propose, the touristic impact along the shore as a parameter for the SEVI index. This parameter will be defined as the number of tourists that visit the town of Tortuguero. This fluctuating population will be counted as extra anthropic pressure on nesting beaches. As tourism increases the urbanization at the edge of the beach is directly influenced, and therefore, reduces the buffer space for a coastal retreat.

Regarding the Biological Vulnerability Index (BVI), this research uses the data collected by the Sea Turtle Conservancy (STC) in the field. The following parameters are proposed to calculate the vulnerability of the nesting at Tortuguero:

1. *Distribution of nesting*

The distribution of sea turtle nest is the spatial location of the total of sea turtles' nests within a season. The number of nests per sector (for each green turtle season) will be used to calculate the biological vulnerability.

2. *Eroded and inundated nests*

A sample of green sea turtle nests was marked during the oviposition, by the STC, in the green sea turtle season **(**from July to November) (Sea Turtle Conservancy, 2017). All the nests marked were daily monitored. The eroded nests are the ones at the edge of an eroded cliff, or loss due to the action of the waves. On the other hand, inundated nests are those covered by the seawater. The number of eroded and inundated nests per sector, per season, will be used to calculate the biological vulnerability.

Due to the data scarcity and uncertainty, experts' opinions and literature information will be used to assign scores and weights to the parameters using the "Analytical hierarchical process" (AHP). The AHP is a process used to select the best alternatives of objective and subjective factors, by assigning weights to these factors and compared them in a matrix (Murali et al., 2013). The AHP is the method that will help to assign importance to the parameters described above and will add more accuracy to the total CVI.

2. Chapter 2: Research Objectives

General objective

To assess the coastal vulnerability of the sea turtle nesting beach of Tortuguero National Park in Costa Rica, for conservation management.

Specific objectives

- To adapt the Coastal Vulnerability Index methodology to include anthropogenic and species-specific parameters of a sea turtle nesting beach
- To categorize vulnerable sections of Tortuguero’s beach, based on geological-physical, anthropogenic and biological parameters.
- To derive recommendations for the management of Tortuguero’s sea turtle nesting beach.

3. Chapter 3: Methodology

3.1. Area of study

This study was carried out in the sea turtle nesting beach of Tortuguero National Park (N10°32’32.94’’, W83°30’08.48’’) (Figure 4). The sampling period corresponds to the green sea turtle nesting season (from July to November). Sampling periods shall be different for each parameter and shall be detailed in sections 3.5.1, 3.5.2, 3.5.3.

The sampled beach is an 8 km portion of the total beach area of the National Park (30 km). Starting at the mouth of "Tortuguero lagoon,” it extends to the south inside the protected area of the national park. This beach section also includes essential interactions, since it takes in the urbanized area of the national park (or town), which generates important impacts on the coastline.

The sampled beach section was selected because of the availability of long-term sea turtle nesting data since this area has been annually monitored by the STC for several decades.

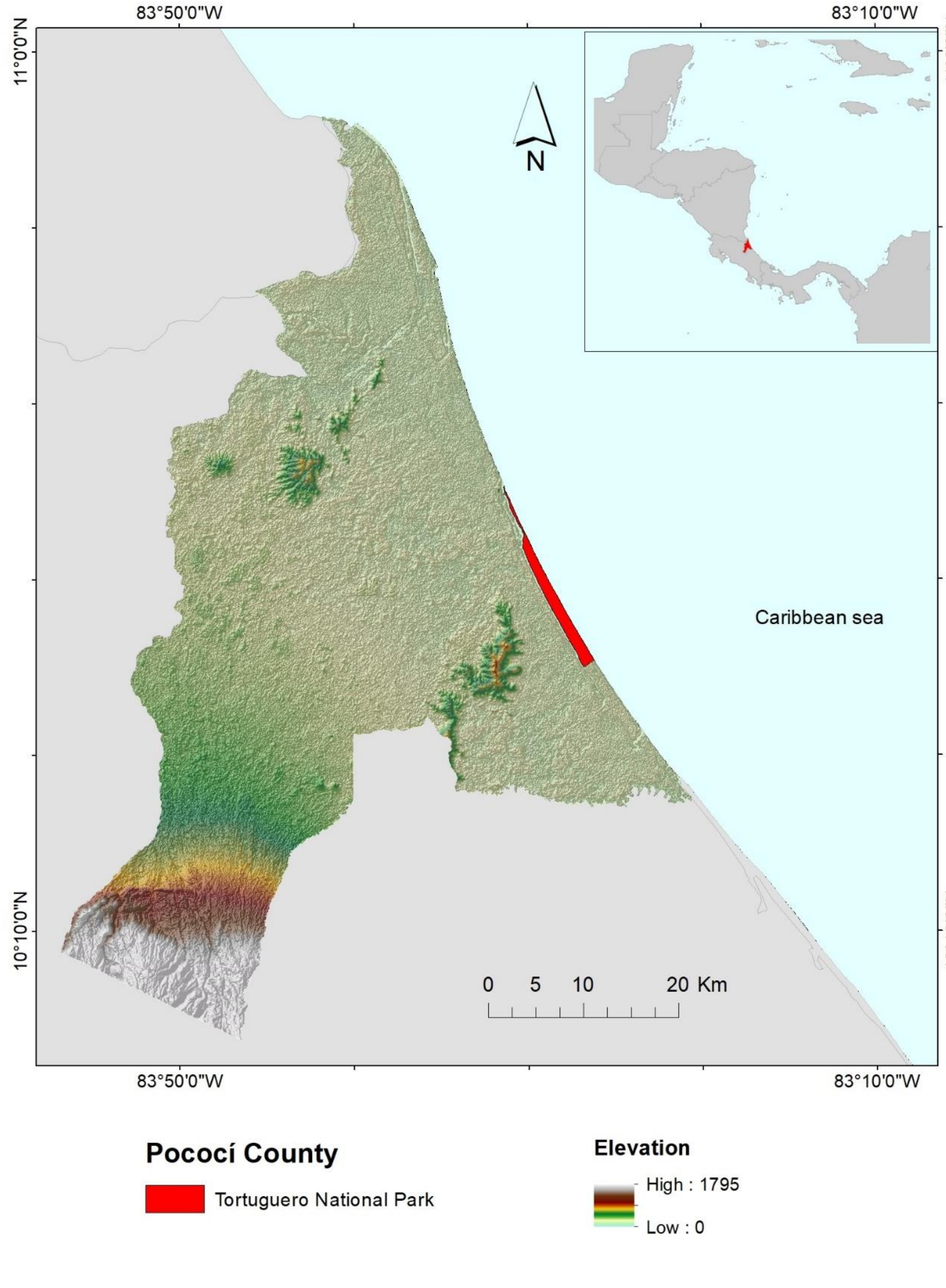


Figure 4: Map showing the location of Pococí canton (county) and Tortuguero National Park. Sources: Grupo para colaborar con datos abiertos Geotecnologias S.A. (2016)

3.2. Adaptation of the CVI in a sea turtle nesting ground

The present study implements a coastal vulnerability assessment in a sea turtle nesting beach. In contrast to other CVIs, this assessment includes two additional sub-indexes an anthropogenic (AVI) and a biological index (BVI)), together with the 'traditional' physical vulnerability sub-index. The physical parameters (PVI) of previous CVI's were selected because they have been widely used in other studies, which makes possible to compare results by using the same method.

But, concerning social and ecological parameters, there is not a set of fixed parameters in studies using the CVI. Previous studies have taken into account social and economic parameters (Boruff, Emrich, & Cutter, 2005; Murali et al., 2013; Willroth, Massmann, Wehrhahn, & Revilla Diez, 2012). Boruff et al. (2005) and Murali et al. (2013), take the physical and socio-ecological parameters as individual groups. Their vulnerability values were calculated separately (sub-index) until finally, these values were merged into a single CVI. On the other hand, Harik et al. (2017) combine anthropogenic stressors with a biodiversity richness index and an environmental sensitivity index to calculate the vulnerability of coastal areas to anthropogenic pollution. This approach did not use a CVI method, but it adapted already existing risk assessment tools to natural ecosystems.

Tortuguero has social and ecological complexity, so its vulnerability calculation must be adapted as best as possible to anthropogenic pressures and adverse effects on the nesting beach. For this reason, this study addresses anthropogenic pressures on the beach and their distribution and negative impacts on the nesting green turtle population. The groups of parameters are the following: physical, anthropogenic, and biological (species-specific) parameters.

3.3. The subunits of analysis

The sampled area was divided into sampling units called sectors. Starting from the mouth of "Tortuguero lagoon," every 200 m a sector was established along the 8 km of the beach of Tortuguero National Park (Figure 5).

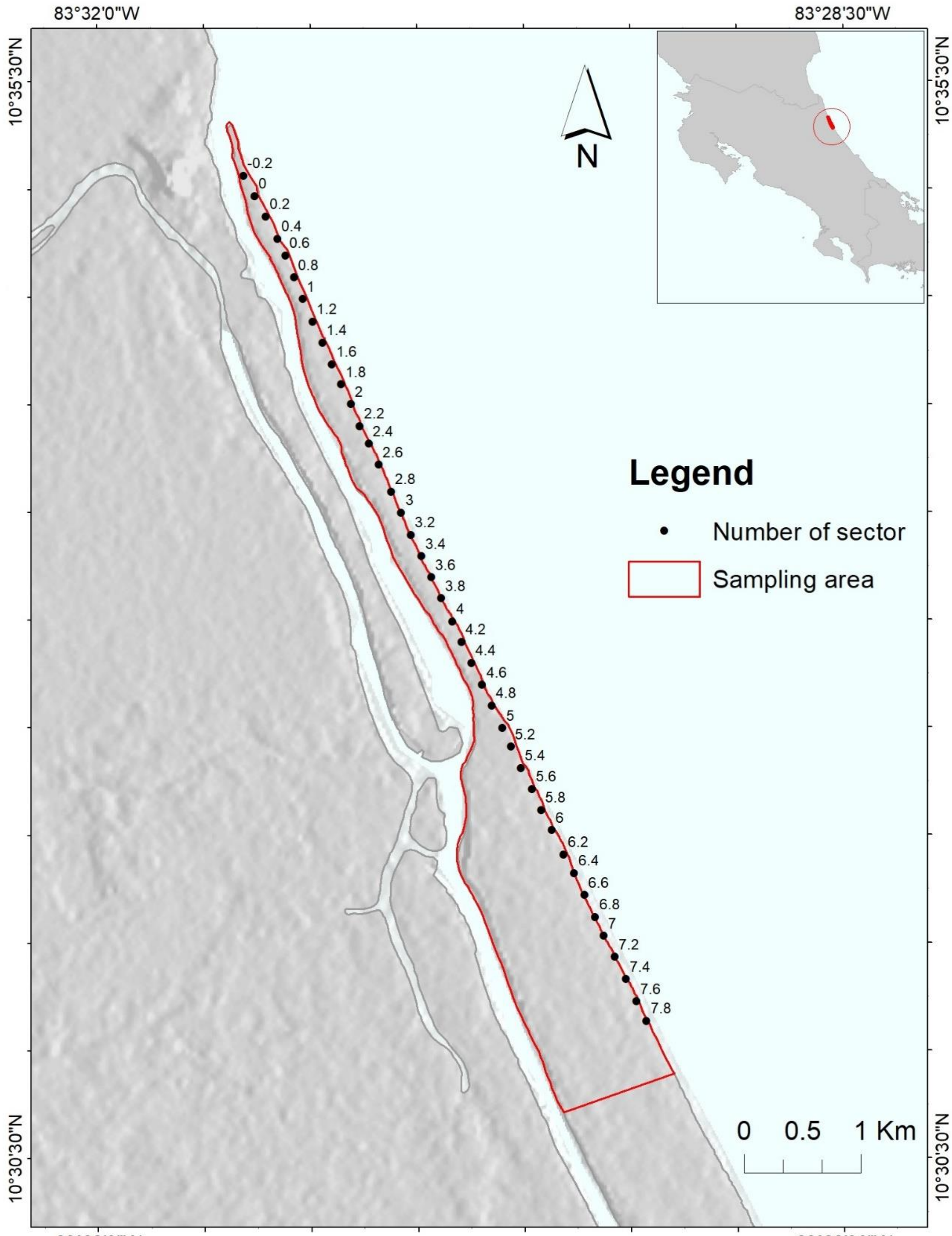


Figure 5: Map showing the sampling units or, in which the study beach of Tortuguero National Park was divided by the Sea Turtle Conservancy. Source: Planet Team, 2019; Grupo para colaborar con datos abiertos Geotecnologias S.A. (2016).

The STC has used these sectors for several decades. Biometric data of nesting turtles and nests are noted for each sector, whose statistics have been presented on the official STC website since the 1997 season. For this study, a field trip was carried out in April 2019 to mark the geographical coordinates of each of these sectors.

3.4. Data sources

Data used to calculate CVI were collected from primary and secondary sources. One of the primary sources used were interviews with experts to assign a value of importance to each parameter with respect to another. Therefore, the comparison with previous CVI methodologies is difficult, because these do not use some of these parameters. Other primary sources used were the in-situ data collected by the STC, which is the non-governmental organization working along the National Park in the conservation of sea turtles in the area. The STC has been taken by several decades biometrical data of each nesting turtle on the beach, of the nests and the physical environment. The data that the STC has shared with this research will be used to calculate the physical parameters (beach profiles) and biological parameters (nesting distribution, inundated, and eroded nests). A field trip was also made in April 2019 to collect the geographic coordinates of each sampling unit or sector and to make a beach profile for that year. The other primary sources were satellite images belonging to Planet Team, (2018) and sea level data of Tide-gauge stations, taken by the Global Sea Level Observing System (2018). These latter data sets were subjected to further analysis to calculate the “shoreline change rate,” “sea level change rate,” “distance to the next urbanized area” and “land cover” parameters.

As secondary sources, data sets of historical weather forecasts, annual reports from government institutions and topographic data of Costa Rica were used to obtain measurements of “significant wave height,” “tidal range,” “coastal regional elevation” and “touristic impact.” The sources and methods for obtaining the values of each parameter of the CVI will be explained in more detail later in this chapter.

3.5.Calculating the CVI for sea turtle conservation management

This study will calculate the Coastal Vulnerability Index (CVI) by applying a methodology based on the methodological framework proposed by Murali et al. (2013) (Figure 6). For each one of the sectors (sub-units of analysis), the CVI will be calculated, in order to spot areas in which nesting is under threat due to a coastal retreat. All the risk variables described further below will be used to calculate a single vulnerability indicator (CVI).

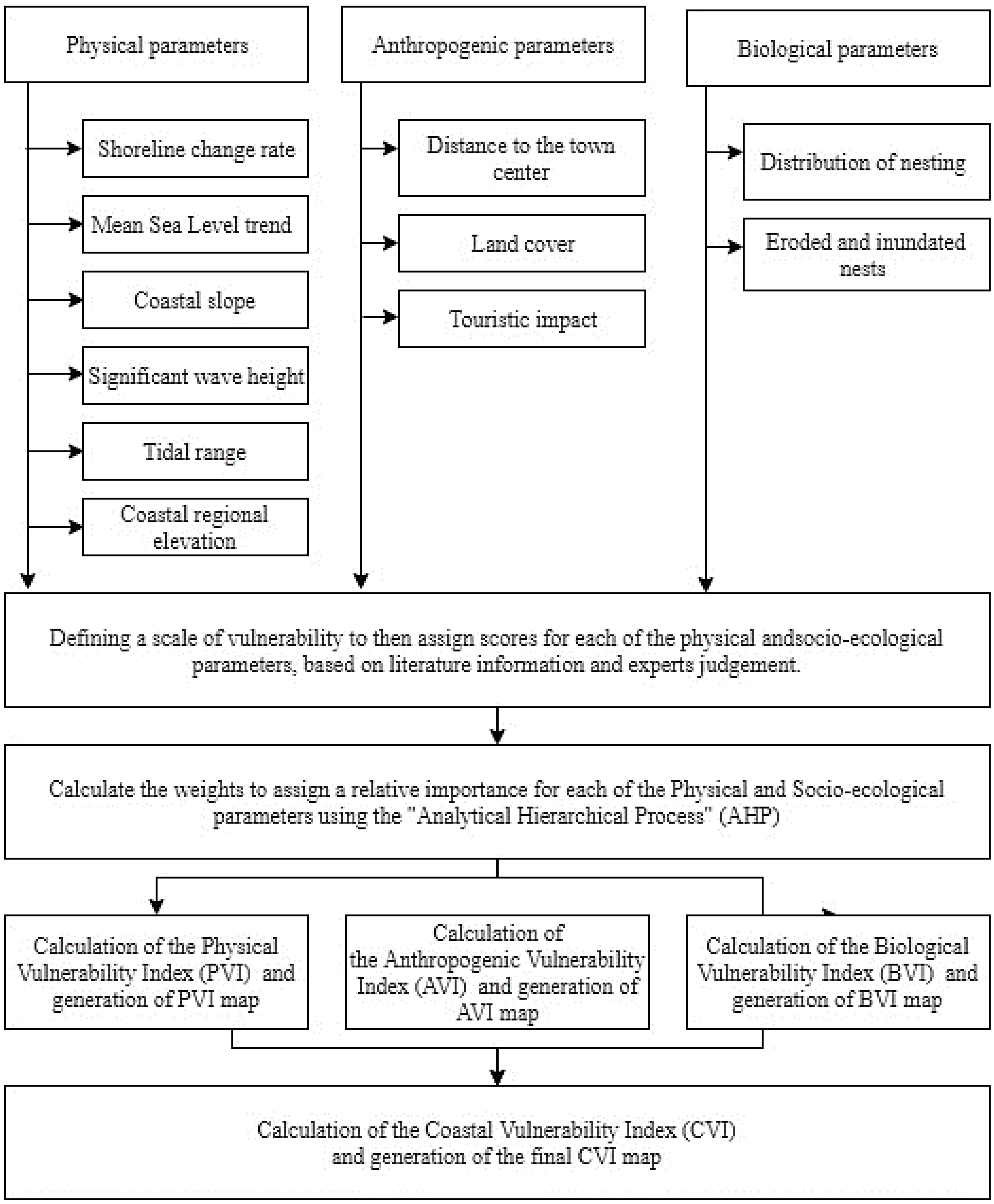


Figure 6: Summary of the methodological framework. Adapted from the flow diagram for the calculation of the CVI and generation of the CVI map in the study of Murali et al., 2013.

