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TESIS DOCTORAL

**El litoral mediterráneo andaluz: características, evolución y
respuesta frente a los procesos naturales y las actuaciones
antrópicas**

**The Mediterranean coast of Andalusia (Spain):
characteristics, evolution and response to natural and
human impacts**

Rosa Molina Gil

Directores:

Giorgio Anfuso

Giorgio Manno

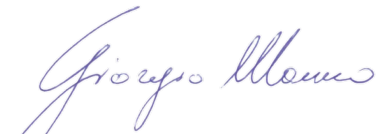
ANEXO II
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D./D^a. Giorgio Anfuso y D./D^a. Giorgio Manno, directores de la tesis doctoral de D./D^a. Rosa Molina Gil, alumna del programa de doctorado Ciencias y Tecnologías Marinas, regulado por el Real Decreto 99/2011, de 28 de enero, por el que se regulan las enseñanzas oficiales de doctorado, informa(n) favorablemente la solicitud de autorización para el depósito de la tesis doctoral de D./D^a. Rosa Molina Gil, titulada “El litoral mediterráneo andaluz: características, evolución y respuesta frente a los procesos naturales y las actuaciones antrópicas“, y desarrollada de acuerdo con los requisitos de control de calidad para las tesis doctorales recogidos en la memoria del programa de doctorado de referencia.

En Puerto Real, a 7 de octubre de 2020



Fdo.: Giorgio Anfuso



Fdo.: Giorgio Manno

NOTA

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Sr. Presidente de la Comisión Académica del Programa de Doctorado _____

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LISTA DE PUBLICACIONES

La memoria de esta tesis se basa en las siguientes publicaciones (Anexos I, II, III y IV), a las cuales se hará referencia con la siguiente numeración:

Molina et al., I	Molina, R.; Manno, G.; Lo Re, C.; Anfuso, G.; Ciraolo, G. Storm Energy Flux Characterization along the Mediterranean Coast of Andalusia. <i>Water</i> 2019 , <i>11</i> , 509; doi: 10.3390/w11030509.
Molina et al., II	Molina, R.; Anfuso, G.; Manno, G.; Gracia Prieto, F.J. The Mediterranean Coast of Andalusia (Spain): Medium-Term Evolution and Impacts of Coastal Structures. <i>Sustainability</i> 2019 , <i>11</i> , 3539; doi: 10.3390/su11133539.
Molina et al., III	Molina, R.; Manno, G.; Lo Re, C.; Anfuso, G. Dune's systems characterization and evolution in the Andalusia Mediterranean Coast (Spain). <i>Water</i> 2020 , <i>12</i> , 2094; doi: 10.3390/w12082094.
Molina et al., IV	Molina, R.; Manno, G.; Lo Re, C.; Anfuso, G.; Ciraolo, G. A Methodological Approach to Determine Sound Response Modalities to Coastal Erosion Processes in Mediterranean Andalusia (Spain). <i>Journal of Marine Science and Engineering</i> 2020 , <i>8</i> , 154; doi: 10.3390/jmse8030154.

RESUMEN

Durante las últimas décadas, los impactos relacionados con la erosión costera han aumentado considerablemente en todo el mundo debido al continuo desarrollo del turismo y ocupación de la costa y a que los procesos erosivos se han visto enfatizados por el cambio climático. Las costas son ambientes cambiantes muy dinámicos que muestran una gran variabilidad temporal y espacial en respuesta a la acción de diferentes y complejos procesos: a escala inter-anual, relacionados con las variaciones estacionales del clima marítimo debido a las distribuciones temporales y espaciales de las tormentas de altas latitudes y tormentas tropicales/huracanes, o como resultado de procesos con largo periodo de retorno, como el impacto de grandes tormentas y tsunamis, la subida del nivel del mar, y las variaciones en los aportes sedimentarios de los ríos. Para prevenir y reducir estos impactos, los gestores costeros necesitan conocer tanto la sensibilidad de los sectores costeros naturales, la cual se relaciona con la energía del oleaje, las características/evolución del litoral y la tendencia del nivel del mar, así como la vulnerabilidad potencial y el valor económico de los sectores urbanizados.

En este trabajo se ha caracterizado el clima marítimo a lo largo de la costa mediterránea de Andalucía (España) considerando una base de datos que abarca el periodo 1979-2014. Así, se han definido las tormentas y clasificado según la energía del oleaje (*Energy flux*) en cinco clases. La energía, número y duración de las tormentas fueron variando a lo largo del litoral estudiado y, en cuanto a los años más energéticos (*stormy years*), fueron nueve, es decir 1980, 1983, 1990, 1992, 1995, 2001, 2008, 2010 y 2013.

En cuanto a la evolución de la línea de costa y la influencia de las estructuras costeras, se han diferenciado 47 unidades a lo largo de la costa mediterránea andaluza y se han calculado y clasificado las tasas de evolución (erosión/acreción/estabilidad), durante el periodo 1956-2016, utilizando la extensión DSAS del programa ArcGIS. Como resultado, 9 unidades registraron acreción, 19 unidades mostraron erosión y otras 19 estabilidad, y en cuanto al balance general, 17 unidades presentaron un balance positivo y 28 negativo, siendo el balance neto de $-29.738,4 \text{ m}^2/\text{año}$. El análisis estadístico llevado a cabo para aclarar la distribución de las zonas estables, en erosión y/o acreción de las áreas evidenció el impacto de las estructuras rígidas: se observó acreción aguas arriba de puertos y espigones y en correspondencia de rompeolas, erosión aguas abajo de puertos y espigones y frente a muros y revestimientos, así como en las desembocaduras de grandes ríos y deltas, y estabilidad en playas de bolsillo y áreas estabilizadas por estructuras costeras y obras de regeneración. Estos resultados se utilizaron para determinar la distribución de sectores costeros *swash-* y *drift-aligned* y las direcciones principales de transporte.

Respecto a la caracterización y la evolución de los sistemas dunares, se han cartografiado diferentes tipos de sistemas dunares, el pie de duna y su fragmentación, y la ocupación antrópica y su evolución durante los periodos 1977-2001 y 2001-2016. En

total, se han delimitado 53 sistemas dunares a lo largo de la costa mediterránea de Andalucía, diferenciando tres tipos de ambientes: dunas embrionarias y móviles (Tipo I), fijadas por céspedes (Tipo II) y estabilizadas (Tipo III). Se ha observado una disminución general de la superficie de los sistemas dunares en el periodo 1977-2001 ($-7,5 \times 10^6 \text{ m}^2$), relacionada con el aumento de la ocupación antrópica ($+2.3 \times 10^6 \text{ m}^2$) y la fragmentación de las dunas, especialmente en las provincias de Málaga y Almería. En el periodo 2001-2016 se registraron cambios menores en el nivel de fragmentación y la superficie de las dunas. Sólo se observó un incremento en la superficie de las dunas en playas estables o en acreción (4 de 53 sistemas), tanto en áreas naturales como antrópicas (normalmente aguas arriba de puertos).

Para determinar una estrategia de mitigación frente a la erosión costera a partir del conocimiento de la sensibilidad de sectores naturales y la vulnerabilidad potencial y el valor económico de sectores urbanizados, se han establecido tres opciones (“*No Action*”, “*Adaptation*” y “*Protection*”) a partir de tres pasos fácilmente aplicables a escala regional en otras áreas: (1) la determinación de la sensibilidad costera en función de la distribución de la energía del oleaje a lo largo de la costa y de la *buffer zone*, es decir, el ancho de playa seca expresada como múltiplo de la posición de la línea de costa predicha para 20 años, (2) la obtención de los usos del suelo y su clasificación en función de su valor económico, y (3) el cruce de los resultados de la sensibilidad y los usos del suelo para la obtención de las mejores opciones de mitigación de la erosión. La opción “*No Action*” se observó en la parte más occidental de la provincia de Cádiz y en algunas áreas al oeste de la provincia de Almería, donde tanto la sensibilidad y el valor del uso del suelo mostraron valores bajos; la opción “*Adaptation*” se registró a lo largo de más de la mitad de la costa estudiada, esencialmente en áreas naturales con alta sensibilidad y en áreas urbanizadas con baja sensibilidad; por último, la opción “*Protection*” se observó en especial en algunas áreas del este y centro de la provincia de Málaga y en la parte oriental de la provincia de Almería, donde tanto la sensibilidad costera como las clases de usos del suelo presentaron valores altos.

ABSTRACT

In past decades coastal erosion related impacts on the world's shorelines have been significantly growing due to ongoing coastal development and tourist occupation as well as to natural erosion/flooding events exacerbated by climatic change. Ocean coastlines are highly dynamic and changing environments since they show great temporal and spatial variability in response to the action of different and complex coastal processes: at an inter-annual time scales, related to seasonal wave climate variations due to temporal and spatial distributions of high latitude storms and tropical storms/hurricanes, or as a result of events with a large return period such as the impact of very energetic storms and tsunamis, sea level rise, and variations in rivers' sediment supplies. In order to prevent and reduce such impacts, coastal managers need to know the sensitivity of natural coastal sectors, which is related to wave energy, beach characteristics/evolution, and sea level trend as well as the potential vulnerability and economic value of the urbanized sectors.

In this research wave climate was characterized along the Mediterranean coast of Andalusia (Spain), for the period 1979-2014. A definition of coastal storm was adopted and used to characterize and classify them into five classes by means of their associated energy flux value. Different behaviors were observed along the coast in terms of energy, number and duration of storms. Nine stormy years (i.e. years with a great cumulative energy) were recorded in 1980, 1983, 1990, 1992, 1995, 2001, 2008, 2010 y 2013.

Concerning coastal evolution and the impacts on it of coastal structures, an amount of 47 units were defined along the studied coast, and evolution rates (erosion/accretion/stability), for the period 1956-2016, quantified by using the DSAS extension of ArcGIS software. As a result, 9 units recorded accretion, 19 erosion and 19 stability and, concerning the beach surface balance, 17 units presented a positive balance and 28 a negative one and a net balance of $-29.738,4 \text{ m}^2/\text{yr}$). The analysis of coastal evolution evidenced the impact of hard structures: accretion was essentially observed up-drift of ports and groins and in correspondence of breakwaters, erosion was observed down-drift of ports and groins and in correspondence of seawalls and revetments, and at largest river deltas, and stability was observed at pocket beaches and coastal areas locally stabilized by protection structures and nourishment works. These results were used to determine the distribution of swash- and drift-aligned coastal sectors and main direction of sediment transport.

Concerning the characterization and evolution of dune systems, they were mapped different types dunes' systems as well as dune toe position and fragmentation, and human occupation and evolution from 1977 to 2001 and from 2001 to 2016. In total, they were delimited 53 dune systems along the Mediterranean coast of Andalusia, differentiating three types: Embryo and mobile dunes, grass-fixed dunes and stabilized dunes. It was observed a general decrease in dunes' surfaces in the 1977-2001 period ($-7.5 \times 10^6 \text{ m}^2$), linked to the increase of anthropic occupation ($+2.3 \times 10^6 \text{ m}^2$), and dunes' fragmentation, especially in Málaga and Almería provinces. During the 2001-2016 period, smaller

changes in the level of fragmentation and in dunes' surfaces were observed. An increase of dunes' surfaces was only observed on stable or accreting beaches (4 out 53 dune systems), both in natural and anthropic areas (usually up-drift of ports).

In order to determine mitigation strategies against coastal erosion by taking into account the sensitivity of natural coastal sectors and the potential vulnerability and economic values of the urbanized sectors, there were established three options ("No Action", "Adaptation" and "Protection") according to three steps easily applicable on a regional scale in other areas: (1) coastal sensitivity was determined as a function of the distribution of wave energy along the coast and the characteristics of the buffer zone, i.e. the dry beach width expressed as a multiple of the 20-year predicted shoreline position, (2) land uses were obtained and classified according to their economic value, and (3) information concerning coastal sensitivity and land uses was crossed to determine the best mitigation strategies to cope with erosion processes. The "No Action" option was observed at the westernmost area of Cádiz Province and at some areas from the west coast of Almería Province, where both coastal sensitivity and land use classes show low values; the "Adaptation" option was recorded along more than one half of the coast studied, essentially at natural areas with high sensitivity and at urbanized areas with low sensitivity; and the "Protection" option was observed especially at some areas from the center and eastern part of Málaga Province and at the easternmost areas of Almería Province, where both coastal sensitivity and land use classes presented high values.

1. INTRODUCCIÓN GENERAL Y OBJETIVOS

1.1. Introducción general

Durante las últimas décadas, los impactos relacionados con la erosión costera han aumentado considerablemente en todo el mundo debido al continuo desarrollo del turismo y ocupación de la costa (Phillips y Jones, 2006; Sanò et al., 2011; Silva et al., 2014; UNWTO, 2015; Rangel-Buitrago et al., 2018) y a los procesos relacionados con el cambio climático (Jones y Phillips, 2011; Masselink et al., 2020), como son la subida del nivel del mar o los cambios en la frecuencia, intensidad y dirección de las tormentas (Bacon y Carter, 1991; Dupuis et al., 2006; Nguyen et al., 2006; Komar y Allan, 2008; Soomere, 2008; Meyer-Arendt, 2011; Cid et al., 2016; Anfuso et al., 2020; Wolf et al., 2020). Todo ello ha ocasionado un aumento del interés científico en los efectos de los procesos de la erosión costera, que han sido objeto de numerosos trabajos de investigación a diferentes escalas espaciales y temporales y utilizando una gran variedad de métodos y series de datos (Crowell et al., 1991; 1993; Jiménez y Sánchez-Arcilla, 1993; El-Asmar, 2002; Alexandrakakis et al., 2015).

El desarrollo costero, que está esencialmente unido al turismo – una de las mayores industrias del mundo (Klein et al., 2004; UNTWO, 2015) – continúa aumentando, encontrándose actualmente alrededor del 50% de las costas mundiales bajo la presión de un desarrollo excesivo (Finkl y Kruempel, 2005; Silva et al., 2014). En Europa, durante el periodo 1990-2000, se ha producido una rápida expansión de las superficies urbanas en las zonas costeras mediterráneas y sur-atlánticas (European Environmental Agency, 2006), con un incremento del 34% en Portugal y del 18% en España, países seguidos de Francia, Italia y Grecia.

Como resultado de esta expansión, las actividades e infraestructuras humanas relacionadas tanto con el turismo como con la industria y la pesca, se han situado extremadamente cerca de la orilla de mares y océanos (Phillips y Jones, 2006; Sanò et al., 2011; Silva et al., 2014) y, por lo tanto, han sido afectadas significativamente por el impacto de tormentas y huracanes que, durante el último siglo, han causado importantes pérdidas económicas junto con decenas de muertes a lo largo de las costas del mundo (Carter, 1988; Bacon y Carter, 1991; Komar y Allan, 2008; Houser et al., 2008).

La erosión costera y los procesos de inundación han reducido el ancho de las playas y los cordones dunares. Dichos procesos producen la pérdida del valor paisajístico de la costa (European Environment Agency, 2005; Mir Gual et al., 2015; Semeoshenkova y Newton, 2016; Anfuso et al., 2017) y cuantiosos daños económicos, ya que la playa es considerada el principal reclamo en los mercados turísticos (Houston, 2013) valorados en billones de dólares (Clark, 1996). Por ejemplo, alrededor del 5% del PIB (Producto Interior Bruto) de España, Francia, Italia, Grecia y Turquía proviene del turismo (UNTWO, 2006) relacionado con el llamado “mercado 3S” (*Sun, Sea and Sand market*) (Dodds y Kelman, 2008).

Las costas son ambientes cambiantes muy dinámicos que muestran una gran variabilidad temporal y espacial en respuesta a la acción de diferentes y complejos procesos, esencialmente relacionados con el oleaje y las corrientes (Komar, 1998). A menudo, los ciclos de erosión/acreción se registran a escalas inter-anales y están relacionados con las variaciones estacionales del clima marítimo debido a las distribuciones temporales y espaciales de las tormentas de altas latitudes y huracanes/tifones (Dolan y Davis, 1992; Masselink y Pattiaratchi, 2001; Donnelly et al., 2001; Anfuso y Gracia, 2005; Komar y Allan, 2008; Anfuso et al., 2020). La erosión se observa tras eventos de tormenta a altas latitudes registradas durante los meses de invierno, y la recuperación de las playas tiene lugar durante el periodo estival en circunstancias climáticas favorables, lo que se conoce como comportamiento “estacional” de la playa (Carter, 1988; Lee et al., 1995; Corbau et al., 1999; Rangel-Buitrago y Anfuso, 2013). En este caso, los procesos de erosión representan un peligro ya que pueden amenazar localmente las estructuras y/o actividades humanas en intervalos de tiempo pequeños, mientras que la recuperación natural de la playa ocurre durante intervalos mayores de tiempo, de semanas a meses (Komar, 1998; Sanjaume Saumel y Gracia Prieto, 2011). Esta recuperación garantiza la formación de una playa ancha y la función de protección asociada a ella, además de su uso turístico, pero la respuesta de las dunas a los eventos erosivos es muy diferente, es decir, la erosión es muy rápida y está asociada a eventos puntuales mientras que la acreción es un proceso que normalmente se produce durante un largo periodo de tiempo, de varios meses a años (Carter, 1991; Sanjaume Saumel y Gracia Prieto, 2011).

Por ello, la determinación de las características, comportamiento y evolución de las dunas costeras necesitan una especial atención en aras de reducir los impactos de los procesos de erosión/inundación, tanto en costas naturales como urbanizadas. Varias investigaciones recientes (Duarte et al., 2013; Fernández-Montblanc, 2020) han identificado a las dunas como uno de los ecosistemas costeros más relevantes como defensa natural capaz de reducir la sensibilidad/vulnerabilidad a la inundación, y por lo tanto, su mantenimiento/emplazamiento se ha considerado como una medida de protección efectiva incluida entre las posibles estrategias “*Disaster Risk Reduction*” (DRR) en varias directivas europeas (European Union, 1992; 2001; 2009; 2011). De hecho, los cordones dunares protegen grandes secciones de costas bajas frente a la inundación durante eventos de tormentas extremas (European Environmental Agency, 2006; Nicholls et al., 2007; Bochev-van der Burgh et al., 2011) y es por ello que la continuidad lateral de las dunas y el nivel de fragmentación de las mismas es extremadamente relevante (Carter, 1991; Church et al., 2001; Pye y Blott, 2008; Sterr, 2008).

Diferente es el caso en el que la erosión costera es el resultado de una larga tendencia debido al impacto de grandes tormentas y tsunamis (Cooper et al., 2004; Scheffers et al., 2005; Sánchez-García et al., 2007), subida del nivel del mar, y variaciones en el aporte sedimentario, relacionadas con la contribución de los ríos y las corrientes longitudinales y transversales. Las contribuciones de los ríos están relacionadas con las variaciones de las lluvias, cambios en los usos del suelo (como por ejemplo el incremento

de la erosión del suelo cuando los bosques y praderas se convierten en granjas y campos de pastoreo) y la construcción de presas y canalización de cauces (Frihy, 1988; Frihy y Komar, 1991; Jiménez y Sánchez-Arcilla, 1993; Senciales y Malvárez, 2003; Pranzini, 2007; Prieto et al., 2012; Berguillos et al., 2016, 2017; Pranzini et al., 2020). Las contribuciones longitudinales y transversales registran variaciones debido a los cambios en el clima marítimo y las corrientes (Shand et al., 2001; Orford et al., 2002) o la acumulación aguas arriba de estructuras antrópicas (p. ej., puertos, espigones, etc., Nordstrom, 2000, 2014; Manno et al., 2016; Molina et al., II). En este caso, los procesos de erosión producen un importante retroceso (parcialmente o sin una recuperación asociada) que en áreas naturales se refleja en procesos de *overwash* y/o erosión de las dunas y playas (Rizzo et al., 2018), además de daños a las estructuras y actividades humanas en sectores costeros urbanizados (Cooper et al., 2004; Rangel-Buitrago y Anfuso, 2015), es decir, las tormentas se convierten en un riesgo natural (Short, 1999).

Para reducir los impactos de las tormentas es necesario entender las características y sensibilidades específicas de la costa, así como una completa comprensión de la naturaleza de las tormentas. En los últimos años, numerosos investigadores han estudiado estos aspectos desde diferentes puntos de vista. En España, Rodríguez-Ramírez et al. (2003) estudiaron registros de tormentas en la costa de Huelva para desarrollar estrategias futuras de gestión y desarrollo apropiados; Mendoza y Jiménez (2008) y Mendoza et al. (2011) presentaron una escala de intensidad del oleaje de tormenta en la costa catalana para caracterizar su variabilidad temporal y espacial; Guisado y Malvárez (2009) y Pintado y García (2015) utilizaron condiciones extremas de oleaje para completar la caracterización de los ambientes morfodinámicos de la Costa del Sol y de Huelva; Ribera et al. (2011), Rangel-Buitrago y Anfuso (2011, 2013), Anfuso et al. (2016a) y Puig et al. (2016) caracterizaron las tormentas a lo largo del litoral atlántico de Andalucía. En las últimas décadas se han utilizado numerosos índices para caracterizar las tormentas, por ejemplo, Halsey (1986) clasificó las tormentas costeras del Atlántico Norte, también llamadas “*northeasters*” o “*nor’easters*”, basándose en un índice de su daño potencial y Dolan y Davis (1992) propusieron un índice de la escala de intensidad para clasificar las “*nor’easters*” en cinco clases, de débil a extrema, basándose en la altura de ola y la duración de la tormenta. Orford et al. (1992) y Orford y Carter (1995) desarrollaron un nuevo índice de tormentas usando los datos de marejadas. Kriebel et al. (1996) propusieron un índice de riesgos de “*nor’easters*” combinando los efectos de la marejada, oleaje y duración de la tormenta, y Zhang et al. (2001) desarrollaron un índice del potencial de erosión de tormentas combinando el efecto de la marea de tormenta, la energía del oleaje y la duración de la tormenta.

En cuanto a las variaciones de la línea de costa, estudios a corto plazo suelen llevarse a cabo a escalas espaciales pequeñas, en periodos de menos de 10 años (Crowell y Leatherman, 1993), utilizando perfiles topográficos o levantamientos 3D de la playa, repetidos a intervalos regulares (Morton, 1979; Gorman et al., 1998; Corbau et al., 1999; Anfuso y Gracia, 2005). Las fotografías aéreas, imágenes de satélite, mapas y planos son herramientas muy útiles para la reconstrucción de los cambios de la línea de costa a largo (>60 años) y medio plazo (entre 60 y 10 años) y para grandes escalas espaciales (Crowell

y Leatherman, 1993; Romine et al., 2010; Anfuso et al., 2011; Rangel-Buitrago et al., 2015).

La predicción de la tendencia futura de la línea de costa debe basarse en el estudio de los cambios que se han producido en ella en un pasado reciente teniendo en cuenta una escala temporal comparable (Leatherman, 1983).

Los estudios a escala regional sobre tasas de cambios de la línea de costa son escasos a pesar de su gran relevancia. Algunos intentos se han desarrollado en EE.UU. (Fletcher et al., 2012) y Europa (Salman et al., 2004). Sin embargo, la comparación de los datos no es fácil ya que aspectos como la definición de la línea de costa o el formato de las series de datos difieren mucho en los distintos estudios (Ponte Lira et al., 2016). Todavía se necesita mucho trabajo a escala regional/nacional para definir el mejor procedimiento en estudios regionales de erosión costera y para obtener una visión amplia de los factores regionales/locales que afectan a la evolución de la costa a medio plazo. Estos datos ayudarían a identificar las causas principales de la erosión en las últimas décadas.

Para reducir los impactos y las pérdidas económicas y humanas asociadas que puedan ocurrir, los gestores costeros necesitan conocer tanto la sensibilidad de los sectores naturales, la cual se relaciona con la energía del oleaje, las características/evolución de las playas y la tendencia del nivel del mar (Coelho et al., 2006; Anfuso y Martínez del Pozo, 2009) así como la vulnerabilidad potencial y el valor económico de los sectores urbanizados (McLaughling et al., 2002; Rangel-Buitrago y Anfuso, 2015).

Las características de la energía del oleaje, especialmente las distribuciones espaciales y temporales y la periodicidad de los eventos más energéticos, son los agentes (*forcing agents*) que conducen los cambios morfológicos de las playas y determinan los procesos de erosión/acumulación (Cooper y McKenna, 2008; Almeida et al., 2011) que también dependen de las dinámicas y características de las playas (p. ej., estado morfológico de la playa, anchura, presencia de cordones dunares, etc., Rangel-Buitrago y Anfuso, 2015).

La actividad humana y la vulnerabilidad de las estructuras dependen de la distancia a la que se encuentren de la línea de costa y de su tipología (Rangel-Buitrago y Anfuso, 2015; Mattei et al., 2019). Siguiendo diferentes criterios, se han obtenido mapas de vulnerabilidad de numerosas áreas alrededor del mundo a través del uso de análisis multivariantes computerizados, modelos numéricos y Sistemas de Información Geográfica (SIG), con investigaciones pioneras llevadas a cabo por Gornitz (1990) y Gornitz et al. (1997) en EE.UU., por Cooper y McLaughling (1998), McLaughling et al. (2002) y el Comité de Cambio Climático (Committee on Climate Change, 2016) en Reino Unido, y por Dodds y Kelman (2008) en Malta y Mallorca.

Una vez determinada la sensibilidad/vulnerabilidad costera, el siguiente paso para los gestores costeros es decidir cuál es la mejor estrategia de mitigación, que incluye inacción, adaptación y protección (Pranzini et al., 2015; Williams et al., 2018). La

inacción (“*No Action*”) es la opción de “no hacer nada”, se adopta en áreas en las que no se requieren acciones. La adaptación (“*Adaptation*”) incluye la acomodación (“*Accomodation*”), es decir la modificación de las estructuras humanas y los cambios del uso del suelo: un área dedicada a la agricultura puede reemplazarse por una salina, y la relocalización (“*Relocation*”) consiste, por ejemplo, en el desplazamiento hacia tierra de actividades/usos humanos. La protección es la opción denominada “*Hold the line*” o “*Protection*”, es decir la defensa y mantenimiento de la actual posición de la línea de costa utilizando estructuras de protección duras o la regeneración artificial de las playas (Committee on Climate Change, 2016). La selección de la estrategia de gestión se basa en el conocimiento de los procesos de erosión (magnitud y causas) y de recomendaciones/legislación (European Commission, 2004). Las consideraciones económicas se basan en un enfoque de análisis costes-beneficios (Cooper y McKenna, 2008) o en un criterio de acción/reacción (Rangel-Buitrago y Anfuso, 2015; Williams et al., 2018).

La costa mediterránea de Andalucía (España) ha registrado una de las mayores tasas de crecimiento urbano a lo largo del litoral español, especialmente en la Costa del Sol (provincia de Málaga) (García et al., 2000), cuya población alcanzó los 1.136.712 habitantes en 2006 (Malvárez, 2012) y continuó creciendo con una tasa del 9.2% entre 2006 y 2011 – lo que corresponde al 50% del incremento demográfico registrado a lo largo del litoral andaluz durante el mismo periodo (Martínez et al., 2015). Hoy en día, la Costa del Sol recibe cerca de 10.000.000 visitantes al año, es decir, el 35% de toda Andalucía, convirtiéndolo en uno de los destinos turísticos más importantes de Europa.

El creciente y significativo interés turístico de las costas andaluzas conlleva a un aumento importante de la ocupación y las actividades humanas y, por tanto, de la presión antrópica cuyo papel se hace cada vez más relevante en los procesos de erosión costera. En este trabajo se pretende realizar un análisis de la evolución y el estado actual de la línea de costa y los sistemas dunares del litoral mediterráneo de Andalucía prestando una especial atención a los efectos de la presión antrópica.

1.2. Objetivos

Dada la importancia que tiene la protección de la costa y el papel tan relevante que asumen los complejos dunares en ésta, se planea realizar un trabajo de investigación que considere tanto la evolución de las playas como de las dunas del tramo costero mediterráneo de Andalucía (España).

La hipótesis de la que partimos es que las playas del litoral mediterráneo andaluz se encuentran en un estado de retroceso y los sistemas dunares sufren continuos episodios de erosión y degrado debido a los agentes marinos y eólicos y a la presión antrópica.

Así, el objetivo principal de este trabajo es el de evaluar la evolución, el estado y condiciones actuales de las playas y dunas del tramo mediterráneo de la costa de Andalucía a través de un análisis histórico a partir de cartografía generada en software GIS (*Geographic Information System*) y un análisis detallado del clima marítimo.

Para ello se plantean tres objetivos:

Objetivo 1: Caracterización del clima marítimo (parámetros de oleaje y determinación de tormentas) y análisis de la energía del oleaje de tormenta a lo largo de la línea de costa.

Objetivo 2: Cartografía de la línea de costa (contacto agua-tierra) para el periodo 1956-2016 y de las dunas (para el periodo 1977-2016) de la costa mediterránea andaluza a partir de ortofotografías aéreas a través de un software GIS y análisis de la evolución de las playas y dunas. Esta fase prevé: a) análisis de la evolución de la línea de costa, teniendo especialmente en cuenta la presencia de estructuras antrópicas (puertos, rompeolas, espigones, etc.) y b) análisis de la evolución de las dunas y definición de los cambios dentro de las diferentes unidades geomorfológicas y la identificación de la presión antrópica.

Objetivo 3: Análisis de los resultados obtenidos en los objetivos 1 y 2 y evaluación de las tendencias presentes y futuras del estado y condiciones actuales de las playas y dunas estudiadas. Proposición de estrategias de mitigación de la erosión costera.

2. ÁREA DE ESTUDIO

El litoral de Andalucía se extiende a lo largo del océano Atlántico, el estrecho de Gibraltar y el mar Mediterráneo, al sur de España. La costa mediterránea andaluza, de 546 km de longitud, se extiende desde el estrecho de Gibraltar hasta la Región de Murcia e incluye, desde el punto de vista administrativo, las provincias de Cádiz, Málaga, Granada y Almería. La línea de costa tiene una orientación predominantemente E-O, con dos sectores orientados a NE-SO situados cerca del estrecho de Gibraltar y en el extremo E de la costa de Almería (Figura 1).

La orografía y la morfología costeras las determina la Cordillera Bética, tectónicamente activa y formada por un conjunto de sierras jóvenes emergidas durante el Mioceno que ocupan más de la mitad de la superficie de la región andaluza, desde Cádiz hasta Almería prolongándose por Murcia, Valencia y Baleares, y alcanzan grandes elevaciones cerca de la costa (las mayores de la Península Ibérica, Villalobos Megía y Pérez Muñoz, 2006), formando una costa muy irregular, con acantilados, bahías y promontorios. Al pie de estas montañas se desarrollan numerosas llanuras costeras de pequeño tamaño, principalmente en la desembocadura de ríos de escasa entidad y ramblas que drenan la cadena montañosa, siendo los más importantes los ríos Guadiaro, Guadalhorce, Guadalfeo, Adra y Andarax (Figura 1). Especialmente durante episodios de fuertes lluvias asociadas al clima semiárido, las arenas y gravas fluviales constituyen un importante aporte de sedimento al sistema playa-duna. En las últimas décadas, los planes de regulación de cuencas hidrográficas han promovido la construcción de presas y embalses que han limitado sustancialmente los aportes sedimentarios a la costa, agravando el retroceso costero, especialmente en los principales deltas (Félix et al., 2012; Prieto et al., 2012; Guisado et al., 2013). Cabe destacar dos áreas en las que la regulación de las cuencas hidrográficas han causado una reducción importante del aporte sedimentario a la costa: al este de la provincia de Almería, en correspondencia de los ríos Alías, Aguas, Antas y Almanzora (Bayo Martínez, 1999) y en la Ensenada de Marbella, en la que desembocan los ríos Guadalmina, Guadaiza, Verde y Real y una red de arroyos y ramblas que actualmente se encuentra en estado de degradación (Del Río et al., 2015).