As a first step, based on literature information and experts' interviews, different scores or ranking for each one of the parameters were calculated. This indicates how vulnerable each sector is according to parameters-specific thresholds. Then, based on experts' interviews, weights were assigned to each parameter concerning others within the same group, using the "Analytical hierarchical process (AHP)" (i.e. one matrix of comparison for all the physical parameters). Afterward, three sub-indexes were calculated separately: Physical Vulnerability Index (PVI), Anthropogenic Vulnerability Index (AVI) and Biological Vulnerability Index (BVI). Finally, these indexes were united in a single coastal vulnerability index (CVI).

3.5.1. Physical parameters of Vulnerability (PVI)

This study includes the most commonly used physical-geological parameters in CVI assessments (Abuodha & Woodroffe, 2006; Kumar et al., 2010; Mahapatra et al., 2013). The physical parameters and the methodology used are described in Table 1.

Table 1: Methodology used to calculate the physical parameters of the Physical Vulnerability sub-index (PVI).

Physical Parameters	Methods
• **Shoreline change rate**	• . The changes in coastline were measured for each sector, using the satellite sources of Planet Team (2017) (4-band PlanetScope Scene, RapidEye Ortho tile, and SkySat Collect imagery) for the green sea turtle season of the period of 2009-2018. The remote sensing data provided by Planet Team was already available with atmospheric corrections, converted to surface reflectance (SR). The ArcMap extension Digital Shoreline Analysis (DSA) was used to calculate the rate of change within the sample period.

	The analysis with the DSA has four main steps (Thinh & Hens, 2017): (a) Establishing default sets parameters (Transects, shoreline calculations, metadata, log file output options); (b) Cast transects (Establishing a transect geodatabase, implementing a casting method using smoothing distances and transect metadata file); (c) Edit (Directly edit individual transects); (d) Calculate the statistics of change (Linear regression rate).
• **Mean Sea Level trend**	• The Copernicus - Marine service information (2019) provides open data of several ocean monitoring indicators. Copernicus has calculated globally, the trends of change of sea surface height above sea level (mean sea level trends), from January 1993 to May 2017. The trend values were calculated by Copernicus using the delayed-time DUACS altimeter sea level gridded data and were distributed by the Copernicus Climate Change Service (C3S) (Copernicus - Marine service information et al., 2019). This data set calculates sea level anomalies based on a stable number of altimeters (two) in the satellite constellation (Copernicus - Marine service information et al., 2019). The trends are derived from a linear regression of the altimeter sea level maps, but they have not been corrected for the GIA (Copernicus - Marine service information et al., 2019). The dataset was interpreted using ArcMap 10.6.
• **Coastal slope**	• The beach slope was calculated in-situ by taken geographical coordinates of two points per sector (200 m length each) using a GPS MAP 78 S. One point was taken on the high-tide line and another one on a sector marker located in the border of the vegetation and the beach. In the past, these points were taken by the STC during beach profile measurements on July 9, 2017, and October 9, 2018 (during the green sea turtle nesting season). These previous data were combined with the data taken during a field

	survey on March 23, 2019, in order to calculate the beach slope at different times in the season.
• **Significant wave height**	• Measured from the trough to crest, the Significant Wave Height (SWH) is the average of the highest one-third of waves (NOAA's National Weather Service, 2018). The dataset used is taken from the freely available historical ocean weather data statistics of MetOcean Solutions (2019). MetOcean Solutions reanalyzes the global datasets calculated by NOAA from the wind-wave model WAVEWATCH III (NOAA's National Weather Service, 2019). MetOcean Solutions shares the average statistics of significant wave height (m) from January 1979 to August 2016.
• **Tidal range**	• The Tidal Range is a measure of the vertical difference between the highest high tide and the lowest low tide, is related to permanent and episodic inundation (Kumar et al., 2010). The Tidal Range will be calculated using data from Moín meteorological station (N09°57'43'', W83°01'31'') of the National Meteorological Institute of Costa Rica (Instituto Meteorológico de Costa Rica, 2019). The tide dataset is available from 2014 to 2018 and is composed of three daily tide heights measurements. The daily tidal range was calculated, to then calculate the monthly and annual tidal range average.
• **Coastal regional elevation**	• The beach elevation was taken in-situ using a GPS MAP 78 S. The geographical coordinates of one point inside the vegetation border was taken on each sector marker. These points were taken during a beach survey on March 23, 2019.

The vulnerability of the PVI parameters was ranked on a scale from 1 to 4, being 1 the lowest risk, and 4 the highest risk (E. Doukakis., 2005). This study used the thresholds for the physical parameters proposed by the previous research of Murali et al. (2013) (Table 2).

Table 2: Vulnerability ranking criteria for physical parameters (PVI) proposed by Murali et al. (2013).

Parameter	**Vulnerability ranking**			
	Very low (1)	Low (2)	High (3)	Very high (4)
Shoreline change rate (m yr^{-1})	Accretion >1	Accretion<1	Coastal retreat <1	Coastal retreat >1
Mean Sea level trend (mm yr-1)	<0	>0 and <1	>1 and < 2	>2
Coastal slope	>1	>0.2 and <1	> 0.1 and <0.2	> 0 and <0.1
Significant wave height (m)	< 0.55	> 0.55 and < 1	> 1 and < 1.25	> 1.25
Tidal range (m)	< 1	>1 and <4	> 4 and <6	> 6
Coastal regional slope elevation (m)	>6	> 3 and < 6	> 0 and < 3	< 0

3.5.2. Anthropogenic parameters of Vulnerability (AVI)

Tortuguero has the particularity of having a town inside the national park, where there is a great tourist development. Due to these conditions, three anthropogenic parameters were included, whose methodology is described in Table 3.

Table 3: Methodology used to calculate the parameters of the Anthropogenic Vulnerability sub-index (AVI).

Anthropogenic Parameters	Methodology
• **Distance to the town center**	• The distance in km that each sector has to the town center, was measure in ArcMap 10.6, using the satellite sources of Planet Team (2017) (4-band PlanetScope Scene, RapidEye Ortho tile, and SkySat Collect imagery) with a spatial resolution of 3 m to 5m per pixel.
• **Land cover**	• A land use/ land cover supervised classification for the surveyed area was created with techniques in ArcMap 10.6 software, using the satellite sources of Planet Team (2017) (4-band PlanetScope Scene, RapidEye Ortho tile, and SkySat Collect imagery) with a spatial resolution of 3 m to 5m per pixel. In this analysis, the area was divided into four classes: Rain forest/vegetated areas, urban areas, sand/beach, and river by applying the maximum likelihood algorithm. Urbanized areas without a vegetation border to the beach and the forest patches were identified. • During this process, a set of complementary measurements of the distance between the high-tide line and the urban areas. These measurements would be used directly for recommendations for the coastal management plans in the area.
• **Touristic impact**	• The number of international and national tourist in Tortuguero National Park was published for the "Instituto Costarricense de Turismo" (ICT) from 2011 to 2017. The rate of growth in the number of tourists will be an indicator of the human presence on the beach.

The vulnerability of most of the AVI parameters was ranked on a scale from 1 to 4, being 1 the lowest risk and 4 the highest risk (E. Doukakis., 2005). The thresholds for the AVI parameters "distance to the town center and land cover" were based on the interviews carried out the STC staff working in the field. The thresholds for "touristic impact" are proposed by the author, based on the increasing number of visitors of TNP published by the "Instituto Costarricense de Turismo" (ICT) (Table 4). The high vulnerability threshold for this parameter will be localized in urban areas. Since these areas have a high concentration of tourists.

Table 4: Vulnerability ranking criteria for anthropogenic parameters (AVI).

Parameter	**Vulnerability ranking**			
	Very low (1)	Low (2)	High (3)	Very high (4)
Distance to the town center	>1.5	≤1.5 > 0.5	≤0.5 >0.2	≤0.2 - 0
Land cover	National Park	Forest with unregulated entrance	Urban areas with vegetation border	Urban areas without vegetation border
Touristic impact	<10% of decrease	No decrease or increase	<10% of increase	>10% of increase

3.5.3. Biological parameters of Vulnerability (BVI)

This sub-index comprises specific parameters of the nesting population of green turtles in Tortuguero. The methods for calculating these parameters are described in Table 5.

Table 5: Methodology used to calculate the parameters of the Biological Vulnerability sub-index (BVI).

Biological parameters	Methodology
• **Distribution of nesting**	• Daily surveys were conducted by the Sea Turtle Conservancy (STC) to record the number of nests laid the night before in each beach sector (the same sectors used in the physical and anthropogenic parameters). The sampling period corresponds to the nesting season of the green sea turtle's species (*C. mydas*), from July to November of 2008 to 2018. The average number of nests per sector in the sampled period is expressed.
• **Eroded and inundated nests (nests yr^{-1})**	• A sample of green sea turtle nests was marked during the oviposition, in the green sea turtle season **(**from July to November) of 2011 to 2018 (Sea Turtle Conservancy, 2017). All the nests marked were daily monitored for two months (until they hatched). The nests eroded are the ones damaged or lost by the action of the waves. The nests inundated are the ones covered by seawater. This parameter shows the number of eroded and inundated nests that each sector has, during the sampling period.

As well as the PVI and AVI parameters, the vulnerability of the BVI parameters was ranked on a scale from 1 to 4, being 1 the lowest risk and 4 the highest risk (E. Doukakis., 2005). The thresholds for the BVI are proposed by the author, based on data sets from the seasons of 2008 to 2018 (Table 6) (Sea Turtle Conservancy, 2017; STC, 2019a; Troëng & Rankin, 2005). For the calculation of the thresholds for the parameter "distribution of nesting," the following process was used:

1. The average nest value per season for 2008-2018 was calculated.

2. The quartiles for the average-values per year were calculated.
3. The ranking of vulnerability was established using quartiles. The average value of each sector will be used to evaluate its vulnerability condition. A sector with a higher number of nests will be less vulnerable in comparison to a sector with a lower number of nests.

For the parameters "inundated nests" and "eroded nests," just the presence of eroded/inundated nests in the sector would be cataloged as high vulnerability (Table 6).

Table 6: Vulnerability ranking criteria for biological parameters (BVI).

Parameter	Vulnerability ranking			
	Very low (1)	Low (2)	High (3)	Very high (4)
Distribution of nesting (Average number of nests per sector)	≥700	≥447<700	≥351 < 447	<351
Eroded and inundated nests (nests yr^{-1})	-	0	≥1	-

3.5.4. Total Coastal Vulnerability Index (CVI)

In this study, the "Analytical hierarchical process" (AHP) was followed to calculate the weights for the PVI, AVI, and BVI using the (Figure 1). The first step was the pair-wise comparison of all physical, anthropogenic, and biological parameters, using scores based on their relative importance (Murali et al., 2013). In this comparison matrix, "each parameter were rated against each of the other parameters, assigning them a relative dominant value between 1 and 9"(Murali et al., 2013). These comparisons and allocation of weights were carried out together with the scientific coordinator of the STC in Tortuguero, Jaime Restrepo, and with the education and outreach coordinator of the same organization, Michelle Dorantes.

After assigning the weights, a priority vector called normalized Eigen vector of the matrix was calculated. This vector is the division of each of the columns by the corresponding sum (Murali et al., 2013). The final step of the AHP, the average values of each row were calculated and used as weights in the hierarchy of the PVI, AVI, and BVI parameters.

The vulnerability of the physical, anthropogenic and biological parameters were ranked on a scale from 1 to 4, being 1 the lowest risk and 4 the highest risk (E. Doukakis., 2005), as previously shown. This study used the thresholds for the physical parameters proposed by Murali et al. (2013) (Table 1). The values of vulnerability for each of the parameters of each beach sector were calculated by multiplying the vulnerability score and the corresponding weighting of each parameter (Murali et al., 2013). Vulnerability maps were generated for each of the parameters; for the sub-indexes PVI, AVI, and BVI; and for the overall CVI. No maps will be shown for the parameters with the same vulnerability value for all the beach sectors.

Most of the CVI vulnerability studies state the index value as the square root of the product of the ranking of factors divided by the number of parameters (Murali et al., 2013). This study used the equation used by Murali et al. (2013), and Diez et al. (2007), which is calculated as the sum of the differentially weighted variables. This equation was the base for calculating the three different CVI's sub-indexes (Equation 1, 2, and 3).

Physical Vulnerability Index (PVI): W_1X_1+ W2X2+ W3X3+ W4X4+ W5X5+ W6X6 (1)

Anthropogenic Vulnerability Index (AVI): $W_1X_1+ W_2X_{2+} W_3X_3$ (2)

Biological Vulnerability Index (BVI): $W_1X_1+ W_2X_2$ (3)

Where W_n is the weight value of each parameter, and X_n is the vulnerability score of each parameter (Murali et al., 2013). The level of vulnerability will be ranked using quartiles (0-

25%, 25-50%, and 75-100%). All the PVI, AVI, and BVI values were divided individually, according to their quartiles.

The total CVI was calculated assuming that the physical (PVI), anthropogenic (AVI) and biological (BVI) parameters contribute equally to vulnerability (Equation 4) (Murali et al., 2013).

$$CVI = (PVI + AVI + BVI)/3 \quad (4)$$

The ranking of the vulnerability for the CVI was done in a similar way as the sub-indexes, that used quartiles to define the vulnerability classes.

4. Chapter 4: Results

4.1. Physical vulnerability parameters

4.1.1. Shoreline Change Rate (m yr-1)

Tortuguero's nesting beach experienced both expansion and regression, during the period 2009-2010. One baseline per year was used to calculate the shoreline changes. A transect, per each sector, was created to measure the specific rate.

The average of shoreline change, or Linear Regression Rate (LRR), for the whole beach, is 0.44 m yr-1, with a maximum of 3.4 m of accretion per year, and a minimum of -6.31 of coastal retreat (Figure 7). Subsequently, according to the thresholds established by Murali et al. (2013) (same thresholds used in this study), the 32 % of the beach has a very low vulnerability (1), the 44% a low vulnerability (2), the 12% a high vulnerability (3), and the other 12% a very high vulnerability (4), for the shoreline change rate parameter (Figure 8).

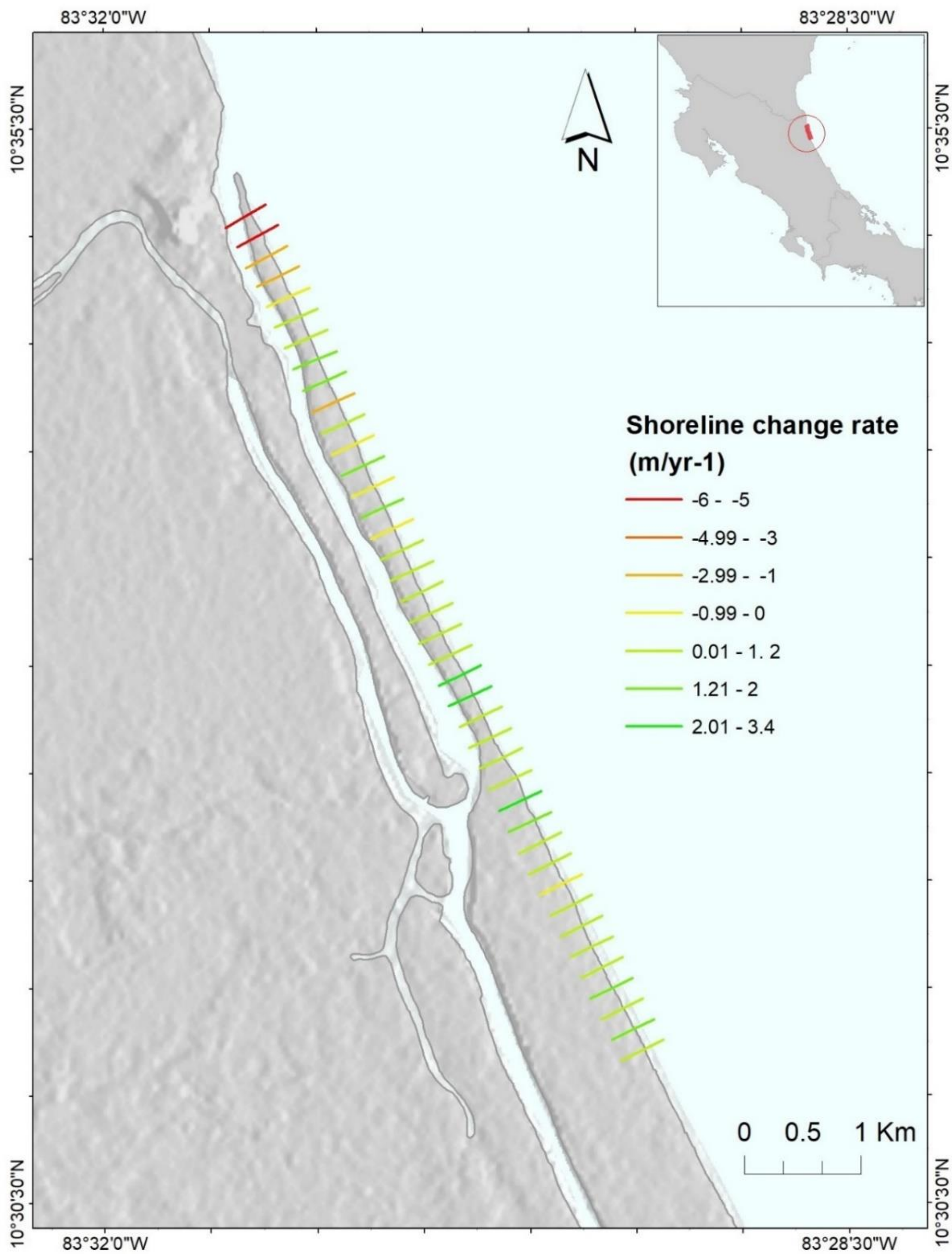


Figure 7: Linear Regression Rate (LRR) of historical shorelines in Tortuguero National Park, during 2009-2018 (using the Digital Shoreline Analysis extension of ArcGIS).

The bars represent the change in meters per year. In the background, the area of Tortuguero is presented in grey and the Caribbean Sea as light blue. Source: Self elaboration using Planet Team (2018) JAXA/METI & ALOS PALSAR (2010) imagery.

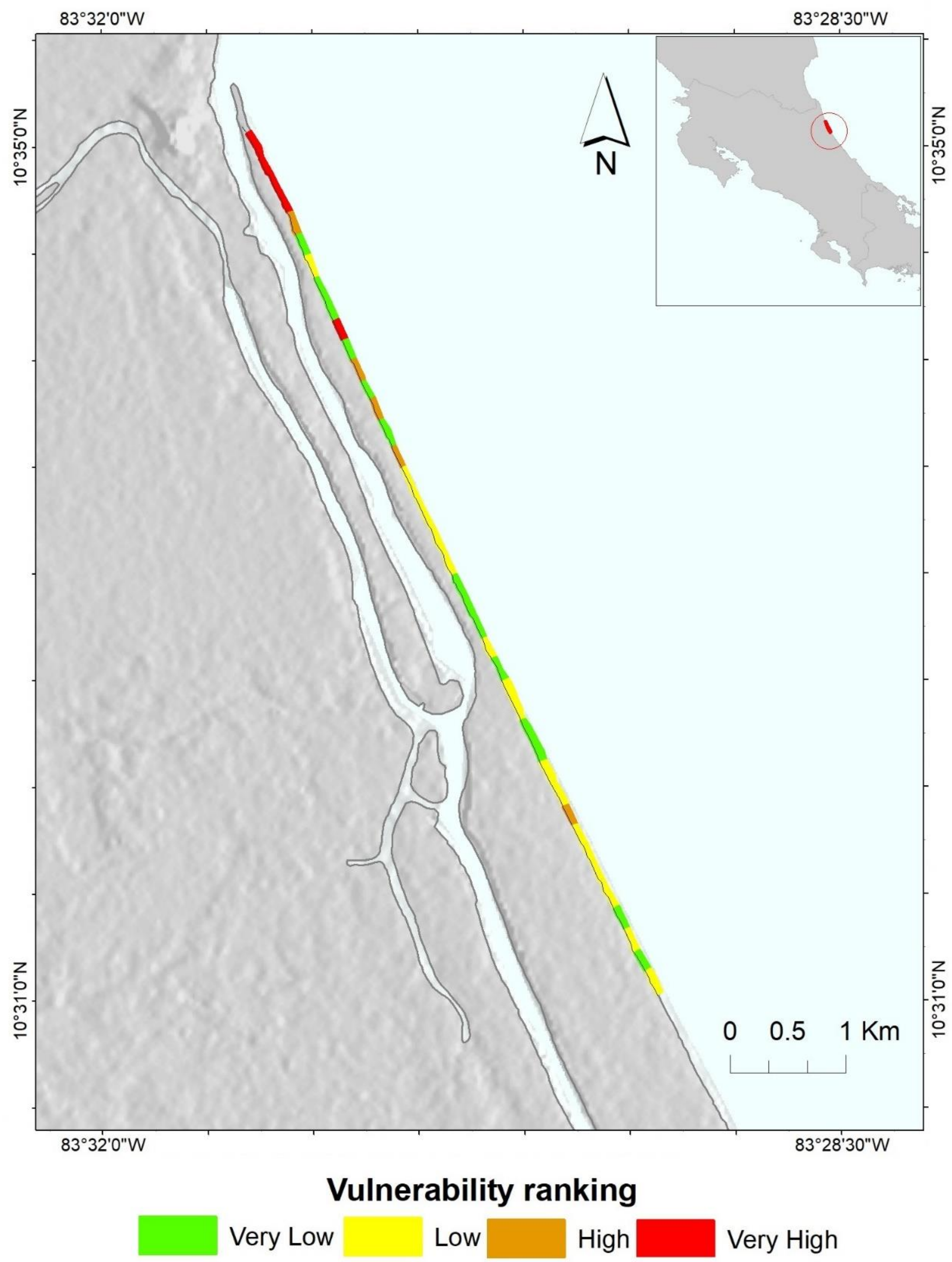


Figure 8: Vulnerability ranking for "shoreline change." Source: Self elaboration using Planet Team (2018) JAXA/METI & ALOS PALSAR (2010) imagery.

4.1.2. Mean Sea level trend (mm yr-1)

Based on the trends of sea level rise already calculated by Copernicus - Marine service information et al. (2019), there is an increase of the sea levels in the surroundings of Tortuguero (Figura 3). For the region, the trend value of increase reported by Copernicus is 4.073 mm per year (mm yr-1). According to the thresholds used in this research, the entire beach of Tortuguero has a very high vulnerability (4), based on the 2 mm yr-1 thresholds for sea level rise (Murali et al., 2013). Copernicus tendency for the area shows for the area of Tortuguero, an increase higher than the global mean of 2mm-3.2 mm yr-1 (Butt et al., 2016; Church & White, 2011; Parris et al., 2012).

4.1.3.Coastal slope

The average slopes per sector were calculated using the data of beach profiles, carried out by the STC on July 9, 2017, and October 9, 2018, in combination with the values of the slope taken in the field, on March 23, 2019. The majority of Tortuguero's beach sectors were below the value of 0.1 (Standard deviation 0.056) (Figure 9). According to the thresholds for coastal slope, most of the beach, the 66%, is under the category of very high vulnerability (4), 17% is under high vulnerability (3) and the other 17% is under low vulnerability (2), based on the coastal slope values (Figure 10).

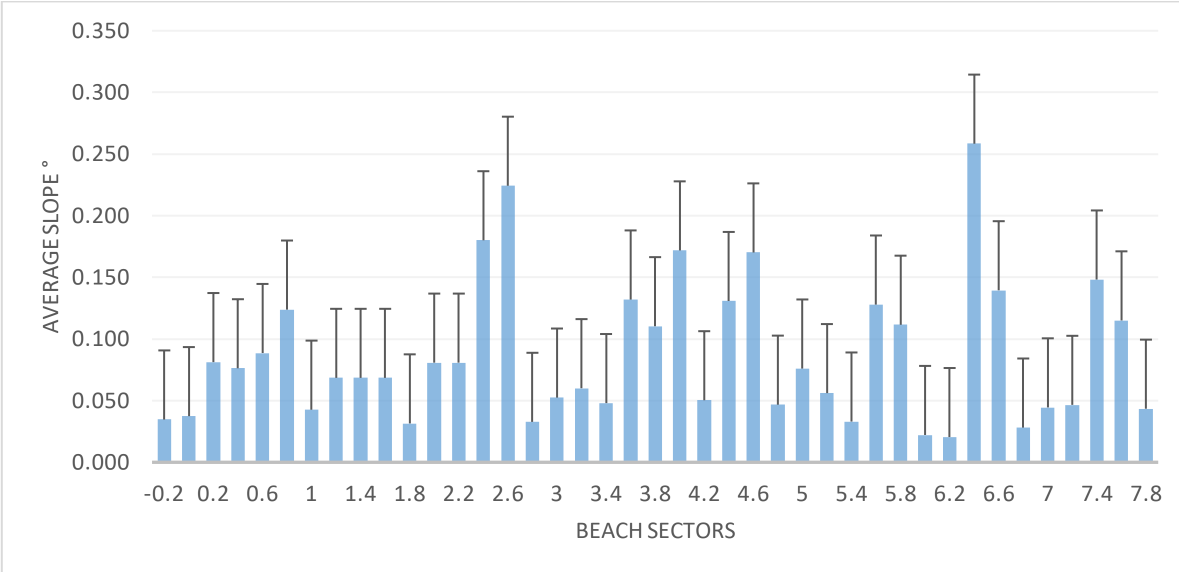


Figure 9: Average slopes per sector, using data of beach profiles on July 9, 2017, October 9, 2018, and March 23, 2019. Source: Self elaboration in collaboration with Sea Turtle Conservancy.

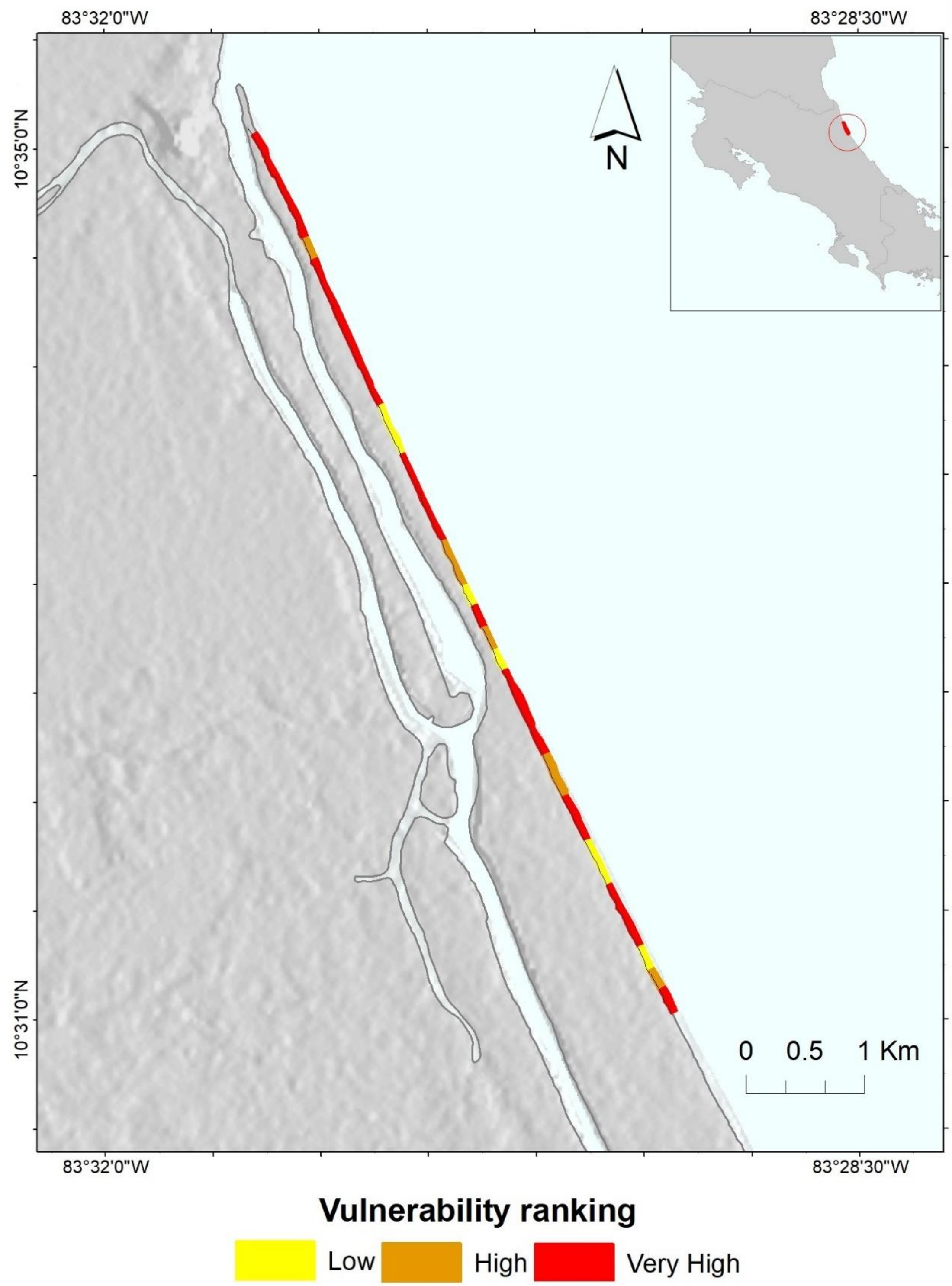


Figure 10: Vulnerability ranking for "coastal slope." Source: Self elaboration using Planet Team (2018) JAXA/METI & ALOS PALSAR (2010) imagery.

4.1.4. Significant Wave Height (m)

The mean significant wave height (January 1979 to August 2016) for the area of Tortuguero is 1.11 m. Though there were some significant monthly variations in the significant wave heights (Figure 11), this value describes the heights for all the beach sampled.

According to the thresholds used in this research, Tortuguero has a ranking of high vulnerability (3) for all the beach sectors. Since the mean significant wave height value is in the range of 1 to 1.25.

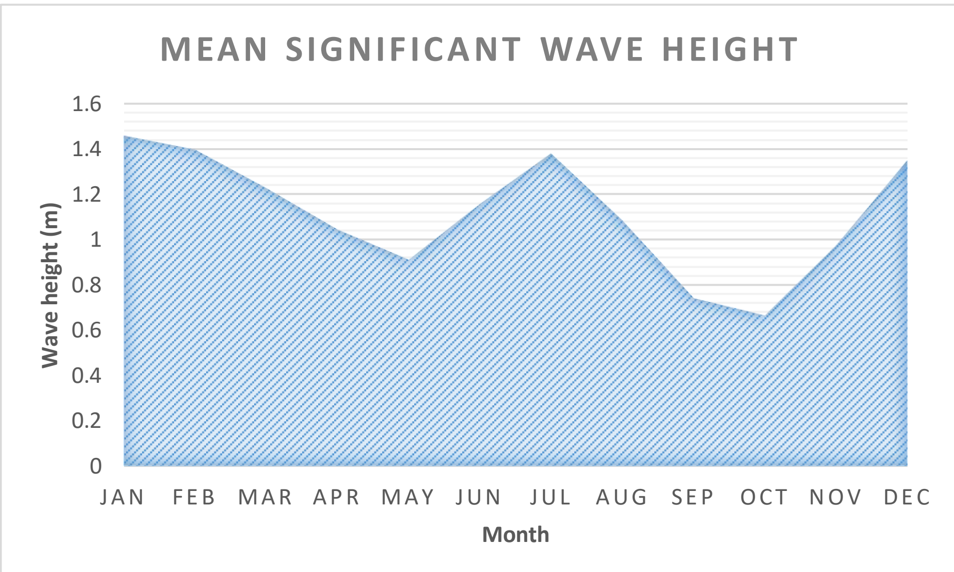


Figure 11: The mean significant wave height for the period of January 2019 to August 2016. (MetOcean Solutions, 2019; NOAA's National Weather Service, 2019).

4.1.5. Tidal Range

Using the daily tidal data of Moín meteorological station, a total mean Tidal-range value was calculated for the period 2014-2018. The mean tidal range for the entire beach of Tortuguero is 0.33 m (Table 7, Figure 12). Therefore, all the beach sectors are classified with a very low vulnerability (1), based on the tidal range values since the vertical differences are smaller than one meter (Murali et al., 2013).

Table 7: Tidal range mean for the Caribbean of Costa Rica, for the years 2014 to 2018 (Instituto Meteorológico de Costa Rica, 2019).

Year	Tidal range average
2014	0.32717655
2015	0.33076721
2016	0.33312417
2017	0.33268297
2018	0.32756042
Total average	0.33026226

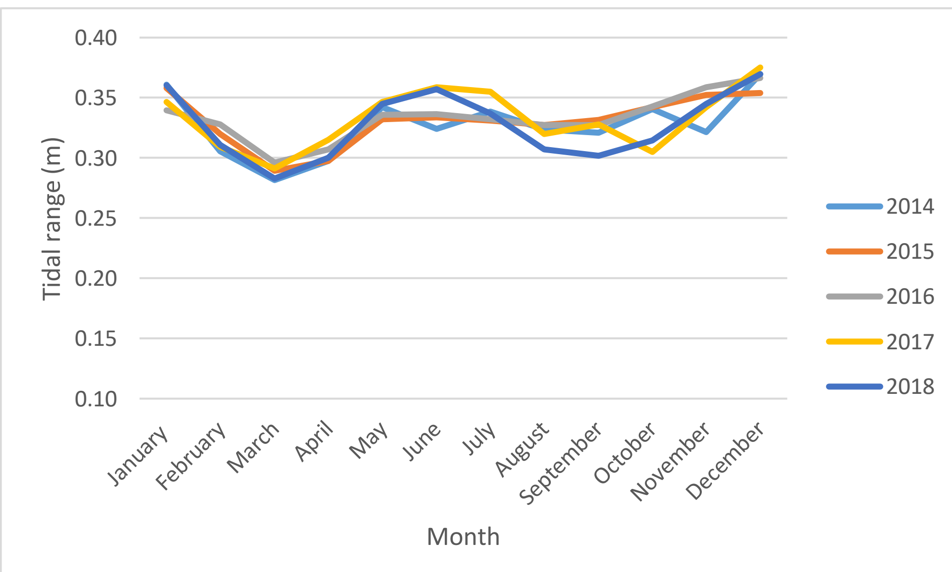


Figure 12: Monthly variation of the mean tidal-range for the period 2014-2018 (Instituto Meteorológico de Costa Rica, 2019).

4.1.6. Coastal regional elevation (m)

Based on the elevation data taken in the field, the nesting beach sampled in Tortuguero has elevations ranging from 1 to 9 meters above sea level (standard deviation 1.5) (Figure 13). Then according to the thresholds used in this research, the 84 % of the beach has a high vulnerability (3), 14% low vulnerability (2) and only the 2 % very low vulnerability (1), for the regional coastal elevation parameter (Figure 14).