Las principales formaciones deltaicas de la costa mediterránea de Andalucía están asociadas a algunos de los ríos de mayor importancia: los ríos Vélez, Guadalfeo, Adra, Andarax y Almanzora y las ramblas de Albuñol y Huarea. El delta del río Vélez es un buen ejemplo de comportamiento erosivo: la desembocadura del río presenta materiales no consolidados que son muy susceptibles a la erosión y se depositan en los márgenes del delta debido a la deriva dominante (Prieto et al., 2012). Esto también ocurre en los deltas de los ríos Guadalfeo y Andarax (Prieto et al., 2012), en el delta del río Nilo (Frihy, 1988; Frihy y Komar, 1991), en el delta del río Ebro (Jiménez y Sánchez-Arcilla, 1993) y en el del río Arno (Pranzini, 2007). Además, desde 1988 la cuenca de este delta se encuentra regulada por varias presas en las que se retiene la carga sedimentaria suspendida (Senciales González y Malvárez, 2003). El delta del río Guadalfeo está asociado a uno de

los mayores sistemas de drenaje de alta energía de la costa mediterránea española y su cuenca se encuentra también regulada por presas que retienen el sedimento y agravan los problemas de erosión del delta produciendo el retroceso de la línea de costa (Berguillos et al., 2016; 2017). Prieto et al. (2012) afirman que el área con mayores tasas de erosión de Andalucía es el delta del río Almanzora, donde ya se registraban altas tasas de erosión en periodos anteriores a la regulación de su cuenca (en el periodo 1956-1979). En 1986 la construcción de la presa de Cuevas del Almanzora provocó la desconexión del delta con su fuente sedimentaria, causando grandes déficits que se reflejan en el comportamiento erosivo generalizado. La cuenca del río Adra también ha sido muy modificada: la construcción del puerto de Adra (en 1947) al oeste del río interrumpió el transporte sedimentario y se originó un nuevo delta tras la desviación del cauce principal del río. La presa de Beninar, construida en 1988, condujo a la construcción de casi un centenar de pequeños espigones a lo largo del lado este del actual delta (Prieto et al., 2012). En muchas de estas áreas se han sucedido numerosos trabajos periódicos de regeneración artificial de playa con el fin de estabilizar la línea de costa (Malvárez et al., 2000; Prieto et al., 2012; Guisado-Pintado y Malvárez, 2015; Berguillos, 2016; 2017).

Respecto a las características de las playas del litoral mediterráneo de Andalucía, se pueden diferenciar dos grandes grupos: las playas de Cádiz, Málaga y Granada, con un ambiente micro-mareal (amplitud mareal < 20 cm), de tipo intermedio a reflectivo que se componen comúnmente por arenas oscuras de medias a gruesas y/o gravas en la desembocadura de ramblas, mientras que las playas de Almería, de tipo disipativo, se componen de arenas finas/medias ricas en cuarzo (Bayo Martínez, 1999; Guisado y Malvárez, 2009; Gracia et al., 2011; Williams et al., 2012; Mooser et al., 2018). A menudo, las playas se ven interrumpidas por sectores rocosos o promontorios que dan lugar a calas o playas de bolsillo (*pocket beaches*) de diferentes tamaños y elevado valor paisajístico (Williams et al., 2012). Las playas de bolsillo tienen la particularidad de que, al ser sistemas sedimentarios restringidos que se encajan entre promontorios rocosos, en general experimentan una conexión muy pequeña o nula con los sistemas colindantes debido a que los promontorios regulan la transferencia del sedimento a lo largo de la costa (Dehouk et al., 2009). Se puede asumir que la corriente longitudinal es débil en este tipo de playas donde la incidencia del oleaje es de tipo shore-normal, al contrario de lo que ocurre en las playas abiertas, y donde el viento juega un papel importante en el control de los procesos tanto en la orilla como en la playa y, por lo tanto, de los cambios morfológicos (Pattiaratchi et al., 1997; Masselink y Pattiaratchi, 1998; Castelle et al., 2006; Dehouck et al., 2009). En las playas de bolsillo, la incidencia del oleaje proviene de una ventana direccional limitada, siendo su energía dinámica y cambiante en diferentes escalas temporales, y absorbidas por la propia playa (Bowman et al., 2009). Una de las características más comunes de las playas de bolsillo es que suelen tener un volumen de sedimento constante, mostrando un comportamiento morfodinámico típico de fluctuación de la línea de costa en la dirección del oleaje, es decir, los sedimentos se mueven de un extremo a otro de la playa sin salir del sistema (Valdemoro y Jiménez, 2006).

En cuanto a ocupación del litoral, las mayores ciudades costeras son Málaga (>500.000 habitantes), Almería (ca. 200.000 habitantes), y las ciudades turísticas situadas

en la parte oeste de la Costa del Sol, es decir Marbella (150.000 habitantes), Fuengirola (80.000 habitantes) y Torremolinos (70.000 habitantes). Málaga es la provincia que ha experimentado la mayor ocupación costera debido a la construcción de estructuras relacionadas con el turismo nacional e internacional (DGPC, 1991). Los puertos comerciales más importantes se encuentran en Almería, Cádiz (especialmente en la Bahía de Algeciras), y Málaga donde, además, se encuentran numerosos puertos deportivos, esencialmente en la Costa del Sol (Malvárez et al., 2000, 2003; Manno et al., 2016).

Respecto a las características climáticas, las provincias de Cádiz, Málaga y Granada tienen un clima mediterráneo con características sub-tropicales; la orientación de la costa y la cordillera Bética favorecen temperaturas medias anuales de unos 13°C y de 19°C en los meses de julio y agosto. Las precipitaciones anuales son de 400 a 900 mm, siendo más abundantes en el área del estrecho de Gibraltar. La provincia de Almería presenta un clima mediterráneo con características sub-desérticas, con episodios de lluvias muy escasos (unos 200 mm/año), y una temperatura media anual de 21°C y de 26°C en julio y agosto (Chica Ruiz y Barragán, 2011).

La costa se expone, en general, a vientos provenientes de E a O y de NNE a SO en el área más oriental de Andalucía (i.e. Carboneras, Figuras 1 y 2), con velocidades mínimas y máximas que oscilan entre los 0,4 a 9,0 m/s (Molina et al., **I**). El oleaje y el flujo de energía durante las tormentas es muy variable (Molina et al., **I, IV**), ya que la costa de la provincia de Cádiz y la costa oriental de la provincia de Almería se ven afectadas principalmente por las tormentas que provienen del este, mientras que las provincias de Málaga, Granada y, parcialmente, Almería están expuestas a tormentas provenientes tanto del este como del oeste (Molina et al., **I, IV**). El oleaje muestra un comportamiento claramente estacional, registrando condiciones de tormenta durante los meses de invierno (Noviembre – Marzo) (Pita López, 2003; Guisado et al., 2013; Molina et al., **I**). Debido a la orientación de la costa, los vientos predominantes del este asociados a condiciones de tormenta dan lugar a condiciones de oleaje que generan una deriva litoral preferente del oeste (Pita López, 2003), aunque en algunos sectores se produce, de forma particular, una deriva opuesta (Guisado et al., 2013; Molina et al., **I**).

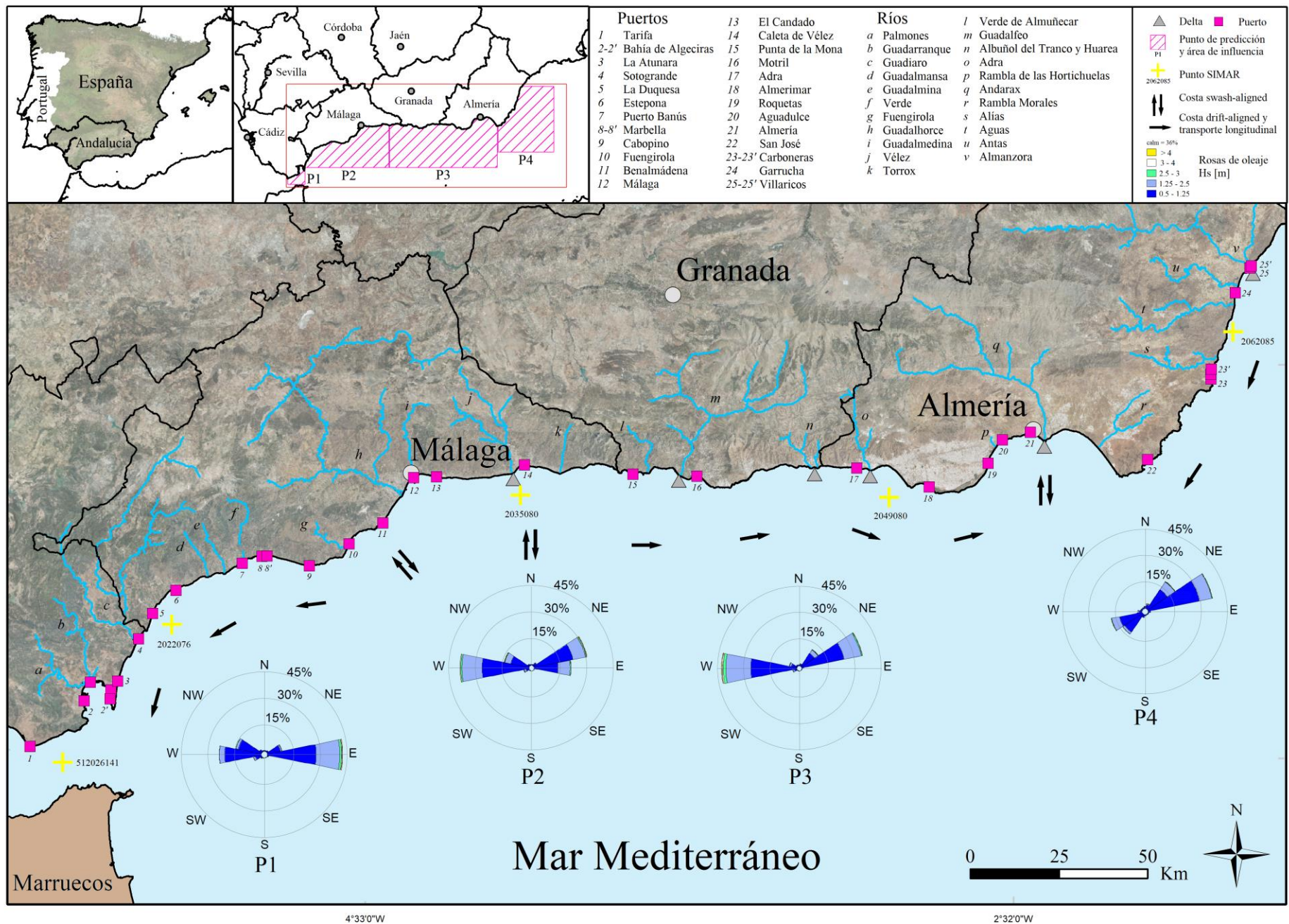


Figura 1. Localización geográfica del área de estudio.

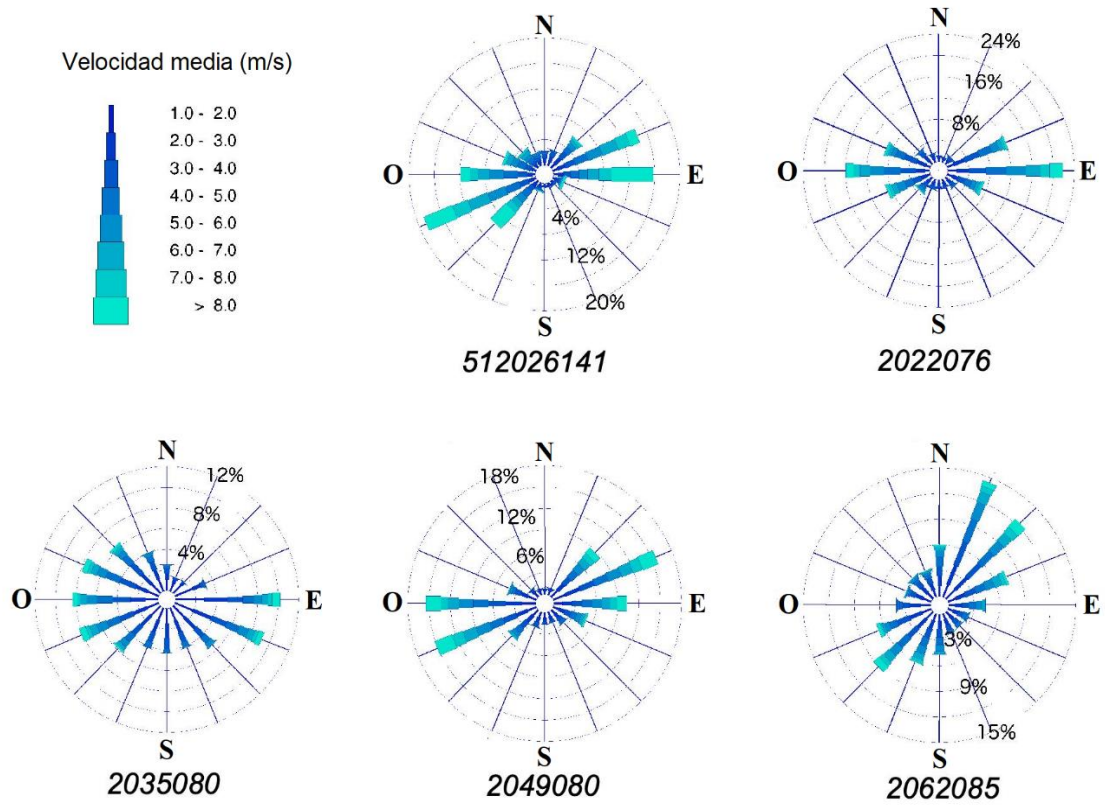


Figura 2. Rosas de viento modificada de Molina et al. (III).

3. METODOLOGÍA

A continuación se describe la metodología utilizada para la obtención de cada objetivo.

Objetivo 1: Caracterización del clima marítimo (parámetros de oleaje y determinación de tormentas) y análisis de la energía del oleaje de tormenta a lo largo de la línea de costa.

La metodología utilizada en este apartado se describe en la publicación I y se resume en el siguiente esquema (Figura 3).

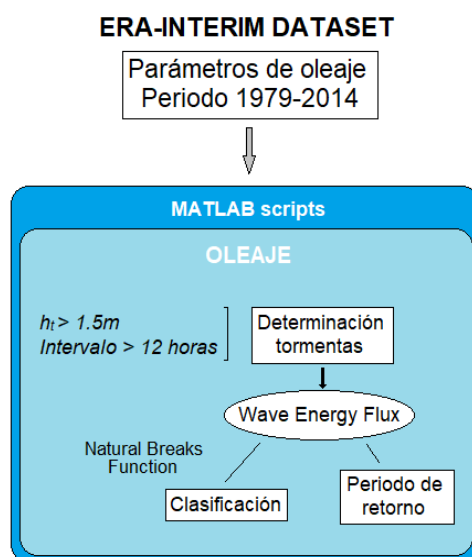


Figura 3. Resumen de la metodología utilizada para la caracterización del clima marítimo.

Las características y energía del oleaje de tormenta se han analizado a partir de los datos obtenidos para el periodo 1979-2014 del Centro Europeo de Previsiones Meteorológicas a Plazo Medio ECMWF (*European Center for Medium-Range Weather Forecasts*). Los datos modelados por el modelo *Wave Model* (WAM) pertenecen al proyecto ERA-INTERIM del ECMWF. Los cuatro puntos de predicción identificados en la costa mediterránea de Andalucía, de O a E, se localizan en: P1, cerca del estrecho de Gibraltar; P2, al este de Málaga; y P3 y P4, al frente y al este de Almería respectivamente (Figura 1). Para la determinación de las tormentas, se ha utilizado la definición de Boccotti (2000) que define una tormenta mediterránea como una secuencia de estados cuyo espectro de altura significativa de ola excede un umbral h_t durante un intervalo de tiempo mayor de 12 horas, considerando además, que entre tormentas consecutivas deben transcurrir al menos 12 horas. El Organismo Puertos del Estado (Ministerio de Fomento, Gobierno de España), en sus Recomendaciones para Obras Marítimas R.O.M. 0.3-91 (Puertos del Estado, 1992), indica que para la costa mediterránea de Andalucía el umbral de altura significativa de ola h_t es de 1,5 m. El parámetro físico escogido en este trabajo para el cálculo de la energía del oleaje de tormenta es el flujo de energía de ola (*Wave Energy Flux*) o potencia de ola por unidad de longitud del frente de ola (P), descrito por

Monteforte et al. (2015) y Lo Re et al. (2019), cuyo cálculo se describe en la publicación **I**.

El análisis de las características y energía del oleaje de tormenta se ha realizado a partir de los datos obtenidos en el Objetivo 1. Para la clasificación de las tormentas se ha seguido la metodología propuesta por Jenks y Caspall (1971) “*the natural breaks function*”, obteniendo cinco clases, de la Clase I (eventos de baja energía) a la Clase V (eventos extremos).

La estimación del periodo de retorno de la energía (P) de cada clase de tormenta y la probabilidad de excedencia se han calculado a partir de la función de distribución acumulativa de Weibull (*Cumulative Distribution Function – CDF*) descrita en Boccotti (2000) y Lo Re et al. (2019), y el periodo de recurrencia R_i y la frecuencia anual de ocurrencia f_0 de las tormentas se calcularon para definir los *Stormy Years*, descritos en Almeida et al. (2012) y Anfuso et al. (2016a). El procedimiento para la obtención de éstos parámetros se describe en la publicación **I**.

Objetivo 2: Determinación de la línea de costa, cartografía de las dunas y análisis de la evolución de las playas y dunas.

La metodología utilizada en este apartado se describe en las publicaciones **II** y **III**, y se resume en el siguiente esquema (Figura 4).

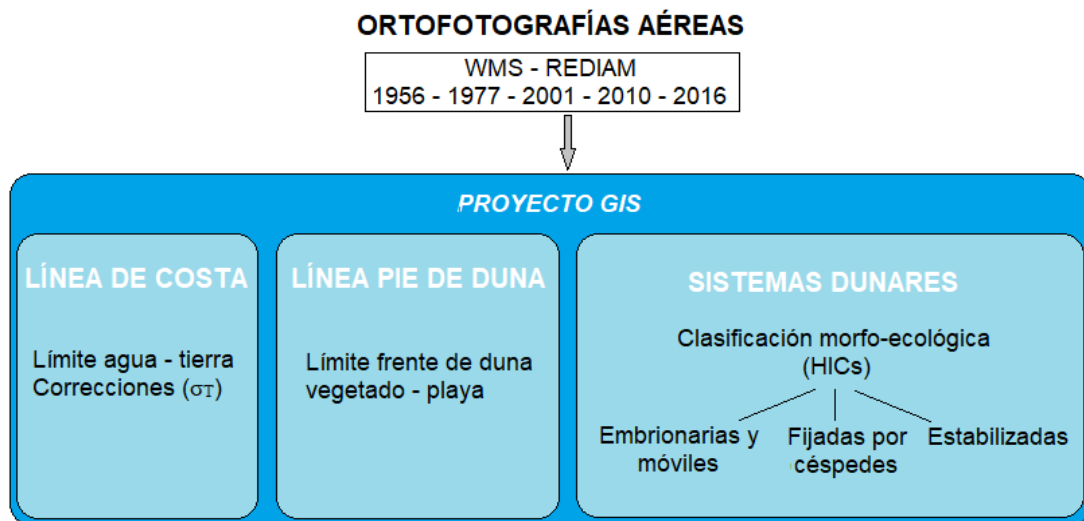


Figura 4. Resumen de la metodología utilizada para el estudio de la evolución de la costa.

Para la determinación de la línea de costa y la cartografía de las dunas se han utilizado las ortofotografías aéreas disponibles de los años 1956, 1977, 2001, 2010 y 2016, obtenidas a través de los servicios *Web Map Services* (WMS) pertenecientes a los servicios *Open Geospatial Consortium* (OGC) de la Red de Información Ambiental de Andalucía (REDIAM) de la Consejería de Agricultura, Ganadería, Pesca y Desarrollo

Sostenible (Junta de Andalucía) y del Centro de Descargas del Centro Nacional de Información Geográfica que, junto a la Dirección General del Instituto Geográfico Nacional (IGN), dirigen el Plan Nacional de Ortofotografía Aérea (PNOA), organismos autónomos adscritos al Ministerio de Fomento (Gobierno de España), (Tabla 1).

Año	Vuelo	Color	Escala	Resolución espacial (m)
1956	1956-57	Blanco y negro	1:10.000	1,0
1977	Iryda 1977-83	Blanco y negro	1:5.000	0,5
2001	2001-202	Blanco y negro	1:10.000	0,5
2010	PNOA 2010-11	Color	1:10.000	0,5
2016	PNOA 2016	Color	1:5.000	0,25

Tabla 1. Características de las ortofotografías aéreas utilizadas.

Las ortofotografías aéreas del año 1956 se han utilizado para el análisis de la evolución de la línea de costa y no para la cartografía de las dunas debido a la baja calidad de las mismas.

Los mapas se han elaborado en un proyecto GIS mediante la aplicación ArcMap del software ArcGIS, utilizando el sistema de referencia WGS84, UTM zonas 29 N y 30 N. Se han cartografiado todos los sistemas dunares con un mínimo de 100 m de longitud de frente de duna, diferenciando las unidades que se describen a continuación:

- Línea de costa;
- Línea de pie de duna;
- Dunas embrionarias y móviles (Tipo I);
- Dunas fijas con céspedes (Tipo II);
- Dunas estabilizadas (Tipo III).

Al ser la costa mediterránea andaluza un ambiente micromareal, la posición de la línea de costa se ha establecido en el límite agua-tierra (Pajak y Leatherman, 2002; Boak y Turner, 2005), y las correcciones se han llevado a cabo teniendo en cuenta las condiciones mareales (σ_{td}) y de run-up (σ_{wr}) de acuerdo a Manno et al. (2017). La precisión de las medidas dependen de la incertidumbre total (σ_T) asociada a la determinación de la posición de cada línea de costa, que a su vez depende de las características propias de las imágenes utilizadas y de los procesos de digitalización (Moore, 2000) cuyos cálculos se describen en la publicación **II**.

La línea del pie de duna se ha establecido en el límite entre el frente de duna vegetado y la playa.

La definición de los ambientes dunares se ha basado en la clasificación morfoecológica descrita en el manual “Las dunas en España” de Sanjaume Saumel y Gracia Prieto (2011) en el que se definen los hábitats dunares costeros más importantes de España.

Para el análisis de la evolución de la costa se han estudiado los cambios producidos en la línea de costa, la variabilidad del cordón dunar incluyendo su vegetación y fragmentación y el efecto de las construcciones antrópicas sobre el tramo costero analizado. Para ello se ha utilizado la cartografía generada con software GIS con el fin de realizar una descripción detallada de los cambios que se han producido en las distintas unidades geomorfológicas estudiadas.

Para la estimación de las tasas de evolución de la línea de costa, se ha utilizado la extensión DSAS del software ArcGIS (Thieler et al., 2009a; Anfuso et al., 2016b) a través de la que se han calculado los parámetros SCE (*Shoreline Change Envelope*), NSM (*Net Shoreline Movement*), WLR (*Weighted Linear Regression*), LRR (*Linear Regression Rate*) y EPR (*End Point Rate*) (Dolan et al., 1991; Thieler et al., 2009b), descritos en la publicación II. El parámetro utilizado para la clasificación de las tasas de evolución fue WLR y la elección de los intervalos para cada clase se basó en el análisis estadístico de los resultados (Tabla 2), descrito en la publicación II.

Clase	Estado de la playa	m/año
1	Acreeión muy alta	$\geq + 1,5$
2	Acreeión alta	$\geq + 0,5; < + 1,5$
3	Acreeión moderada	$\geq + 0,2; < + 0,5$
4	Estabilidad	$> - 0,2; < + 0,2$
5	Erosión moderada	$> - 0,2; \leq - 0,5$
6	Erosión alta	$> - 0,5; \leq - 1,5$
7	Erosión muy alta	$\leq - 1,5$

Tabla 2. Definición de las clases de evolución.

El análisis de la distribución de las clases de evolución de acuerdo a su localización (libres de estructuras, en correspondencia, aguas arriba o abajo de estructuras de protección y puertos) se realizó a través del software estadístico “R” (<http://www.r-project.or>).

El análisis de la evolución de los sistemas dunares y la ocupación antrópica se realizó a través de cálculos de superficies y de la fragmentación del pie de duna, utilizando los programas ArcGIS y MATLAB. Debido a la heterogeneidad de los sistemas, los valores obtenidos de fragmentación se normalizaron de acuerdo a una distancia constante utilizando un Índice de Fragmentación (*F Index*) clasificándola en tres clases. Todos estos cálculos se describen en la publicación III.

Objetivo 3: Análisis de los resultados obtenidos en los Objetivos 1 y 2 y evaluación de las tendencias presentes y futuras del estado y condiciones actuales de las playas y dunas estudiadas. Proposición de estrategias de mitigación de la erosión costera.

Las estrategias de mitigación de la erosión costera propuestas en este trabajo se han obtenido combinando la sensibilidad costera con la información de los usos del suelo (Figura 5).

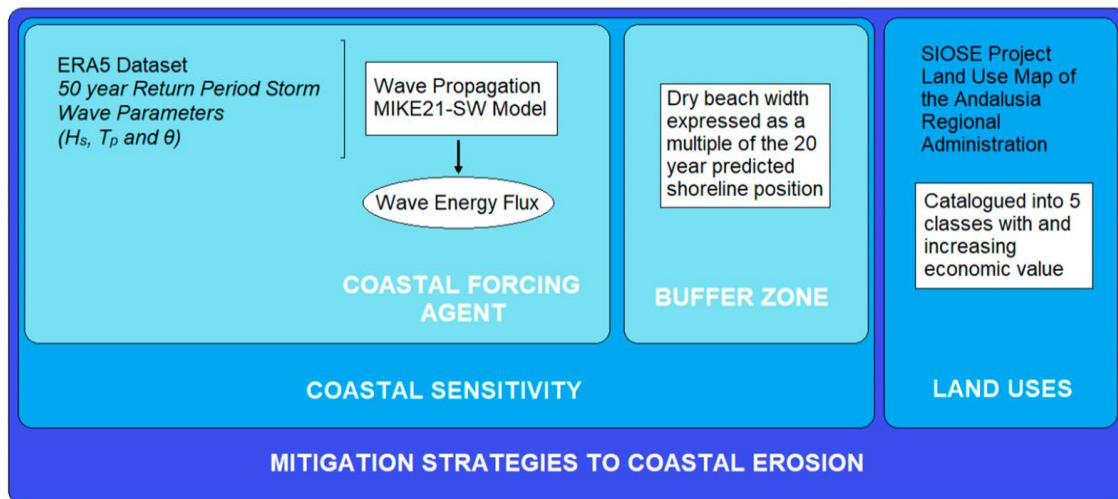


Figura 5. Resumen de la metodología utilizada para la determinación de las estrategias de mitigación de la erosión costera (Molina et al., **IV**).

La sensibilidad costera se ha obtenido combinando, mediante una media aritmética, los datos de energía del oleaje de tormenta con el ancho de la playa que forma una “*buffer zone*” frente al oleaje. Así, la sensibilidad será función del ancho de playa seca expresado como múltiplo de la posición de la línea de costa predicha para veinte años. Los usos del suelo se han obtenido a partir del proyecto SIOSE (Sistema de Información de Ocupación del Suelo de España) de la Junta de Andalucía, clasificándolos en 5 categorías, según su valor económico. Esta metodología se describe en detalle en la publicación **IV**.

Con los resultados obtenidos de esta combinación de factores, tal como se ha descrito en detalle en la publicación **IV**, se han propuesto tres opciones como estrategias de mitigación de la erosión costera: i) inacción (*No Action*), no se requieren acciones ya que los usos del suelo son de valor económico bajo y existe una sensibilidad baja o nula; ii) adaptación (*Adaptation*), que incluye la acomodación, es decir, la modificación de las estructuras existentes, y/o la relocalización de las estructuras hacia tierra; y iii) protección (*Protection*), la implantación de estructuras duras de protección y/o la ejecución de obras de regeneración artificial de playa, cuando el valor económico del uso del suelo y su sensibilidad son altos.

4. RESULTADOS Y DISCUSIÓN

4.1. Caracterización del clima marítimo

Los datos obtenidos de altura de ola para el periodo estudiado no presentan una tendencia general, sin embargo, muestran un comportamiento estacional, similar al observado por Rangel-Buitrago y Anfuso (2013) en el sector atlántico de Andalucía. En general, los valores medios mensuales más altos de altura máxima significativa de ola (H_{m0max}) se han observado en el periodo de invierno (diciembre – marzo), concretamente en los meses de marzo (Puntos 1, 2 y 4) y febrero (Punto 3) (Figura 1), debido a la fuerte incidencia de vientos del este durante esos meses que favorecen un importante oleaje proveniente de la misma dirección. Por el contrario, los valores medios más bajos de H_{m0max} se observan durante los meses de verano (julio – agosto) y el mes de septiembre (Figura 1).

Respecto a las direcciones de aproximación del oleaje, los datos reflejan claramente la orientación de la costa y el clima marítimo predominante (Figura 1). El Punto 1 se encuentra muy próximo al estrecho de Gibraltar pero protegido del mar de fondo proveniente del Atlántico. En este punto predominan fuertes vientos del E asociados a la superficie del gradiente de presión que se sitúa sobre el estrecho de Gibraltar cuando el anticiclón de las Azores se sitúa sobre la Península Ibérica y en el norte de África se produce un pronunciado centro de bajas presiones (Dorman et al., 1995), lo que provoca la generación de frentes de oleaje prevalentes del E, con alturas de ola de 0,5 – 1,25 m (c. 30% de los casos) y 1,25 – 2,5 m (c. 10%). Los puntos 2 y 3 se sitúan en el sector central del área de estudio, expuestos a vientos y oleaje provenientes tanto del E como del O y del E-NE. Específicamente, en el Punto 2, el oleaje que proviene de las direcciones E y N es equivalente al oleaje proveniente del O; en el Punto 3, debido al incremento del *fetch* del oeste, la componente O es mayor en los frentes del NE, además, debido a la orientación de la costa, en este punto se observa un incremento de la componente NE respecto al Punto 2. En el Punto 4, a pesar de la prevalencia de la dirección de aproximación E-NE, la componente NE se hace más evidente que en el Punto 3. Este punto se encuentra protegido del O debido a su orientación (NNE-SSO) y el oleaje proveniente del tercer cuadrante presenta esencialmente componentes SO y O-SO (Figura 1).

En cuanto a las tormentas registradas durante el periodo estudiado, los puntos en los que se registró un mayor número de tormentas fueron el 2 y el 3, y su distribución respecto a las diferentes clases – Clase I (débil), Clase II (moderada), Clase III (significativa), Clase IV (severa) y Clase V (extrema) –, fue muy similar en todos ellos. Los resultados obtenidos sobre la distribución mensual de todas las tormentas son muy similares a los obtenidos por Dolan y Davis (1992), Moritz y Moritz (2006), Mendoza y Jiménez (2008), Mendoza et al. (2011), Rangel-Buitrago y Anfuso (2011, 2013) y Anfuso et al. (2016b). En cuanto a su distribución temporal, las tormentas de clases I y II se observan durante todo el año; las tormentas de Clase III se registran en los meses de

invierno y primavera (octubre – mayo), con una ocurrencia mínima en los meses de verano: en junio (8 tormentas), agosto (2 tormentas) y septiembre (2 tormentas); las tormentas de Clase IV se observan de noviembre a marzo y las de Clase V sólo se registraron de diciembre a marzo (especialmente en febrero y marzo con 7 y 5 eventos respectivamente). Cabe destacar que las tormentas de clases II y III son muy frecuentes en el mes de marzo debido a la aproximación del oleaje generado por los vientos del E y SE, muy frecuentes en primavera.

En cuanto a las direcciones de aproximación de las tormentas según su clasificación energética se evidencia como, en correspondencia del Punto 1, las clases I y II provienen principalmente del E con una pequeña componente O y las clases III, IV y V, prácticamente en su totalidad (>95% de los datos registrados en cada clase), provienen del E (Figuras 1 y 6). En el Punto 2, la suma de las direcciones E y E-NE es prácticamente igual a la de la componente O y refleja claramente, con un pequeño incremento de la componente E, lo observado en cuanto al aumento del oleaje en las figuras 1 y 6. En el Punto 3, las direcciones de aproximación muestran en general el incremento del oleaje presentado en las figuras 1 y 6 con un incremento importante de la componente O en todas las clases. En el Punto 4, las direcciones de aproximación son consistentes respecto al patrón direccional del oleaje observado en las figuras 1 y 6. En este último punto son más numerosas las tormentas que provienen de E-NE y desaparecen aquellas que provienen del SO.