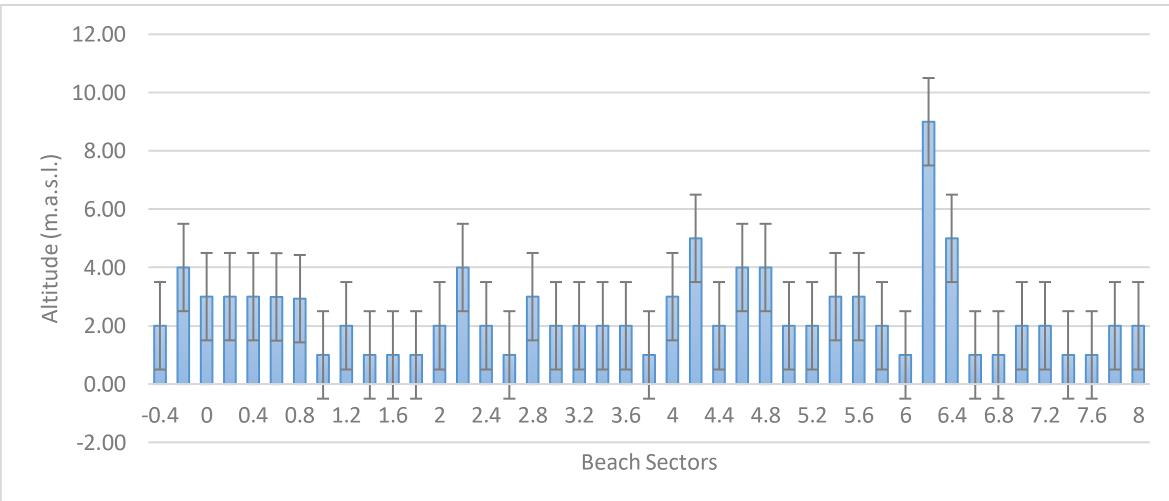


Figure 13: Altitude of the beach sectors. Source: Self elaboration.

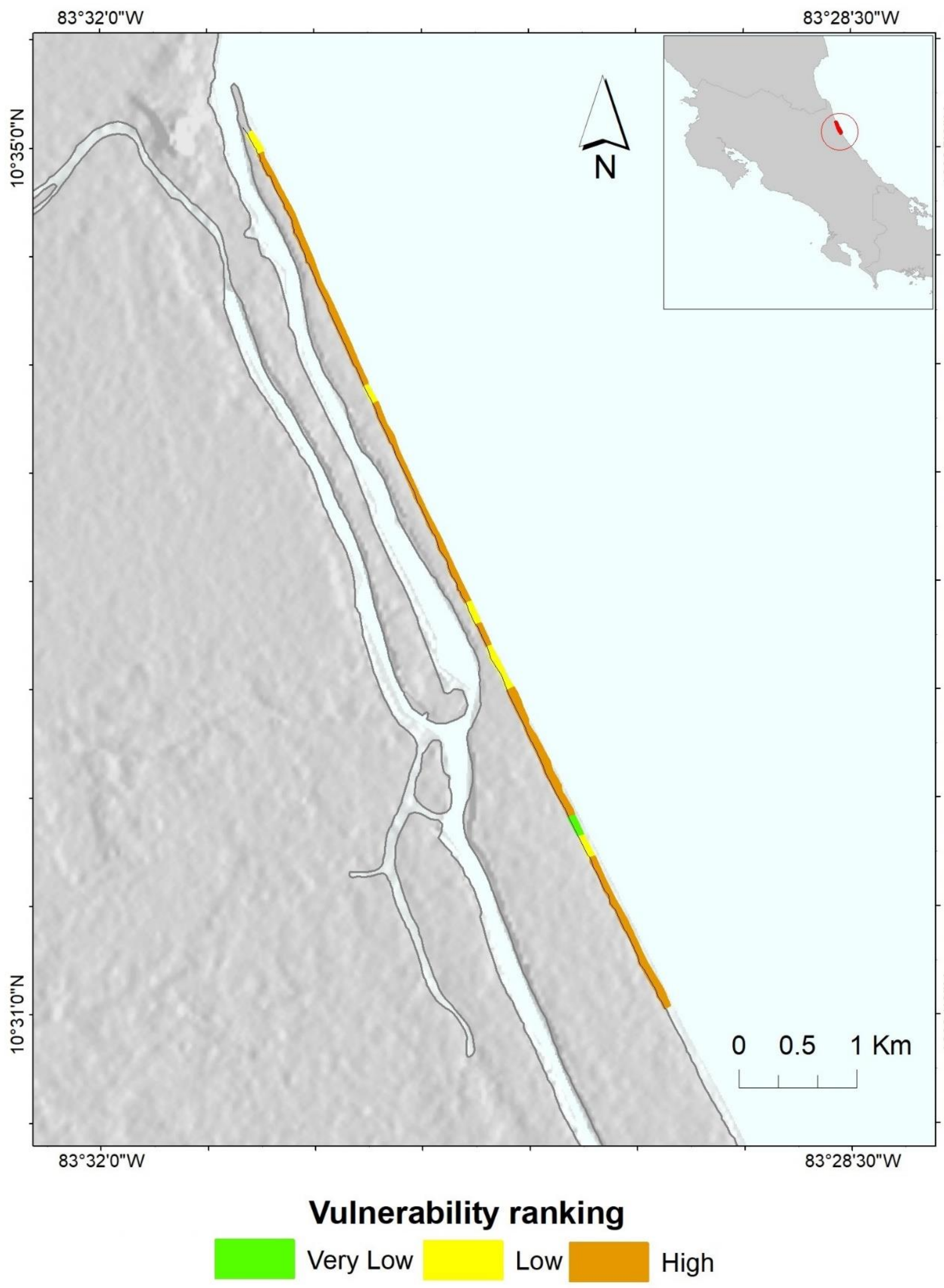


Figure 14: Vulnerability ranking for "coastal regional elevation." Source: Self elaboration using Planet Team (2018) JAXA/METI & ALOS PALSAR (2010) imagery.

4.1.7. Physical Vulnerability Index (PVI)

The weights of each physical parameters were calculated, based on experts' interviews, following the Analytical Hierarchical Process (AHP) (Table 8). The calculated weights were consistent according to the Consistency Ratio of the AHP (CR $\leq$ 0.1) (Table 9).

Table 8: Weight values assigned for each of the physical parameters using the Analytical Hierarchical Process.

Parameter	Weights
Tidal range	30
SWH	27
SLR	18
Shoreline change	15
Costal regional elevation	6
Coastal slope	5

Table 9: Estimation of the consistency of the physical parameters.

Parameters	Consistency values
λ max	6.448
n	6
CI	0.090

CR	0.07
Constant	1.24

The physical vulnerability sub-index (PVI) was calculated for each beach sector, using equation 1 of the methodology chapter. The minimum value of PVI is 226, the median value is 246, and the maximum is 281. These values were used to create the PVI vulnerability categories using quartiles (Table 10). Focusing on the PVI, the 17% of the sampled beach is under the category of very low vulnerability, 29% low, 29% high and the 24% under a very high vulnerability (Figure 15).

Table 10: Vulnerability categories for the Physical Vulnerability sub-index (PVI).

Category	PVI Values
Very Low	<235
Low	≥235 < 246
High	≥246 < 253
Very-high	>253

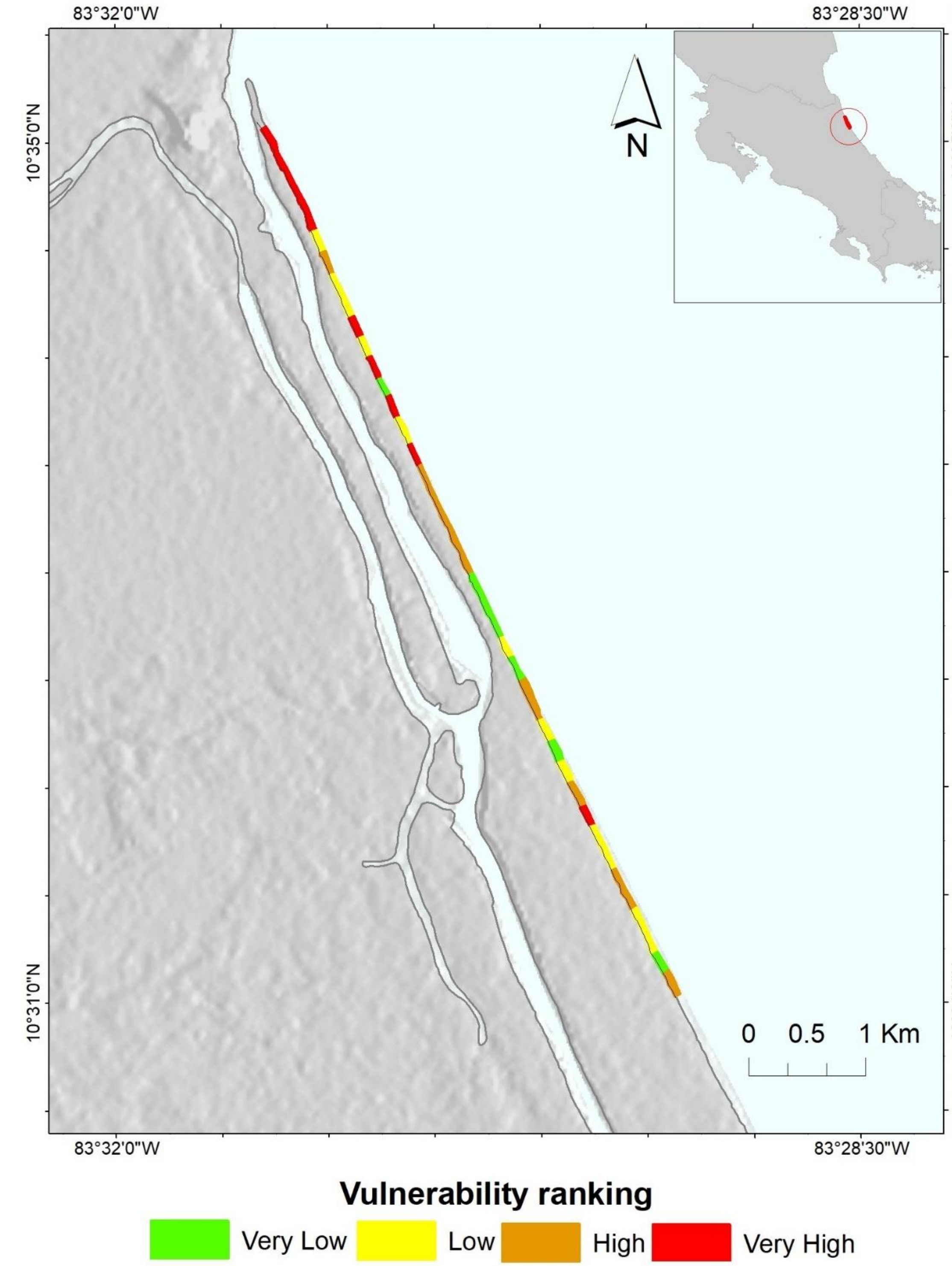


Figure 15: Physical Vulnerability Index map. Source: Self elaboration using Planet Team (2018) JAXA/METI & ALOS PALSAR (2010) imagery.

4.2. Anthropogenic Vulnerability parameters (AVI)

4.2.1. Distance to the town center

The town center, or place with the most human influence, was located in sector 4.8 (on the main beach entrance, in front of the town's school). Each of the beach sectors measures 200 m, which means that the difference in distance between adjacent sectors, with respect to the town center, is 200 m. Figure 16 shows the vulnerability ranking with respect to the thresholds proposed for Tortuguero in this research.

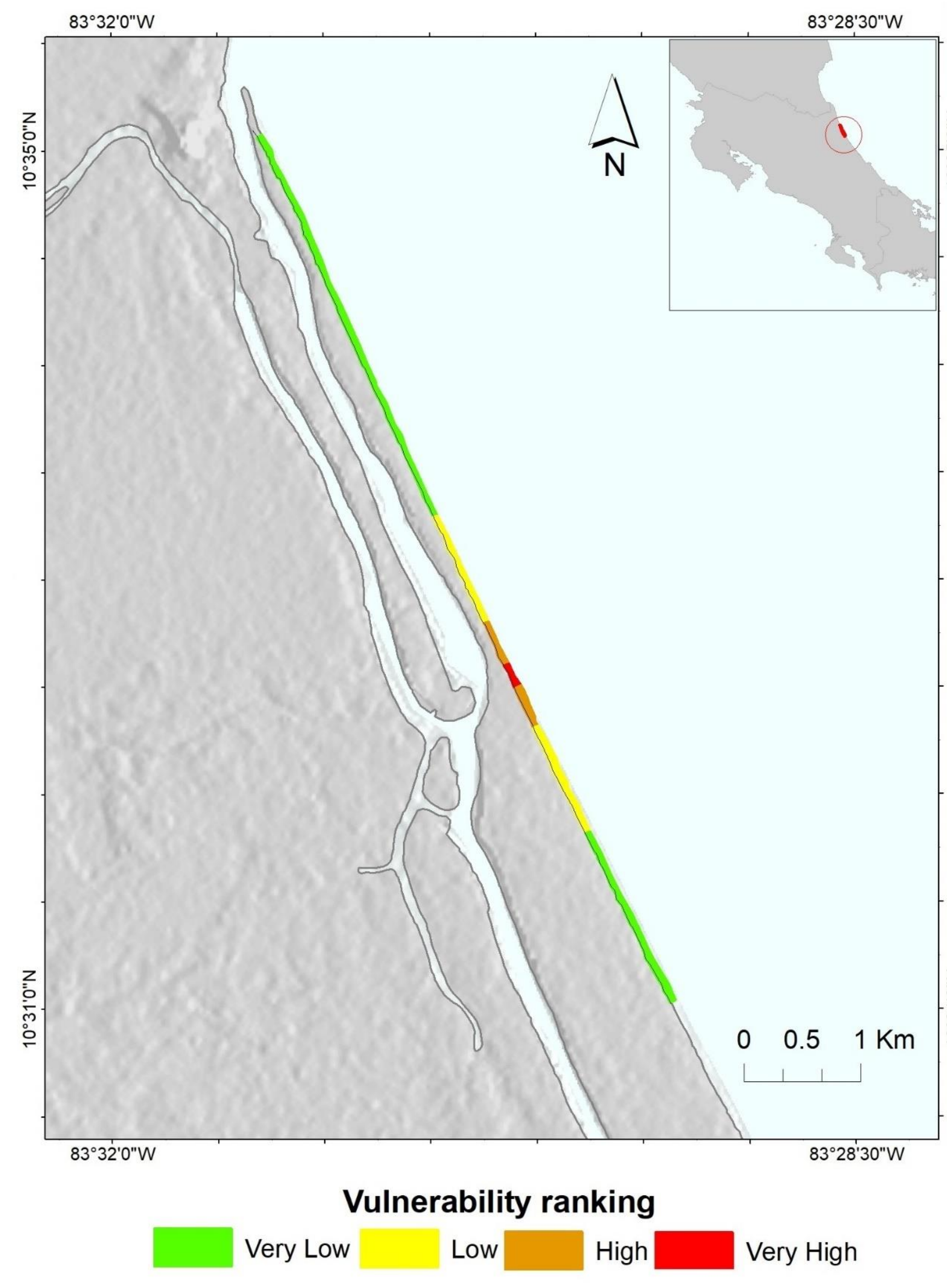


Figure 16: Vulnerability ranking for "Distance to the Town Center." Source: Self elaboration using Planet Team (2018) JAXA/METI & ALOS PALSAR (2010) imagery.

4.2.2. Land Cover

The cover analysis for the area of Tortuguero was calculated using a supervised classification in ArcMap 10.6. In this map, it is possible to observe that there is a lack of vegetation barrier between the beach and the highly urbanized areas (Figure 17). Therefore, the beach sectors, in front of these areas without vegetation barrier, were considered under a very high vulnerability (4) (Figure 18). The sectors in front of vegetated areas were classified as low vulnerability (2) (places protected but with unrestricted access), and with very low vulnerability (inside the national park).

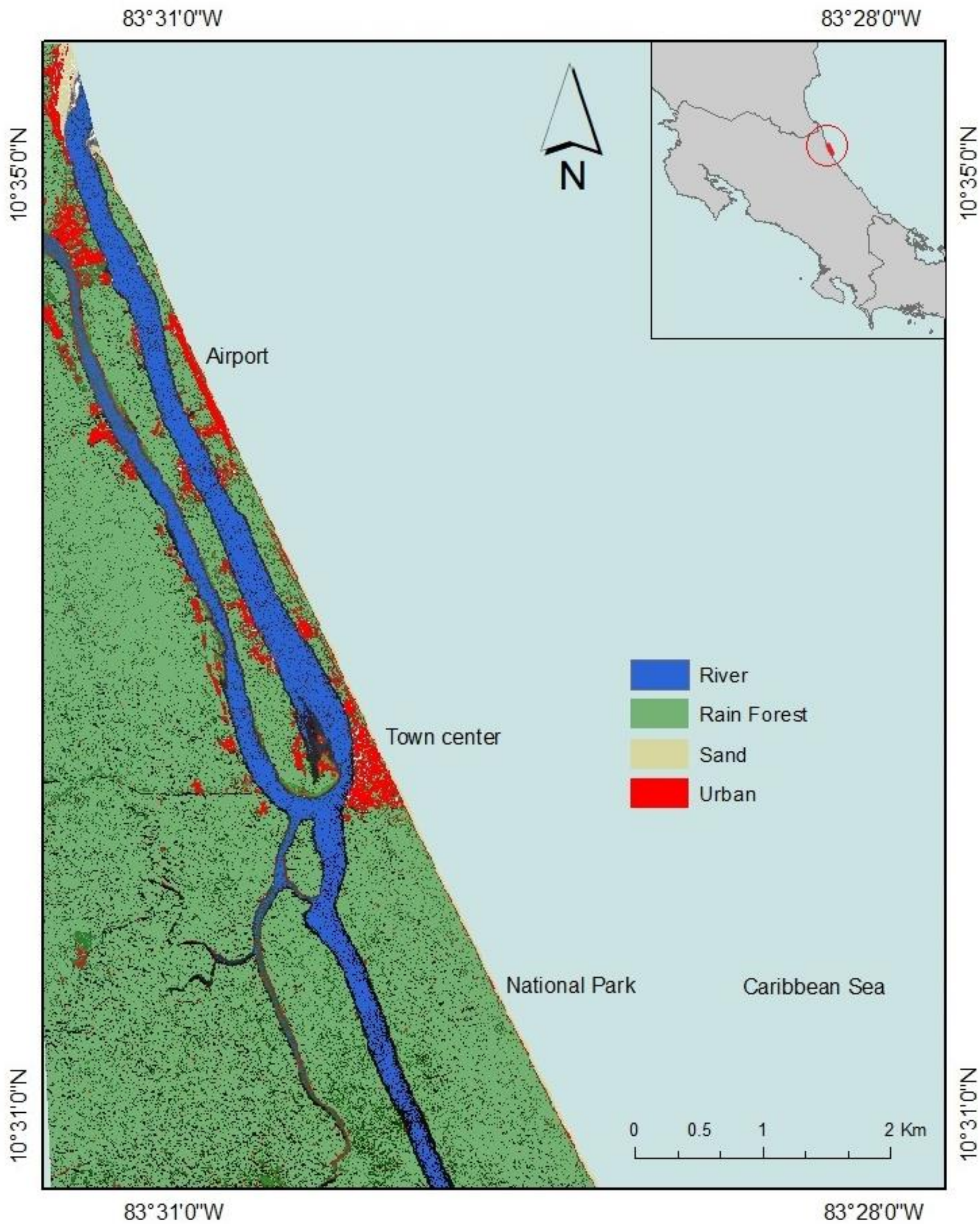


Figure 17: Land cover classification for the area of Tortuguero National Park. Source: Self elaboration using Planet Team (2018) imagery.

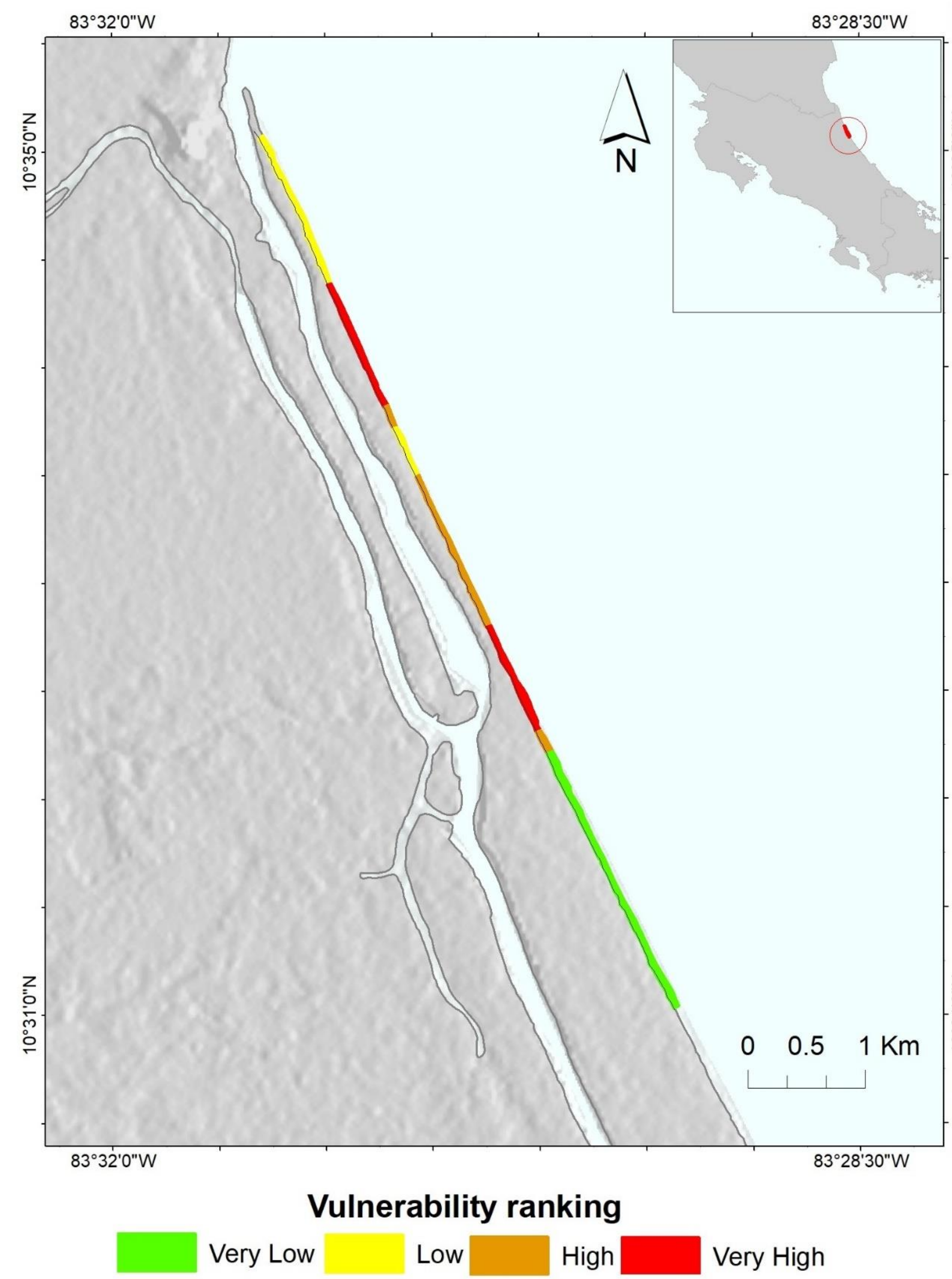


Figure 18: Vulnerability ranking for "Land Cover." Source: Self elaboration using Planet Team (2018) JAXA/METI & ALOS PALSAR (2010) imagery.

In addition, the distance of the buildings from the high tide line was measured (Table 11). This information will serve to discuss the current location of the buildings, concerning the limits allowed in Costa Rican legislation, and will not be used within the calculation of the CVI.

Table 11: Distance of the urbanized areas with respect to the hide tideline and the width of the strip of land. Source: Calculated using imagery of Planet Team (2019).

Edification	Sector number	Distance from the hide-tide line (m)	Distance from the hide-tideline to the river (m)
Airport	1.2	61.7	167.9
	1.4	44.7	189.1
	1.6	42.3	225.5
	1.8	62.1	269.57
	2	44.6	257.8
Laguna Lodge	2.4	134.9	244.19
Mawamba Lodge	3.8	65.8	188.73
Sea turtle conservancy	4.2	66.1	132.4
Housing	4.4	45.2	118.2
Miss Junies Lodge	4.6	66.8	146.4
Town area (housing, hostels, restaurants, parks, etc.)	4.8	47.7	183.73
	5	91.66	276.54
	5.2	47.8	424.7
	5.4	77.8	556.7

4.2.3. Touristic Impact

For the period of 2011 to 2017, the area of Tortuguero National Park has experienced a rate of change of 7% of increase. Although the number of tourists per year shows a weak linear correlation (R^2= 0.2163; p= 0.47) (Figure 19). According to the thresholds proposed for the "touristic impact" anthropogenic parameter, an increase of 7% will fall into the classification of high vulnerability (3) (Figure 20).

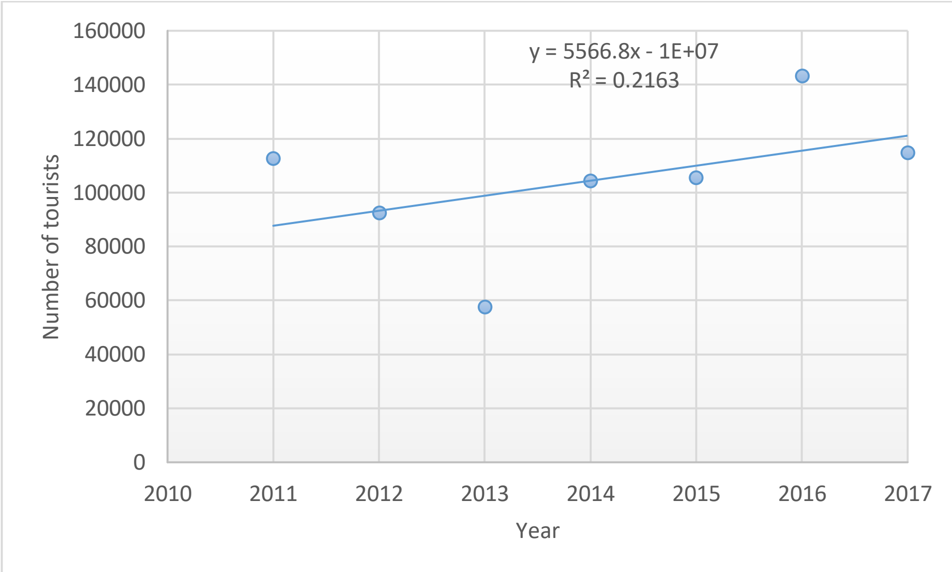


Figure 19: Number of tourists that visited Tortuguero National Park, during the period of 2011 to 2017. Source: Instituto Costarricense de Turismo, (2017).

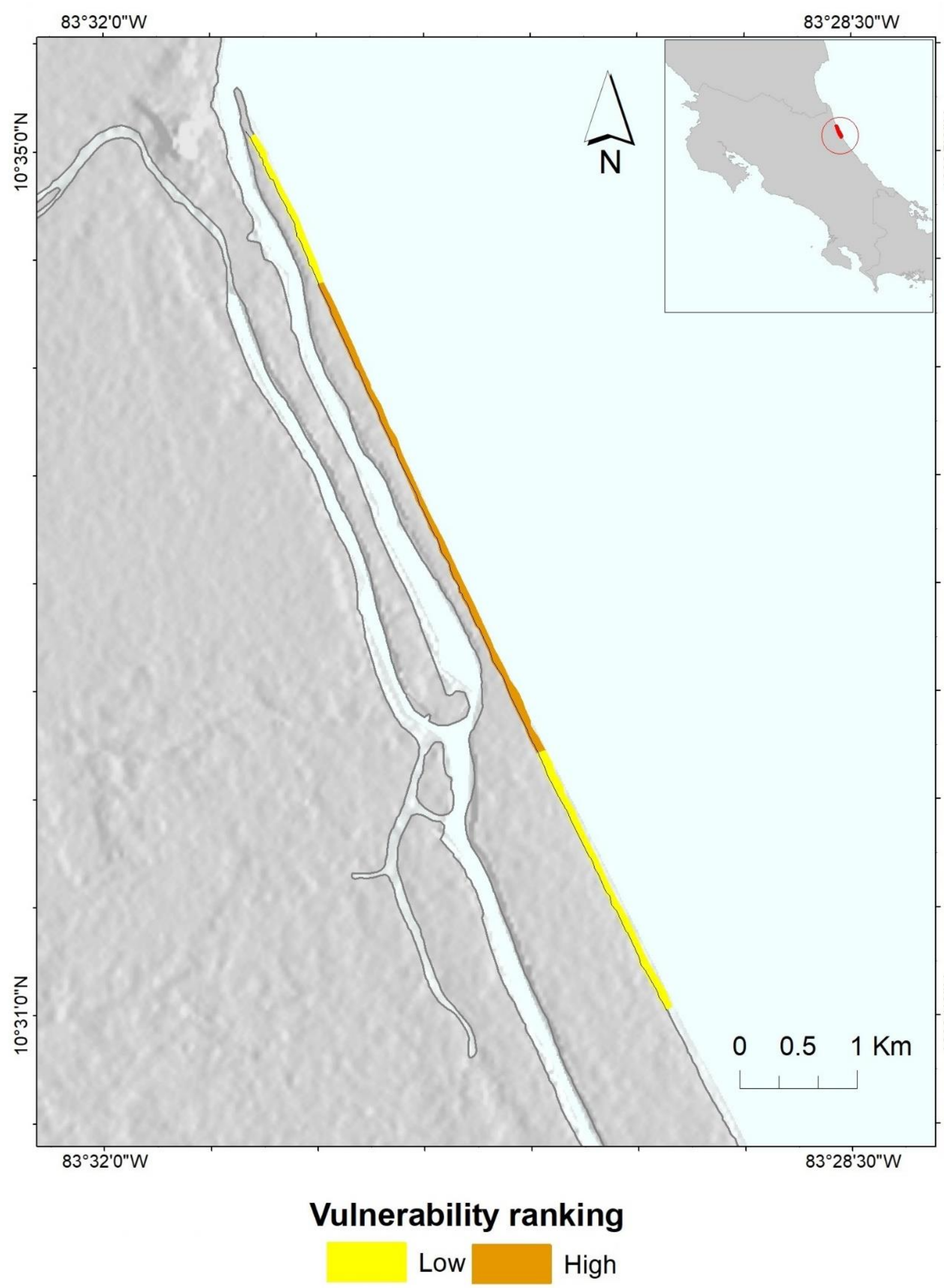


Figure 20: Vulnerability ranking for "Touristic impact." Source: Self elaboration using Planet Team (2018) JAXA/METI & ALOS PALSAR (2010) imagery.

4.2.4. Anthropogenic Vulnerability Sub-Index (AVI)

The weights of each anthropogenic parameters were calculated, based on experts' interviews, following the Analytical Hierarchical Process (AHP) (Table 12). The calculated weights were consistent according to the Consistency Ratio of the AHP (CR ≤ 0.1) (Table 13).

Table 12: Weight values assigned for each of the anthropogenic parameters using the Analytical Hierarchical Process.

Parameter	Weights
Land cover	68.1
Distance to the town center	21,6
Touristic impact	10.3

Table 13: Estimation of the consistency of the anthropogenic parameters.

Parameters	Consistency values
λ max	3.003
n	3
CI	0.001
CR	0.0
Constant	0.58

The anthropogenic vulnerability sub-index (AVI) was calculated for each beach sector, using equation 2 of the methodology chapter. The minimum value of AVI is 120, the median value is 188, and the maximum is 390. Like the PVI sub-index, these values were used to create the AVI vulnerability categories using quartiles (Table 14). For the anthropogenic sub-index, 20% of the sampled beach is under the category of very low vulnerability, 27% under low, 27% under high and the 27% under a very high vulnerability (Figure 21).

Table 14: Vulnerability categories for the Anthropogenic Vulnerability sub-index (PVI).

Category	AVI Values
Very Low	<132
Low	≥132 < 188
High	≥188 < 324
Very-high	>324

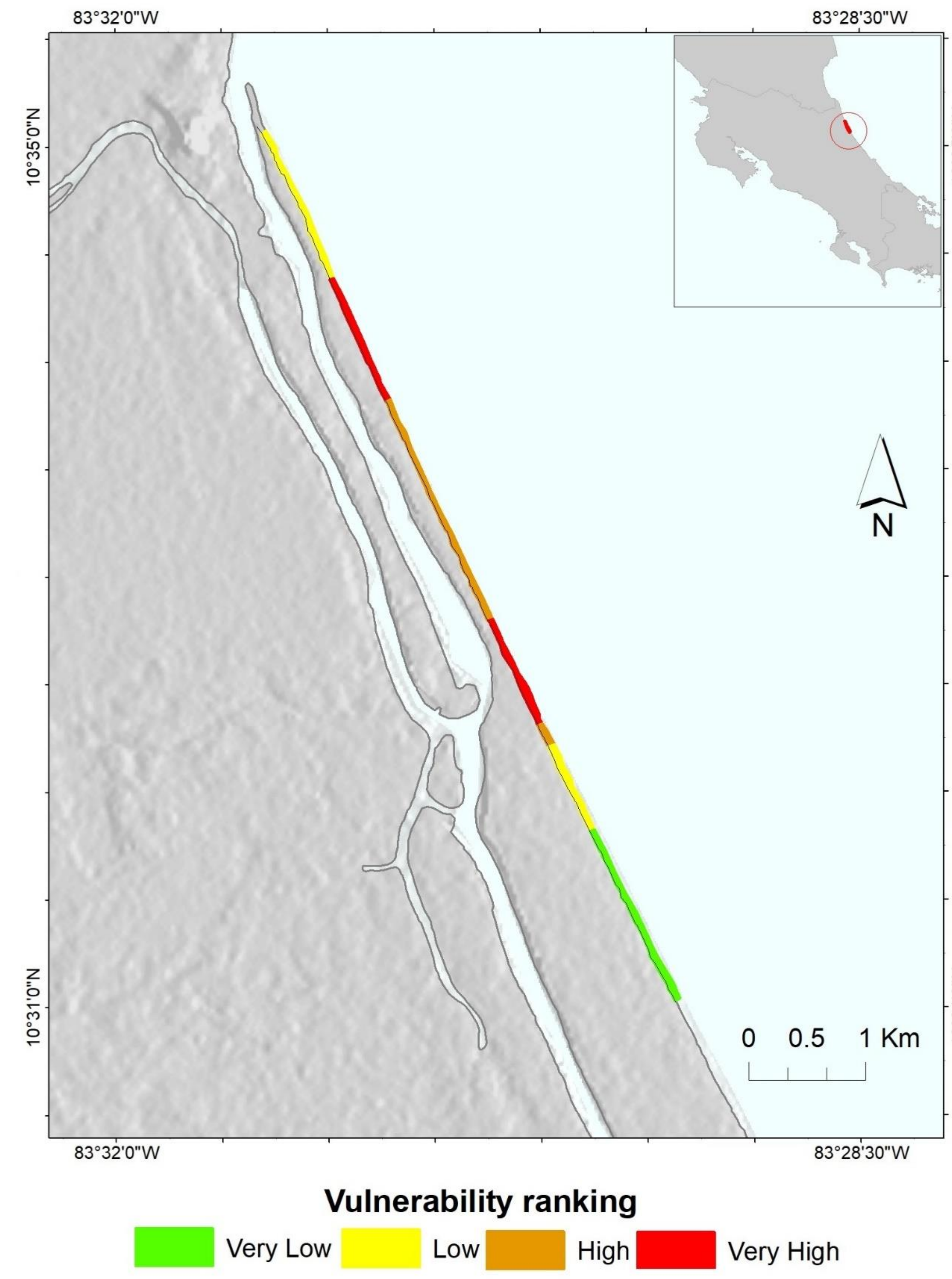


Figure 21: Anthropogenic Vulnerability Sub-Index map. Source: Self elaboration using Planet Team (2018) JAXA/METI & ALOS PALSAR (2010) imagery.

4.3. Biological vulnerability parameters

4.3.1. Distribution of nesting

The distribution of nests along the sampled beach was highly variable, for the green sea turtle season of 2008 to 2018 (Figure 22). The sector that had more nests on average was 993. While the sector with fewer nests on average was 74. According to the vulnerability thresholds for this parameter (calculated using the nesting data quartiles), 29% of the beach is under a very low vulnerability, 20% under low, 27% under high and 24% under very high vulnerability (Figure 23).