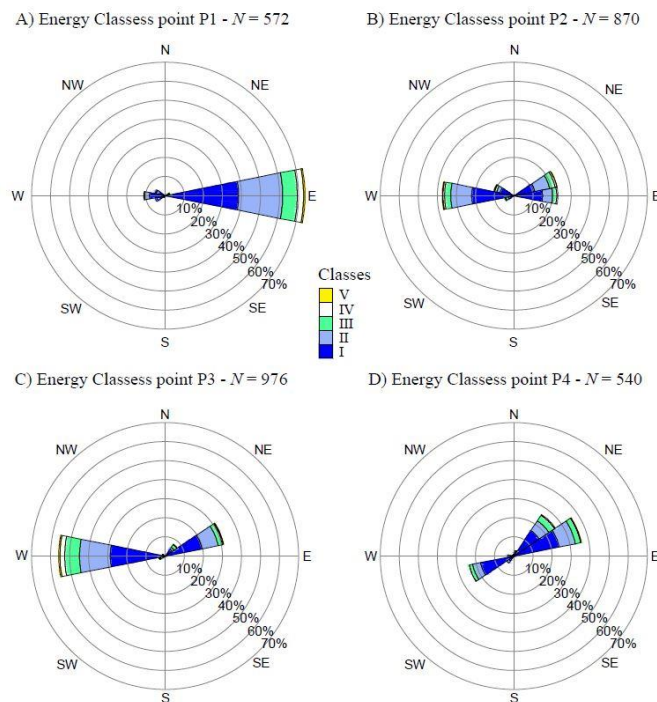


Figura 6. Rosas de *Energy Classes* E_f de los cuatro puntos de predicción. (A) P1, (B) P2, (C) P3, (D) P4, modificado de Molina et al. (I).

En cuanto a la frecuencia anual de ocurrencia de las tormentas (f_0), los valores se asemejan a los obtenidos por Anfuso et al. (2016a) en las áreas de Huelva y Cádiz. En los puntos centrales de la costa (Puntos 2 y 3), la frecuencia de ocurrencia de las tormentas

menos energéticas (I, II y III) es del 100%, mientras que en el resto, la Clase III varía desde el 76,9% al 100% (Punto 1) y del 43,5% al 100% (Punto 4). Las clases más energéticas (Clases IV y V) varían de la misma forma en cuanto a su distribución espacial, siendo más frecuentes en los puntos centrales (Puntos 2 y 3). Los puntos más energéticos (Puntos 2 y 3) son los que registran mayores porcentajes de ocurrencia, por lo que se puede afirmar que la costa entre Málaga y Almería es encuentra muy expuesta a tormentas pertenecientes a las cinco clases energéticas (Figura 7).

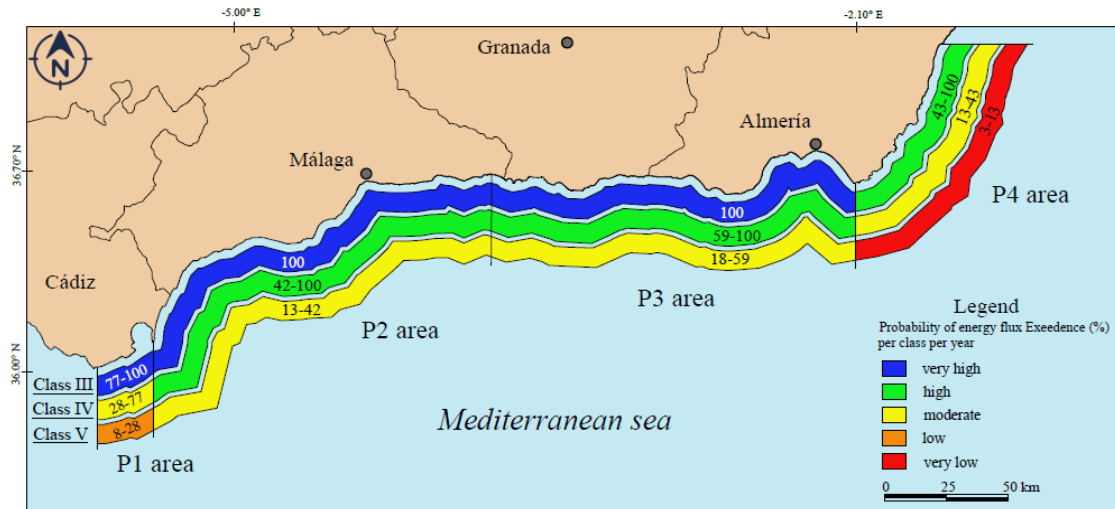


Figura 7. Probabilidad de excedencia del *Energy Flux* (%) de tormentas de clase III, IV y V en el área de influencia de cada punto estudiado, modificado de Molina et al. (I). Los valores que se muestran corresponden a los resultados obtenidos en Molina et al. (I).

De acuerdo a Rangel-Buitrago et al. (2011), se han considerado las tormentas de clases III, IV y V como los eventos que producen un daño costero importante y, por ello, son las clases que se han tenido en cuenta para la caracterización/cuantificación de los *stormy years*, es decir de los años con más energía (obtenida sumando la energía de cada evento) o más tormentas (la suma de todas las tormentas registradas en el año). De acuerdo a la distribución anual de la energía, se observan nueve años energéticos: 1980, 1983, 1990, 1992, 1995, 2001, 2008, 2010 y 2013. Los datos analizados no presentan una tendencia clara pero sí muestran un comportamiento cíclico, tal y como se muestra en los resultados de los cálculos de periodo de retorno descritos en Molina et al. (I). La comparación de la distribución de los *stormy years* obtenidos en este trabajo con los observados por Rangel-Buitrago et al. (2011) en la región atlántica de Andalucía, muestra un comportamiento opuesto debido a que las tormentas en la región mediterránea de la costa andaluza están vinculadas esencialmente a los vientos provenientes del este mientras que en la región atlántica se encuentran vinculadas a los vientos del oeste.

4.2. Línea de costa y sistemas dunares

4.2.1. Evolución de la línea de costa

De las 47 unidades estudiadas, 9 unidades (70,35 km) presentan la prevalencia de clases de acreción, 19 unidades (89,9 km) presentan prevalencia de estabilidad y otras 19 unidades (124,07 km) muestran prevalencia de clases de erosión. Ninguna de ellas muestra acreción muy alta como clase representativa y sólo una unidad muestra erosión muy alta (Figura 8).

La distribución de las diferentes clases se muestra en la Figura 8, en la que se observan dos grandes áreas en erosión a lo largo del SO de la provincia de Málaga y al E de la provincia de Almería y una extensa área constituida por cuatro unidades con acreción muy alta se sitúa al este de la provincia de Málaga. Dentro de esta gran área se intercalan dos áreas estables, una de ellas cerca de Torremolinos (provincia de Málaga) y otra en La Herradura (provincia de Granada). Respecto a las clases de acreción, la más frecuente es la acreción alta (0,5 – 1,5 m/año), y es resultado del emplazamiento de numerosas estructuras de protección costera y trabajos de regeneración artificial de playa. Las clases de erosión se observan en áreas cercanas a puertos y estructuras de protección, en deltas y desembocaduras de ríos que han sido intervenidos. Por último, la clase de estabilidad se observa en playas de bolsillo y en algunas zonas que han sido estabilizadas con estructuras de protección costera. Para determinar con mayor detalle la influencia de las estructuras antrópicas en la evolución de la línea de costa, se ha analizado la distribución de las clases de evolución de acuerdo a la localización de dichas estructuras, en otras palabras, se ha analizado si una zona estaba localizada aguas arriba, aguas abajo o en correspondencia de una estructura, o si se localizaba en áreas “naturales”, es decir tramos del litoral sin estructuras. Además, se han tenido en cuenta las características de las estructuras, la dirección de los frentes de aproximación del oleaje y la dirección prevalente de transporte longshore (Molina et al., **II**).

Sectores naturales

En la costa mediterránea de Andalucía, los sectores costeros naturales estudiados muestran una tasa media de erosión de 0,17 m/año y no se registra acreción en ninguno de ellos (Molina et al., **II**), (Figura 9a). Es más, las áreas estudiadas situadas en deltas y desembocaduras de ríos son las que muestran tasas de erosión más elevadas, de 0,62 m/año de media, alcanzando valores de erosión alta y muy alta. Algunos ejemplos son los deltas de los ríos Adra y Andarax con valores de hasta 1,88 y 1,00 m/año respectivamente, y la desembocadura del río Aguas, con 1,15 m/año, en la provincia de Almería, o el delta del río Vélez y la desembocadura del río Verde en la provincia de Málaga, con valores respectivamente de hasta 3,71 y 0,82 m/año (Molina et al., **II**).

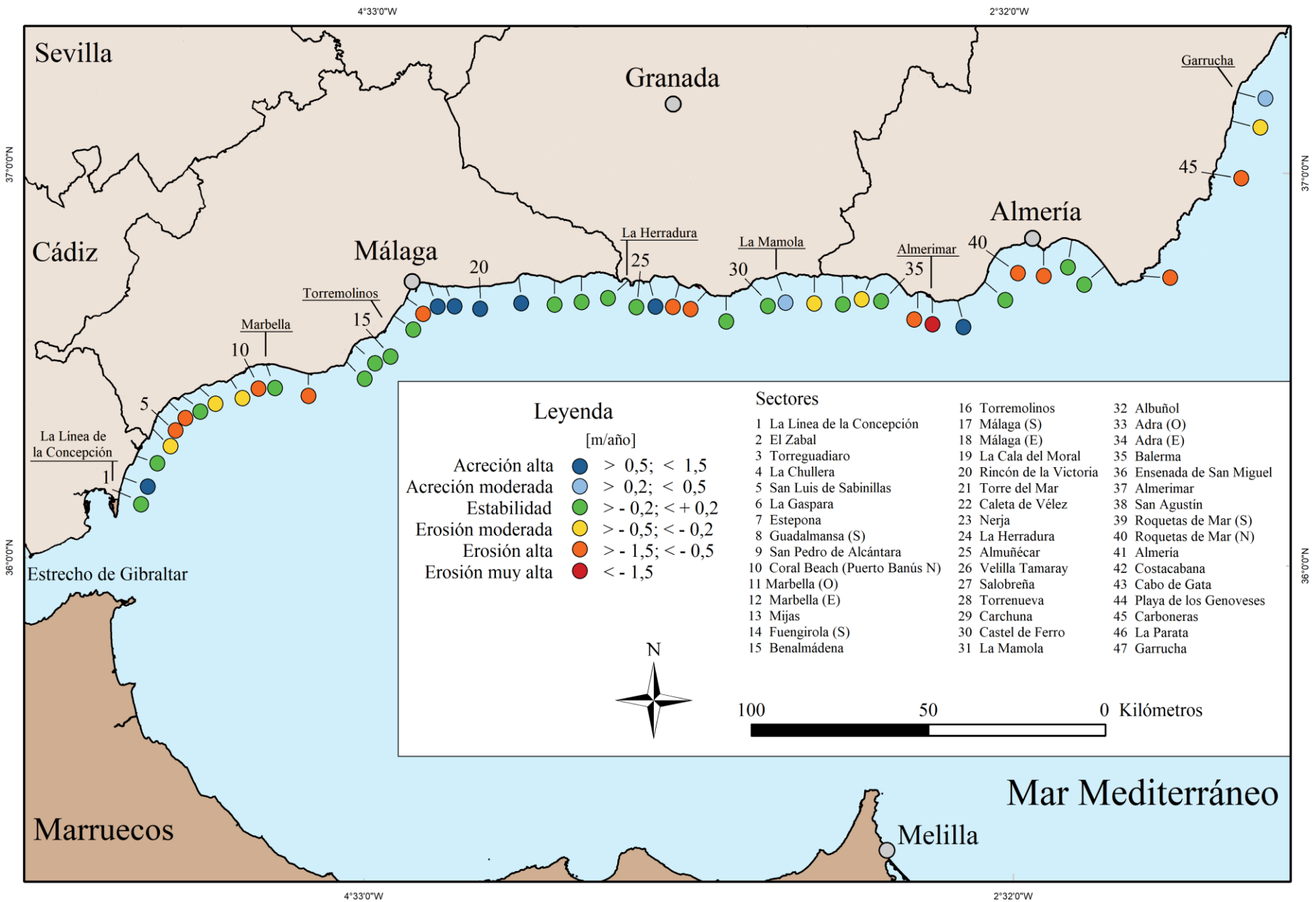


Figura 8. Evolución de la línea de costa.

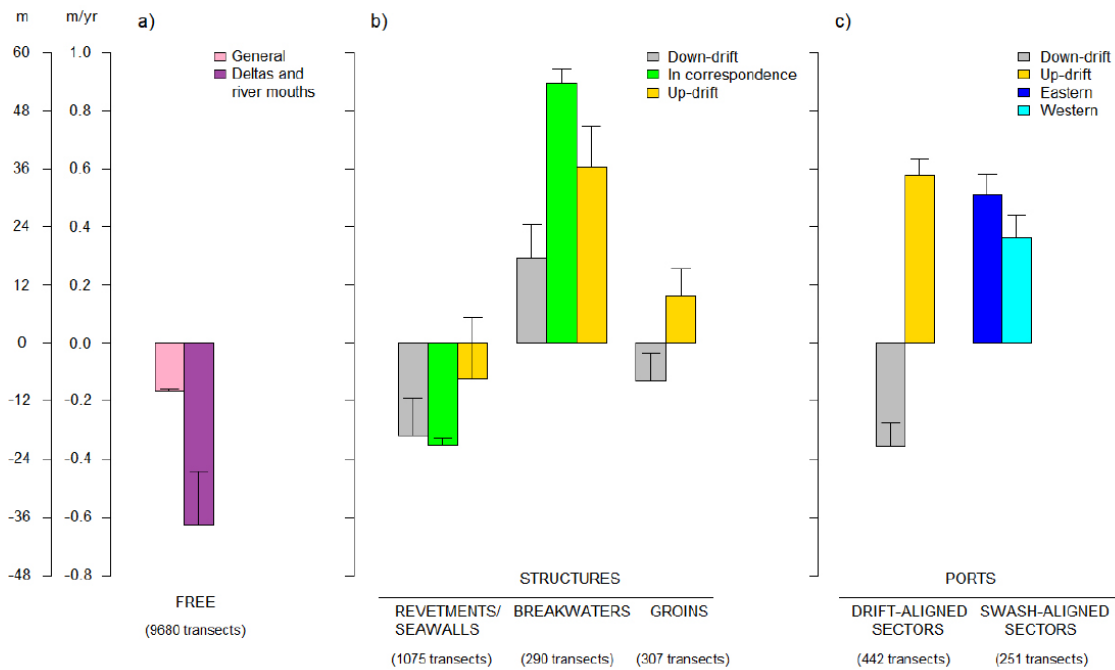


Figura 9. Valores y tendencias de las tasas de evolución según su localización, obtenido de Molina et al. (II): a) en áreas libre de estructuras, diferenciando entre áreas libres en general y áreas localizadas en correspondencia de desembocaduras fluviales y deltas; b) áreas aguas arriba, aguas abajo o en frente a estructuras (muros/revestimientos, rompeolas y espigones); y c) aguas arriba y abajo de puertos en costas *drift-aligned* y lados este y oeste de puertos en costas *swash-aligned*. Entre paréntesis se muestra el número de transeptos estudiados de cada tipo.

En la provincia de Almería, la evolución erosiva de los deltas de los ríos Andarax y Adra, y de la zona más oriental de la provincia (Figuras 1 y 8), está muy influenciada por la naturaleza torrencial de esos ríos y otros arroyos, además de por la progresiva construcción de presas que reducen considerablemente los aportes sedimentarios al litoral (Bayo Martínez, 1999; Viciano Martínez-Lage, 2007). Esta tendencia general se ha observado también en otros deltas en Andalucía como los de los ríos Vélez y Guadalfeo (Figura 1, Prieto et al., 2012), en los deltas del río Ebro en Cataluña (Jiménez y Sánchez-Arcilla, 1993), del Nilo en Egipto (Frihy, 1988; Frihy y Komar, 1991), del Arno en Italia (Pranzini, 2007) y del Hoeya en Korea (Kim et al., 2017), y en otros lugares del mundo (Syvitski et al., 2005).

En las playas de bolsillo (*pocket beaches*), se observa estabilidad (Molina et al., II) y un comportamiento típico pivotante (Valdemoro y Jiménez, 2006), como por ejemplo en la playa de La Herradura, en la provincia de Granada (Figuras 1 y 8). Este comportamiento se debe a que las playas de bolsillo son sistemas sedimentarios restringidos que experimentan muy poca o ninguna conexión con otros sistemas debido a la presencia de promontorios rocosos que las limitan (Dehouck et al., 2009).

Sectores influenciados por estructuras antrópicas (presas y estructuras de protección)

En sectores arenosos, la distribución espacial de áreas de acreción, erosión y estabilidad se encuentran esencialmente influenciadas por el emplazamiento de estructuras de protección costeras, puertos y promontorios naturales, y por la forma en la que estas estructuras interactúan con el oleaje, tal y como se ha observado en otras áreas (Manno et al. 2016; Anfuso et al., 2007; Bray et al., 1995; Pranzini et al., 2018a; Sanuy y Jiménez, 2019).

Como se ha mencionado antes, los ríos han visto menguada su capacidad para aportar sedimento al litoral debido a las numerosas intervenciones que se han llevado a cabo en los últimos años. Como ejemplo, en el río Verde (provincia de Málaga, Figuras 1 y 8), se encuentra la presa de La Concepción, la obra de ingeniería fluvial más importante de la Costa del Sol (Del Río et al., 2015), con un embalse de 2,14 km² de superficie, una capacidad de 57 x 10⁶ m³ y una longitud de río afectada de 5 km. Antes de la construcción de esta presa, el río Verde constituía la principal fuente de sedimento del área costera de Marbella (Del Río et al., 2015; Del Río y Malvárez, 2016, 2017).

Respecto al efecto de las estructuras de protección costeras, éste varía dependiendo del tipo de estructura (Molina et al., **II**), como se observa en la Figura 9 b. Los muros y revestimientos reflejan la energía del oleaje, restringiendo la migración natural del sedimento hacia tierra e induciendo a la erosión y a la pérdida de las playas que se encuentran frente a estas estructuras (Griggs, 2005; Dugan et al., 2011). Específicamente, las áreas estudiadas que se localizaron frente a este tipo de estructuras, así como las que se encontraban aguas arriba y abajo de ellas, se caracterizaron por registrar valores de erosión altos (desde 0,13 a 0,35 m/año, Molina et al., **II**), Figura 9 b). En cuanto a los rompeolas, éstos producen tómbolos (Nordstrom, 2000; Miles et al., 2001), muy frecuentes en la provincia de Málaga (p. ej., Málaga y Puerto Banús, Figura 1). En las áreas caracterizadas por la presencia de rompeolas se registró acreción, especialmente donde estas estructuras eran muy numerosas. Este tipo de estructuras son mucho más efectivas reteniendo sedimentos respecto a los espigones y muestran valores medios de acreción de hasta 0,89 m/año, cercanos a los valores que se registran aguas arriba de puertos (Molina et al., **II**, Figura 9 b y c). Las estructuras perpendiculares a la orilla (diques y espigones) y los puertos actúan como límites absolutos o permeables de celdas (Bray et al., 1995) que afectan a la circulación de la zona de surf y, normalmente, producen acreción aguas arriba y erosión aguas abajo, tal como observado también por Rangel-Buitrago et al. (2012, 2018) a lo largo de la costa caribeña de Colombia o por Anfuso et al. (2013) en el sureste de Sicilia. En este trabajo, los valores medios registrados en las áreas aguas arriba y abajo de estas estructuras reflejan el efecto del transporte longitudinal: valores medios de acreción aguas arriba de 0,16 m/año y de erosión aguas abajo de 0,13 m/año (Molina et al., **II**, Figura 9 b). En cuanto a las áreas cercanas a puertos, éstas se dividen en dos grupos: áreas aguas arriba y abajo cuando los puertos se encuentran en sectores costeros *drift-aligned* (áreas costeras donde se observa una dirección clara de transporte longitudinal) y áreas este y oeste cuando los puertos se

encuentran en sectores *swash-aligned* (áreas costeras donde la dirección de transporte es bidireccional y/o transversal) (Molina et al., **II**).

Las áreas localizadas aguas arriba de los puertos registraron los valores más altos de acreción respecto a aquellas localizadas en correspondencia de todos los demás tipos de estructuras, y los valores de erosión se observaron en áreas aguas abajo (Figura 9 c), como por ejemplo en el puerto de Sotogrande, en la provincia de Cádiz, y el puerto de Garrucha en la provincia de Almería (Figura 1, Molina et al., **II**), una tendencia común a lo largo de costas arenosas (Dugan et al., 2011; Miles et al., 2001). Los puertos situados en sectores *swash-aligned* muestran acreción a ambos lados (Molina et al., **II**, Figura 9 c). La forma y dimensiones de las playas recién formadas dependen de las características de las estructuras y del régimen de oleaje, tal y como han observado diferentes autores en diversas áreas (Manno et al., 2016; Anfuso et al., 2012; Bray et al., 1995).

Para prevenir el desarrollo de procesos erosivos en áreas aguas abajo es muy común el emplazamiento progresivo de nuevas estructuras, generando el llamado “efecto dominó” (Cooper et al., 2009). Este proceso, observado con frecuencia en la costa mediterránea (Manno et al., 2016; Anfuso et al., 2012 y 2013; Sabatier et al., 2009), traslada y amplifica los procesos de erosión en áreas aguas abajo. Un ejemplo de ello es la construcción del puerto de Almerimar (Figura 1), en la provincia de Almería, en 1978; de acuerdo a Viciana Martínez-Lage (2007), la estructura causó la desaparición en la zona aguas abajo de 20.000 m² de superficie de playa. En 1996, se construyeron dos estructuras para reducir la erosión costera; estas estructuras resultaron inefectivas provocando la pérdida de más de 135.500 m² de superficie (Viciana Martínez-Lage, 2007). Hoy en día se llevan a cabo regeneraciones artificiales periódicas para mantener la playa. Otra causa importante de erosión, además de la construcción de las estructuras, ocurrió durante el periodo 1956-1988 cuando se produjeron extracciones ilegales de más de 5 millones cúbicos de arena de las playas y dunas en la zona de Punta Entinas – El Sabinar (Figura 1) (Viciana Martínez-Lage, 2007).

Cabe señalar que la evolución de la línea de costa no se ha producido siempre de manera uniforme, es decir, se ha registrado una inversión en la tendencia, normalmente de erosión a acreción, en muchos lugares puntuales en los que la tendencia erosiva se ha contrarrestado con la construcción de estructuras costeras y/o regeneraciones artificiales de playa, por ejemplo en Puerto Banús y en La Línea de la Concepción (Figura 1, Molina et al., **II**).

Sectores costeros *swash-* y *drift-aligned*

Se dice que un sector costero tiene una tendencia *drift-aligned* cuando es resultado de un transporte claro unidireccional, mientras que un sector costero con tendencia *swash-aligned*, es el resultado de un transporte longitudinal bidireccional y/o transversal (Davies, 1980; Nordstrom, 2000). Para su determinación se pueden utilizar los análisis de la forma en planta de playa y su variación temporal, que a su vez dependen del clima

marítimo (Sanuy y Jiménez, 2019; Wiggins et al., 2019) y de las características de las estructuras naturales y humanas (Bray et al., 1995).

En la costa mediterránea de Andalucía se han identificado dos grandes áreas de costa *swash-aligned*: en la Costa del Sol (provincia de Málaga) y en el golfo de Almería. En concreto, la costa de Málaga se encuentra fuertemente urbanizada (Manno et al., 2016; Malvárez et al., 2000) y cuenta con numerosas estructuras de protección costera. Para contrarrestar los procesos de erosión ligados a las recurrentes tormentas, fueron inyectadas grandes cantidad de sedimentos que alteraron la dinámica natural del área. Además, las características dinámicas del área han sido alteradas por la construcción de numerosos espigones que, sucesivamente, fueron sustituidos por rompeolas, dando lugar a la formación de tómbolos (Malvárez et al., 2000) y a una costa *swash-aligned* estable (Manno et al., 2016).

Respecto a las principales direcciones de transporte presentadas en Molina et al. (II) (Figura 1), éstas reflejan los resultados de las rosas de oleaje y las direcciones de aproximación de las tormentas presentadas en Molina et al. (I). La parte más occidental de la costa estudiada (*drift-aligned*) se encuentra protegida, debido a su situación geográfica, del oleaje atlántico y expuesta a los frentes del E que forman un ángulo de unos 45 grados con la línea de costa; la dirección principal de transporte observada en esta área confirma estos datos, mostrando una tendencia principal de transporte NE-SO en La Línea de la Concepción y Sotogrande, donde el puerto, construido en 1987, interrumpe claramente el transporte longitudinal (Molina et al., II, Figura 10).

En la parte central del área de estudio (Figura 1), con tendencia *drift-aligned*, el viento y el oleaje se aproximan por el O, E y E-NE, siendo la componente O prevalente debido al incremento del *fetch* geográfico del oeste. Por lo tanto, los frentes de oleaje *offshore* son generalmente paralelos a la costa y los eventos más energéticos se aproximan desde esas direcciones (Molina et al., I).

Como observaron en Suffolk (UK) Burningham y French (2017), el clima marítimo bimodal tiene un fuerte control en el movimiento del sedimento a lo largo de la costa. La dirección de transporte O-E fue observada en la parte central del área de estudio, por ejemplo en Adra (Molina et al., II, Figura 1). Dicha tendencia es evidente en su puerto, en el que, en 1947 se construyó un dique para eliminar los problemas de aterramiento (Bayo Martínez, 1999). En la parte más oriental de la costa estudiada, orientada NNE-SSO y con tendencia *drift-aligned*, prevalecen las direcciones de transporte del E-NE formando un ángulo de unos 30 grados con la costa (Figura 1); esto se confirma por las evidencias observadas en el marco de este trabajo por ejemplo en correspondencia del puerto de Garrucha (Molina et al., II, Figura 10).



Figura 10. Ejemplos de sectores *drift-* y *swash-aligned* obtenidos de Molina et al. (II) en correspondencia de los puertos de Sotogrande (a), Adra (b) y Garrucha (c).

4.2.2. Evolución de los sistemas dunares

En cuanto a los sistemas dunares, se han calculado y clasificado las superficies de las dunas y se ha analizado la variación de éstas para el periodo 1977-2016. Un total de 15 sistemas dunares desapareció durante el periodo estudiado, 7 de ellos localizados en la provincia de Málaga, otros 7 sistemas en la provincia de Almería y un sistema en la provincia de Cádiz. La comparación de la superficie total de dunas en erosión y en acreción muestra un claro balance negativo en 49 de los 53 sistemas y positivo para los 4 sistemas restantes, localizándose estos 4 últimos en la Playa del Rinconcillo (38.884,4 m²), las desembocaduras de los ríos Guadarranque (19.262,8 m²) y Guadalquítón (260.531,7 m²) en la provincia de Cádiz y en el área natural protegida de Albufera de Adra (6.708,5 m²) en la provincia de Almería. Los sistemas que han registrado mayor erosión se localizan en la provincia de Almería, siendo el mayor de ellos Punta Entinas – El Sabinar (4.166.157,9 m²) seguido del área situado en Vera (567.841,2 m²) y la Ensenada de San Miguel (557.765,0 m²) (Figura 11). Finalmente, para determinar con mayor detalle la influencia de la presión antrópica sobre la evolución de las dunas, se han calculado las superficies ocupadas por estructuras y/o intervenciones humanas dentro de cada sistema dunar y su continuidad lateral a partir de un índice de fragmentación del pie de duna (Molina et al., III).

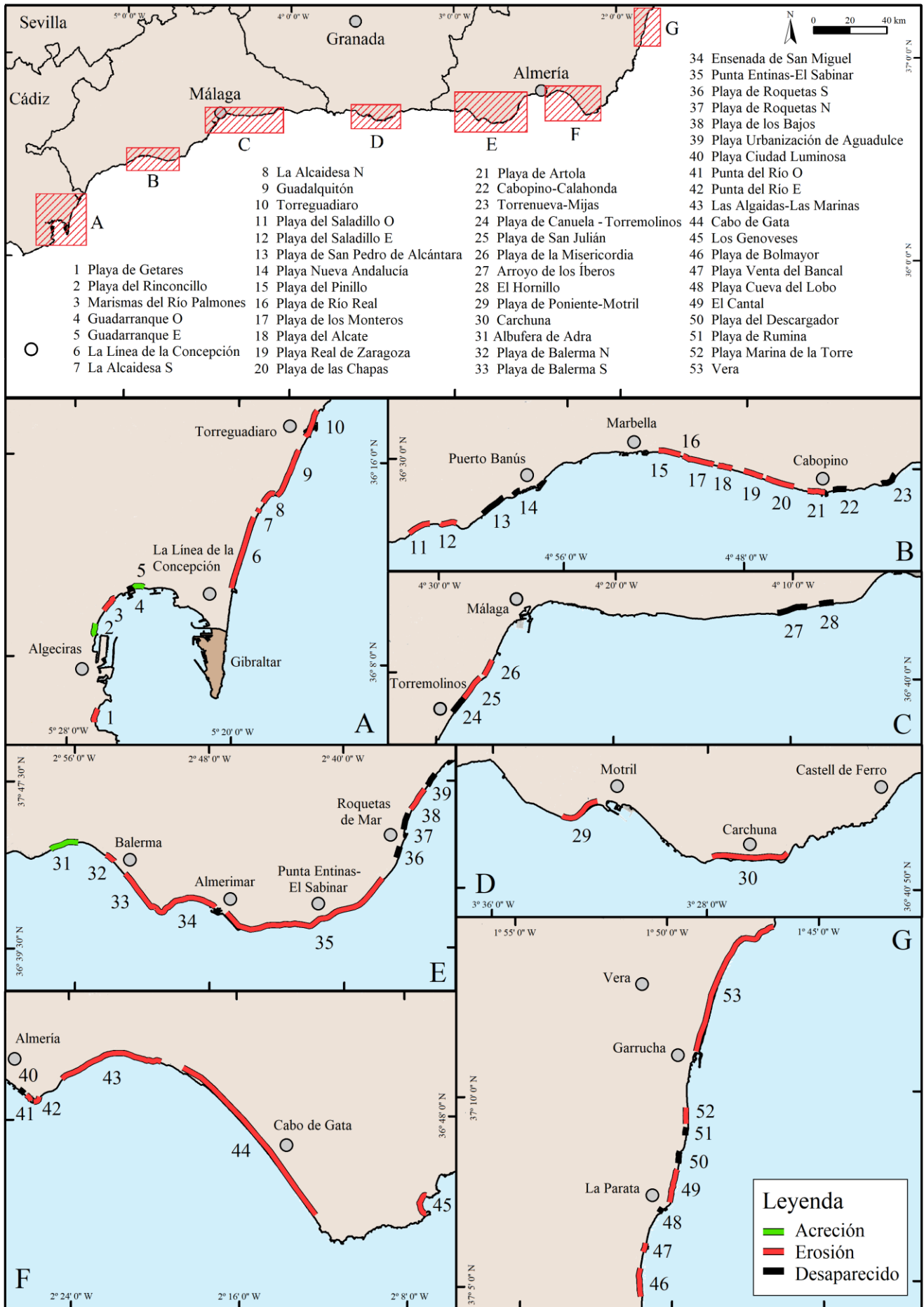


Figura 11. Resultados de la evolución de los sistemas dunares.

La erosión o la completa desaparición de los sistemas dunares se pueden producir como consecuencia de actividades humanas o por procesos naturales (Hesp, 2002; Sanjaume y Pardo-Pascual, 2011), descritos con mayor detalle en Molina et al. (III), siendo los impactos antrópicos los más evidentes en el área de estudio, especialmente en las costas de las provincias de Málaga y Almería (Bayo-Martínez, 1999; Viciano Martínez-Lage, 1999; 2007; Malvárez et al., 2000; Sanjaume y Pardo-Pascual, 2011; Bardají et al., 2011; Gracia et al., 2011; Prieto et al., 2012; Gómez-Zotano, 2014; Del Río y Malvárez, 2016; Manno et al., 2016; Castaño Camero et al., 2017; Díez-Garretas et al., 2019; Molina et al., III).