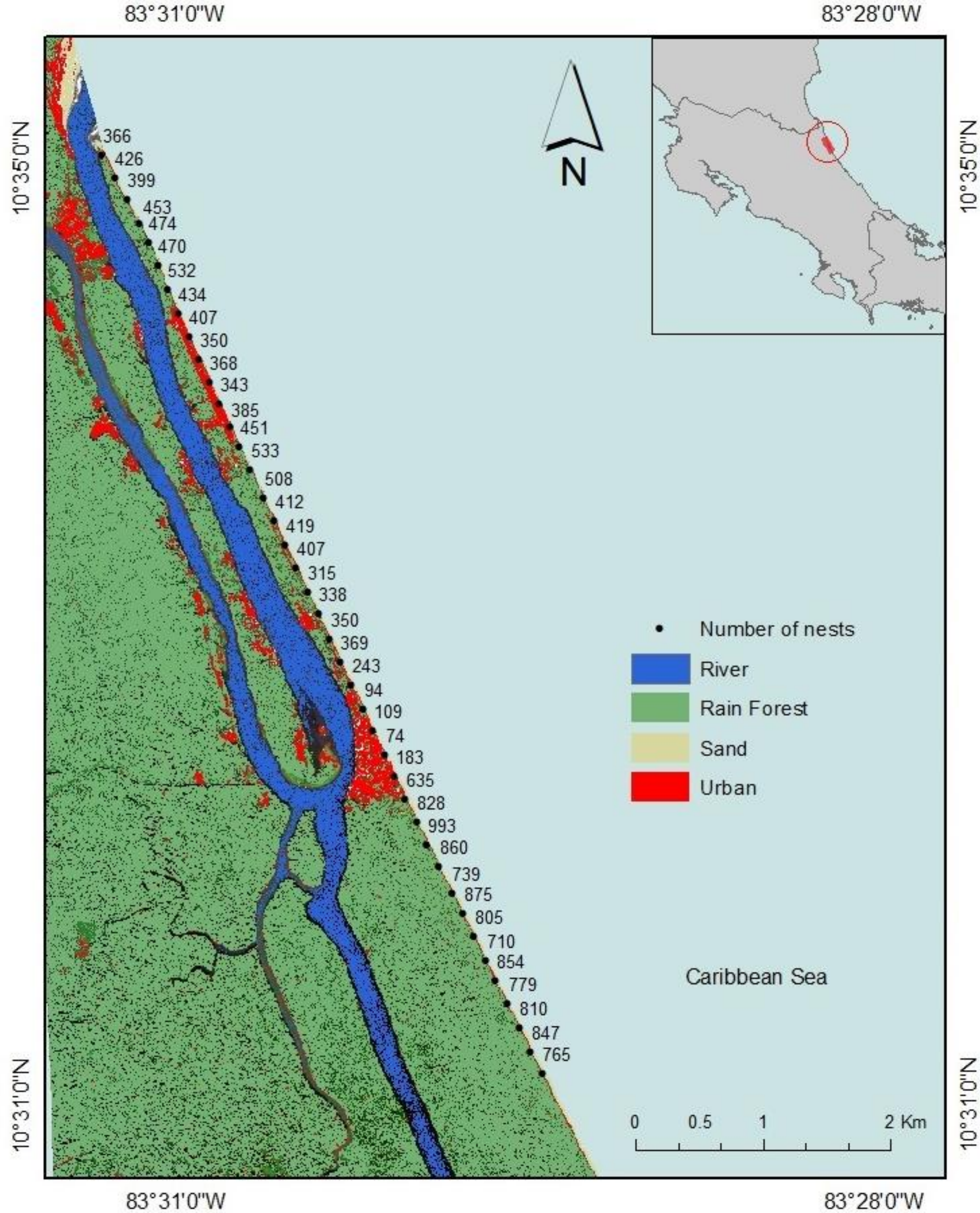


Figure 22: Land cover map with the average green sea turtle nests (Chelonia mydas) for each beach sector, for the nesting seasons of 2008 to 2018. Source: Nesting data provided by the Sea Turtle Conservancy (STC).

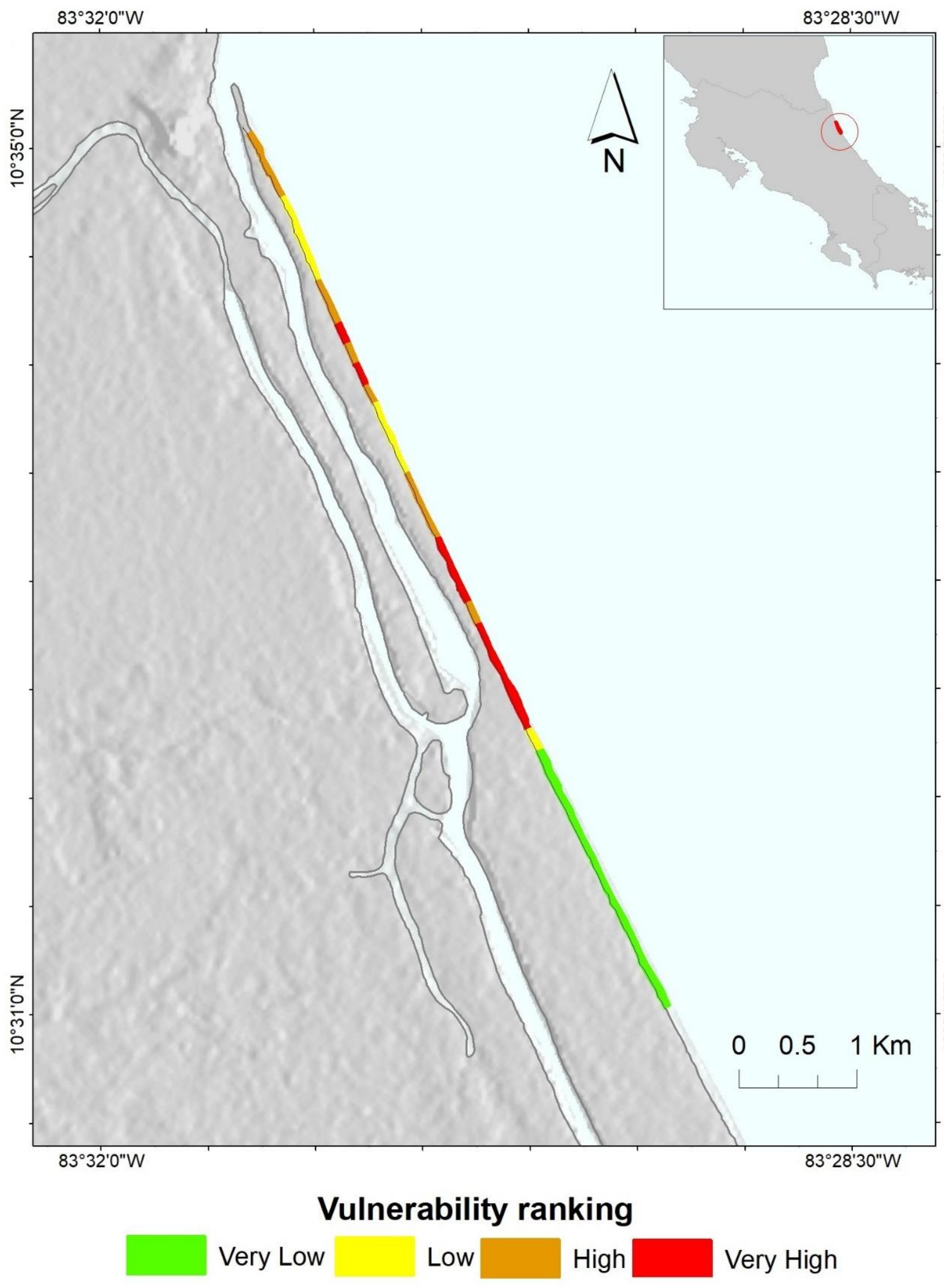


Figure 23: Vulnerability ranking for "Distribution of nests." Source: Self elaboration using Planet Team (2018) JAXA/METI & ALOS PALSAR (2010) imagery.

4.3.2. Eroded and inundated nests

From 2011 to 2018, the STC reported a total of 24 eroded nests and 1 inundated nest (Figure 24). The sectors with more eroded nests were the 2.6 and the 6.6, with 3 eroded nests each, since 2011. According to the thresholds for this parameter, 41% of the beach (17 sectors) is under a high vulnerability (3) because of the presence of partial or complete loss of some nests (Figure 25).

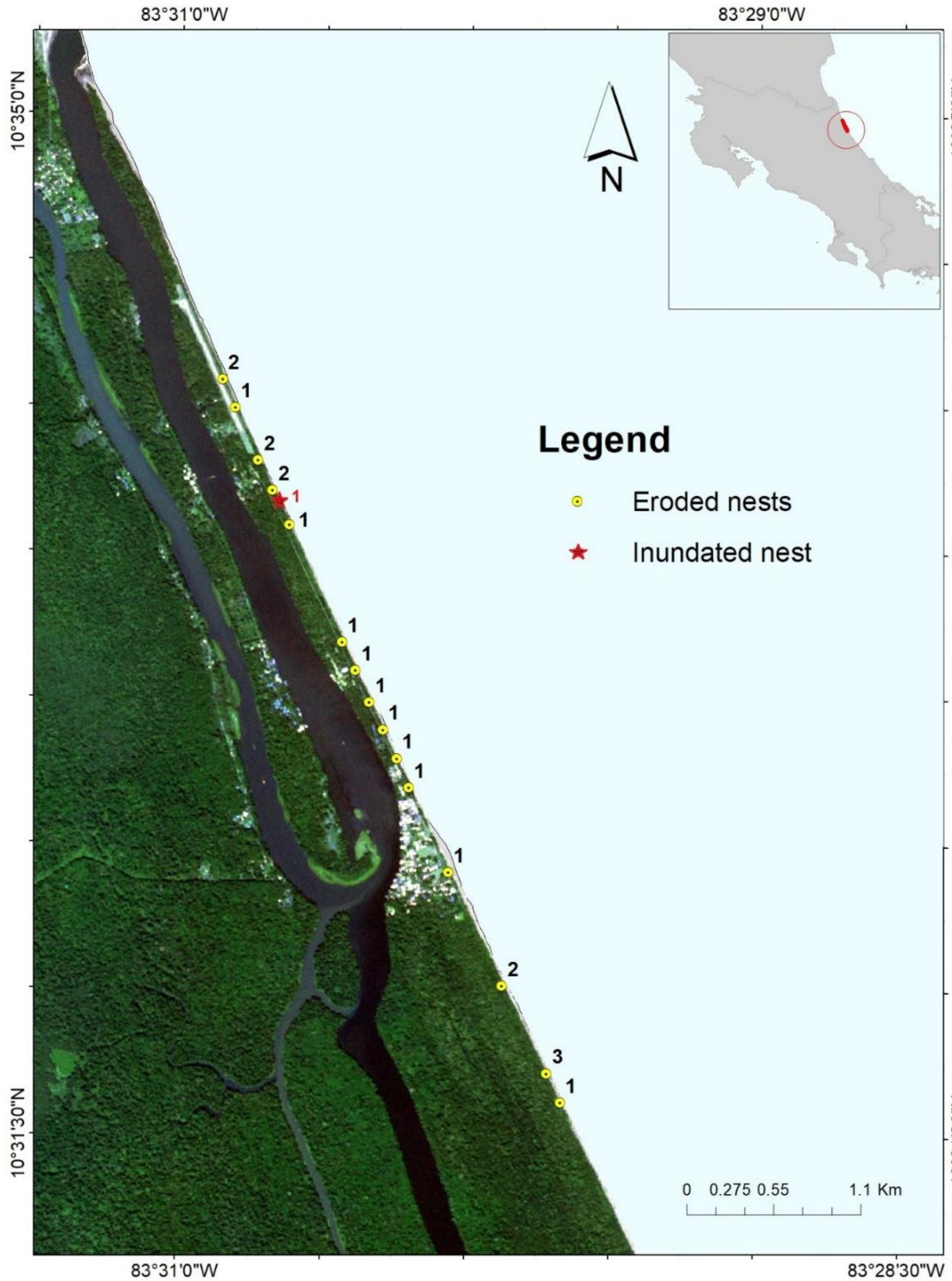


Figure 24: Location of eroded and inundated nests in the sampled beach in Tortuguero. Nesting data provided by the Sea Turtle Conservancy (STC), with Planet Team (2018) imagery. In the background, the area of Tortuguero is shown as green in the Planet Team Image, and the Caribbean Sea is shown as light blue.

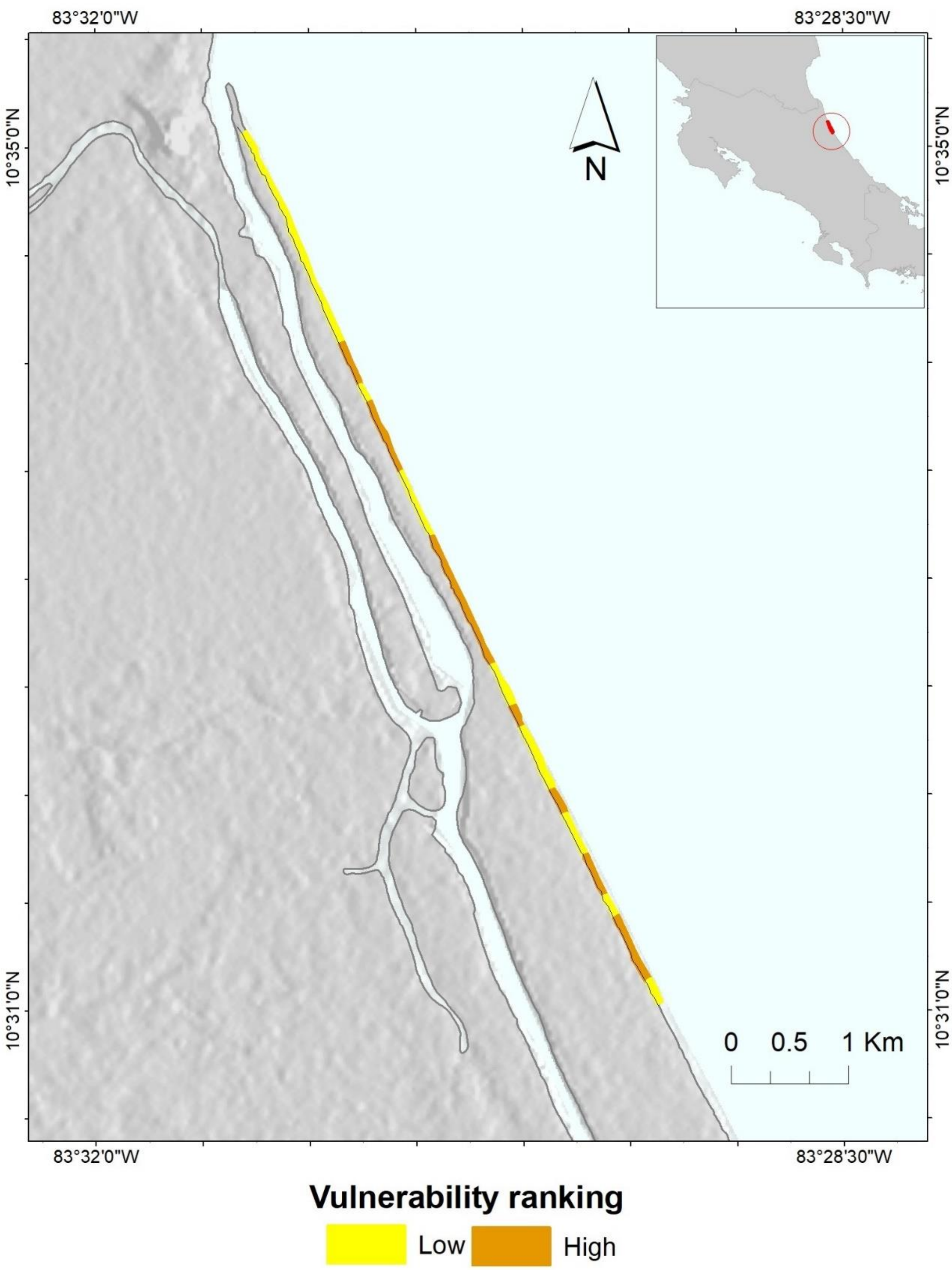


Figure 25: Vulnerability ranking for "eroded and inundated nests" of Chelonia mydas, for 2011-2018. Source: Self elaboration using Planet Team (2018) JAXA/METI & ALOS PALSAR (2010) imagery.

4.3.3. Biological Vulnerability Index (BVI)

Both biological parameters have the same weight (50%) since there were just two parameters in the sub-index to calculate them through the AHP. The biological vulnerability sub-index (BVI) was calculated for each beach sector, using equation 3 of the methodology chapter.

The minimum value of BVI is 150, the median value is 250, and the maximum is 300. Like the other two sub-indexes, these values were used to create the BVI vulnerability categories using quartiles (Table 15). For the biological sub-index, 15% of the sampled beach is under the category of very low vulnerability, 27% under low, 29% under high and the 29% under a very high vulnerability (Figure 26).

Table 15: Vulnerability categories for the Anthropogenic Vulnerability sub-index (PVI).

Category	AVI Values
Very Low	<200
Low	≥200 < 250
High	≥250 < 300
Very-high	>300

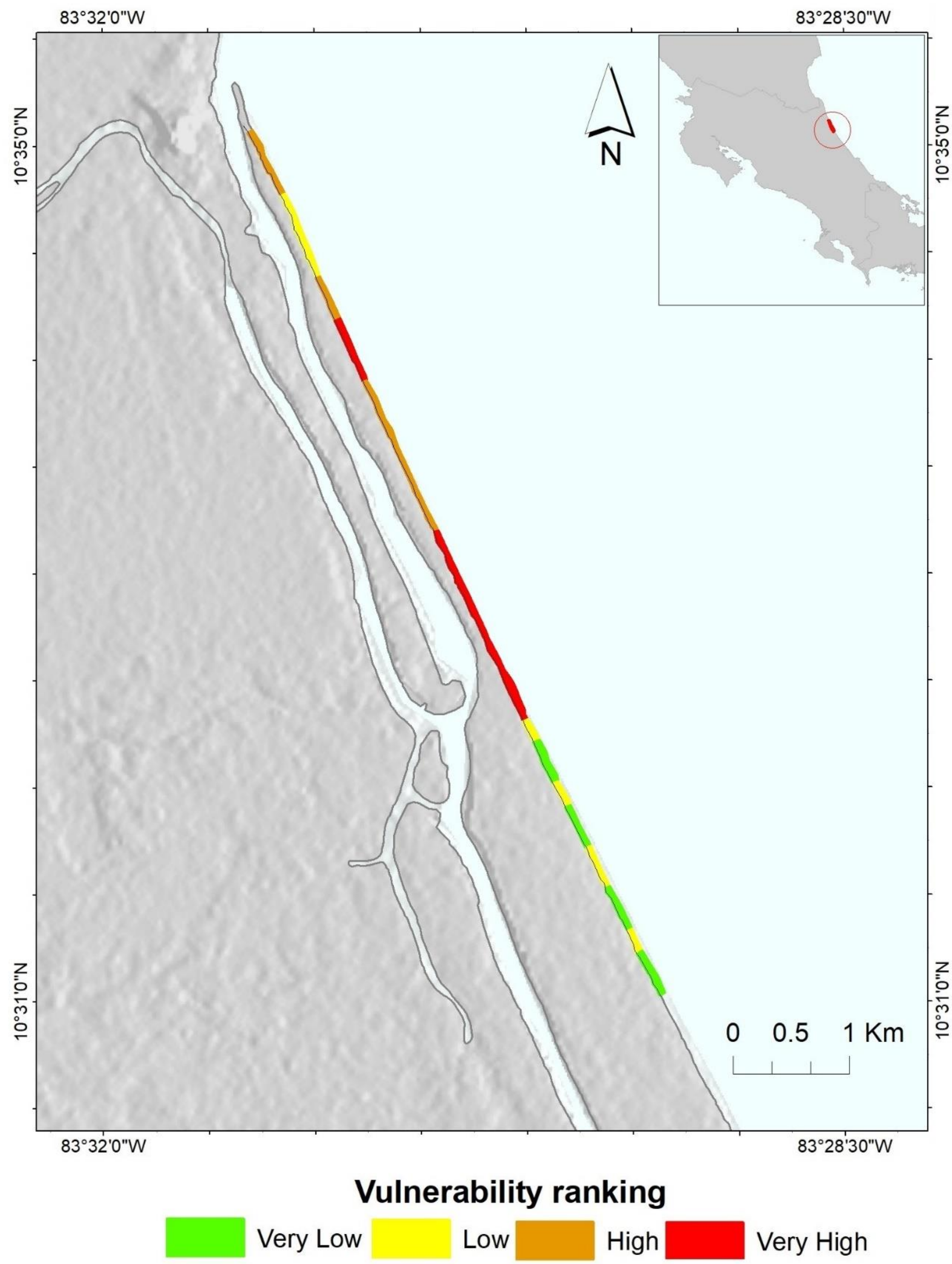


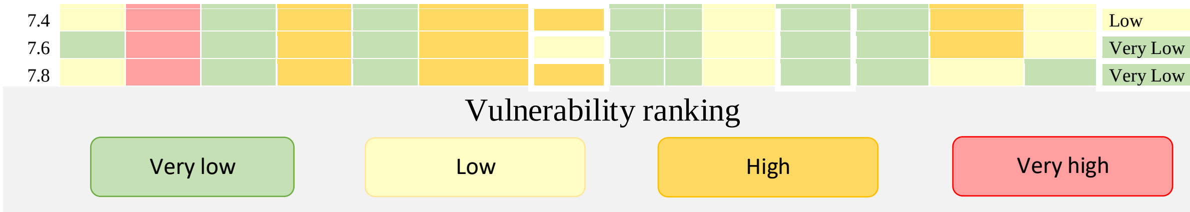
Figure 26: Biological Vulnerability Sub-Index map. Source: Self elaboration using Planet Team (2018) JAXA/METI & ALOS PALSAR (2010) imagery.

4.4. Coastal Vulnerability Index (CVI)

The CVI value for each sector compiles the PVI, AVI, and BVI sub-indexes. In this calculation is considered that the three sub-indexes contribute equally to the coastal vulnerability of Tortuguero's sampled beach (Table 16).

Table 16: Results summary. Total CVI vulnerability for each beach sector, together with the compilation of the scores of each parameter of the PVI, AVI and BVI sub-indexes.

	Physical							Anthropogenic				Biological			
Sector	Shoreline change rate	Mean sea level rise	Coastal slope	Significant wave height	Tidal range	Coastal regional elevation	PVI	Distance to the town	Land cover	Touristic impact	AVI	Distribution of nesting	Eroded and inundated nests	BVI	CVI score
-0.2															Low
0															High
0.2															High
0.4															Low
0.6															Low
0.8															Low
1															Low
1.2															High
1.4															High
1.6															Very High
1.8															High
2															Very High
2.2															High
2.4															High
2.6															Low
2.8															Low
3															High
3.2															High
3.4															High
3.6															Very High
3.8															Very High
4															Very High
4.2															High
4.4															Very High
4.6															Very High
4.8															Very High
5															Very High
5.2															Very High
5.4															High
5.6															Very Low
5.8															Very Low
6															Low
6.2															Very Low
6.4															Very Low
6.6															Low
6.8															Low
7															Very Low
7.2															Very Low



Equation 4 (methodology chapter) was followed to calculate the total Coastal Vulnerability Index (CVI). The minimum value of CVI is 73.32, the median value is 80.24, and the maximum is 90.24. The categories vulnerability of CVI were calculated using quartiles (Table 17).

For the total CVI index, 20% of the sampled beach is under the category of very low vulnerability, 27% under low, 29% under high and the 24% under a very high vulnerability (Figure 27).

Table 17: Vulnerability categories for the Anthropogenic Vulnerability sub-index (PVI).

Category	AVI Values
Very Low	<185
Low	≥185 < 236
High	≥236< 286
Very-high	>286

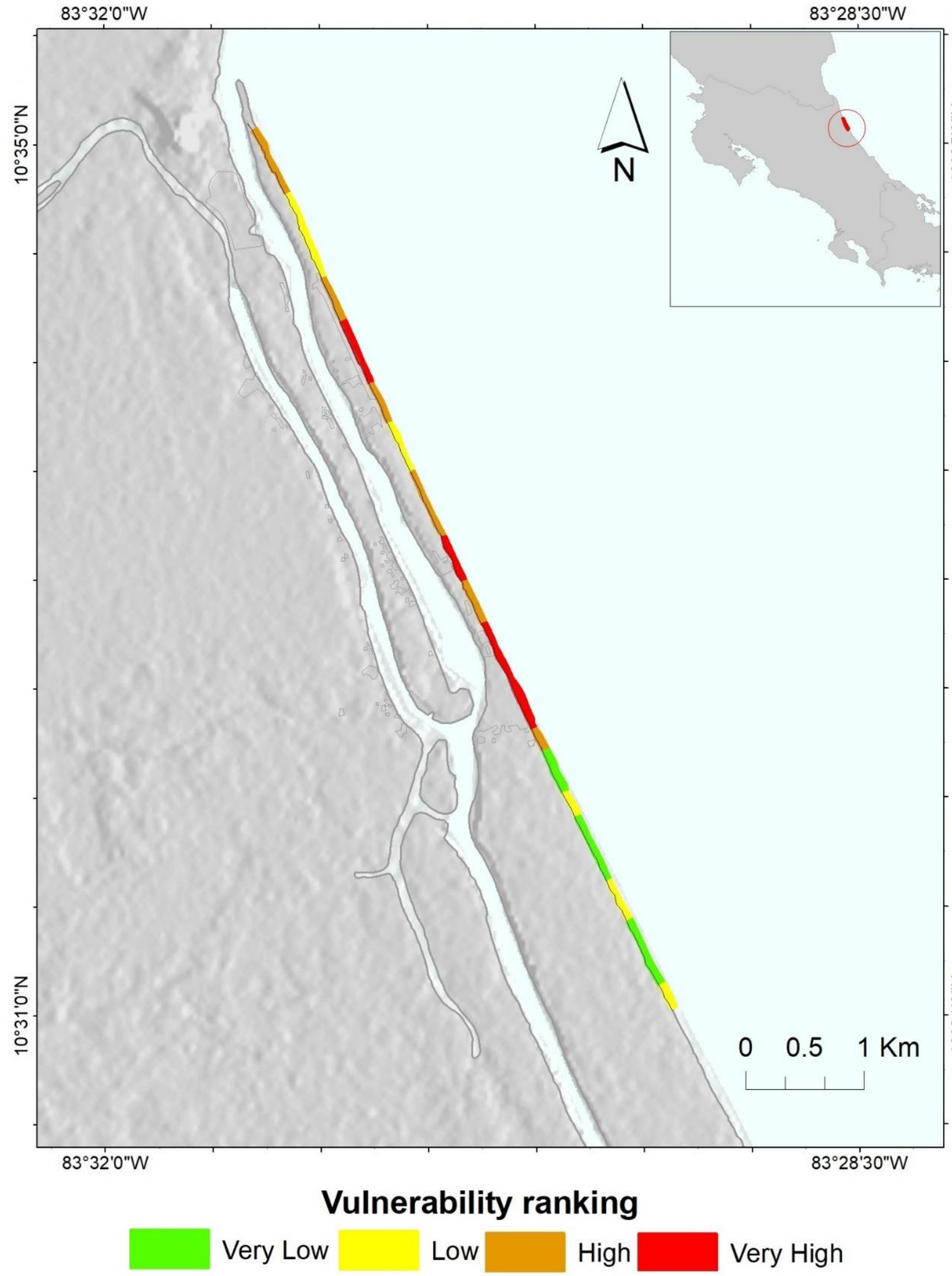


Figure 27: Total Coastal Vulnerability Index (CVI) map. Source: Self elaboration using Planet Team (2018) JAXA/METI & ALOS PALSAR (2010) imagery.

5. Chapter 5: Discussion

5.1. Limitations of the methodology

The major challenge, when doing a multi-temporal analysis, is to find data of the same period of time, for all the parameters considered. This has been a pioneer study in the area, that has included datasets freely available from different sources. Therefore, the time periods for all parameters were not uniform. For example, a longer data-period is needed to correctly assess the “touristic impact” parameter, as the linear correlation analysis shows a weak relation (R^2= 0.2163). Currently, the information on the number of tourists that visit the national park annually is available for a short period (2011-2017). This might increase the influence of outlier data on the analysis.

Concerning the physical parameter of shoreline change, the low availability of high-resolution satellite images for the month of the peak of the nesting season (September), makes factors, such as rainfall regime, affect the shoreline change calculations. Also, the imagery used to calculate this change were not available for the same period as Copernicus’ trends of sea level rise (1993-2017). For the future, when there is the availability of more extended datasets, it is recommended to look for possible interactions between the changes in beach dimensions and changes in sea levels in the area. To give a better solution to future work, it is recommended to standardize the methodologies of in-situ measures, for example, measuring all beach profiles more with GPS instead with a measuring tape.

5.2. Coastal Vulnerability Index for sea turtle conservation management

The CVI values for each sector were the combination of physical, anthropogenic, and biological sub-indexes. Each of these sub-indexes will be discussed below.

5.2.1. PVI parameters

Addressing individually the results of each parameter, the first of the physical parameters or "shoreline change rate" shows an average change of accretion of +0.44 m per year. However, the vulnerability for this parameter highly varies between sectors. The beach sectors that experience beach retreats up to -6.31 (sectors -0.2 to 0.6), were the ones closer to the river mouth (Figure 4). In this case, the beach retreat should not be attributed to the influences of sea level, due to the dynamic nature of the estuarine areas. On the other hand, other areas that have experienced beach retreat are located 1 km south-east, in the sectors close to the airport and the nearest hotel (sectors 1.6, 2 and 2.4).

Most of the sectors, closer or inside of the protected area of the National Park, have experienced little variation over the period of 2009 to 2018. For this reason, the sectors in this area can be considered less vulnerable to nesting. However, this study analyzed just one RapidEye image per green sea turtle season. Therefore, the variation values might not show how the seasonal changes, and the changes induced by storms and meteorological events, may affect the beach.

Regarding the second physical parameter "mean sea level trend," the changes calculated by Copernicus, for the period of 1993 to 2017, show a local increase of 4.073 mm per year (Copernicus - Marine service information et al., 2019). Even though the majority of Tortuguero's shoreline has not experienced dramatic beach retreat rates, this value is higher than the global mean (2-3.2 mm yr-1 for 1993-2010) (Butt et al., 2016; Church & White, 2011), which represents a potential threat in the future.

To correlate global warming with sea level rise, the IPCC works with different scenarios. The projections indicate an increase of 0.26 to 0.77 m of global mean sea levels by 2100 if the global warming temperatures stay on the modest value of +1.5 °C by 2100 (Masson D. et al., 2018). Overall, all scenarios show that the sea levels will rise at least 0.2 m and no more than 2.0 m by 2100 (with a high confidence >9 in 10 chance) (IPCC, 2014a). Taking this rise into account, the nesting of sea turtles in Tortuguero National Park is highly vulnerable, since it is improbable to reach only a 1.5°C of warming by 2100, especially when the current increase has already reached 1°C (Masson D. et al., 2018). This potential sea level rise can be translated into higher rates of beach retreat. For that case, Tortuguero does not have a large buffer to protect the sea turtle nesting against the advance of the sea towards the land. Since it has an elongated shape and it is surrounded by the sea and the river on each side.

Fuentes et al. (2009) implemented a different approach to estimate the impacts of sea level rise on the green turtle nesting beaches in the northern Great Barrier Reef. They used some of the IPCC's sea level rise scenarios to estimate that 38% of the sampled beaches would be affected by sea level rise, which might increase the egg mortality (Fuentes et al., 2009). When compared to the case of Tortuguero (even though this study did not work with IPCC-scenarios of sea level rise), it can be inferred that the survival of the nests could decline dramatically in the future, if it continues with a sea level rise trend of +4 mm per year. Although there are no widespread coastal retreats in the area yet for the sampling period (2009-2018).

For the third physical parameter, "Coastal slope," almost all the beach presents slope values considered with a very high vulnerability towards sea level rise. Meanwhile, Tortuguero's narrow beach with low slopes makes the nests more vulnerable to the action of waves and tides during storms. Previous studies have used the same thresholds for this parameter, like the one of Murali et al. (2013) and Kumar et al. (2010). Murali worked in Puducherry on the east coast of India and found that the majority of the beach was under a low vulnerability. While Kumar worked in Orissa on the northeast coast of India, raking most of the beach as highly vulnerable. The two studies differed from the present study by measuring the slope using remote sensing data. This study has the advantage of in-situ measurements, which increases the accuracy of the estimations, although it is essential to note that Tortuguero has a very dynamic beach. Therefore, the values represent the slopes at a specific time in time.

The fourth parameter measured was the "mean significant wave height." Figure 6 shows the existence of annual variations in the significant wave heights, probably due to the change in rainfall patterns between the dry and rainy seasons. In the nesting season for green sea turtles (starting from late July until early December), a decrease in wave height corresponding to the dry season can be observed. Even so, the average value of the significant wave height for the region is in a high vulnerability ranking. In general, the Caribbean region of Costa Rica has high-energy beaches, where local changes depend on the area's bathymetric environment and other ocean-meteorological processes (Lizano R., 2009). More research is needed to understand the beach morphodynamic in Tortuguero, documenting the erosive processes and sediment transport by waves, during the rainy and dry season.

The parameter "tidal range" shares some similarities with the "significant wave height." Both are oceanographic parameters, and their measurements have been taken at Moin Harbour (9°59′00″N 83°02′00″W). In Figure 7, the monthly variations of the tide ranges show a stable behavior, for the months of the green sea turtle season of 2014 to 2018. Based on these values, Tortuguero’s beach is under a very low vulnerability. The Central American Caribbean region has tides with lower horizontal range, compared with the tides of the Pacific side (Lizano R., 2009). This can be the result of ocean-atmospheric processes that are generated in this region, given the shape of the continental shelf (Lizano R., 2009). But research is needed to study the platforms in Central America and the Caribbean (Lizano R., 2009).

The last physical parameter measured was the “coastal regional elevation.” The studies of Murali et al. (2013) and Kumar et al. (2010) used Digital Elevation Models (DEM) as data sources for this parameter. However, this research has a study site with a large forest area (with canopies higher than 20 m). This tall vegetation cover, together with the DEM’s vertical error (between 10 to 25m) (NASA/METI/AIST/Japan Spacesystems, 2009), could lead to an overestimation of the elevation. For that reason, this research used in-situ GPS elevations, which reduced the error in the estimations of the vulnerability. The majority of the beach has low elevations, with a ranking of 84% percent of high vulnerability. With low elevation and slope, the sea turtle nesting in Tortuguero is particularly susceptible to the effects of sea level rise.

5.2.2. AVI parameters

The first of the AVI parameters, "distance to the town center," gives an introduction to the anthropogenic influence of the area. It is based on the principle that the closer a sector is to the most urbanized area, the more likely it is that new hotels or settlements will be built. It has also been observed that the proximity to urbanized areas generates deforestation of the vegetation border (or line of vegetation in front of the beach). This is closely linked to the following parameter called "land cover." In the land cover/land use classification, a lack of vegetation border can be observed in front of the urbanized areas. The critical points are Tortuguero’s airport, the town center, and the nearby areas. The airport zone also showed coastal retreat values in the PVI.

Tourism is the most important driver in the higher urbanization in the area. Since 2011, there has been an increase of 7 % in the number of tourists, which could bring more pressure to the area. The touristic development in Tortuguero has attracted a greater investment from the hotel industry and a growth in the local businesses. This economic growth is very beneficial for the community as it promotes a stable source of income. But without the proper regulation, this growth can lead to the degradation of the protected area, affecting the buffer area or vegetation border of the beach. In the analysis of “touristic impact,” only urbanized areas were marked with high vulnerability.

For the overall AVI, the areas under a high and very high vulnerability are urbanized areas and those with few vegetation borders. The sectors within the national park's protected area are less vulnerable to the anthropogenic pressures considered in this study.