En el área de estudio se han encontrado muy pocos casos de sistemas dunares en áreas naturales que permanezcan sin alterar, bien por la ocupación de su superficie o por la presencia de estructuras de protección costeras y, en general, se encuentran en erosión (Molina et al., III).

Las condiciones para la formación y el desarrollo de las dunas han sido discutidas por un gran número de autores quienes concuerdan que los factores más importantes que controlan la relación del sistema playa-duna son la variación temporal de los aportes sedimentarios y los regímenes de viento (Hesp, 1984; 2002; Nordstrom, 2000; Martínez y Psuty, 2008; Psuty, 2008). En este trabajo, los pocos casos de sistemas dunares en acreción se asocian a procesos naturales de sedimentación, o ligados a la presencia de estructuras antrópicas, registrados en las playas directamente ubicadas en frente de los sistemas o al suministro de sedimento de los ríos que desembocan en su correspondencia (Molina et al., III).

Sistemas en erosión

Respecto a los 53 sistemas dunares estudiados, todos menos 4 registraron una reducción de su superficie, o incluso su desaparición (Figura 11, Molina et al., III), especialmente en los lugares donde los sistemas se han visto afectados por intensas intervenciones humanas (Gómez-Zotano, 2014; Díez-Garretas et al., 2019; Castaño Camero et al., 2017; Bayo Martínez, 1999; Viciano Martínez-Lage, 1999; 2007; Bardají et al., 2011; Gracia et al., 2011) y, secundariamente, por la pérdida de superficie producida por la erosión de la línea de costa (Viciano Martínez-Lage, 2007; Fernández-Salas et al., 2009; Malvárez et al., 2019). La mayor pérdida de superficie de dunas se produjo en el periodo 1977-2001 debido a la ocupación urbana masiva de las áreas costeras, no obstante, en el periodo 2001-2016 se ha observado una disminución de la superficie de las dunas debido a que las principales causas de su destrucción registradas en el periodo anterior cesaron parcialmente (Molina et al., III). Aún se siguen observando casos de desaparición por ocupación urbana, especialmente en la provincia de Málaga (Gómez-Zotano, 2014; Molina et al., III), sin embargo, la presión antrópica derivada del uso turístico de las playas y la disminución de las contribuciones de los ríos no fueron tan evidentes en el periodo 1977-2001 (Malvárez et al., 2000; Castaño Camero et al., 2017;

Bayo Martínez, 1999; Viciano Martínez-Lage, 1999; 2007; Bardají et al., 2011; Gracia et al., 2011).

La pérdida de superficie de dunas ha estado relacionada con la fragmentación del pie de duna (es decir, el incremento de la discontinuidad del cordón dunar), la cual es un factor a considerar para la estimación de la vulnerabilidad costera y la sensibilidad de las dunas (Gracia Prieto et al., 2009; García-Mora et al., 2001; Rangel-Buitrago y Anfuso, 2015; Rizzo et al., 2018) ya que un sistema dunar fragmentado es más sensible a la inundación temporal que se da durante las tormentas (Carter, 1991; Gracia Prieto et al., 2009; Rangel-Buitrago y Anfuso, 2015; Rizzo et al., 2018; Kraus et al., 2002; Ceia et al., 2010). En este estudio, los sectores más fragmentados (y por tanto más susceptibles) se han observado en un área natural en el lado oeste del delta del río Andarax en la provincia de Almería (se trata del sistema más fragmentado, Figuras 1 y 11), y el sistema dunar de la playa de Las Chapas en la provincia de Málaga, situado en un área urbana fuertemente desarrollada (Figuras 1 y 11, Molina et al., **III**). En la mayoría de los sectores la fragmentación de las dunas se debe principalmente a la apertura de caminos y a su progresiva expansión debido a procesos de erosión marinos y eólicos, también observados en otras áreas por Gracia Prieto et al. (2009), Pintó et al. (2014), Rangel-Buitrago y Anfuso (2015) y Rizzo et al. (2018). Debido al detalle de las ortofotografías utilizadas en este estudio, las discontinuidades causadas por procesos de *overwash* se han podido detectar en muy pocos lugares.

En resumen, la mayoría de los sistemas dunares que han mostrado una disminución en su superficie han sido afectados por factores antrópicos, subrayando la importancia de las ocupaciones urbanas y agrícolas que han sido muy relevantes en las provincias de Málaga y Almería (Molina et al., **III**).

Sistemas en acreción

En cuanto a los 4 sistemas dunares que han registrado acreción, el incremento de los sistemas situados en la Bahía de Algeciras (Molina et al., **III**, Figuras 1 y 11) está asociado a los procesos de sedimentación registrados en sus respectivas playas (Molina et al., **II**; REDIAM. WMS, Tasas de Erosión en el Litoral Andaluz. <http://www.juntadeandalucia.es/medioambiente/site/rediam>) que reciben un suministro de sedimento de los ríos Palmones y Guadarranque (Gracia et al., 2011). Además, estas playas se localizan cerca de dos grandes estructuras de protección costeras que promueven los procesos de sedimentación. En el caso del sistema observado en El Rinconcillo en 2001, comenzó a formarse tras la expansión del puerto de Algeciras (Molina et al., **III**, Figuras 11 y 12). Sin embargo, los sistemas en Guadalquítón y Albufera de Adra (Figuras 1 y 11) se encuentran en áreas que han registrado una erosión importante (Molina et al., **II**; REDIAM. WMS, Tasas de Erosión en el Litoral Andaluz. <http://www.juntadeandalucia.es/medioambiente/site/rediam>) y una ocupación antrópica significativa ligada al desarrollo urbano en el caso de Guadalquítón y a una intensa ocupación agrícola en el caso de la Albufera de Adra. El sistema dunar de Guadalquítón

registró su mayor incremento durante el periodo 1977-2001, y fue debido a la degradación de la vegetación que facilitó la migración hacia tierra de las dunas (Molina et al., **III**). La formación de grandes dunas móviles en esta área se debe también a los fuertes vientos del este (Molina et al., **I**, Figura 1), en especial en playas orientadas a esa dirección (Molina et al., **II**). En el caso del sistema dunar de la Albufera de Adra, se produjo una importante pérdida de superficie de dunas en el periodo 1977-2001 debido a la erosión de la línea de costa y a la importante presión antrópica (intensas actividades agrícolas) (Molina et al., **II**; Prieto et al., 2012; REDIAM. WMS, Tasas de Erosión en el Litoral Andaluz. <http://www.juntadeandalucia.es/medioambiente/site/rediam>); sin embargo, la sedimentación que se produjo en el extremo norte del sistema (Molina et al., **II**; REDIAM. WMS, Tasas de Erosión en el Litoral Andaluz. <http://www.juntadeandalucia.es/medioambiente/site/rediam>) apoyó el desarrollo de dunas móviles (Molina et al., **III**).



Figura 12. Playa del Rinconcillo, de Molina et al. (**III**). En esta playa se registró un aumento de la superficie del sistema dunar de 732,26 m² en el periodo 2001-2006. (A) 1977, (B) 2001 y (C) 2016.

Evolución de los tipos de dunas

Muchos de los sistemas dunares estudiados en este trabajo han sido descritos por diferentes autores (Gómez-Zotano, 2014; Díez-Garretas et al., 2019; Bayo Martínez, 1999; Viciano Martínez-Lage, 1999; 2007; Bardají et al., 2011; Gracia et al., 2011; Fernández-Salas et al., 2009; Malvárez et al., 2019), pero ninguno de ellos ha proporcionado una descripción de todo su conjunto a lo largo de la costa mediterránea de Andalucía.

Al contrario que en costas con influencia mareal en las que la contribución sedimentaria se puede obtener a través de la exposición periódica de la llanura intermareal, en costas micro-mareales como es la costa mediterránea, es la playa seca la principal fuente sedimentaria de los sistemas dunares (Bardají et al., 2011). Además,

cuando las playas se componen de gravas, como es el caso de muchas playas de Málaga y Almería, es más difícil asegurar la fuente de sedimento arenoso necesario para los sistemas dunares y, por ello, los ríos pasan a ser los proveedores principales del sistema (Bardají et al., 2011). Como se ha dicho anteriormente, los sistemas fluviales de la costa mediterránea de Andalucía son en su mayoría cortos o de carácter estacional y, en general, proveen a las playas un sedimento de tamaño grueso. Además, el relieve acentuado observado cerca de la costa y la presencia de playas reflectivas, representan grandes limitaciones para el desarrollo de sistemas dunares (Bardají et al., 2011).

Otros puntos a tener en cuenta son la intensidad y la dirección de los vientos predominantes que, para ser efectivos para la formación de dunas, deben soplar perpendicularmente a la costa. Las provincias de Cádiz (en especial) y Almería constituyen áreas favorables para la formación de dunas debido a su orientación perpendicular a los vientos predominantes (Molina et al., **I**, **III**). De acuerdo a Bardají et al. (2011) y Gracia et al. (2011), la parte central de la costa de Andalucía es paralela a los vientos predominantes que dan lugar a un importante transporte longitudinal paralelo a la costa que alimenta diferentes sistemas dunares, p. ej., el sistema dunar de Artola-Cabopino (Bardají et al., 2011; Malvárez et al., 2019).

A la hora de analizar la evolución de cada uno de los tipos de dunas, cabe destacar que cada tipología representa un claro estado de evolución, desde las dunas embrionarias y móviles (Tipo I) hasta las dunas estabilizadas (Tipo III) (Hesp, 1984; 2002). El incremento durante el periodo 1977-2016 de las dunas estabilizadas (Tipo III) se debió a la progresiva evolución de las dunas fijadas por céspedes (Tipo II) (Molina et al., **III**), un proceso natural descrito por Hesp (1984; 2002).

Las variaciones de superficie de los diferentes tipos de sistemas dunares fueron relativamente homogéneas (Molina et al., **III**). A excepción de la provincia de Cádiz, el resto de provincias mostraron una disminución de los tres tipos de dunas en el primer periodo y, en el segundo periodo, una disminución de los tipos I y III junto al incremento de las dunas de tipo II en todas las provincias excepto Almería (Molina et al., **III**). La disminución general registrada en el periodo 1977-2001 se debió principalmente a la ocupación urbana, la explotación agrícola intensiva y la extracción de arenas – actividades que no fueron reguladas hasta la aprobación de la Ley de Costas en 1988 (Gómez-Zotano, 2014; Malvárez et al., 2000; Díez-Garretas et al., 2019; Castaño Camero et al., 2017; Bayo Martínez, 1999; Viciano Martínez-Lage, 1999; 2007; Bardají et al., 2011; Gracia et al., 2011). La destrucción de las dunas se evidencia especialmente en las provincias de Málaga y Almería, donde han desaparecido sistemas de dunas completos (Molina et al., **III**): en la provincia de Málaga se perdió una superficie total de 1.766.711 m², de la que cerca de 1 x 10⁶ m² correspondían a dunas de tipo II y cerca de 600.000 m² fueron dunas de tipo III y, en la provincia de Almería, se perdió una superficie de unos 56.300.000 m², de la cual unos 4.360.000 m² correspondieron a dunas de tipo II. Algunos ejemplos de trabajos que han cuantificado la pérdida de superficie de dunas en áreas específicas son el de Viciano Martínez-Lage (2007) que cuantificó una pérdida de 262 ha de dunas en el Paraje Natural de Punta Entinas – El Sabinar, en la provincia de Almería, debido a las

extracciones de arenas, o el trabajo de Gómez Zotano (2014) que cuantificó una reducción del 44,5% de la superficie de dunas durante el periodo 1956-2007 en el área de El Saladillo, en la provincia de Málaga.

El incremento, en el periodo 2001-2016, de la superficie de las dunas de tipo II en la provincia de Málaga estuvo ligado a la degradación de las dunas de tipo III, evidenciado especialmente en el área oeste de la ciudad de Marbella que fue fuertemente afectada por el desarrollo urbano (Molina et al., **III**), una tendencia muy común en la provincia de Málaga (Gómez-Zotano, 2014; Malvárez et al., 2000; 2003). El incremento de las dunas de tipo III en la provincia de Almería se debió a la estabilización de las dunas de tipo II, en especial en el área comprendida entre Albufera de Adra y Almerimar y en Cabo de Gata, cuyas líneas de costa son estables (Molina et al., **II**). En general, en la provincia de Cádiz, se observó un pequeño incremento de dunas de tipo III, y el resto de tipos registraron pequeñas variaciones (Molina et al., **III**). Este comportamiento se debió a una presión antrópica baja, las condiciones estables e incluso en acreción del área (Molina et al., **II**; REDIAM. WMS, Tasas de Erosión en el Litoral Andaluz. <http://www.juntadeandalucia.es/medioambiente/site/rediam>) y a la acción de los fuertes vientos del este que favorecen el crecimiento y la movilidad de las dunas (Gracia et al., 2011).

4.3. Estrategias de mitigación

Tal y como se ha introducido en este trabajo, las estrategias de mitigación que se proponen están basadas en la combinación de los parámetros de sensibilidad costera y los tipos de usos del suelo. A continuación, se realiza un breve análisis de los parámetros utilizados, descritos en Molina et al. (**IV**).

4.3.1. *Wave forcing*

Los parámetros considerados como *forcing agents* por Rangel-Buitrago y Anfuso (2015), siguiendo numerosas investigaciones (Rangel-Buitrago y Anfuso, 2013; Rizzo et al., 2018; Almeida et al., 2011; Stockdon et al., 2006; Pye y Blott, 2008; Di Risio et al., 2017; Pascuali et al., 2019), son la altura de ola, la marea de tormenta, el grado de exposición del litoral a los frentes de oleaje (Gracia et al., 2006) y el rango mareal (McLaughlin y Cooper, 2010). En este trabajo se ha utilizado la energía del oleaje (E_f , *Energy Flux*) asociada a eventos de condiciones muy energéticas, es decir, tormentas con un periodo de retorno de 50 años, debido a que no fue posible calcular la marea de tormenta (*storm surge*) y el rango mareal es uniforme a lo largo del área estudiada. Se ha considerado que la distribución a lo largo de la costa de la E_f del oleaje representa de forma adecuada a los *forcing agents*, ya que ésta se obtiene como resultado del proceso de propagación del oleaje y por lo tanto, refleja muchos de los factores acumulativos que

determinan la forma en la que la energía del oleaje se distribuye a lo largo de la costa (p. ej., el grado de exposición del litoral y las características batimétricas locales).

El oleaje de tormenta que se aproxima por el ENE afecta predominantemente al área más oriental de la costa mediterránea de Andalucía, desde Cabo de Gata hasta el límite administrativo de la Región. El resto de la costa se expone esencialmente a frentes de oleaje de tormenta provenientes del OSO (Molina et al., **IV**). El área central de la costa estudiada se caracteriza por la alternancia de vientos y oleaje del E y O, como se observa en la Costa del Sol (Guisado y Malvárez, 2009; Guisado et al., 2013; Malvárez et al., 2019) y en este trabajo (Molina et al., **IV**).

4.3.2. Buffer Zone

Una amplia playa seca representa una eficiente *buffer zone* contra los procesos de erosión por tormentas, aunque este parámetro, a menudo se considera de forma subjetiva. La sensibilidad costera se suele expresar a través de tasas de erosión en muchos estudios regionales y locales (Gortniz et al., 1994; García-Mora et al., 2001; Raji et al., 2013), y debido a que éstas tasas varían de manera considerable de un lugar a otro (Rangel-Buitrago y Anfuso, 2015; Di Risio et al., 2017; Molina et al., **II**), resulta muy difícil el uso y aplicación de una metodología única para este fin. Teniendo en cuenta que la función protectora de la playa seca está fuertemente relacionada con su amplitud y las tasas de erosión locales, en este trabajo se ha considerado para el cálculo de la sensibilidad costera utilizar el ancho de playa como múltiplo de la posición de la línea de costa predicha para los próximos 20 años (Molina et al., **IV**).

Para demostrar la asunción de que el ancho absoluto de playa seca es inefectivo como indicador de la *buffer zone* ya que las tasas de erosión varían de sitio en sitio, se han comparado los resultados obtenidos en Molina et al. (**II**) para las tasas de evolución de la costa mediterránea de Andalucía con los resultados de la estimación del ancho de playa expresado como múltiplo de la línea de costa predicha para los próximos 20 años (Molina et al., **IV**):

- En ocasiones existe una correspondencia directa entre el ancho de la playa seca y su tendencia a la erosión o a la acreción, como por ejemplo El Zabal (SO de la provincia de Cádiz), que presenta una amplia playa que alcanza los 101,4 m de ancho, clasificada como “muy amplia” en Molina et al. (**IV**) y con “acreción alta” en Molina et al. (**II**), o Los Genoveses (E de la provincia de Almería), con un ancho de playa de hasta 3,91 m, clasificada como “muy estrecha” en Molina et al. (**IV**) y con “erosión alta” en Molina et al. (**II**).
- No obstante, en muchos otros casos no se cumple esta premisa, como por ejemplo en el Parque Natural de Punta Entinas – El Sabinar (provincia de Almería) donde, pese a que su playa se clasifica como “muy estrecha” (Molina et al., **IV**), presenta la clase “acreción alta” utilizada en Molina et al. (**II**), y al contrario, en Salobreña y Carboneras (provincia de Almería) que presentan

anchos de playa de hasta 196,8 y 111,6 m respectivamente (“muy amplia”), la tasa de evolución que presentan pertenece a la clase “erosión alta” de Molina et al. (II).

4.3.3. Usos del suelo

Las categorías de usos del suelo que se han utilizado en este trabajo coinciden, en general, con las propuestas por McLaughling et al. (2002), McLaughling y Cooper (2010) y Rangel-Buitrago y Anfuso (2015) y, con el fin de disponer categorías más objetivas y bien establecidas, se han utilizado los datos de la web oficial de la Junta de Andalucía, basados en el Proyecto SIOSE, que es una continuación del Proyecto Europeo CORINE. Una de las ventajas de utilizar estas categorías es que se basan en el sistema de clasificación HILUCS (Hierarchical INSPIRE Land Use Classification System) de la Directiva europea INSPIRE y están integradas en el “Land Monitoring Service” del Programa Copernicus (Earth Observation Programme) y, por lo tanto, es compatible con la clasificación de usos del suelo europea y de fácil acceso a escalas europeas y globales.

Otros aspectos en los que se podrían centrar futuras investigaciones son el porcentaje de área urbanizada que se ha expresado en función de la densidad de las infraestructuras humanas y coincide, en general, con los índices “engineered frontage” (Özyurt y Ergin, 2009; 2010), “coastal construction index” (Li y Li, 2011), y numerosos sub-índices caracterizados por McLaughling y Cooper (2010) (p. ej., “settlements”, “roads”, “railway”).

4.3.4. Estrategias de mitigación

Tal y como apunta Williams y Micallef (2009), una buena gestión de playas debe disponer de una base de datos del sistema-playa y los ambientes asociados a él y de los procesos de erosión/sedimentación que allí se producen. Toda esta información sirve para identificar tendencias, sus implicaciones y origen y proveen una base sobre la cual diseñar planes de manejo costero, la consiguiente evaluación de estos planes y los posibles rediseños de las estrategias.

La metodología que se propone en este trabajo (Molina et al., IV) representa una herramienta valiosa para los gestores costeros a una escala regional, que se puede aplicar fácilmente en diferentes áreas costeras alrededor del mundo en las que se disponga de información básica sobre los parámetros descritos.

Las tres opciones que se han propuesto son: “No Action”, “Adaptation” y “Protection”.

La opción “No Action” se ha aplicado en áreas donde la sensibilidad costera y las clases de usos del suelo son bajas. Esto se ha observado en el área más occidental de la provincia de Cádiz y en algunas áreas del oeste de la provincia de Almería (Molina et al.,

IV). A corto plazo, no se requieren intervenciones en estas áreas, sin embargo, a largo plazo, hay que prestar atención a los posibles cambios en la tendencia costera debido a los procesos relacionados con el cambio climático, como serían por ejemplo los cambios en la intensidad de las tormentas o la subida del nivel del mar (Gornitz, 1990; Gornitz et al., 1997; Committee on Climate Change, 2016), aunque éste último proceso (subida del nivel del mar) parece no ser un problema muy relevante en estas áreas (Criado-Aldeanueva et al., 2008; Tsimplis et al., 2011; Puertos del Estado, 2017).

La opción “*Adaptation*” se ha relacionado, en parte, al gran nivel de urbanización y comportamiento erosivo de la costa mediterránea de Andalucía, los cuales han sido bien documentados por numerosos autores (Bayo Martínez, 1999; Malvárez et al., 2000; Viciano Martínez-Lage, 2007; Javaloy et al., 2008; Guisado-Pintado y Malvárez, 2015 Manno et al., 2016; Molina et al., **II**). Específicamente, la opción de adaptación correspondió a más de la mitad de la costa estudiada, abarcando esencialmente en dos casos principales (Molina et al., **IV**): (1) áreas naturales con alta sensibilidad y (2) en áreas urbanizadas con valores bajos de sensibilidad. Algunos ejemplos del primer caso se encuentran al este de la provincia de Almería (áreas naturales al sur de Carboneras, en La Parata y al norte de Garrucha), y del segundo caso, al suroeste de la provincia de Cádiz (La Línea de la Concepción) y en la provincia de Málaga (Puerto Banús y la Costa del Sol en general). Además, a pesar de que los valores de subida del nivel del mar que se han registrado en estas áreas son de unos pocos milímetros por año (Criado-Aldeanueva et al., 2008; Tsimplis et al., 2011; Puertos del Estado, 2017), se espera que los problemas de erosión aumenten en las próximas décadas. Como esta metodología se ha aplicado a una escala regional grande, no ha sido posible distinguir o proponer estrategias específicas de adaptación acordes a la sensibilidad costera y a la distribución/tipología de los usos de suelo, por lo que se deben llevar a cabo futuras investigaciones a escalas espaciales más pequeñas a fin de recomendar la mejor estrategia de adaptación que van desde la estrategia “*land use change*” (p. ej., un área agrícola se puede transformar en una zona de pastoreo (Pethick, 2001; Hansom, 2001; Williams et al., 2018)) hasta la estrategia “*relocation*” (p. ej., el movimiento tierra adentro de una carretera costera, Pranzini et al., 2015), como puede ser el caso de la principal autovía de Andalucía (A-7 Autovía del Mediterráneo) a su paso por Mijas y Fuengirola (provincia de Málaga) y la carretera nacional (N-340) a su paso por algunos sectores de Vélez – Málaga (provincia de Málaga) y Adra (provincia de Almería). En otras localizaciones, la adaptación se debe dedicar a la modificación de estructuras de protección existentes, como propone Costa y Coelho (2013), o a su abandono de acuerdo a la estrategia “*do nothing*” (Pranzini et al., 2015). Este podría ser el caso de las áreas de Puerto Banús y de muchas playas urbanas de la costa de Málaga protegidas por estructuras costeras que han sido modificadas en numerosas ocasiones a lo largo de las últimas décadas (Manno et al., 2016). Estas estructuras necesitan un mantenimiento periódico y/o modificaciones (p. ej., reducción de rompeolas o espigones), reduciendo de este modo su impacto paisajístico (Pranzini et al., 2018a). Las estructuras de protección duras se pueden retirar parcialmente (Manno et al., 2016) y se pueden implementar proyectos de regeneración artificial de playa para

aumentar o mantener el ancho de playa seca y, por lo tanto, aumentar su capacidad de carga (Pranzini et al., 2018b).

La opción “*Protection*” se aplica en sectores costeros caracterizados por presentar valores altos tanto de sensibilidad como de clases de usos del suelo, esto es, áreas urbanizadas con *buffer zones* estrechas y valores medios/altos de *coastal forcing*. Esto se observa en áreas como La Gaspara (SO de la provincia de Cádiz), Marbella y Mijas (centro de la provincia de Málaga) y Balerna (Golfo de Almería) (Molina et al., **IV**). En estas áreas se requerirá en un futuro próximo la implementación de estrategias de mitigación y la determinación de las modalidades de defensa está relacionada con la tendencia costera y las características y usos del suelo.

5. CONCLUSIONES

Para prevenir y reducir la erosión costera y los daños a estructuras humanas es muy importante caracterizar el clima marítimo local, es decir la distribución de la energía a lo largo del litoral y sus variaciones estacionales, anuales y tendencias en las últimas décadas, y llevar a cabo una cartografía la línea de costa y de los sistemas dunares, así como estudiar y comprender sus tendencias pasadas y futuras.

El clima marítimo varía de manera considerable a lo largo de la costa mediterránea de Andalucía, desde un área relativamente protegida cerca del Estrecho de Gibraltar, exclusivamente afectada por frentes de oleaje y tormentas del este, pasando por un área central (provincias de Málaga, Granada y el oeste de Almería) muy energética y expuesta tanto a frentes y tormentas del este como del oeste, hasta otra área (este de la provincia de Almería) de baja energía que, debido a su orientación, está muy expuesta a los frentes y tormentas del este y protegida de los del oeste.

En cuanto a la evolución de la línea de costa, el área de estudio se dividió en 47 unidades; 9 unidades registraron prevalencia de clases de acreción, 19 registraron prevalencia de estabilidad y otras tantas el prevalencia de procesos erosivos. Un balance positivo se observó en 17 unidades mientras que 28 presentaron un balance negativo.

Respecto a la influencia de las estructuras costeras, se ha observado acreción en áreas esencialmente localizadas aguas arriba de puertos y espigones y en correspondencia de rompeolas. Las áreas costeras frente a muros y revestimientos han mostrado siempre erosión, la cual fue también relevante aguas abajo de puertos y espigones, así como en las desembocaduras de grandes ríos y deltas (p. ej., Los deltas de los ríos Vélez y Adra en las provincias de Málaga y Almería, y el río Verde en Málaga). Estabilidad se observó en muchas playas de bolsillo y en áreas estabilizadas por estructuras de protección costeras (p. ej., La Herradura en Granada o La Línea de la Concepción en Cádiz).

La distribución de sectores costeros *drift-* y *swash-aligned* y las direcciones del transporte, que dependen principalmente de la orientación de la costa respecto a los frentes predominantes de aproximación del oleaje, se han reconstruido a partir del análisis de la evolución y forma de la línea de costa y de cómo ésta ha interactuado con estructuras de protección y puertos. Todo ello, junto a la complejidad de la costa mediterránea andaluza en lo que a orografía y morfología se refiere, y al oleaje asociado a los vientos provenientes del este y del oeste, hacen que dentro de las principales bahías predominen sectores costeros *swash-aligned* (p. ej., Bahía de Málaga y Golfo de Almería), mientras que en el resto de la costa son los sectores *drift-aligned* los más representados. Sin embargo, la dirección y el sentido de las corrientes de deriva predominantes cambian de un sector a otro: hacia el sur, en los sectores orientados NE-SO (la parte oriental de la provincia de Almería y la parte mediterránea de la provincia de Cádiz) y hacia el este en los sectores centrales (las provincias de Málaga, Granada y la parte occidental de la provincia de Almería).

En relación a la evolución de los sistemas dunares, de los 53 sistemas estudiados, todos menos 4 registraron una reducción de su superficie, o incluso desaparecieron, especialmente durante el periodo 1977-2001 cuando fueron afectados por severas intervenciones humanas, como el emplazamiento de edificios y construcciones turísticas, en especial en la provincia de Málaga y la expansión agraria en la provincia de Almería y, secundariamente por procesos de erosión costera. La pérdida de los sistemas dunares se asoció a la fragmentación del pie de duna, principalmente como consecuencia de la apertura de caminos y su progresiva expansión debida a procesos erosivos eólicos y/o marinos. Un incremento de la superficie de las dunas se observó tanto en áreas naturales como antrópicas en las provincias de Cádiz y Almería, en playas en acreción y/o estables, normalmente en áreas aguas arriba de puertos, o debido a la acción de fuertes vientos del este en playas orientadas hacia esa dirección.

En cuanto a los tipos de dunas estudiados, esto es, dunas embrionarias y móviles (Tipo I), fijadas por céspedes (Tipo II) y estabilizadas (Tipo III), durante el periodo 1977-2001 se registró, en la mayoría de las provincias, una disminución de la superficie de los tres tipos de dunas. En el periodo 2001-2016, en todas las provincias excepto Almería, se registró una disminución de las dunas de tipo I y III y un aumento de las de tipo II. Este incremento de dunas de tipo II estuvo vinculado a la degradación de las dunas de tipo III en áreas muy antropizadas. En Almería se produjo un incremento de dunas de tipo III, en el periodo 2001-2016, en áreas estables y en acreción.

Es posible determinar una estrategia de mitigación frente a la erosión costera a partir del conocimiento de la sensibilidad de sectores naturales y la vulnerabilidad potencial y el valor económico de sectores urbanizados. La metodología que se propone en este trabajo es fácilmente aplicable a escala regional en otras áreas por lo que puede considerarse de gran valor para los gestores costeros. Las tres opciones que se han propuesto son: “*No Action*”, “*Adaptation*” y “*Protection*”, que se han establecido en función de la sensibilidad de los sectores costeros y el valor económico del uso del suelo.

La opción “*No Action*” se propuso para áreas donde la sensibilidad costera y las clases de usos del suelo son bajas. La opción “*Adaptation*” se ha asociado, en parte, al gran nivel de urbanización y al comportamiento erosivo del litoral. En concreto, esta opción se ajusta de forma ideal a más de la mitad del área de estudio, y esencialmente concierne áreas naturales con alta sensibilidad y áreas urbanizadas con valores bajos de sensibilidad. La opción “*Protection*” se propuso para sectores costeros que presentan valores altos tanto de sensibilidad como de clases de usos del suelo. En estos sectores será necesaria en un futuro cercano la implementación de alguna estrategia de mitigación.

En definitiva, la costa mediterránea de Andalucía muestra una tendencia general erosiva en cuanto a la evolución de la línea de costa y de los sistemas dunares, siendo la ocupación y presión antrópica y el clima marítimo factores fundamentales a tener en cuenta en su evolución. La ocupación de la costa y la presión antrópica junto con la implementación de estructuras de protección han aumentado considerablemente en las últimas décadas, generando sectores costeros más vulnerables a la erosión. Tanto en costas naturales como urbanizadas, se podrían estudiar en un futuro los efectos de

tormentas individuales, representativas de cada clase energética, para comprender mejor cómo afecta a la costa. La importancia de los efectos de grupos de tormentas también es significativa ya que la erosión y los daños a estructuras costeras dependen en gran medida del efecto energético cumulativo de las tormentas, el espaciado temporal entre éstas y las tasas de recuperación natural del litoral.

Los resultados obtenidos en este trabajo sobre la evolución de la línea de costa y los sistemas dunares pueden utilizarse para mejorar las bases de datos sobre las características de la costa mediterránea andaluza, sobretodo de las dunas, cuyo estudio se ha enfocado en pasado a nivel local sin tener una visión global. Finalmente, los datos obtenidos abren una puerta a la utilización de soluciones para la protección del litoral basadas en la mejora de los ecosistemas costeros que complementen o sustituyan al tradicional enfoque basado en la construcción de obras de defensa rígidas.

CONCLUSIONS

In order to prevent and reduce coastal erosion and damages to human structures, it is very important to characterize the local sea climate, i.e. energy distribution along the coast, its annual and seasonal behavior and trends in recent decades, and the mapping of the coastline and dune systems, as well as to understand their past and future trends.

Wave climate considerably varies along the Mediterranean coast of Andalusia, from a relatively sheltered area close to the Gibraltar Strait, exclusively affected by easterly wave fronts and storms, to a very energetic central area (Málaga, Granada and western Almería provinces), exposed to both western and eastern wave fronts and storms, and to a low-energy area (eastern Almería Province) that, because of coastal orientation, is very exposed to eastern and sheltered to western fronts and storms.

Regarding coastal evolution, the studied coast was divided into 47 units; 9 units recorded essentially accretion, 19 recorded stability and 19 the prevalence of erosive processes. A positive balance was observed in 17 units meanwhile 28 units recorded a negative balance.

Concerning the influence of coastal structures, it was observed as accretion areas were essentially located up-drift of ports and groins and in correspondence of breakwaters. Coastal areas in front of walls and revetments always recorded erosion, which was also relevant down-drift of ports and groins, as well as at the mouths of largest rivers and deltas (e.g. Vélez and Adra river deltas in Málaga and Almería provinces and Verde River in Málaga). Stability was observed at several pocket beaches and at areas stabilized by coastal protection structures (e.g. La Herradura in Granada Province or La Línea de la Concepción in Cádiz Province).

Distribution of drift- and swash-aligned coastal sectors and longshore transport directions, which mainly depend on coastal orientation with respect to the prevailing wave approaching fronts, was reconstructed from the analysis of shoreline trend and shoreline plan form, which is linked to the way it interacted with protection structures and ports. All this, together with the complexity of the Andalusian Mediterranean coast in terms of orography and morphology, and the wave fronts associated with eastern and western winds, gave rise to swash-aligned coastal sectors in correspondence of the main embayments (e.g. Málaga Bay and Almería Gulf), while in the rest of the coast drift-aligned sectors were the most represented. Nevertheless, the direction and sense of prevailing drift currents change from one sector to another: southwards in the NE-SW (eastern Almería Province and Mediterranean part of Cádiz Province) and eastwards in the central sectors (Málaga, Granada and western Almería provinces).

About the evolution of the 53 systems dunes' systems, all but 4 recorded a reduction of their surface, or even disappeared, especially during the 1977-2001 period, when they were affected by hard human interventions, such as the emplacement of buildings and touristic constructions, especially at Málaga province, and agricultural

expansion at Almería province and, secondarily, at places, by shoreline erosion processes. Dunes' loss was linked to fragmentation of the dune toe, mainly due to the opening of pathways and to their progressive expansion due to marine- and wind-induced erosion processes. An increase of dunes' systems surface was observed in both natural and anthropic areas in Cádiz and Almería provinces, in accreting and stable beaches, usually on the up-drift side of ports or due to strong east winds on the east-facing beaches. Concerning the studied types of dunes, i.e. embryo and mobile dunes (Type I), grass-fixed dunes (Type II) and stabilized dunes (Type III), during the period 1977-2001, a decrease in the surface of the three types of dunes was recorded in most of the provinces. In the period 2001-2016, in all provinces except Almería, there was a decrease in the dunes of types I and III and an increase of those of Type II. The increase of Type II was linked to the degradation of Type III, observed in the 2001–2016 period at very anthropized areas. During the 2001-2016 period, in Almería Province was recorded an increase of Type III in stable and accreting coastal sectors.

Mitigation strategies against coastal erosion were determined according to the sensitivity of natural sectors and the potential vulnerability and economic value of urbanized coastal sectors. The methodology proposed in this research is easily applicable on a regional scale in other areas, therefore it being of interest for coastal managers. The three proposed options were: “No Action”, “Adaptation” and “Protection”, which have been established based on the sensitivity of the coastal sectors and the economic value of land uses. The “No Action” option was proposed for areas where both coastal sensitivity and land use classes show low values. The “Adaptation” option was partially linked to the great level of urbanization and the general erosive behavior. Specifically, this option was found to be ideal along more than one half of the studied coast, essentially at natural areas with high sensitivity and urbanized areas with low sensitivity values. The “Protection” option was proposed for coastal sectors where both coastal sensitivity and land use classes presented high values. In such areas, the implementation of coastal mitigation strategies will be required in future years.

Overall, the Mediterranean coast of Andalusia shows a diffuse erosive trend concerning shoreline and dunes' systems and essentially linked to the occupation and anthropic pressure and erosive marine processes. Coastal occupation and anthropic pressure, together with the implementation of protection structures, in the last decades have been considerably increasing coastal sensitivity to erosion processes. In both natural and urbanized coasts, the effects of individual storms, representative of each energetic class, could be studied to better understand how they specifically affect the coast. The importance of the effects of groups of storms is also significant since erosion and damage to coastal structures greatly depend on the cumulative energy effect of storms, their temporal spacing and the natural recovery rates of the coastline.

Results obtained in this research on shoreline and dunes' systems evolution can be used to improve existing databases on the characteristics of the Andalusian Mediterranean coast, especially of dunes' systems that, in the past, has been limited to characterize them at local scale and not at a regional one. Finally, the data obtained could

give useful indications to protect the coastline by the improvement of coastal ecosystemic solutions that complement or replace the traditional approach based on the construction of hard defense structures.

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ANEXOS






Anexo I

Publicación I. Storm Energy Flux Characterization along the Mediterranean Coast of Andalusia.

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Article

Storm Energy Flux Characterization along the Mediterranean Coast of Andalusia (Spain)

Rosa Molina ¹, Giorgio Manno ², Carlo Lo Re ^{2,*}, Giorgio Anfuso ¹
and Giuseppe Ciralo ²

¹ Department of Earth Sciences, Faculty of Marine and Environmental Sciences, University of Cádiz, Polígono del Río San Pedro s/n, 11510 Puerto Real, Spain; r.molina.gil@gmail.com (R.M.); giorgio.anfuso@uca.es (G.A.)

² Department of Engineering, University of Palermo, Viale delle Scienze, Bd. 8, 90128 Palermo, Italy; giorgio.manno@unipa.it (G.M.); giuseppe.ciralo@unipa.it (G.C.)

* Correspondence: carlo.lore@unipa.it; Tel.: +39-238-965-24

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Abstract: This paper investigates wave climate and storm characteristics along the Mediterranean coast of Andalusia, for the period 1979–2014, by means of the analysis of wave data on four prediction points obtained from the European Centre for Medium-Range Weather Forecasts (ECMWF). Normally, to characterize storms, researchers use the so-called “power index”. In this paper, a different approach was adopted based on the assessment of the wave energy flux of each storm, using a robust definition of sea storm. During the investigated period, a total of 2961 storm events were recorded. They were classified by means of their associated energy flux into five classes, from low- (Class I) to high-energetic (Class V). Each point showed a different behavior in terms of energy, number, and duration of storms. Nine stormy years, i.e., years with a high cumulative energy, were recorded in 1980, 1983, 1990, 1992, 1995, 2001, 2008, 2010, and 2013.

Keywords: energy flux; storm classification; stormy year; coastal erosion; Andalusia coast

1. Introduction

Coastal areas are extremely important in Mediterranean countries since they host the majority of their population and economic activities [1]. Over the last few decades, one of the faster urban developments has occurred along the Spanish Mediterranean coast, especially at the Costa del Sol [2]. As a result of this expansion, human activities and buildings were placed extremely close to the shore [3]; therefore, they are now threatened by natural hazards influenced by climate change-related processes such as sea-level rise and increases in storm frequency and intensity [4,5]. To reduce storm impacts, it is necessary to understand specific coastal characteristics and sensibilities as well as to fully comprehend storm nature. In recent years, several researchers have studied these aspects from different viewpoints. In Spain, Rodríguez-Ramírez et al. [6] studied storm records on the Huelva coast to obtain appropriate future development and management strategies; Mendoza and Jiménez [7] and Mendoza et al. [8] presented an intensity scale for wave storms on the Catalan coast to characterize their spatial and temporal variability; Guisado and Malvárez [9] and Pintado and García [10] used extreme wave conditions to complete the characterization of the morpho-dynamic environments of the Costa del Sol and Huelva areas; Anfuso et al. [11] and [12,13] characterized storms along the Atlantic side of Andalusia. In recent decades, coastal scientists have used several indexes to characterize storms, e.g., Halsey [14] ranked north-east Atlantic coastal storms (northeasters or nor'easters) based on a damage potential index and Dolan and Davis [15] proposed an intensity scale index to classify nor'easters into five classes, from weak to extreme, based on wave height and storm duration. Orford et al. [16] and

Orford and Carter [17] used the role of storm surge to develop a new storm index. Kriebel et al. [18] proposed a nor'easter risk index by combining the effects of storm surge, wave, and duration and Zhang et al. [19] developed a storm erosion potential index by combining the effect of storm tide, wave energy, and duration. This paper analyzes a 35-year wave climate dataset obtained from the European Centre for Medium-Range Weather Forecasts (ECMWF) for four available prediction points equally spaced along the Mediterranean coast of Andalusia (south of Spain). This allowed the definition and assessment of storm characteristics and their spatial and temporal distribution along the investigated area. To characterize the storms, a new approach was adopted, assessing the real wave energy flux of each storm, using a robust definition of the storm itself. During the investigated period, a total of 2961 storm events were recorded. These were classified according to five classes of storms, from low (Class I) to high-energetic (Class V). Results obtained are useful to understand potential impacts of both single and grouped storms, and hence put in place the appropriate prevention and mitigation strategies.

2. The Study Area

This study is focused on the wave climate of the Andalusia Mediterranean coast, a very populated area whose land cover has experienced important changes during recent decades [20]. Málaga is the province that has experienced the most important coastal occupation, in particular due to the construction of structures related to national and international tourism [20]. The coast is a micro-tidal environment (tidal range < 20 cm, [9]), about 546 km long, and including four provinces, i.e., Cádiz, Málaga, Granada, and Almería (Figure 1).

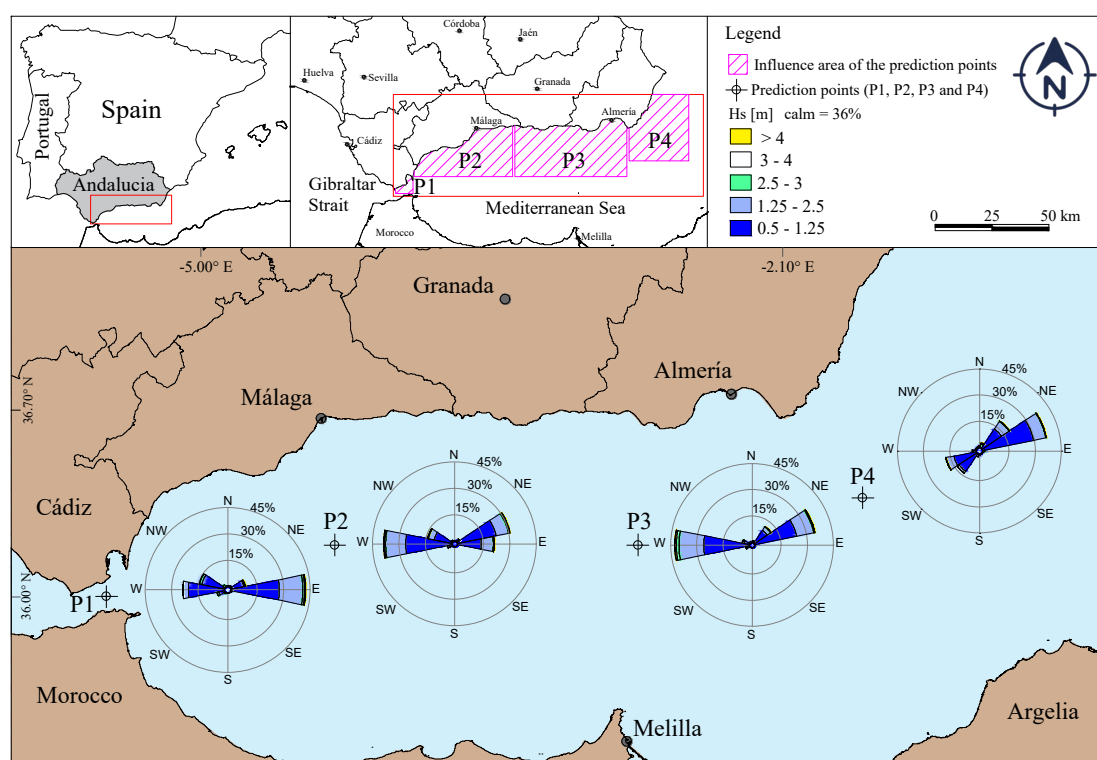


Figure 1. Geographic location of the study area and wave rise (1979–2014) for each prediction point.

There are many Andalusian coastal areas that suffer erosion problems [21], typically linked to very energetic storms producing severe damage to coastal structures. For example, Figure 2 shows the damage produced in winter 2015 by a western storm at Alumñecar (Granada Province). This storm particularly affected the beaches of San Cristobal and La Herradura. At the former, the extreme wave run-up broke the facilities for summer tourism, and at the latter, storm waves reached the road at several points, depositing cobbles and sand that endangered people the circulation of vehicles.



Figure 2. Severe damage after a western storm in winter 2015 at the Reina Sofia Promenade (Almuñecar), photo by europapress.

On the Mediterranean Andalusian coast, the beaches are rectilinear and composed of medium to fine and dark to golden sands and, especially in Granada and Almería, cliffed sectors are observed. The near-shore area generally shows high slope values and intermediate and reflective morpho-dynamic states linked to a narrow continental shelf [22]. This sector is exposed to winds from E and SE with minimum and maximum wind speed values that range from 0.4 to 0.9 m/s [9].

3. Methods

With the aim of characterizing the wave climate of the studied area, four prediction points were identified along the Mediterranean Andalusian coast; at each point, wave rises and the monthly means of maximum wave height $H_{m0,max}$ were calculated. The wave rises give information about the direction and intensity of incoming waves, whereas the monthly wave height means give information about the seasonal characteristics of the Mediterranean Andalusian coast. To identify each single storm, the definition of [23] was adopted, which allowed calculation of the energy flux by using the linear deep-water wave theory and, finally, classification of energy flux, preferring this parameter to empirical ones.

3.1. Wave Climate Preliminary Analysis

Wave climate analysis was carried out using wave data modelled by the ECMWF by means of the WAVE Model (WAM). This numerical model, which solves the energy balance equation, forecasts wave climate that is then subjected to quality controls ensuring its consistency [24] (<https://www.ecmwf.int/en/elibrary/16951-wave-model> accessed on January 2019). This paper used MATLAB scripts to analyze wave characteristics along the Mediterranean coast of Andalusia for the period 1979–2014, obtained by the ECMWF within the framework of the ERA-INTERIM project. The four prediction points, from W to E, used in this paper, are Point 1, close the Strait of Gibraltar, Point 2, east of Málaga, and Points 3 and 4 in front and east of Almería, respectively (Figure 1). Each temporal series is formed by 51,860 data points recorded over a period of 35 years (1 January 1979–30 January 2014) which is enough to analyze potential trends of increasing wave heights, the presence of climate-controlled cycles, or annual variations due to climate events [5].

3.2. Storm Classification Using the Energy Flux

To determine storm events, the definition used was the one given by [23], i.e., a Mediterranean Sea storm is a sequence of sea states in which the spectrally significant wave height exceeds the

threshold h_t and does not fall below this threshold for a continuous time interval greater than 12 h. He also considered that the time interval between consecutive single storms must be greater than 12 h. The government agency “Puertos del Estado” [25] suggested, for the Mediterranean coast of Andalusia, adopting a threshold value $h_t = 1.5$ m. Boccotti [23] suggests adopting the same value for the threshold (h_t) because it is 1.5 times the mean yearly significant wave height. Following the aforementioned criteria, 2961 storms were selected for the period 1979–2014.

Many studies (e.g., [7,8,11–13]) based the classification of storms on the use of the Dolan and Davis [15] “Storm Power Index”. In this paper, a physically based parameter was preferred, namely, wave energy flux [26,27]. Wave energy flux, or wave power per unit of wave-front length (P), was calculated using the following equation:

$$P = \frac{\rho g^2}{64\pi} T_e H_{m0}^2 \left[\frac{W}{m} \right] \tag{1}$$

where ρ is water density, g is the gravity acceleration, T_e is the energy period that represents the period of the sinusoidal wave with the same energy as a real sea state (for which a JONSWAP spectrum is about 90% of the peak period) and H_{m0} is the spectrally significant wave height. To obtain an accurate estimation of the total energy (E_{tot}^i) of each storm [26–29] the energy flux was time-integrated:

$$E_{tot}^i = \int_0^{d_i} P dt \left[\frac{Wh}{m} \right] \tag{2}$$

where the d^i is the duration of i -th storm. Using Equations (1) and (2) the total energy of each of the 2961 storms was calculated.

For example, two storms at the prediction Point P3 are shown in Figure 3. The first storm started on 25 February 2009 and the second on 4 March 2009. Figure 3a shows the H_{m0} values of the two storms identified by means of the threshold $h_t = 1.5$ m. The corresponding energy flux P and the total energy E_{tot}^i (Equations (1) and (2)) is shown in Figure 3b.

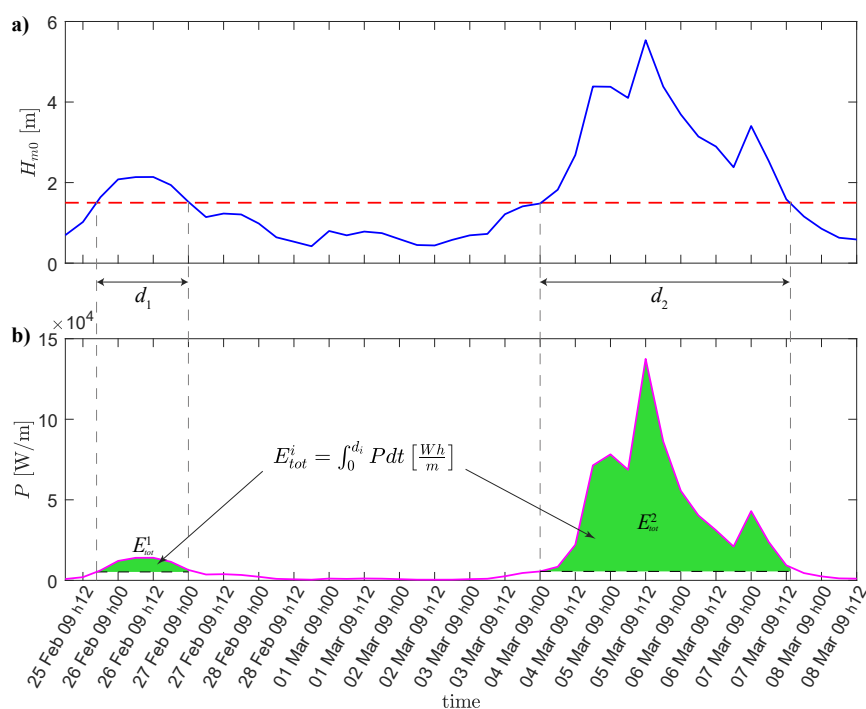


Figure 3. (a) Spectrally significant wave height H_{m0} , during the storms of 25 February and 4 March 2009 at the prediction Point P3. The dashed red line is the spectrally significant wave height threshold $h_t = 1.5$ m, d_1 and d_2 are storm duration. (b) Energy flux during time and total storm energy.

The method proposed by [30], i.e., “the natural breaks” function, was used to classify storm events into five classes, from Class I (low-energetic events) to Class V (high-energetic events).

The Return Period of the Energy Flux of Storms

For the estimation of the return period of the energy flux (P) of each storm class, the probability of exceedance was fitted with a modification of the Weibull Cumulative Distribution Function (CDF) described in [23,31]:

$$F(P) = e^{-\left(\frac{P}{w}\right)^u} [\%] \quad (3)$$

where w and u parameters that depend on the location under examination. Using the auxiliary variables $X = 100 \cdot \ln(2.5 \cdot P)$ and $Y = 100 \cdot \ln[\ln(1/F(P))]$ [23,31], in the coordinate system X, Y , the data points should lie on a straight line. Thus, the parameters of Equation (3) can be easily estimated by fitting those data points by means of the least-squares method.

The above-mentioned Weibull CDF is related to the return period T_r by means of

$$T_r = \frac{1}{\lambda \cdot F(P)} [\text{year}] \quad (4)$$

where λ is the mean number of events per year. Consequently, for the lower and upper limit of each storm class, the probability of exceedance and the return period were calculated.

3.3. Stormy Year

For the sake of continuity with previous research [11,32], the definition of stormy year was adopted here. In particular, for each prediction point, stormy year empirical recurrence period (R_i) and annual frequency of occurrence (f_o) were assessed by using the equations:

$$R_i = \frac{(n+1)}{m} [\text{year}] \quad (5)$$

$$f_o = \frac{1}{R_i} [\%] \quad (6)$$

where R_i is the recurrence interval calculated for n number of years (35 in this paper), m is the number of events that occurred within the date-range of interest, and f_o is the yearly frequency of occurrence of the event. For each prediction point, two values of R_i and f_o were calculated using a minimum and a maximum threshold, respectively. The minimum threshold is the mean of total energy (μ) calculated within the whole period of 35 years, the maximum threshold is $\mu + \sigma$, where σ is the standard deviation of the total energy.

4. Results and Discussion

4.1. Wave Height Characterization

Wave height data did not present a general trend along the investigated period, but a clear seasonal behavior was recognized, as observed by Rangel-Buitrago and Anfuso [13] on the Atlantic sector of Andalusia. As a general trend, higher average values of monthly maximum spectrally significant wave heights ($H_{m0,max}$) were observed during the winter season, i.e., the December–March period and, specifically, Points 1, 2 and 4 recorded maximum values in March and Point 3 in February (Figure 4). High values recorded in March are linked to the great importance of eastern waves due to regnant winds during such months. Lower average $H_{m0,max}$ values were observed during the summer time, i.e., July, August, and September, ranging from 1.7 m at Point 1 to 2.1 m at Point 3. Dealing with the behavior of each analyzed point, Point 3 showed the highest values in all years, always followed by Point 2; but during June, July, and August, Point 4 recorded greater values than Point 2 (Figure 4).

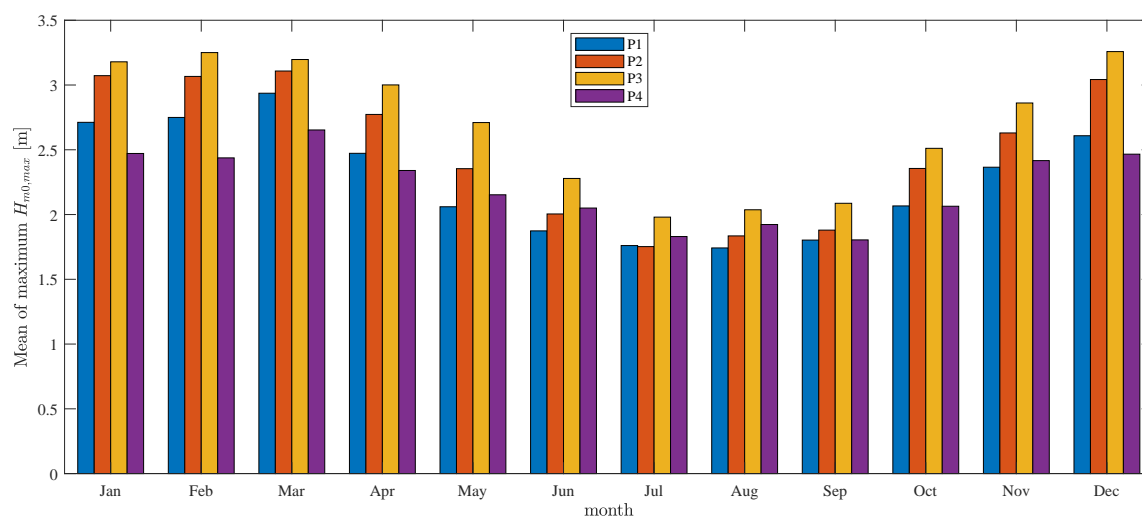


Figure 4. Average values of monthly maximum spectral significant wave heights $H_{m0,max}$.

Approaching directions observed at different points clearly reflected coastal orientation and prevailing marine climate (Figure 1). Point 1 is close to the Strait of Gibraltar but sheltered to the Atlantic swell waves. East approaching fronts, with prevailing wave height classes of 0.5–1.25 m (c. 30%) and 1.25–2.5 (c. 10%), clearly prevailed at this prediction point (Figure 1) and were linked to the strong easterly winds associated with a surface pressure gradient over the Gibraltar Strait when the Azores high pressure is located over the Iberian Peninsula, while there is pronounced low pressure over northern Africa [33]. Points 2 and 3 are situated at the central part of the investigated area, so they are exposed to winds and waves from W and E and E-NE directions; specifically, at Point 2, E and N approaching waves are equivalent to W approaching fronts. At Point 3, the western component prevailed on the north-east approaching direction because of the increase of the western geographic fetch; an increment of the NE component was also observed since this point is more exposed to this approaching direction with respect to Point 2 because of coastal orientation (Figure 1). At Point 4, despite the prevalence of the E-NE approaching direction, the NE component becomes even more evident than at Point 3. Furthermore, since this latter point is sheltered to the west because of coastal orientation (NNE-SSW oriented), waves approaching from the third quadrant essentially present SW and W-SW components.

4.2. Storm Characterization

During the investigated period, a total of 2961 storm events were categorized into five classes, i.e., Class I (weak), Class II (moderate), Class III (significant), Class IV (severe), and Class V (extreme). Points 3 and 2 recorded the highest number of storms (Figure 5). The distribution is similar at all points, with a clear dominance of events belonging to Classes I and II: 87.4% in Point 1, 86.6% in Point 2, 83.1% in Point 3, and 90.4% in Point 4 (Table 1, Figure 5). Mean wave height value of each class did not present great spatial variations, i.e., all points recorded similar values of wave height for the same class. Concerning maximum and minimum wave height values per class, a clear and general trend was not observed, e.g., Point 4 presented the lowest wave height value for Class III but the highest for Classes IV and V (see Table 1).

Table 1. Storm characteristics at each prediction point: class, energy (E_{tot}), frequency of storms, significant wave height (H_{m0}) peak period (T_p), and duration (D).

Point	Class	E_{tot} [Wh/m]			Frequency [%]		H_{m0} [m]		T_p [s]	D [days]
		Min	Max	Mean	Mean	Standard Deviation	Mean	Mean		
1	I	108	503	265	59.6	2.01	0.26	6.5	0.9	
	II	503	1100	730	27.8	2.61	0.37	7.4	1.9	
	III	1100	2102	1509	8.3	3.27	0.48	8.1	2.9	
	IV	2102	4179	2624	3.5	3.64	0.65	8.5	4.2	
	V	4179	9165	5635	0.7	4.68	0.98	9.7	4.8	
2	I	108	503	272	58.9	2.05	0.29	6.5	0.9	
	II	503	1100	749	27.6	2.65	0.38	7.4	2.0	
	III	1100	2102	1484	9.9	3.13	0.50	7.9	3.3	
	IV	2102	4179	2752	2.3	3.76	0.62	8.6	4.8	
	V	4179	9165	5551	0.4	4.73	0.76	9.2	6.9	
3	I	108	503	270	55.0	2.05	0.28	6.5	0.9	
	II	503	1100	739	28.0	2.69	0.39	7.4	1.9	
	III	1100	2102	1460	12.4	3.22	0.47	8.0	3.1	
	IV	2102	4179	2775	3.4	3.99	0.52	8.9	4.4	
	V	4179	9165	5632	0.9	4.87	0.74	9.5	7.0	
4	I	108	503	280	67.1	2.03	0.27	6.8	0.9	
	II	503	1100	712	23.2	2.52	0.35	7.6	2.0	
	III	1100	2102	1408	8.3	3.12	0.46	8.3	3.0	
	IV	2102	4179	2802	0.9	4.34	0.60	9.6	3.3	
	V	4179	9165	5248	0.3	5.18	0.49	10.6	3.7	

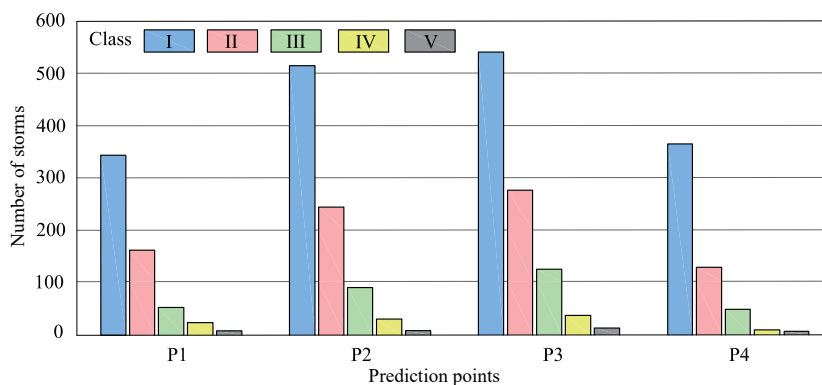


Figure 5. Distribution of storm events per class at each point.

Regarding wave period, the same storm classes of different points presented similar values. Higher wave period variations among classes were recorded at Points 2 and 3 (Table 1). The mean storm duration presented an increase from Class I to Class V at each point (especially Points 2 and 3) and important differences among points (Table 1). Figure 6 reports the monthly distribution of all storms (i.e., the sum of all events recorded at each points) per class. Results are very similar to those obtained by [7,8,11–13,15,34] in their respective studies. Concerning temporal distribution, Classes I and II storms were observed along the whole year. Class III storms were recorded in winter and spring seasons (from October to May), with a minimal occurrence during summer months, i.e., June (8 storms), August (2 storms), and September (2 storms). Class IV storms were observed from November to March, and Class V storms were only recorded from December to March (especially in February, with 7, and March, with 5 events). It is interesting to observe that Classes II and III are very frequent in March, because it relates to approaching waves generated by E and SE winds that are quite frequent in springtime.

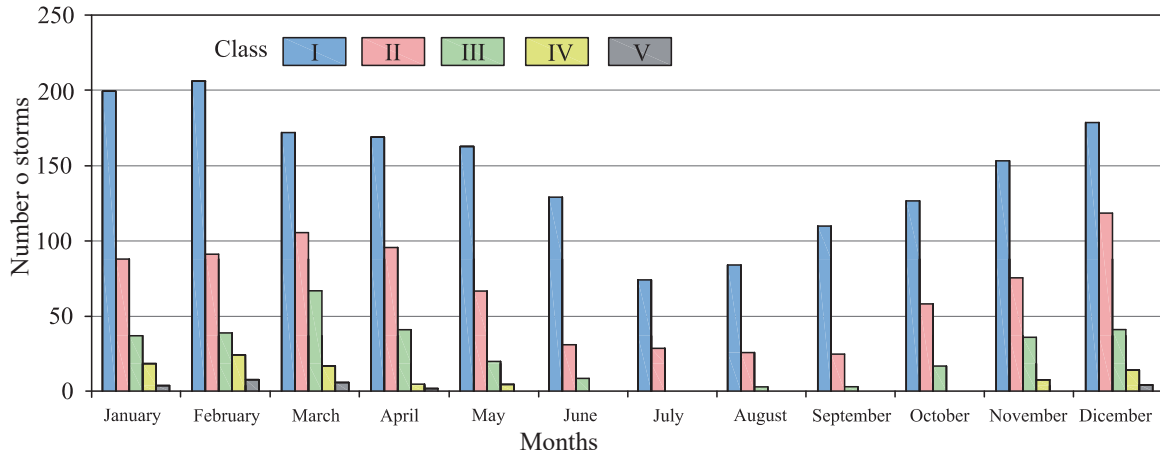


Figure 6. Monthly distribution of all storm events per class and month.

Concerning approaching directions, at Point 1, Classes I and II mainly approached from the east with a small western component (Figure 7) and Classes III, IV and V almost exclusively (>95% of records for each class) approached from E and were linked to the predominant eastern storm waves (Figure 1). At Point 2, the sum of the E and E-NE directions is broadly equivalent to the western component (Figure 7) and clearly reflects, with a slight increase of the eastern component, the wave rise shown in Figure 1. At Point 3, storm energy classes approaching directions (Figure 7) broadly reflect wave rise presented in Figure 1 with an increase of the importance of the western component for all storm classes. At Point 4 (Figure 7), the storm approaching directions are consistent with the wave direction pattern observed in Figure 1. At Point 4, more numerous storms approach from the E-NE direction and disappear in the SW direction. The return period (T_r) of Classes III, IV, and V events at each prediction point are shown in Table 2.