On the Pacific coast of Costa Rica, a study was conducted in the Playa Grande National Park, which has the most important nesting beach for Leatherback turtles, in the Costa Rican Pacific (Drews & Fonseca, 2009a). This area is also one of the most visited tourist sites in the country, as it is also one of the most visited surf sites in the country (Drews & Fonseca, 2009a). Massive hotel development and expansive urbanization put pressure on coastal ecosystems, with aquifers and wetlands most affected (Drews & Fonseca, 2009a). Drews and Fonseca modeled flooding based on a DEM and IPCC sea level rise scenarios.

Comparing the case of Playa Grande with that of Tortuguero, there are some similarities in the lack of regulation in the urbanizations near these National Parks. In the case of Playa Grande, some of the buildings are within the limits of the National Park, and instead of being expropriated by the Government, there was a draft law (proposed by the Government) that suggests the reduction of the width of the National Park (Drews & Fonseca, 2009a). This shows a lack of visualization of the potential impacts that rising sea levels would have on the buildings near the coast (Drews & Fonseca, 2009a). Tortuguero experiences a similar case, with the particularity of the informality in land tenure. Officially the urbanized lands of Tortuguero National Park belong to JAPDEVA, but land tenure permits had been granted in the past (COOPRENA R. L., 2007). The lack of monitoring of the new constructions by the authorities has allowed the construction of buildings in prohibited places. As a result, there is an increase in new beachfront tourist accommodations, outside the distance allowed by Costa Rican environmental legislation (COOPRENA R. L., 2007).

5.2.3. BVI parameters

The biological parameters considered in this research are specific to the population of green sea turtles that nest in Tortuguero. In the results of the "distribution of nests," it is possible to appreciate the positive impacts of local efforts and conservation policies in Costa Rica, Nicaragua, and Panama. But this success in sea turtle conservation could be affected by a potential loss of the nesting habitat.

In the study area, the average of nests per sector (each 200 m) was 509 nests, for 2008-2018. Although the average number of nests was highly variable along the beach, this variation also can be explained by specific requirements of the green sea turtle species when choosing a nesting site, such as beach width, slope, etc. (Karen A. Bjorndal & Bolten, 1992; Whitmore & Dutton, 1985). In this study, the factor that most determines the distribution of nests are the urbanized areas. In sectors within the town area, the number of nests decreases dramatically (Figure 24). In contrast, in the national park, nesting increases to >700 nests per sector. Momentarily, this decrease in the number of nests, in the village area, maybe due to the absence of edge vegetation that allows the lights of the buildings to reach the beach (Kamrowski, Limpus, Moloney, & Hamann, 2012).

As for the parameter "eroded and inundated nests," nest losses were found in sectors in the airport area, in the town area and within the national park. The loss of nests may be due to: erosive processes (Spainer, 2010); the advance of the sea towards the land (in the case of one nest)(Fujisaki et al., 2018); and, the location of the nests selected by females green sea turtles (occasionally, some females can choose the nest site near the high tide line) (Karen A. Bjorndal & Bolten, 1992). Nonetheless, regardless of the locations, the changes in tidal regime during storm events and the beach retreat, as a result of the increase in sea levels, can result in a greater nests loss in the future (Fujisaki et al., 2018; Spainer, 2010). The loss of nesting habitat can increase the density of nests in a particular sector, which may surpass the carrying capacity of the beach (Fujisaki et al., 2018; Mazaris et al., 2009). It is estimated that the minimum area needed to create a nest, without disturbing another nest, is between 0.75 to 1.4 m for green sea turtles (Hendrickson, 1958; Tiwari, Bjorndal, Bolten, & Bolker, 2006; Mazaris et al., 2009). For Tortuguero, areas suitable for nesting, without rates of beach retreat and away from urbanized areas, may experience an increase in the number of nests in the future.

For the BVI sub-index, it was found that the sites where green turtle nesting is most vulnerable are within urbanized or open-access areas. With an imminent sea level rise, the sectors within the national park will have a buffer of forest, for the beach retreat process to take place. On the contrary, the sectors within the urbanized area have buildings close to the beach (house, hotels, airport, etc.) and deforestation of the vegetation border, which obstruct the process of recovery of the beach. In addition, the current urbanization causes light-pollution on the beach, which has a negative effect on nesting (Dimitriadis et al., 2018). Other factors that affect nesting are the excessive presence of people during the nesting process (Campbell, 1994), poaching of nesting females or eggs, pollution, etc. These threats are not only present during the reproductive phase of the life cycle of the sea turtles that nest in Tortuguero. There are also threats along migrations to feeding grounds. The same green turtles that nest in Tortuguero also migrate to Nicaragua and other countries in the Caribbean (Sea Turtle Conservancy, 2017). After Nicaragua signed the Convention on International

Trade in Endangered Species of Fauna and Flora (CITES), in the 1970s, and during the civil war (1980-1988) the hunting of green turtles decreased considerably (Lagueux, 1998). But since the armed conflict ended in Nicaragua, poaching is estimated to have increased to capture levels higher than ever (Lagueux, 1998). Although conservation efforts already exist at the regional level in the Caribbean (Troëng & Rankin, 2005), it is necessary to have more long-term researches to adequately address the impacts of human-induced pressures on sea turtles nesting habitats.

5.2.4. Coastal Vulnerability Index

According to the coastal vulnerability calculation, or CVI, more than 50% of the beach is found to be under the vulnerability categories of high to very high. The anthropogenic pressures considered in subindex AVI (distance to the most urbanized area, land uses, and tourism growth) directly influence the results of subindex BVI (Table 16). The results of the CVI behave in a similar way to those of the AVI and BVI, so it can be inferred that the coastal vulnerability in the rest of the beach is strongly related to human impact.

It should be noted that for the calculation of this index, it was assumed that the sub-indexes PVI, AVI, and BVI contribute in the same way to the vulnerability of this nesting beach. More studies that consider the influence over the coast of the physical-geographical, socio-economic, and species-specific factors, are needed in order to know the degree of importance of each of these sub-indexes.

Focusing on physical parameters, the result of sea level rise trends in the area show that Tortuguero needs to maintain its ability to adapt to climate change. The total value of the CVI indicates that unregulated urbanization could not only reduce the nesting activity in sectors in front of these areas but also reduce the buffer line in the case of a potential beach retreat. Tortuguero's future, as well as many nesting beaches, depends on its ability to adjust to change, by retreating inland in the presence of sea level rise (Drews & Fonseca, 2009a). Nonetheless, without losing the ecological conditions that allow sea turtles to nest (Drews &

Fonseca, 2009a). This will be possible, as long as the urbanization stays within a safe distance (Drews & Fonseca, 2009a).

Based on the BVI parameters, Tortuguero's green sea turtle nesting shows the positive effects of long-term conservation strategies over the recuperation of endangered sea turtle species, supporting Troëng & Rankin (2005) assumptions. But these conservation efforts should also aim to protect habitats and not just individual species.

In practice, there are many proposed strategies that can be implemented to counteract the effects of shoreline retreat. But any management strategy must take into consideration the possible impacts on sea turtles and local flora and fauna. Management plans should be based on wildlife requirements. Some of the mitigation strategies that take into consideration only the physical loss of the beach and not the habitat role are (a) coastal protection structures (breakwaters, groynes, and sea walls) and (b) periodic beach nourishments (Jongejan et al., 2016; Ranasinghe & Stive, 2009). But on a sea turtle nesting beach, building barriers within the sea, or on the beach, would directly affect nesting females. Beach nourishments could also affect the hatching success (or the number of hatchlings that hatch from a nest), as the incubation of sea turtle eggs is extremely sensitive to external agents (fungi, bacteria and chemical pollution) (Eckert & Eckert, 1990; Güçlü, Bıyık, & Ahiner, 2010; Phillott & Parmenter, 2001; Sarmiento-Ramírez et al., 2010). That is why, it is necessary to implement coastal management measures that are not applied directly on the beach area.

One feasible proactive management option to mitigate shoreline retreat is the implementation of laws that restrict expansive beachfront urbanization (Jongejan et al., 2016; Wainwright et al., 2014). This would require the use of coastal setback lines to define the limit where development is prohibited (Jongejan et al., 2016; Wainwright et al., 2014). The setback lines are regulations that prohibit constructions within a set distance from the sea (Fish et al., 2008). Setback lines have the capacity to mitigate the beach retreat by providing a buffer zone that allows the natural movement of beaches in response to perturbation (Fish et al., 2008). In the case of sea turtle nesting beaches, Fish et al., (2008) support the implementation of adequate setback regulations that help reduce habitat loss and maintain ecological conditions of the nesting ground (Mazaris et al., 2009). To calculate the setback lines, it is necessary first to estimate: long-term beach recession rates, taking into account the gradient of longshore sediment transport; and specific beach recession after a storm event (Jongejan et al., 2016). For this reason, more research is needed at Tortuguero beach that adds episodic physical variables, such as storm events, El Niño events, etc.

A characteristic of coastal areas is that they are a center of attraction for commerce, housing, and various industries (Mahapatra et al., 2013). They are areas of high economic importance due to rapid economic development, large population migrations, and urban development (Mahapatra et al., 2013). In the case of Tortuguero, as in many coastal protected areas, this has resulted in the deforestation of the vegetation that borders the beach and in constructions very close to this one. The lack of regulation and monitoring can be compared to the case of the nesting beach of the Playa Grande National Park, in the Pacific of Costa Rica. This problem demonstrates the lack of precautionary and predictive measures in the face of rising sea levels (Drews & Fonseca, 2009a). Instead, it could compromise in the medium and long term the ecological function of nesting beaches, affecting a vital conservation objective (Drews & Fonseca, 2009a).

Monitoring of land use restrictions is necessary. The presence of institutions, such as the municipality of Pocosí, JAPDEVA, MINAE and the National Institute of Tourism, is fundamental to verify that the current buildings are within the retirement established by the legislation of Costa Rica (Dirección Legal. Instituto Costarricense de Turismo, 1977). According to the law on the terrestrial maritime zone n° 6043, the withdrawal that the constructions must have with respect to the high tide line is minimum of 200 m (Dirección Legal. Instituto Costarricense de Turismo, 1977). During the calculations of the rate of shoreline change, complementary measurements of the distances between the high tide line and the urbanized areas were carried out (Table 11). These measurements show that none of the buildings on the beachfront comply with the retirement of 200 m. Most of the public area of Tortuguero is less than 250 m wide. The presence of buildings in these sectors is not only outside the legislation; it is also highly vulnerable to rising sea levels. The sectors within the National Park present fewer obstacles to the sea inland advance because they do not have any buildings that block the process of shoreline retreat. Also, the width of the terrestrial strip within this zone is superior to 550 m.

For the public area of Tortuguero, prioritizing economic development, rather than the requirements of the shoreline to maintain their viability as habitats, could hinder regulations such as setback lines. Setback lines that are located further inland will be less likely to experience beach loss (Jongejan et al., 2016; Vrijling, Van Gelder, & Litjens -Van Loon, 2002). Although in Tortuguero it would be difficult to implement a broad setback line since all the buildings are located within the thinnest sections of land. Nonetheless, long-term data sources, such as the ones of the STC, can provide valuable information that could help with the calculation of a best-fitting setback line. The further climate change mitigation and adaptation plans should seek the most significant benefit for the ecosystems, as well as for the local community. Therefore, it is important to achieve a more responsible touristic growth developing strategies that will positively affect the natural resources of the National Park. This would involve regular monitoring, the presence of authorities that rectify the buildings that are not within the permitted retirement, and further calculations of a setback line (Drews & Fonseca, 2009a).

This approach aimed to evaluate the coastal vulnerability of the sea turtle nesting beach of the Tortuguero National Park; working based on adaptations of the CVI framework to best fit the socio-economic conditions of the site, as well as to the biological conditions of the nesting population of green sea turtles. This approach can be used effectively by decision-makers in the area to generate management plans to preserve the coastline (Murali et al., 2013). The generated biological vulnerability maps could also be used as indicators of the vulnerability of sea turtle nests, towards climatic and coastal hazards, and anthropogenic pressures.

5.3. Practical implications of the findings

Unlike other CVI approaches, this research not only included the physical parameters of vulnerability but also sought to compile parameters that were relevant to the study area. Comparing with other CVI calculations, the combination of biological long-term data with remote sensing techniques and socio-economic data generates a more comprehensive approach to determine the vulnerability of the site.

This new CVI approach was very appropriate for Tortuguero because this area has the availability of long-term information, for each of the species of sea turtles that nest on its beach. Since this has been the first attempt to calculate the coastal vulnerability of a nesting beach using this methodology, it is proposed to use more parameters in the calculation of the CVI, for future research. In particular, the STC not just records biometric data of the nesting sea turtles and nets, they also collected physical, climatic and socio-economic data that could be used to add more factors to further the analysis.

It is important to generate a more holistic view in assessments of the effects of climate change on habitats. More research combining geographical, climatic, social, economic, and biological aspects of each species, is needed to make adequate estimations that can be used for the management of protected areas. Approaches like this one could be applied to the entire beach of Tortuguero and to other nesting beaches, which may be already experiencing shoreline retreat. Since worldwide, there are many sea turtle conservation programs that have multi-temporal databases, for biological and physical parameters, that could calculate coastal vulnerability using this methodology.

5.4. Recommendations

The following section shows suggestions for local stakeholders and decision-makers to generate shoreline management strategies.

This CVI approach is recommended for estimating the vulnerability of sea turtle nesting habitats for conservation. For the enhancement of the long-term data sources in Tortuguero, it is suggested the following:

1. To calculate the CVI also for the leatherback sea turtle season. This calculation would allow having annual information that will make possible to compare: variations between dry and rainy seasons, beach dimensions between storm events, and the overall affectations of the two species.

2. Where possible, monitor in-situ the physical parameters. Some of the inaccuracies in this study were due to the lack of long-term databases. Therefore, it would be more convenient and accurate to make measurements directly at the site.
3. It is highly recommended to mark the coordinates of all nests with GPS. This would allow a spatial view of the vulnerability of nests to sea level rise. It would also allow mapping and collection of the altitude of the nests.
4. It is also necessary to measure beach profiles more regularly, throughout the leatherback and green sea turtle season and especially after a storm event. It is suggested to standardize the profile measurements using a GPS, as it minimizes human error and it is possible to collect distance and elevation data.
5. In terms of tourist impact, the indicator of the number of people that each hotel can accommodate (number of rooms and beds per hotel) could be added. This parameter is already measured by the SCT, so it is possible to include it in the calculations of the CVI.
6. It is crucial to monitor the progress of the urban area. This can be done by analyzing the increase of urbanization using areal or satellite images and in-situ monitoring as well. During the light census periodically measured by the STC, data of the location of properties that are very close to the beach, new buildings on the beach front, and areas where edge vegetation has been deforested can be collected. This information is important for the generation of shoreline management plans.

Due to the presence of sea turtle nesting, the implementation of protective “structures” (breakwaters, seawalls, groynes, etc.) and beach nourishments are not suggested to be applied as climate change adaptation measures, since they could directly affect nesting females and nests. For all urbanized and open access areas, it is recommended to implement non-invasive management measures, that seek to adapt to changes in sea levels and in the storm surge regime. For this purpose, the presence of the authorities and institutions in charge of ensuring the integrity of the terrestrial maritime zone is fundamental (Municipality of Pococí, Instituto Costarricense de Turismo, MINAE) (La Gaceta Nº 230, 2002).

The calculation and implementation of a setback line (retirement that the buildings should have with respect to the sea) were proposed as the most feasible management measure. Because all the buildings are within the narrowest strip of land of Tortuguero, the minimum withdrawal in Costa Rican legislation is not suitable for this site. It is necessary to carry out research that seeks to adjust the retirement distance of the legislation, considering the physical, economic and ecological factors of the area. Reforestation campigns carried out by members of the local community, NGOs and governmental institutions can help to the rapid recovery of this setback lines at the beachfront.

It should be noted that trends in sea level rise are dramatic for the area (Copernicus - Marine service information et al., 2019). Based on these rising trends, researches that work with IPCC sea level rise scenarios are needed. Previously, studies with this focus have been conducted on sea turtle nesting beaches in Costa Rica, showing that IPCC scenarios for sea level are an excellent tool for calculating setback lines (Drews & Fonseca, 2009a). Early and proper planning can contribute to the future of Tortuguero as a crucial nesting habitat for green sea turtles in the region.

5.5.Conclusions

From this study, it was possible to identify the great need that Tortuguero has to adapt to future changes resulting from climate change. Analyzing only the physical vulnerability parameters used by classical CVI approaches, the physical-geographical and oceanographic characteristics (coastal slope, significant wave height, elevation) make Tortuguero susceptible to the physical changes caused by sea level rise (R. Klein & Nicholls, 1999; Mahapatra et al., 2013).Tortuguero does not currently have high shoreline retreat values, but the trends in sea level rise were identified as alarming for the area. Using only these parameters (PVI), the most vulnerable sectors would be located near the river mouth. But to avoid the simplification of the vulnerability of this nesting ground, this addapted CVI assessment also takes into account the effects that the social systems (AVI sub-index) have on the ecological system (BVI sub-index) and their potential effects on green sea turtles.

Because of this adaptation it was possible to identify a direct influence of the anthropogenic parameters on the biological vulnerability. Both AVI and BVI sub-indexes had high vulnerability categories distributed similarly along the beach, from which it was inferred that urban development on the beachfront is a factor that highly determines the nesting distribution. The areas with greater urbanization experience greater coastal vulnerability compared to protected areas within the National Park This aspect provided evidence relevant enough to assure that unregulated urbanization not just affects the green sea turtle nesting distribution but also reduces the buffer line necessary to cope with the inland advance of the sea.

Based on these results, this study highly recommends the implementation of laws that restrict expansive beachfront urbanization and the calculation and application of setback lines as a coastal management strategy. This setback lines can be used to regulate and establish a safe retirement area for buildings that will allow the urbanized area of Tortuguero to adjust to the imminent sea level rise. Therefore, it is necessary to carry out research to calculate the appropriate setback line dimensions for the town of Tortuguero. After the implementation of the setback lines, another suitable measure are reforestation campaigns, that can help to restore these areas on the beachfront in front of the urbanized areas.

This pioneering study shows the importance of adapting CVIs and other risk assessments to the specific conditions of a particular species, in order to estimate the vulnerability of a habitat.

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