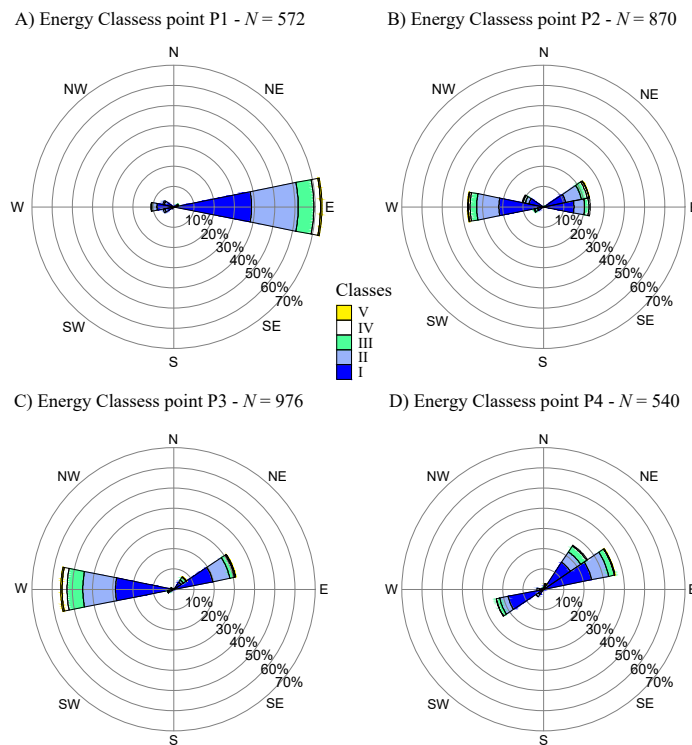


Figure 7. Energy flux roses at all prediction points. (A) Point P1, (B) Point P2, (C) Point P3, (D) Point P4. N is the total number of storm events.

At Points 2 and 3 the yearly the probability of energy flux exceedance for Class III storms was 100%, varying from 76.9% to 100% at Point 1 and from 43.5% to 100% at Point 4 (Table 2). For Class IV, the probability of occurrence ranged from 41.7% to 100% and from 58.8% to 100% at Points 2 and 3 respectively, and from 27.8% to 76.9% at Point 1 and from 12.7% to 43.5% at Point 4. Class V probability of exceedance have minimum percentages of 12.7% and 18.5% at Points 2 and 3, and 8.4% at Point 1 and 3.3% at Point 4. Mentioned values are broadly similar to observations carried out by Anfuso et al. [11] near the areas of Huelva and Cádiz, i.e., the less energetic zones of Cádiz Gulf. It is observed that the most energetic points (i.e., Points 2 and 3) have the highest percentages of probability of energy flux exceedance (Figure 8), so the facing littoral, i.e., the coast between Málaga and Almería, is very exposed to storms belonging to all classes, and especially to most energetic ones (III, IV, and V) that can have a great impact on both natural and urbanized sectors.

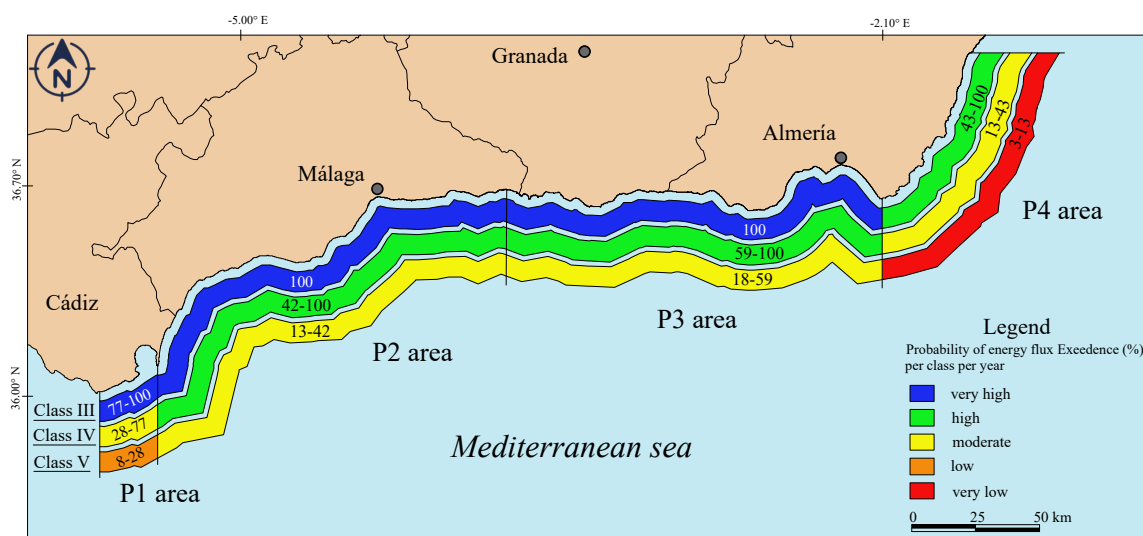


Figure 8. Energy flux probability of exceedance (%) of storms per class III, IV, and V at each point in the coastal area of influence. The percentage values per class as reported on Table 2 are superimposed in the colored stripes.

4.3. Characterization of Stormy Years

In this paper, a special attention was devoted to the yearly cumulative characteristics of storms, i.e., their number, duration, and energy. In fact, as observed by Ferreira [35], the relationship between storms and beach erosion (and/or damage to human structures) varies according to single storm characteristics, storm grouping, and coastal response/morpho-dynamic behavior. Concerning the characterization/quantification of stormy years, only Classes III, IV, and V were considered since these events are the ones that produce important coastal damage according to [12]. With respect to energy data, a similar trend was recorded at the four points, with a similarity observed among Points 1, 2, and 3 (Figure 9).

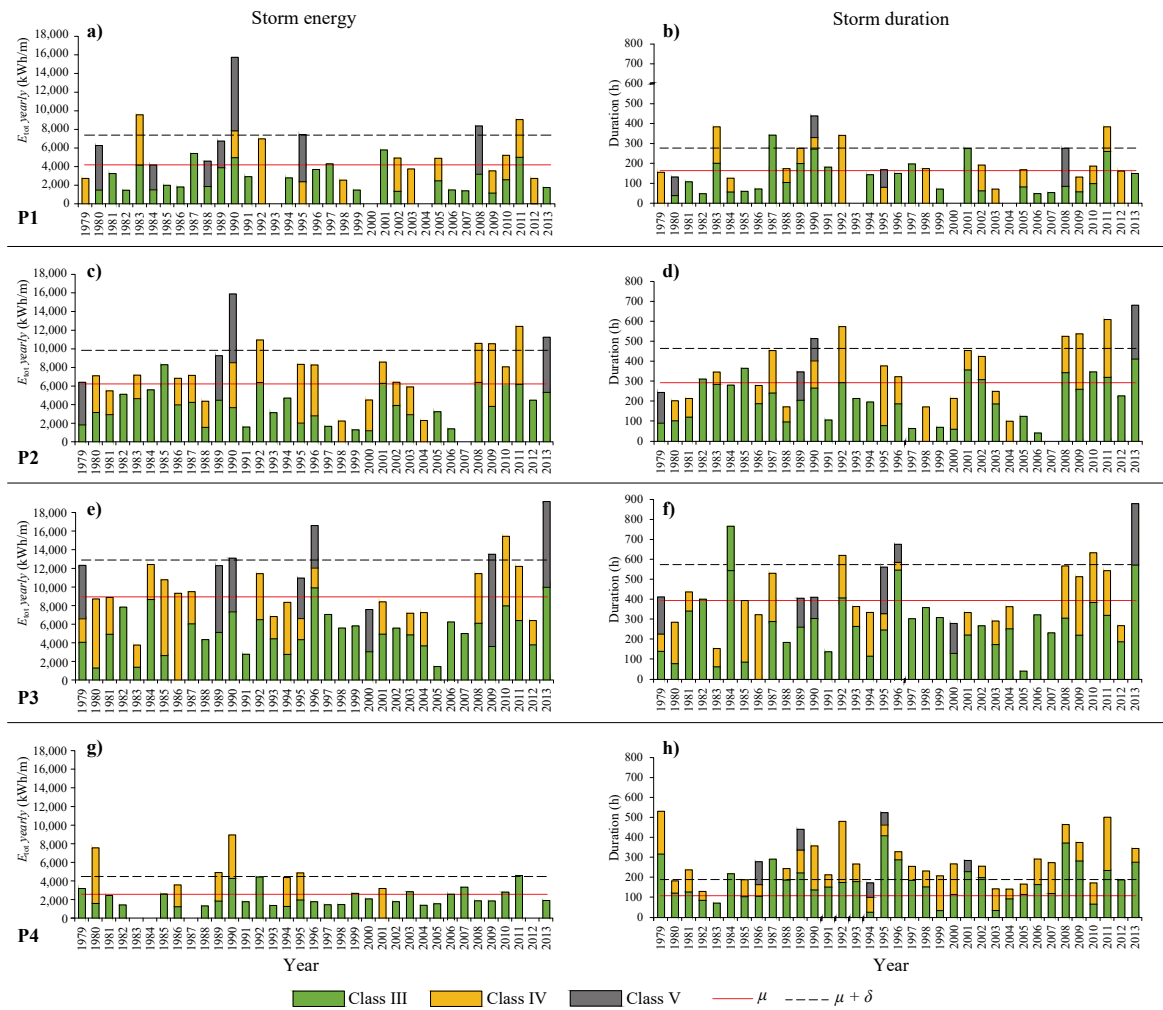


Figure 9. In the left column: the total energy of storms per year for Classes III, IV, and V. At (a) Point P1, (c) Point P2, (e) Point P3, and (g) Point P4. In the right column: the corresponding durations of storms (b) Point P1, (d) Point P2, (f) Point P3, and (h) Point P4. Red and dashed lines respectively represent the average value (μ) and the average plus one standard deviation ($\mu + \sigma$).

Dealing with yearly energy distribution, it was possible to observe nine energetic years, i.e., 1980, 1983, 1990, 1992, 1995, 2001, 2008, 2010, and 2013. Anomalies were recorded at Point 3, which differed in four of the nine aforementioned years; at Point 1, which recorded a low-energy year in 2013 (i.e., essentially Classes I, II, and III), and at Point 4, which recorded low energy values in 1983, 1984, and 2008 and high values in 1986 and 2007 (Figure 9). Analyzed data of stormy years did not present a clear trend; as an example, yearly distribution of cumulative energy presented a correlation factor (r^2) that ranged from 10^{-5} for Point P2 to 2×10^{-4} for Point P4, but showed a cyclical behavior as highlighted by the calculation of the return period. The recurrence interval and the yearly frequency of occurrence are presented in Table 3 according to the distribution of yearly cumulative energy values (Figure 9). Per each Point, two values of recurrence interval (and frequency of occurrence) are presented, and refer to the mean value and the mean plus one standard deviation of yearly cumulative energy. The frequency of occurrence of stormy year was higher at Point 2 with 17% and 53%, respectively, for the lower and higher energy value, i.e., a low-energetic storm year is observed every 1.9 years and a high-energetic year presents a recurrence interval of 6 years. Point 4 recorded longer recurrence intervals, which ranged from 2.6 to 9 years (39% and 11% values of frequency), respectively, for higher and lower energetic stormy years. Points 1 and 3 presented average values (Table 3).

Table 2. Return period (T_r) and probability of energy flux exceedance ($F(P)$) for the lower and upper limit of each Class (III, IV, V) calculated using Weibull CDF Equation (3). The minimum values are highlighted with blue-colored font.

Point		Class III		Class IV		Class V	
		min	max	min	max	min	max
P1	T_r [year]	<1	1.3	1.3	3.6	3.6	11.9
	$F(P)$ [%]	76.9	100	27.8	76.9	8.4	27.8
P2	T_r	-	<1	<1	2.4	2.4	7.9
	$F(P)$	-	100	41.7	100	12.7	41.7
P3	T_r	-	<1	<1	1.7	1.7	5.4
	$F(P)$	-	100	58.8	100	18.5	58.8
P4	T_r	<1	2.3	2.3	7.9	7.9	30.1
	$F(P)$	43.5	100	12.7	43.5	3.3	12.7

Table 3. Stormy year recurrence interval (R_i) and yearly frequency of occurrence (f_o) calculated from Equation (4), considering yearly cumulative energy values (Figure 9), for each prediction point (Table 1).

Point	Stormy Year			
	R_i [year]		f_o [%]	
	min	max	min	max
P1	2.2	7.2	14	44
P2	1.9	6.0	17	53
P3	2.2	7.2	14	44
P4	2.6	9.0	11	39

Regarding the cumulative storm duration (Figure 9), the trend was not clear. From one side, there is a good correspondence between the number of storms and storm duration within each point, that is, years with many storms also recorded a high cumulative yearly storm duration. Such correspondence was also observed with yearly energy values distribution. On the other hand, no correspondence was observed among different points. A comparison of stormy year distribution recorded in this paper with the one observed by [12] for the Atlantic region of Andalusia showed the opposite behavior linked to the fact that storms on the Atlantic side of Andalusia are essentially related to the predominance of western approaching fronts; meanwhile, on the Mediterranean side [36], they are essentially linked to eastern approaching fronts.

5. Conclusions

To prevent and reduce coastal erosion and damages to human structures, as well as the comprehension of past and future climate trends and beaches' annual and seasonal behavior and evolution, it is very important to characterize the local sea climate. This paper shows as wave climate considerably varies along the Mediterranean coast of Andalusia, from a relatively sheltered area (Point 1) close to the Gibraltar Strait, exclusively affected by easterly wave fronts, to a very energetic central area (Points 2 and 3) exposed to both western and eastern fronts, and to a low-energy area (Point 4) that, because of coastal orientation, is sheltered to western and very exposed to eastern fronts. This behavior is evident when analyzing wave approaching data: main approaching storm directions for high-energy events ranged from E at Point 1, from E to W at Point 2 (only from W for Class V), from W with a small E-NE component at Point 3, and from NE at Point 4 with secondary W-SW components for Classes III and IV (13.33% W for Class III and 20% SW for Class IV). Points 2 and 3 were the most energetic points due to high-energy events approaching from western directions. Stormy years were considered years with a great cumulative energy of Classes III to V events. Nine stormy years were

selected during the investigated period, i.e., 1980, 1983, 1990, 1992, 1995, 2001, 2008, 2010, and 2013. Finally, this study highlighted that the yearly probability of energy flux exceedance of more energetic events is higher in the central sector of the studied area, i.e., at Points 2 and 3, Class III events have a 100% probability; Class IV have a 41.7 to 100% probability; and Class V have a 12.7 to 58.8% probability of energy flux exceedance, so this area has a high sensitivity to storm impacts. Future investigations should be devoted to the analysis of the effects on natural and urbanized coastal environments of single representative storms of each storm class to better understand how an increase in energy and storm duration affects coastal behavior, which is strictly linked to beach morpho-dynamic state, and damages to human structures. Secondly, the effects of storm groupings should be better investigated since erosion and damages to coastal structures greatly depend on cumulative storm energy, on separation between storm events, and on natural beach recovery rates.

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Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

The following abbreviations and symbols are used in this manuscript:

CDF	Cumulative Distribution Function
ECMWF	European Centre for Medium-Range Weather Forecasts
ERA-Interim	ECMWF Reanalysis (from January 1979 onward)
POT	Peak Over Threshold
WAM	Wave Model

Symbols

d^i	Duration of i -th storm
E_{tot}^i	Total energy i -th storm
$F(P)$	Weibull Cumulative Distribution Function of energy flux
f_o	Frequency of occurrence related to the empirical recurrence interval
g	Gravity acceleration
H_{m0}	Spectral significant wave height
$H_{m0,max}$	Monthly mean of maximum spectral wave height within the studied date-range (35 years)
h_t	Wave height threshold for storm definition
λ	Mean number of events per year
m	Number of events (upper threshold) within the studied date-range (35 years)
μ	Mean of total energy within the studied date-range (35 years)
N	Number of storm events
P	Energy flux or wave power per unit of wave-front length
R_i	The stormy year empirical recurrence interval
ρ	Water volumetric mass density
σ	Standard deviation of total energy within the studied date-range (35 years)
T_e	Energy period
T_r	Return period related to the probability of exceedance
u	Weibull function second parameter
w	Weibull function first parameter
X	Abscissa of auxiliary variable for linear fitting
Y	Ordinate of auxiliary variable for linear fitting

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Anexo II

Publicación II. The Mediterranean Coast of Andalusia (Spain): Medium-Term Evolution and Impacts of Coastal Structures.

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Article

The Mediterranean Coast of Andalusia (Spain): Medium-Term Evolution and Impacts of Coastal Structures

Rosa Molina ¹, Giorgio Anfuso ^{1,*}, Giorgio Manno ² and F. Javier Gracia Prieto ¹

¹ Department of Earth Sciences, Faculty of Marine and Environmental Sciences, University of Cádiz, Polígono del Río San Pedro s/n, 11510 Puerto Real, Spain

² Department of Engineering, University of Palermo, Viale delle Scienze, Bd. 8, 90128 Palermo, Italy

* Correspondence: giorgio.anfuso@uca.es; Tel.: +34-956-016167

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Abstract: This paper shows coastal evolution along the Andalusia Region (Spain) and the impacts on it of coastal structures. The study area was divided into 47 units to calculate the erosion/accretion/stability (or evolution) rates by using the DSAS extension of ArcGIS software. Evolution rates were divided into different classes from “Very high accretion” to “Very high erosion”. As a result, 9 units recorded accretion, 19 stability and 19 erosion. Further, 17 units presented a positive balance and 28 units a negative one, showing a negative net balance of 29,738.4 m²/year corresponding to the loss of 1784.30 km² of beach surface in the 1956–2016 period. The distribution of evolution areas along the studied coast was carried out by means of the “R” project for statistical computing. The analysis evidenced the impact of rigid structures: accretion was essentially observed up-drift of ports and groins and in correspondence of protection structures, especially of breakwaters. Erosion classes were observed down-drift of ports and groins and in correspondence of revetments/seawalls, and at largest river deltas, and “stability” was observed at pocket beaches and coastal areas locally stabilized by protection structures. Last, results were used to determine the distribution of swash- and drift-aligned coastal sectors and main direction of sedimentary transport.

Keywords: coastal evolution; DSAS; groin; port; pocket beach; river delta

1. Introduction

Over past decades, coastal erosion related impacts on the world shorelines have been significantly growing due to ongoing coastal development and tourist occupation [1–3] as well as to climatic change-related processes [4], such as sea level rise, the increasing height of extreme waves, or changes the frequency of storms and their intensity [5–8]. This has enhanced scientific interest on the effects of coastal erosion processes, which have been investigated over various time-scales using a variety of methods and data sets according to the study time spans [9–13].

Studies on short-term shoreline dynamics are usually carried out at small spatial scales, during a time span of less than 10 years [10], by using beach topographical profiling or 3D surveys, repeated at regular intervals [12,14–16]. Vertical aerial photographs, satellite images, maps and charts are very useful tools for the reconstruction of coastline changes at long (>60 years) and medium (between 60 and 10 years) temporal scales and large spatial scales [10,17–19].

The prediction of the future coastline trend must be based on the study of coastal changes which have occurred in the recent past taking into account a comparable time scale [20]. This is of especial interest in tourist areas because of the potential damage to human structures and related economic activities and the loss of beaches, which are considered as a major player in tourist markets [21] since

they are worth billions of tourist dollars [22]. As an example, in Spain, France, Italy, Greece and Turkey, tourism receipts account for some 5% of the gross domestic product [23], these countries accounting for “the most significant flow of tourists, a sun, sea and sand (3S) market” [24].

Over the last decades, the Andalusia Mediterranean coast (Spain) recorded one of the fastest rates of urban development along the Spanish littoral and even in Europe. In the Costa del Sol (Málaga Province), population reached 1,136,712 [25] and population increase continued at an annual rate of 9.2% between 2006 and 2011—corresponding to 50% of the demographic increase recorded along the Andalusia littoral during the same period [26]. Nowadays, Costa del Sol receives ca. 10,000,000 visitors per annum, i.e., 35% of all Andalusia visitors, making it one of the most important tourist destinations in Europe.

Regional-scale studies on shoreline rates of change are scarce, despite their high relevance. Some attempts have been made in the USA [27] and Europe [28]. However, inter-comparison of data is not easy since aspects such as shoreline definition or dataset formats are very different from diverse studies [29]. Much work is still needed at a regional/national scale to define the best procedure in regional coastal erosion studies and to obtain a broad view of the regional/local factors affecting short- to medium-term coastal evolution. These data would help in the identification of the main causes of coastal erosion in recent decades.

In this paper, aerial orthophotographs integrated into a GIS project, were used to reconstruct shoreline evolution during a 60-year period in the Mediterranean coast of Andalusia, a more than 500 km long sector of the southern Iberian coast. Special attention was devoted to investigate the impacts of ports and rigid protection structures on coastal evolution. In fact, the studied coast experienced significant erosion problems related to the large developments built during recent decades, primarily the construction of ports, harbors, groins and human settlements [30,31]. All those structures, especially ports and groins, have produced a great impact on the littoral drift, as observed in similar Mediterranean areas by the authors of [32–36]. Additionally, quantification of erosion rates in the studied area is very important because shoreline retreat takes place over a human time-scale. Consequently, the recorded data can be used to determine safe construction setbacks, to evaluate the efficiency of coastal protection structures, and to elaborate coastal erosion management and land use plans [22,37,38].

2. Study Area

The littoral of Andalusia extends along the Atlantic Ocean, the Gibraltar Strait and the Mediterranean Sea (Spain, Figure 1). The Mediterranean littoral is 546 km in length and extends from Gibraltar Strait to the Murcia Region, administratively including the provinces of Cádiz, Málaga, Granada and Almería. It has a prevailing rectilinear E-W outline, with two NE-SW easterly facing sectors, one near the Gibraltar Strait and the other in the easternmost sector (Almería coast).

Coastal orography is dominated by the Betic Range, a tectonically active mountain chain that reaches high elevations close to the coast (more than 2200 m a.s.l. at some points). The coast is irregular and shows cliffs, embayments and promontories. Several small coastal plains develop at the foot of these coastal mountains, especially extended at the mouth of short rivers and *ramblas* draining the chain, the most important being Guadiaro, Guadalhorce, Guadalfeo, Adra and Andarax rivers (Figure 1). Some of them develop wave-dominated deltas at their mouths, as a response to the important water erosion affecting their respective catchments, all of them affected by a typical semiarid climate. Especially under episodic heavy rainfalls, reworked fluvial sands and gravels constitute important sediment supplies to the beach system. In the last decades, river basin regulation plans involving water management for tourist and agricultural purposes, has brought to the construction of dams and reservoirs that have systematically limited sediment supplies to the coast and have promoted coastal retreat in most deltas of the region [30,39,40].

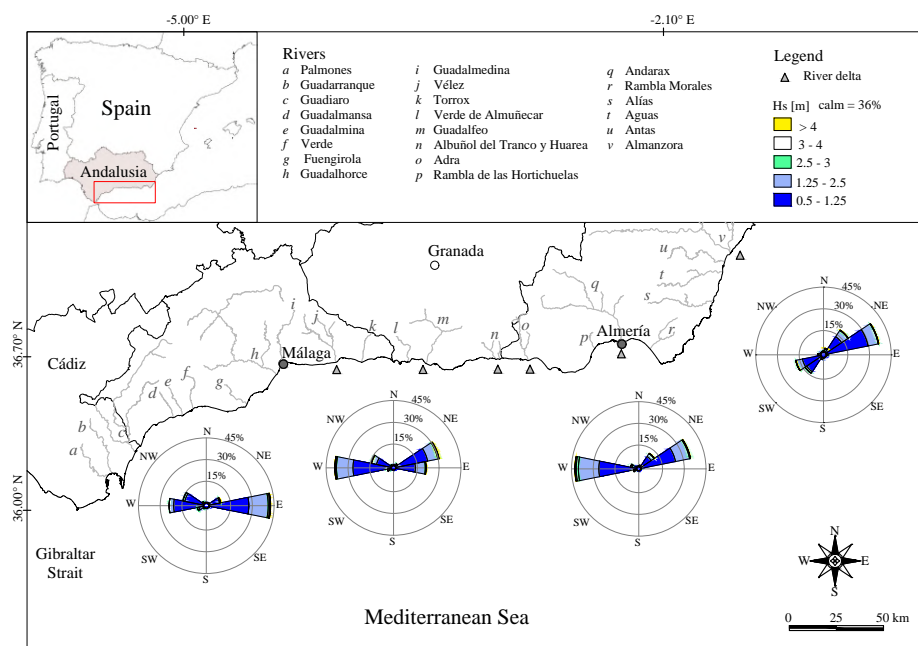


Figure 1. Location map with wave roses for four prediction points.

Beaches are usually composed of medium to coarse dark sands and/or pebbles at *ramblas* mouths. They are often interrupted by rocky sectors and headlands that give rise to pocket beaches (*calas*) of different sizes. Beaches generally show intermediate to reflective morphodynamic states [30].

The coast is a micro-tidal semidiurnal environment (tidal range < 20 cm) [41] exposed to winds blowing from SE to SW with minimum and maximum velocities ranging from 0.4 to 9.0 m/s. The wave climate and storm energy, along the Andalusian coast is very variable [42]. The coasts close to Gibraltar Strait are mainly affected by eastern storms, whereas the central coasts (Málaga and Almería areas) are exposed both to western and eastern storms. Finally, the easternmost portion of the Andalusian coast (Figure 1) is NNE–SSW oriented and primarily exposed to eastern storms [42].

Waves show a clear seasonal behavior with storm conditions being recorded during November–March (i.e., the winter season [30,43]). Due to shoreline orientation, predominant easterly winds and associated storm waves give rise to sea wave conditions generating a prevailing westward littoral drift [43]. Winds from western directions and associated sea waves as well as swell waves that only rarely filter from the Atlantic Ocean, give rise to an opposing drift, which is particularly important in certain coastal sectors and/or periods [30].

3. Methodology

A general evaluation of the erosion/accretion state of the Andalusia coast was previously made by REDIAM Red [44], although only aerial photographs taken in 1977 and 2009 were used; some more detailed analysis at given problematic areas included data from 1956. In this study, aerial orthophotographs from five different years (i.e., 1956, 1977, 2001, 2010 and 2016) and scales (Table 1) were used to reconstruct and quantify shoreline evolution over a medium-term period (60 years, according to criteria proposed by Crowell et al. [10]). Photo interpretation and Geographic Information System (GIS) methods were applied for data processing. The orthophotos were obtained by the Web Map Services (WMS) developed by the Junta de Andalucía (i.e., the Regional Government) following the Open Geospatial Consortium (OGC) interoperability standards. All information was presented in metric Projected Coordinate System WGS84, UTM zones 29 N and 30 N.

Table 1. Characteristics of aerial orthophotographs used. Available online at the website: <http://www.juntadeandalucia.es>.

Year	Flight	Colour Film	Scale	Spatial Resolution (m)
1956	1956–57	Black and white	1:10,000	1.0
1977	Iryda flight 1977–83	Black and white	1:5000	0.5
2001	2001–02	Colour	1:10,000	0.5
2010	PNOA 2010–11	Colour	1:10,000	0.5
2016	PNOA 2016	Colour	1:5000	0.25

The Andalusia shoreline is composed by cliffed (ca. 195 km, marked with a coarser line in Figure 2) and sandy sectors (ca. 350 km). Cliff sectors evolution was not quantified because their changes were within the accuracy of the method used. The temporal and spatial coastal evolution of the rest of the coast was covered by this paper except for a few sectors that were not included due to their small spatial dimension and/or the absence of aerial orthophotographs. The most important beach systems evolution was analyzed by dividing the studied area into 47 units, limited by natural or artificial structures (Table A1). Shore-normal transects were drawn at each unit with a spacing fixed at 25 m, obtaining a total of 11,494 transects along 284.95 km of coastal length (Figure 2).

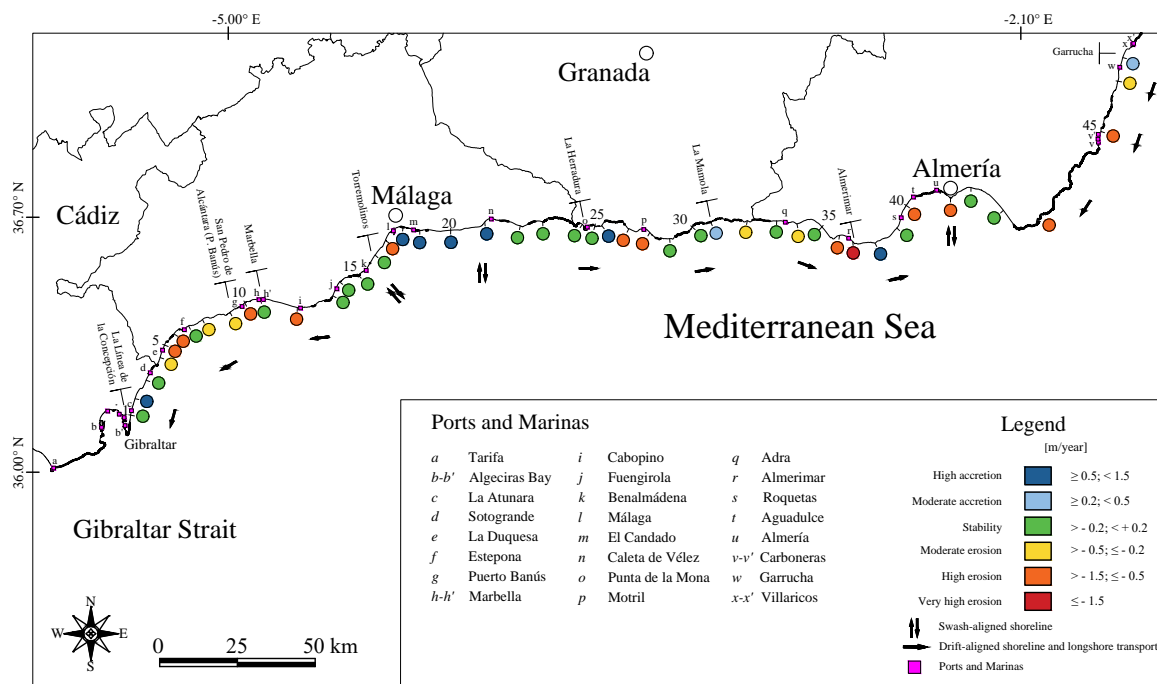


Figure 2. Distribution and characteristics of investigated units, indication of areas with a clear drift-aligned (marked with an arrow showing the prevalent longshore transport direction) or swash-aligned (marked with shore normal double arrows) shoreline trends, location of ports and cliff sectors (marked with a coarser shoreline).

Computation of change rates between shorelines at each transect was made by using the DSAS extension of ArcGIS [45,46] by calculating the Shoreline Change Envelope (SCE) and the Net Shoreline Movement (NSM) [47]. The SCE method deals with variability at each transect taking into account the maximum spatial recorded displacement of shoreline, regardless of the time span along which it was recorded. The NSM is associated with the dates of only two shorelines and it reports the distance between the oldest (1956) and youngest (2016) shorelines for each transect although this movement may be not the maximum shoreline displacement recorded.

Erosion/accretion/stability (or evolution) rates were obtained by using [48]: (i) the “Weighted Linear Regression” (WLR), e.g., more reliable data are given greater emphasis or weight towards determining a best-fit line and considers all used shorelines; (ii) the “Linear Regression Rate” (LRR), which is determined by fitting a least-squares regression line to all shoreline points for a particular transect; and (iii) the “End Point Rate” (EPR), which is calculated by dividing the distance of shoreline movement by the time elapsed between the oldest and the most recent shoreline.

The precision and accuracy of aerial photogrammetric measurements depend on the total uncertainty (σ_T) associated with the determination of each shoreline position, which was sorted out by using the following relation [49]:

$$\sigma_T = \sqrt{\sigma_d^2 + \sigma_p^2 + \sigma_r^2 + \sigma_{co}^2 + \sigma_{wr}^2 + \sigma_{td}^2} \quad (1)$$

Such total uncertainty depends on documents own characteristics and digitalizing process [50], i.e., the digitalizing error (σ_d), accuracy linked to pixel size (σ_p), ortho-rectification error (σ_r), image co-registration error (σ_{co}), and on shoreline definition and position determination. In fact, shoreline is usually taken as the water/land contact, especially in microtidal environments [51–54] or as the seaward vegetation limit, dune foot, or cliff top, in mesotidal environments [10,55,56]. Given the micro-tidal nature of the studied coast and the absence of foredune ridges in most part of the zone, in this work, the shoreline position was defined as “the water line at the time of the photo” [53,54] and corrections were carried out according to wave run-up (σ_{wr}) and tidal conditions (σ_{td}) in the sense of Manno et al. [49]. Both parameters were calculated for the five areas in which the investigated littoral was divided. Calculated values of mentioned errors/uncertainties per each shoreline are presented in Table A2.

Evolution rates were calculated for the whole considered period and all the investigated shorelines, following the (previously described) WLR method and divided into seven classes (Table 2). The choice of intervals was based on the results obtained by means of the statistical analysis of the WLR data obtained with DSAS. It was considered that the 50% of the total data corresponded to “Moderate accretion”/“Moderate erosion” classes; values up to the 95% of the total data corresponded to “High accretion”/“High erosion” classes; and values >95% of the total data corresponded to “Very high accretion”/“Very high erosion” classes. It was decided to use the ± 0.2 interval as “Stability class” because it corresponds to the most frequent small changes related to seasonal oscillations (Table A3).

The “R” Project for Statistical Computing (<http://www.r-project.org/>) was used to create interaction plots to describe evolution classes distribution according to their location in areas free of structures and in correspondence of (or close to) coastal protection structures (revetments/seawalls, breakwaters and groins) and ports.

Finally, the analysis of the distribution of accretion/erosion/stability classes in relation to ports and rigid structures location allowed to determine drift- and swash-aligned coastal sectors and main direction of longshore transport.

Table 2. Definition of beach evolution classes.

Class	Beach State	m/year
1	Very high accretion	$\geq +1.5$
2	High accretion	$\geq +0.5; < +1.5$
3	Moderate accretion	$\geq +0.2; < +0.5$
4	Stability	$> -0.2; < +0.2$
5	Moderate erosion	$> -0.5; \leq -0.2$
6	High erosion	$> -1.5; \leq -0.5$
7	Very high erosion	≤ -1.5

4. Results

Within each unit, the most represented evolution class was considered as representative, as shown in Figure 2. A balance among eroded, accreted and stable beach areas was also calculated within each unit: at all cases (but 5) the unit balance coincided with the most represented evolution class (Table A3). None of the 47 units showed “Very high accretion” and only one unit (i.e., no. 37) presented “Very high erosion”. Specifically, 9 units, corresponding to 2854 transects (or 70.35 km), recorded accretion; 19 units, i.e., 3647 transects (or 89.9 km), stability; and 19 units, i.e., 4993 transects (or 124.07 km), erosion (Figure 2).

Taking into account the length inhomogeneity of the units, the balance was calculated between erosion, accretion and stability areas at each unit, and also at a global scale after considering all transects investigated. A total of 17 units had a positive balance (34,873.5 m²/year) and 28 a negative one (−64,611.9 m²/year). Overall, the investigated coast showed a negative net balance corresponding to the loss of 1784.30 km² of beach surface in the 1956–2016 period.

The distribution of the different classes of accretion, erosion and stability is presented in Figure 2. Two large erosion zones are evident along the SW area of Málaga Province and east of Almería Province (Figure 2). A large zone constituted by four “High accretion class” units was recorded at the eastern end of Málaga Province located between two areas of “Stability class”, one close to Torremolinos, and the other to La Herradura.

Concerning **accretion classes**, an example was observed east of Málaga (Units 18–21, Figure 2); as a result of the emplacement of several defence structures and nourishment works, a 31.1 km in length accretion coast was generated. At the unit close to Málaga (Unit 18, Figures 2 and 3), the most frequent evolution class observed was “High accretion”.

Among all the studied units, only two showed “Moderate accretion” and it was strictly related to the emplacement of structures. One example of this case is the area close to La Mamola (Unit 31, Figure 4): at the western edge of the unit, the beach is currently protected by six groins. Previously, there were eight shorter groins; three of them were removed and the easternmost structure was emplaced between 2001 and 2010 (Figure 4).

Erosion classes were mostly observed in the westernmost end of Málaga Province (between Units 4 and 10, Figure 2), close to the ports of La Duquesa, Estepona, and Puerto Banús, and a large number of coastal structures.

A similar trend was observed at Almerimar unit (Unit 37, Figures 2 and 5) where approximately 32 km² of beach surface were eroded during the 1956–2016 period. Coastal evolution of this unit was greatly linked to the construction in 1978 of the port of Almerimar (Figure 5).

Erosion classes were also frequently observed at river deltas. The evolution of Adra area (Unit 34, Figure 2) is presented in Figure 6. “Very high” and “High erosion” classes were observed on the area between the old and the present delta, especially at a 400 m long sector on the east side of the current mouth of the Adra River (Figure 6) whose basin was greatly modified during last decades: the construction, west of the river delta, of the port of Adra, interrupted the sedimentary transport and a new delta front was originated due to the artificial deviation of the main river channel (Figure 6).

The area including San Pedro de Alcántara (Unit 9) and Coral Beach (Unit 10, Figures 2 and 7), is constituted by two adjacent coastal units separated by Puerto Banús Port. This is a good example of shoreline evolution under the influence of reduced river supplies and massive development of structures. The area shows the presence of four rivers and seven streams, a port, several coastal structures and a strong anthropic impact (Figure 1).

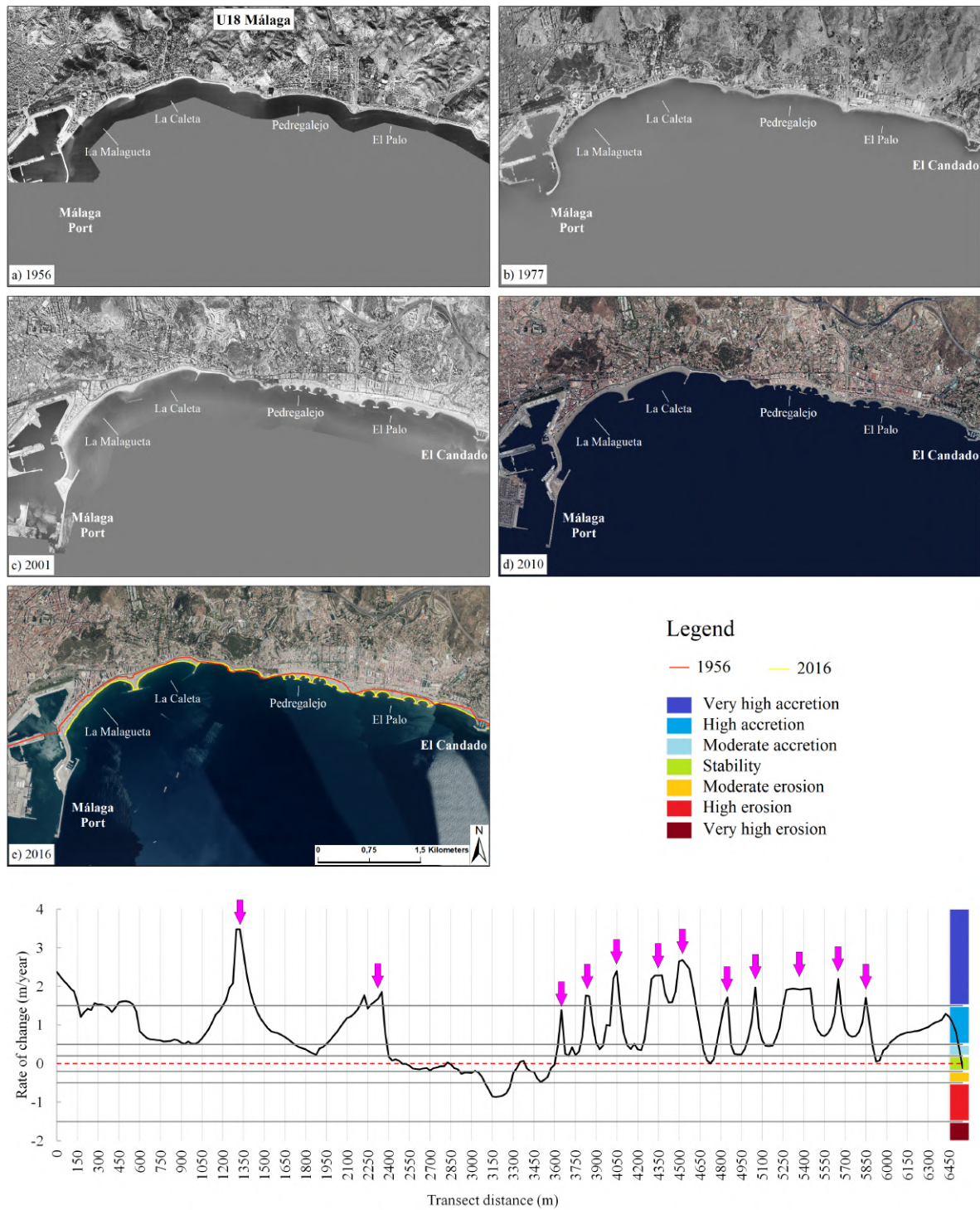


Figure 3. Evolution of Málaga area (Unit 18) from 1956 (a) to 2016 (e). “Moderate” to “Very high accretion” classes (Table A3) were recorded on the lee side of the breakwaters at La Malagueta Beach (up to +3.48 m/yr) and at La Caleta Beach (up to +1.86 m/yr), and in response to the structures emplaced at Pedregalejo and El Palo beaches (up to +2.68 m/yr). The first structure of Málaga Port was emplaced in 1588 and it was modified and enlarged several times, the last one in 1998. Arrows indicate the position of protection structures.

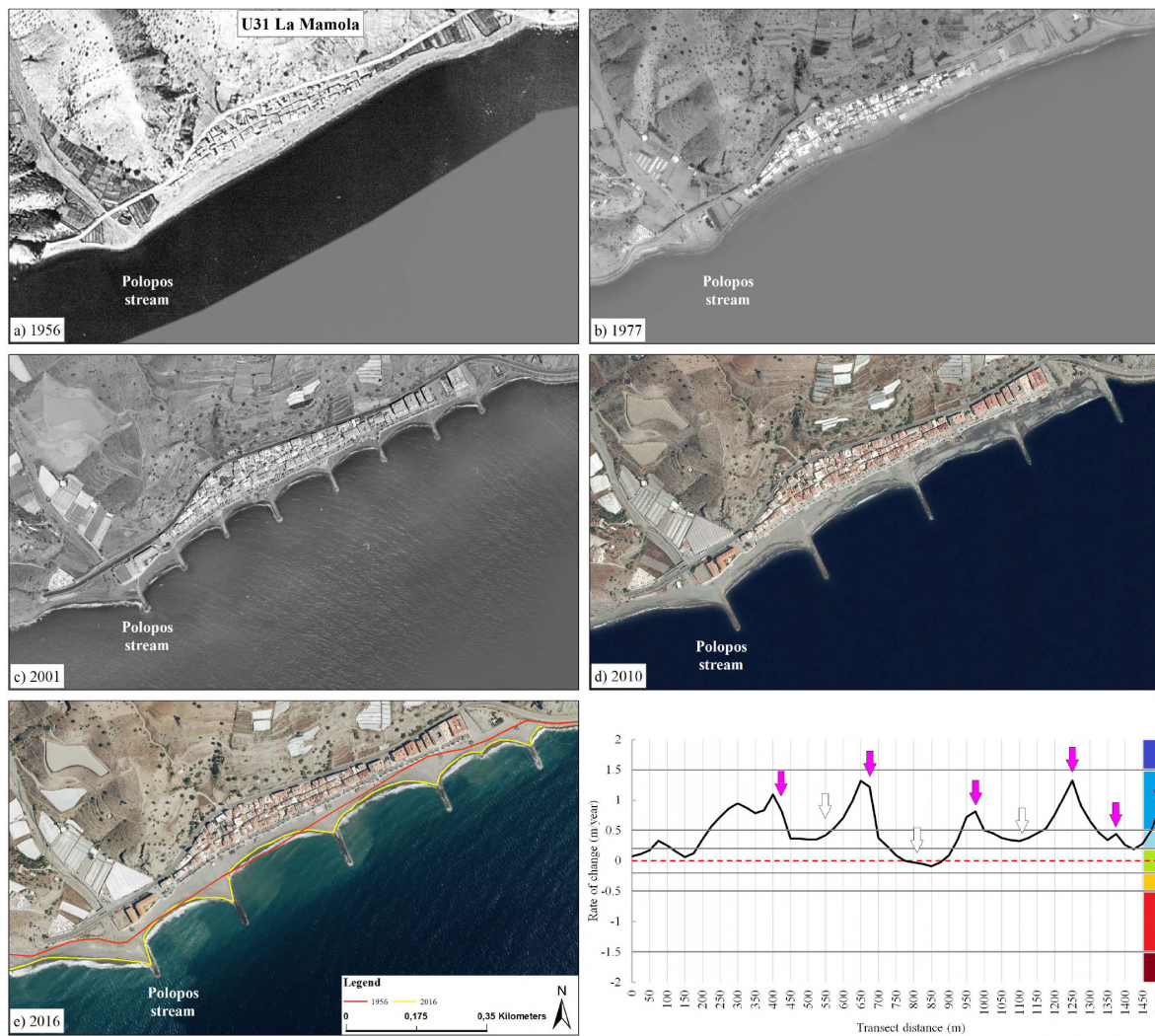


Figure 4. Evolution of La Mamola (Unit 31) from 1956 (a) to 2016 (e). “Moderate accretion” class represents 29.0% of the unit, corresponding to 1.05 km (Table A3) and the net beach surface evolution for the 1956–2016 period was positive (19,230 m², i.e., 320.50 m²/yr). In 1977, great erosion was observed east of the Polopos Stream mouth. In the 2001 aerial orthophoto, eight protection structures that did not solve erosion problems can already be observed. In the following years, such structures were modified and new ones were employed. Colored arrows indicate the position of present structures and white arrows those of previous ones.

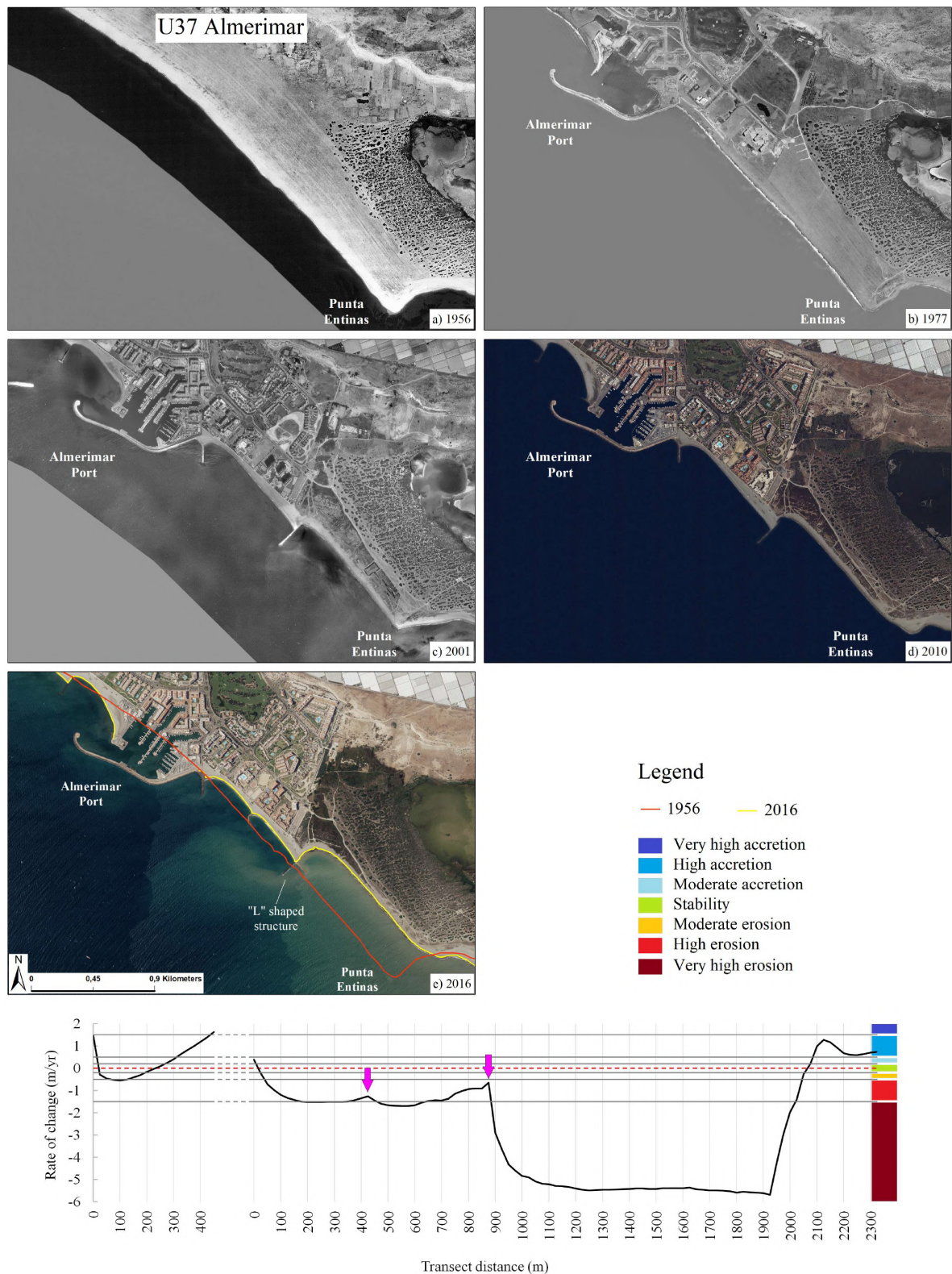


Figure 5. Evolution of Almerimar (Unit 37) from 1956 (a) to 2016 (e). It is the only unit that showed “Very high erosion” (63.8%, or 1.5 km) and the net beach surface evolution for the 1956–2016 period was negative (382,815 m², i.e., 6380.25 m²/yr). At the urbanized area situated between the port and the “L” shaped breakwater, erosion rates ranged between “High” and “Very high erosion” east of the port and of the “L”-shaped structure. Arrows indicate the position of protection structures.

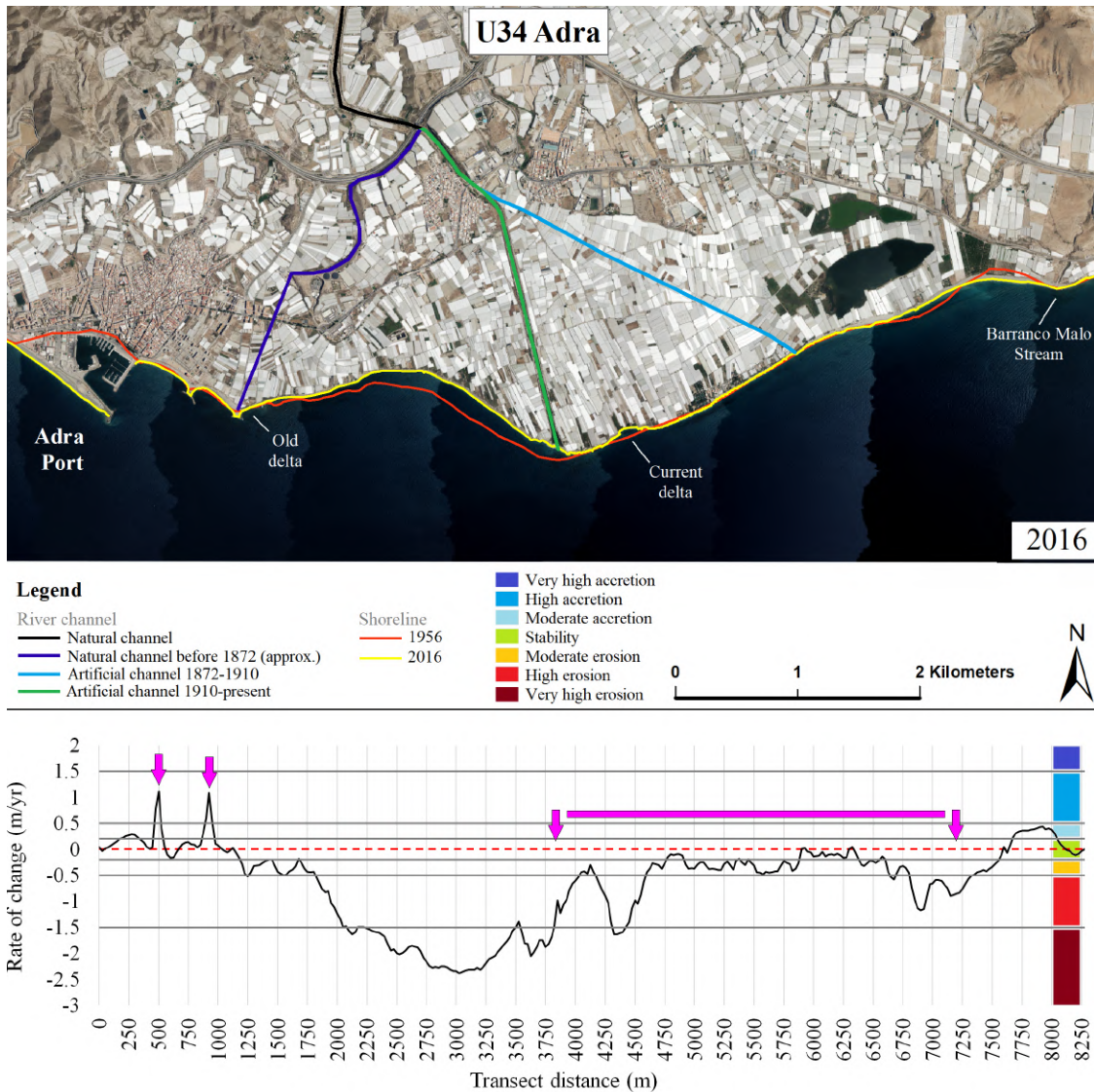


Figure 6. Delta of the Adra River (Unit 34) with the evolution of the main river channels [57]. The main (i.e., western) dock of the port was constructed in 1947. This unit prevalently recorded “Moderate erosion” (28%, or 2.32 km) and a negative beach surface balance since 258,315 m² (or −4305.25 m²/yr) were lost in the 1956–2016 period. “Accretion class” were observed in correspondence of the breakwaters (up to 1.12 m/yr) emplaced east of the port and in the easternmost part of the unit (up to 0.44 m/yr). Arrows indicate the position of protection structures and the continuous line the area where 100 small groins are located.

At San Pedro de Alcántara, erosion zones were located at western side of coastal structures and promontories and in correspondence of some rivers mouths, especially at Guadaiza River. Accumulation was observed east of Puerto Banús Port: this produced erosion at Nueva Andalucía Beach where breakwaters were emplaced forming tombolos that favored the migration of erosion problems at nearby areas, i.e., at Guadaiza River mouth, an area already eroding because of the decrease of river sediment supplies. In the 1970s, the emplacement of eight structures at Nueva Andalucía, favored accretion values up to 1.34 m/year (Figure 7).

At Coral Beach, “High erosion” was observed close to the mouth of the Verde River and the sector eastern of the port showed “High” and “Moderate accretion” values (Figure 7). A coastal structure, indicated with an arrow in Figure 7b,c), was built between 1956 and 1977 and retired between 2004 and 2006.

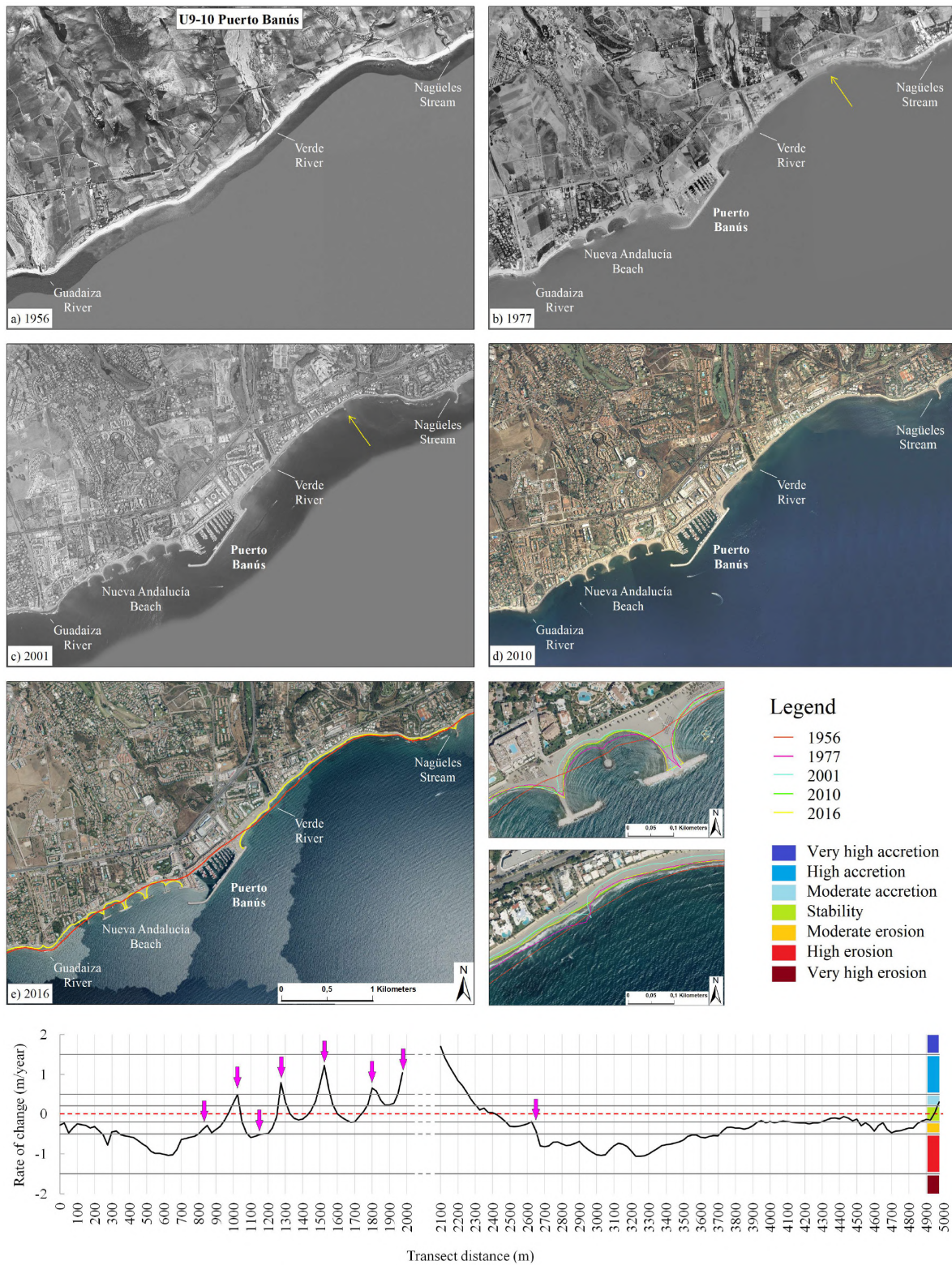


Figure 7. Evolution of Puerto Banús (Units 9 and 10) from 1956 (a) to 2016 (e). The port named Puerto Banús was constructed in 1970. Concerning units evolution, San Pedro de Alcántara (Unit 9), 10.25 km in length, and the adjacent Coral Beach (Unit 10), 2.9 km of length, are limited to the SW by Guadalmanza River and to the NE by the groin at the mouth of Nagüeles Stream. The most frequent class was “Moderate erosion” for Unit 9 (45.5%, i.e., 4.7 km) and “High erosion” for Unit 10 (36.2%, i.e., 1.05 km). Beach surface evolution recorded a negative trend at both units, i.e., $-1533.6 \text{ m}^2/\text{yr}$ for Unit 9 and $-579.75 \text{ m}^2/\text{yr}$ for Unit 10. Examples of coastal trend changes are also presented. Arrows indicate the position of protection structures.

Stability classes were observed at several pocket beaches (especially between Málaga and Granada provinces) and at few areas stabilized by coastal protection structures (e.g., La Línea de la Concepción).

La Herradura (Unit 24, Figure 8) represents a stable pocket beach that presented light accretion in its eastern edge, close to Punta de la Mona headland.

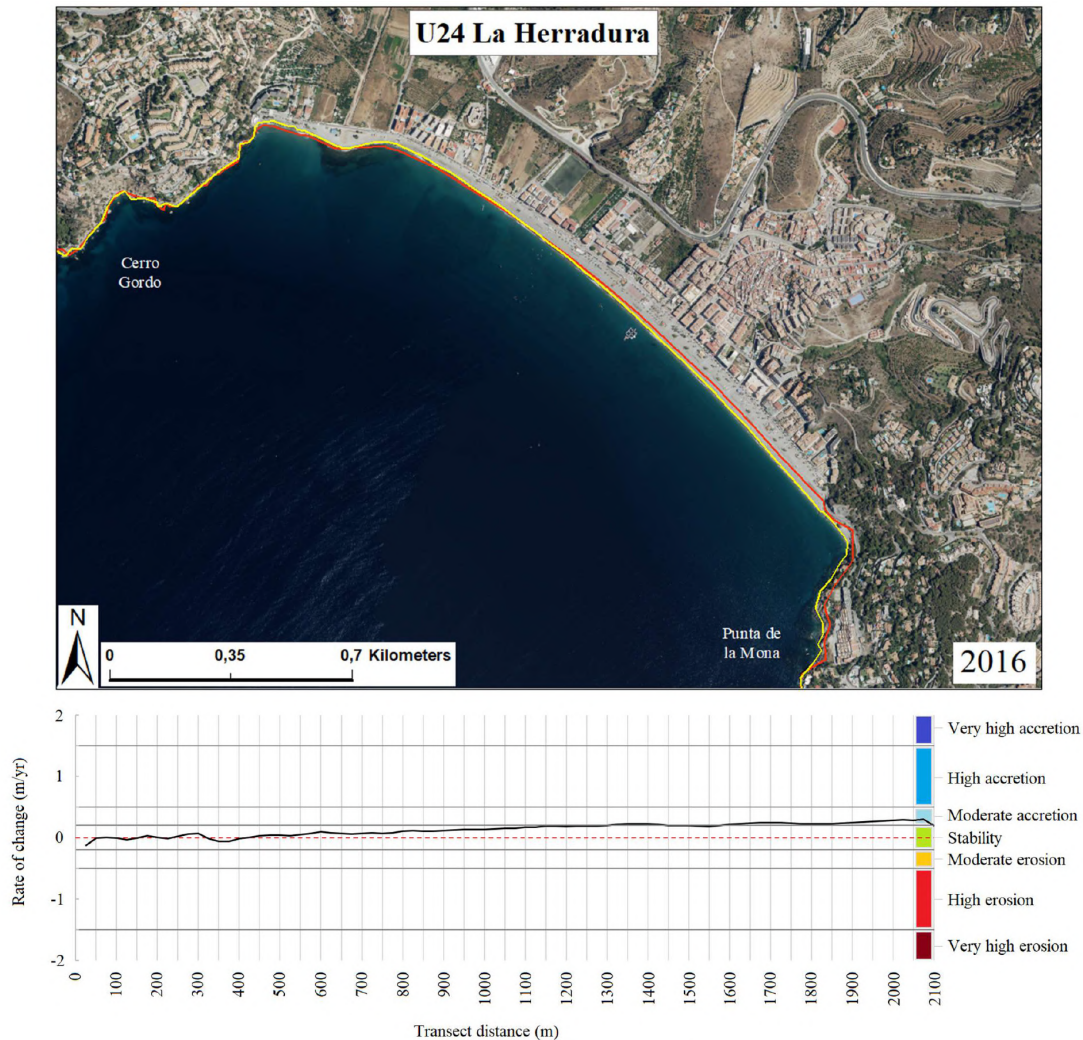


Figure 8. Evolution of La Herradura Beach (Unit 24). About 2 km in length, this beach is limited by two large rocky headlands, i.e., Cerro Gordo on the west, and Punta de la Mona on the east side. The most frequent class was “Stability” (70.2%, i.e., 1.4 km) and the net beach surface evolution was positive ($24.25 \text{ m}^2/\text{yr}$).

La Línea de la Concepción (Unit 1, Figures 2 and 9) is about 2.3 km in length. It is a very urbanized unit that counts with a promenade along the entire beach and several short groins.

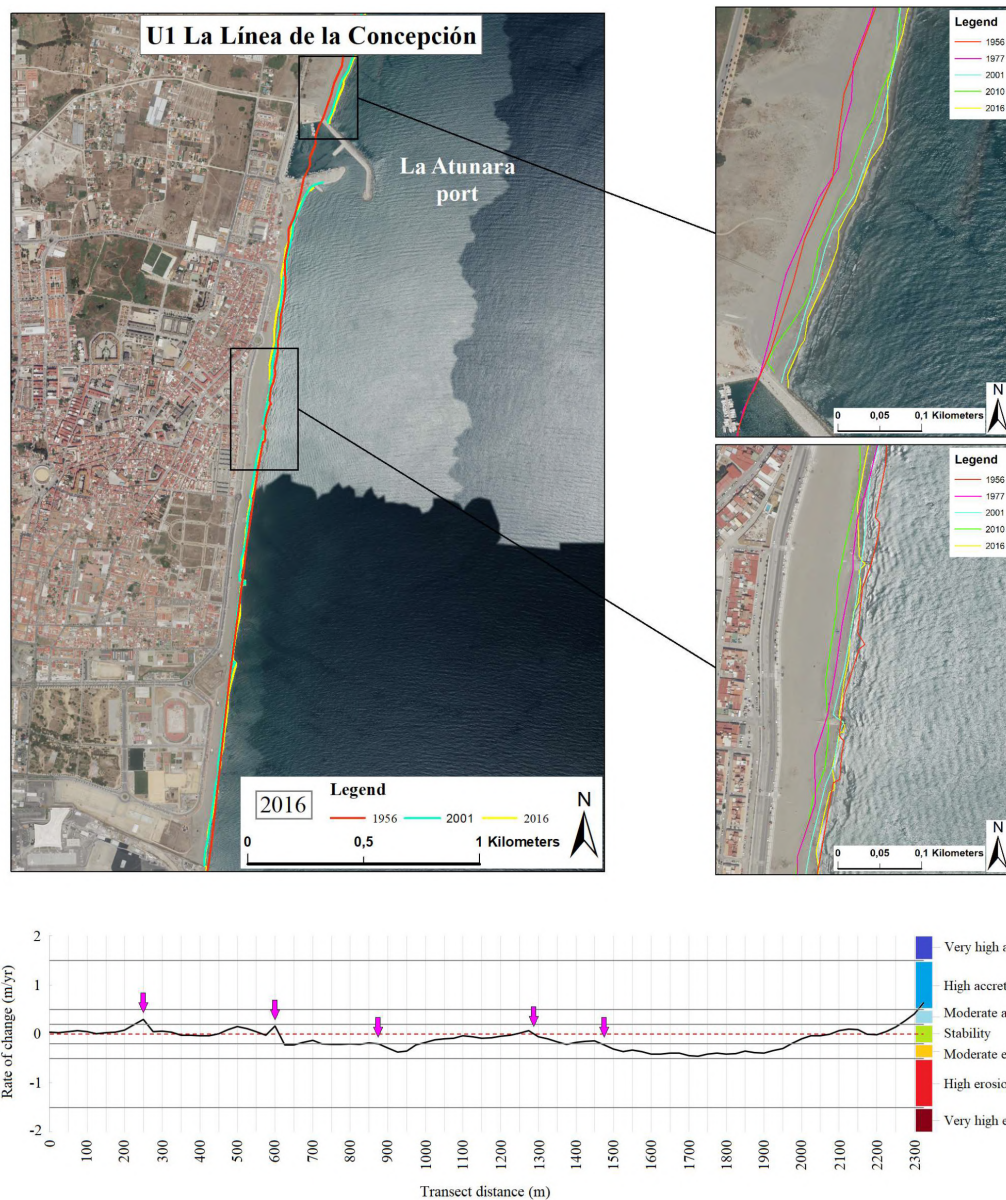


Figure 9. Evolution of La Línea de la Concepción (Unit 1). At this unit the most frequent class was “Stability” (60.6%, i.e., 1.4 km) and beach surface evolution was negative ($-97.75 \text{ m}^2/\text{yr}$). Accretion was observed in the southernmost part of the unit close to a small groin (up to 0.3 m/yr), and of the port (0.64 m/yr), which was constructed in 1994. “Moderate erosion” was observed at the central area of the unit (-0.37 m/yr) and up-drift of the easternmost groin (-0.46 m/yr). Examples of coastal trend changes are also presented. Arrows indicate the position of protection structures.

5. Discussion

This section discusses the distribution of erosion/accretion/stability classes (or evolution classes) according to their location, i.e., up-drift, down-drift or in correspondence of coastal structures, or in “natural” areas free of structures. Then, the distribution of evolution classes was analyzed considering structures location/characteristics and wave approaching front directions to determine the distribution of swash- and drift-aligned costal sectors and prevalent longshore transport direction.

5.1. Evolution Classes at Natural Coastal Sectors

Transects located at natural areas (Figure 10a), i.e., areas with no ports and protection structures, recorded average retreat rates of 0.17 m/year . Special attention was devoted to the behavior of

transects located at deltas and river mouths (Figure 10a), which showed average retreat rates of 0.62 m/year, reaching high and very high erosion values, e.g., 1.88 m/year at Adra Delta, 1.00 m/year at Andarax Delta and 1.15 m/year at Aguas River mouth, in Almería Province. Retreat rates of 3.71 and 0.82 m/year were, respectively, recorded at Vélez River Delta and at Verde River mouth in Málaga Province.

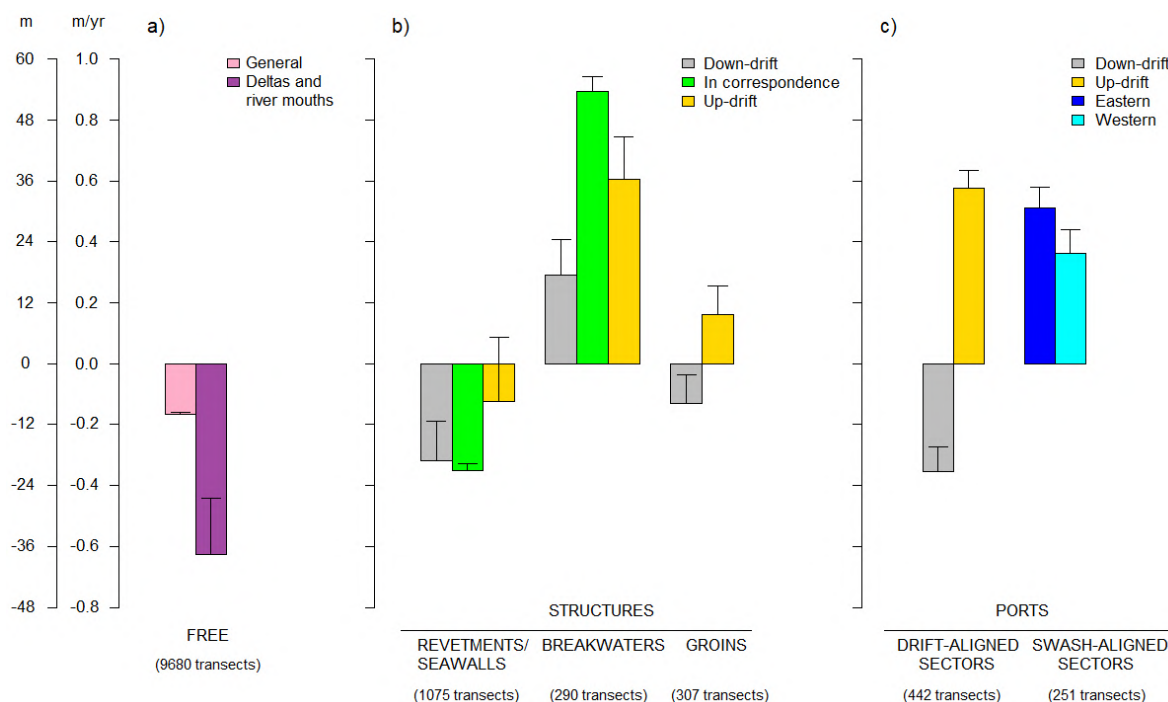


Figure 10. Interaction plots giving evolution values and trends of transects at: (i) free areas, distinguishing between transects located at any general place and in correspondence of rivers and deltas (a); (ii) transects located up- and down-drift or in correspondence of seawalls/revetments, breakwaters and groins (b); and (iii) at up- and down-side of ports in drift-aligned coastal sectors and eastern or western side of ports in swash-aligned coastal sectors (c) (Figure 2).

In Almería, the erosive evolution of the deltas of Andarax and Adra rivers, and of the eastern zone of the province, were greatly influenced by the torrential nature of those rivers and other streams, as well as by the progressive construction of dams that greatly reduced sediment inputs to the littoral [58,59], a common trend also observed at other places by Syvitski et al. [60] and Kim et al. [61]. The Beninar Dam, built in 1988 in the Adra River, brought to the construction of about 100 small groins along the east side of the current delta [39].

The Vélez River delta is a good example of an erosive behavior. The delta apex is very susceptible to erosion: a divergence of transport was observed at such location and sediments were accumulated at both sides of the apex [39], this being a common trend also observed at the Guadalfeo and Andarax deltas [39], as well as on the Nile [62,63], Ebro [11] and the Arno [64] deltas. Since 1988, several dams were emplaced in the basin of the Vélez River that significantly reduced fluvial sedimentary load [65]. Accretion was observed at the eastern area of the delta because of the emplacement of coastal structures and periodic nourishment works [39,66,67].

Located on the Verde River, La Concepción Dam is the most important fluvial engineering work of Costa del Sol [68], with an artificial lake surface of 2.14 km², a volume capacity of 57×10^6 m³ and an affected river length of 5 km. Before dam construction, the Verde River constituted the main source of sediment to the Marbella coastal area [68–70].

Transects located at pocket beaches showed the prevalence of stability values and a typical pivoting behavior [71], e.g., La Herradura (Unit 24, Figure 8). This is because pocket beaches are

restricted sedimentary systems, i.e., they experience little or no connection to other systems because the presence of rocky headlands limiting them [72].

5.2. Evolution Classes versus Coastal Structures Location and Characteristics

In sandy sectors, the spatial distribution of accretion, erosion and stability areas is essentially influenced by the emplacement of protection structures, ports and existing natural headlands and the way such structures interact with the incoming waves, as observed at different areas by the authors of [31,34,73–75].

Concerning the effect of coastal protection structures, seawalls and revetments reflect wave energy; this process restricts the natural inland migration of sediments and, consequently, induces erosion and beach losses in front of them [76,77], as also observed in this paper. Specifically, 1075 transects were linked to the presence of revetments and seawalls and, even though they were located in correspondence, up- or down-drift of structures, they were always characterized by high erosion values (from 0.13 to 0.35 m/year, Figure 10b).

Breakwaters produce tombolos [78,79], as widely observed at Málaga Province (e.g., Málaga and Puerto Banús, Figures 3 and 7) at these areas accretion classes were recorded, especially where structures were very numerous. Specifically, 290 transects were located in correspondence and up- or down-drift of breakwaters. This typology of structure was much more effective in retaining sediments than groins and showed average accretion values up to 0.89 m/year, close to the ones recorded up-drift of ports (Figure 10b,c).

Shore-normal structures (i.e., groins and jetties) and ports act as absolute or permeable cell limits [73] that affect surf zone circulation usually producing accretion up-drift and erosion down-drift, as extensively observed by Anfuso et al. [34] along the Caribbean coast of Colombia or by Anfuso et al. [80] in southeastern Sicily. This was also recorded in this paper: transects located close to groins clearly reflected longshore transport effect, i.e., up-drift accretion with average values of 0.16 m/year and average down-drift values of 0.13 m/year (Figure 10b).

Concerning transects located close to ports, they were divided into two groups, i.e., up- and down-drift transects when ports were located in drift-aligned coastal sectors (i.e., in a coastal area where a clear longshore transport direction was observed; see Figure 2 and Section 5.3) and in eastern and western transects when they are close to ports located in swash-aligned sectors (see Figure 2 and Section 5.3).

Regarding ports located in drift-aligned areas, transects located up-drift recorded the greatest accretion classes respect to other typologies of structures and erosive transects were observed in down-drift areas (Figure 10c), e.g., at Sotogrande Port in Cádiz Province and at Garrucha Port in Almería, a common trend observed along sandy coasts [77,79]. Ports located in swash-aligned sectors showed accretion at both sides (Figure 10c). The form and dimensions of the newly formed beaches depend on the characteristics of the structures and wave regime as observed by different authors (e.g., [31,34,73]).

Commonly, the development of erosion processes in down-drift areas was prevented with the progressive emplacement of new structures generating the so called “domino” effect [81]. This process, frequently observed along the Mediterranean coast [31,34,38,80], translates and amplifies erosion processes in down-drift areas. An example was the construction of the port of Almerimar (Figure 5) in 1978; according to [59], it caused the down-drift disappearance of 20,000 m² of beach surface. In 1996, two structures were successively emplaced to reduce coastal erosion; these structures proved to be ineffective and caused the loss of more than 135,500 m² [59]. Nowadays, periodic artificial nourishments are carried out to maintain this beach. Despite the emplacement of structures, an important cause of beach erosion during the 1956–1988 period was the illegal extraction of more than 5 million cubic meters of sand from beaches and dunes in Punta Entinas–Sabinar zone [59].

Last, shoreline evolution was not always uniform, i.e., recorded an inversion of trend, usually from erosion to accretion, as observed at several erosion spots where the erosive trend was contrasted

by the emplacement of coastal structures and/or artificial nourishments, e.g., at Puerto Banús (Figure 7) and at La Línea de la Concepción (Figure 9).

5.3. Swash- and Drift-Aligned Coastal Sectors

The analysis of beach plan form and its temporal variation, which depends on wave climate [75,82] and natural and human structures characteristics [73], can be used to determine coastal sectors with drift-aligned or swash-aligned shoreline trends. Drift-aligned shoreline sectors are the result of a clear unidirectional transport while swash-aligned shoreline sectors are the result of a bidirectional longshore transport and/or a cross-shore transport [31].

Swash-aligned shoreline form was observed at two extended areas: at Costa del Sol (Málaga) and in the Gulf of Almería (Figure 2). The former (Málaga, Unit 18) is shown in Figure 3: this is a strongly urbanized coast [31,66], with a large number of coastal protection structures. Huge amounts of sediments, which altered the natural dynamics of the area, were injected to counteract erosion processes linked to recurrent storms. Further alteration to the dynamic characteristics of this area was caused by the construction of many groins, successively replaced by breakwaters, which favored the creation of tombolos [66] and the formation of a stable, swash-aligned coast [31].

Concerning the main transport directions observed in this paper (Figure 2), they reflected wave roses (Figure 1) and storms approaching directions presented by Molina et al. [42]. The drift-aligned, easternmost part of the investigated littoral is sheltered, because of its geographic location, to the Atlantic swell waves and exposed to east approaching fronts forming an angle of ca. 45 degrees with the shoreline; the main sediment transport direction observed at this area confirmed such data showing a NE-SW main transport trend at La Línea de la Concepción (Unit 1, Figure 9) and at Sotogrande where the port, constructed in 1987, clearly interrupted longshore transport (Figure 11a).



Figure 11. Examples of drift-and swash-aligned shoreline sectors. Stogrande Port (a) was constructed in 1987, Adra Port (b) in 1947 (the first emplacement) and the construction of Garrucha Port (c) started in 1931 and the last modification was carried out in 2009.

At the central part of the studied coast (Points 2 and 3, Figure 1), which is drift-aligned, wind and waves approached from W, E and E-NE directions, the W component prevailing due to the increase of the western geographic fetch. Hence, offshore wave fronts are broadly normal to the coast and the most energetic events approached from these directions too [42].

As observed in Suffolk (UK) by Burningham and French [83], the bimodal wave climate has a strong control on sediment movement alongshore. The W-E transport direction was observed in the central part of the investigated littoral, e.g., at Adra (Unit 34, Figures 6 and 11b) with a clear evidence at Adra Port where a dock was built in 1947 to avoid infilling problems [58]. The eastern coast of the studied area, which is drift-aligned, is NNE-SSW oriented so it is sheltered to the W, and the E-NE approaching directions prevail (forming an angle of ca. 30 degrees with the shoreline, Point 4, Figure 1); this is confirmed by the NE-SW transport direction observed in this study, e.g., at Garrucha (Unit 47, Figure 11c).

6. Conclusions

This study analyzed the evolution, during a 60-year time span, of the Mediterranean coast of Andalusia, making special emphasis on the impact of coastal structures. The coast was divided into 47 units of different lengths and, within each unit, the evolution rates were calculated by using the DSAS extension of ArcGIS software. Along the investigated area, 9 units recorded accretion, 19 recorded stability and 19 erosion. Seventeen units presented a positive balance and 28 units a negative one. The investigated littoral showed a negative net balance of 29,738.4 m²/year corresponding to the loss of 1784.30 km² of beach surface in the 1956–2016 period.

Concerning the influence of coastal structures, it was observed as accretion areas were essentially observed up-drift of ports and groins and in correspondence of breakwaters. Coastal areas in front of revetments always recorded erosion, which was also relevant down-drift of ports and groins, as well as at the mouths of largest rivers and deltas. Stability was observed at several pocket beaches and at areas stabilized by coastal protection structures. The analysis of shoreline trend and form as well as the influence of coastal protection structures and ports in promoting erosion or accretion processes, allowed to reconstruct the distribution of drift- and swash-aligned coastal sectors and longshore transport directions, mainly depending on coastal orientation with respect to the prevailing wave approaching fronts. This is a quite complex, indented coast associated with an active alpine orogen contacting the sea, affected by two prevailing winds blowing parallel to the main direction of the coast. As a result, swash-aligned coastal sectors predominate inside the main embayments (e.g., Málaga Bay and Almería Gulf), while the rest is represented by drift-aligned sectors. Nevertheless, the direction and sense of prevailing drift currents change from one sector to another, e.g., southwards in the NE-SW oriented sectors, eastwards in the central sectors.

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Appendix A

Table A1. Characteristics of the studied units. * Cardinal points indicate the location of the Harbour/Port.

ID	Coastal Name	Morphology	Number of the Defence Structures			Close to Harbour/Port (*)
			Groins	Breakwaters	Revetments	
1	La Línea de la Concepción	Straight coast	7	–	–	Yes (N)
2	El Zabal	Straight coast	–	–	–	Yes (S)
3	Torreguadiaro	Straight coast and Pocket beach	3	–	–	Yes
4	La Chullera	Straight coast	1	–	1	Yes (N)
5	San Luis de Sabinillas	Straight coast	–	–	–	Yes (S)
6	La Gaspara	Straight coast and Pocket beach	2	–	3	Yes
7	Estepona	Straight coast	2	1	–	Yes (N)
8	Guadalmansa (S)	Straight coast	1	–	1	No
9	San Pedro de Alcántara	Straight coast	11	5	1	No (SW); Yes (NW)
10	Coral Beach (Puerto Banús \$N4)	Pocket beach	1	–	–	Yes (SW)
11	Marbella (W)	Straight coast	2	1	–	Yes (NW)
12	Marbella (E)	Pocket beach and Straight coast	12	–	–	Yes (W)
13	Mijas	Straight coast	–	–	–	Yes (W)
14	Fuengirola (S)	Straight coast	2	1	1	Yes
15	Benalmádena	Straight coast	6	2	2	Yes (NE)
16	Torremolinos	Straight coast	–	–	2	Yes (SW)
17	Málaga (S)	Straight coast	1	–	–	Yes (NE)
18	Málaga (E)	Straight coast	1	13	2	Yes (W and E)
19	La Cala del Moral	Pocket beach	1	1	1	No
20	Rincón de La Victoria	Straight coast	–	–	5	No
21	Torre del Mar	Straight coast	10	2	2	Yes
22	Caleta de Vélez	Straight coast	1	–	5	No
23	Nerja	Pocket beach	–	–	1	No
24	La Herradura	Pocket beach	–	–	–	No
25	Almuñécar	Pocket beach	–	–	–	No
26	Velilla Tamaray	Pocket beach	3	1	1	No
27	Salobreña	Straight coast	2	–	–	Yes (E)
28	Torrenueva	Pocket beach	4	4	–	Yes (W)
29	Carchuna	Straight coast	–	–	–	No
30	Castel de Ferro	Pocket beach	–	4	–	No
31	La Mamola	Straight coast	5	–	2	No
32	Albuñol	Straight coast	2	–	1	No
33	Adra (E)	Straight coast	8	–	–	Yes (E)
34	Adra (W)	Straight coast	88	2	9	Yes (W)
35	Balerma	Straight coast	8	–	–	No
36	Ensenada de San Miguel	Pocket beach	1	–	–	Yes (E)
37	Almerimar	Pocket beach	3	1	–	Yes (NW)
38	San Agustín	Straight coast	–	–	–	No
39	Roquetas de Mar (S)	Straight coast	2	–	1	Yes (N)
40	Roquetas de Mar (N)	Straight coast	–	1	–	Yes (N and S)
41	Almería	Straight coast	4	1	–	Yes (W)
42	Costacabana	Straight coast	6	–	–	No
43	Cabo de Gata	Straight coast	–	–	–	No
44	Playa de los Genoveses	Pocket beach	–	–	–	No
45	Carboneras	Pocket beach	–	–	–	Yes
46	La Parata	Straight coast	–	–	–	No
47	Garrucha	Straight coast	3	2	–	Yes (S)

Table A2. Shoreline determination error for each document used (Equation (1)).

Year	Error Components (m)						
	σ_d	σ_p	σ_r	σ_{co}	σ_{wr}	σ_{td}	σ_T
Area 1 (1–12 units)							
1956	7.60	1.00	4.00	0.50	2.60	11.70	14.80
1977	2.10	0.50	3.30	0.50	2.60	11.70	12.60
2001	2.10	0.50	1.00	1.00	2.60	11.70	12.30
2010	1.90	0.50	0.50	0.00	2.60	11.70	12.10
2016	0.70	0.25	0.50	0.00	2.60	11.70	12.00
Area 2 (13–23 units)							
1956	7.60	1.00	4.00	0.50	2.80	7.20	11.60
1977	2.10	0.50	3.30	0.50	2.80	7.20	8.70
2001	2.10	0.50	1.00	1.00	2.80	7.20	8.20
2010	1.90	0.50	0.50	0.00	2.80	7.20	8.00
2016	0.70	0.25	0.50	0.00	2.80	7.20	7.80
Area 3 (24–37 units)							
1956	7.60	1.00	4.00	0.50	3.20	4.30	10.20
1977	2.10	0.50	3.30	0.50	3.20	4.30	6.70
2001	2.10	0.50	1.00	1.00	3.20	4.30	5.90
2010	1.90	0.50	0.50	0.00	3.20	4.30	5.70
2016	0.70	0.25	0.50	0.00	3.20	4.30	5.40
Area 4 (38–43 units)							
1956	7.6	1.00	4.00	0.50	3.10	2.80	9.60
1977	2.10	0.50	3.30	0.50	3.10	2.80	5.80
2001	2.10	0.50	1.00	1.00	3.10	2.80	4.90
2010	1.90	0.50	0.50	0.00	3.10	2.80	4.60
2016	0.70	0.25	0.50	0.00	3.10	2.80	4.30
Area 5 (44–47 units)							
1956	7.60	1.00	4.00	0.50	3.30	1.40	9.40
1977	2.10	0.50	3.30	0.50	3.30	1.40	5.40
2001	2.10	0.50	1.00	1.00	3.30	1.40	4.40
2010	1.90	0.50	0.50	0.00	3.30	1.40	4.10
2016	0.70	0.25	0.50	0.00	3.30	1.40	3.70

Table A3. Results of coastal evolution during the 1956–2016 period. Blue numbers indicate the most frequent class. * Unit net balance: A, accretion; E, erosion.

Unit	Name	Accretion (%)			Stability (%)	Erosion (%)			Unit Net Balance *	Longitude (km)	Morphology
		Very High	High	Moderate	Moderate	High	Very High				
1	La Línea de la Concepción	0.0	1.1	3.2	60.6	35.1	0.0	0.0	E	2.3	
2	El Zabal	0.0	53.2	36.2	10.6	0.0	0.0	0.0	A	7.5	
3	Torrequebruna	0.0	1.2	9.0	25.3	20.4	21.6	22.4	E	6.0	
4	La Chullera	0.0	0.5	1.0	16.7	41.4	39.9	0.5	E	5.0	
5	San Luis de Sabinillas	0.8	1.7	5.9	22.9	25.4	43.2	0.0	E	2.9	
6	La Gaspara	0.0	0.0	0.0	0.9	15.1	83.9	0.0	E	5.4	Drift aligned
7	Estepona	5.5	28.6	14.3	50.5	1.1	0.0	0.0	A	2.2	NE-SW
8	Guadalmansa (S)	0.0	0.0	0.0	45.9	50.0	4.1	0.0	E	7.3	
9	San Pedro de Alcántara	0.0	4.4	4.9	14.6	45.5	30.7	0.0	E	10.2	
10	Coral Beach (Puerto Banús N)	0.9	5.2	2.6	20.7	34.5	36.2	0.0	E	2.9	
11	Marbella (W)	0.0	6.5	22.0	61.8	8.1	1.6	0.0	A	3.0	
12	Marbella (E)	0.6	5.8	2.7	26.6	31.4	32.9	0.0	E	12.8	
13	Mijas	0.0	7.0	5.7	49.4	20	14.5	3.5	E	10.0	
14	Fuengirola (S)	0.0	1.9	20.1	50	26.9	1.1	0.0	E	6.5	
15	Benalmádena	3.4	17.9	22.8	48.1	6.6	1.1	0.0	A	8.7	
16	Torremolinos	0.0	21.2	24.0	24.5	13.1	11.4	5.8	A	8.9	
17	Málaga (S)	2.1	2.1	2.6	23.7	9.8	53.1	6.7	E	4.8	Swash aligned
18	Málaga (E)	22.4	43.7	12.5	13.3	4.9	3.0	0.0	A	6.5	
19	La Cala del Moral	1.2	42.7	28.0	28.0	0.0	0.0	0.0	A	2.0	
20	Rincón de La Victoria	1.5	33.6	14.7	25.0	13.2	8.0	3.8	A	16.2	
21	Torre del Mar	0.0	31.0	24.0	17.1	11.2	8.9	7.8	A	6.4	
22	Caleta de Vélez	0.0	7.1	9.5	33.5	24.9	24.9	0.0	E	8.0	
23	Nerja	0.0	0.0	4.3	47.8	47	0.9	0.0	E	2.8	
24	La Herradura	0.0	0.0	29.8	70.2	0.0	0.0	0.0	A	2.1	
25	Almuñécar	0.0	2.3	14	83.7	0.0	0.0	0.0	A	1.0	
26	Velilla Tamaray	15.7	39.3	30.7	14.3	0.0	0.0	0.0	A	3.5	
27	Salobreña	22	14.4	8.0	9.8	11.0	23.1	11.7	A	6.6	
28	Torrenueva	3.4	22.8	15.9	23.4	6.2	28.3	0.0	A	3.6	
29	Carchuna	0.0	3.5	2.5	77.1	15.9	1.0	0.0	E	5.0	Drift aligned
30	Castel de Ferro	0.0	14.9	5.7	56.3	10.3	12.6	0.0	E	2.1	W-E
31	La Mamola	0.0	15.9	29.0	28.3	19.3	7.6	0.0	A	3.6	
32	Albuñol	16.2	12.7	6.4	24.5	36.8	3.4	0.0	E	5.1	
33	Adra (E)	0.0	0.6	12.5	78.8	8.1	0.0	0.0	A	4.0	
34	Adra (W)	0.0	1.5	6.9	24.1	28.0	19.0	20.5	E	8.3	
35	Balerna	0.0	0.0	0.9	75.8	22.7	0.6	0.0	E	8.4	
36	Ensenada de San Miguel	0.5	9.9	3.5	5.4	4.5	76.2	0.0	E	5.0	
37	Almerimar	0.0	10.6	1.1	1.1	2.1	21.3	63.8	E	2.3	
38	San Agustín	0.0	25.1	13.7	11.3	10.7	23.4	15.8	E	12.6	
39	Roquetas de Mar (S)	0.0	0.0	2.4	34.1	20.2	30.8	12.5	E	5.2	
40	Roquetas de Mar (N)	0.3	2.0	1.0	22.4	33.4	40.8	0.0	E	7.4	Swash aligned
41	Almería	1.0	14.1	11.5	23	15.3	35.1	0.0	E	7.8	
42	Costacabana	0.0	1.4	2.5	82.0	11.2	3.0	0.0	E	9.1	
43	Cabo de Gata	0.0	0.0	5.7	55.4	27.0	11.8	0.0	E	12.6	
44	Playa de los Genoveses	0.0	0.0	0.0	13.8	23.1	63.1	0.0	E	1.6	
45	Carboneras	9.0	11.2	2.2	6.0	34.3	37.3	0.0	E	3.3	Drift aligned
46	La Parata	1.5	7.5	6.0	3.6	52.4	28.9	0.0	E	8.6	NE-SW
47	Garrucha	2.7	5.7	29.7	24.3	3.8	13.3	20.5	E	7.0	

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Anexo III

Publicación III. Dune's systems characterization and evolution in the Andalusia Mediterranean Coast (Spain).

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Article

Dune Systems' Characterization and Evolution in the Andalusia Mediterranean Coast (Spain)

Rosa Molina ¹, Giorgio Manno ^{2,*}, Carlo Lo Re ² and Giorgio Anfuso ¹

¹ Department of Earth Sciences, Faculty of Marine and Environmental Sciences, University of Cádiz, Polígono Río San Pedro s/n, 11510 Puerto Real, Spain; r.molina.gil@gmail.com (R.M.); giorgio.anfuso@uca.es (G.A.)

² Department of Engineering, University of Palermo, Viale delle Scienze, Bd. 8, 90128 Palermo, Italy; carlo.lore@unipa.it

* Correspondence: giorgio.manno@unipa.it; Tel.: +39-091-23896524

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Abstract: This paper deals with the characterization and evolution of dune systems along the Mediterranean coast of Andalusia, in the South of Spain, a first step to assess their relevant value in coastal flood protection and in the determination of sound management strategies to protect such valuable ecological systems. Different dune types were mapped as well as dune toe position and fragmentation, which favors dune sensitivity to storms' impacts, and human occupation and evolution from 1977 to 2001 and from 2001 to 2016. Within a GIS (Geographic Information System) project, 53 dune systems were mapped that summed a total length of ca. 106 km in 1977, differentiating three dune environments: (i) Embryo and mobile dunes (Type I), (ii) grass-fixed dunes (Type II) and (iii) stabilized dunes (Type III). A general decrease in dunes' surfaces was recorded in the 1977–2001 period ($-7.5 \times 10^6 \text{ m}^2$), especially in Málaga and Almería provinces, and linked to dunes' fragmentation and the increase of anthropic occupation ($+2.3 \times 10^6 \text{ m}^2$). During the 2001–2016 period, smaller changes in the level of fragmentation and in dunes' surfaces were observed. An increase of dunes' surfaces was only observed on stable or accreting beaches, both in natural and anthropic areas (usually updrift of ports).

Keywords: dune characterization; anthropic occupation; fragmentation index; dune surface

1. Introduction

Human interest in coastal processes and evolution has greatly increased in recent decades due to the increment of human developments recorded in coastal areas [1] and the impacts of extreme events, such as hurricanes and storms [2,3], the effects of which are enhanced by sea level rise and other climatic change-related processes, such as the increasing height of extreme waves, or changes in the tracks, frequency and intensity of storms [4–7]. Coastal development, which is essentially linked to tourism—one of the world's largest industries [8]—continues to increase, and some 50% of the world's coastline is currently under pressure from excessive development [1]. In Europe, the rapid expansion of urban artificial surfaces in coastal zones during the 1990–2000 period [9] has occurred in the Mediterranean and South Atlantic areas, namely Portugal (34% increase) and Spain (18%), followed by France, Italy and Greece.

Activities and infrastructures related to tourism and other human developments too (e.g., fishing and industrial activities) are significantly affected by the impacts of storms and hurricanes that, over the past century, have caused huge economic losses along with high mortality rates along the world's coastlines [10–13]. Coastal erosion and flooding processes have reduced beach and dune ridges' width and produced the loss of associated touristic, aesthetic and natural values [14–17].

Beach erosion/accretion cycles are often recorded at an inter-annual time scale and are related to seasonal wave climate variations due to temporal and spatial distributions of high-latitude storms and hurricanes/typhoons [3,18–22]. Erosion is observed after storm events, at high latitudes recorded during winter months, but beach recovery takes place during fair weather conditions, which is known as “seasonal” beach behavior [10,23], and in general happens at longer time intervals, from weeks to months [24,25]. Hence, natural beach recovery guarantees the reformation of a wide beach and its associated protection function and touristic use, but dune response to erosive events is very different. Meanwhile, dune erosion is always very rapid and time located accretion is a process that usually takes place with low rates over a long time, from several months to years in the Andalusia Atlantic littoral [26]. Hence, the determination of coastal dune characteristics, behavior and evolution need special attention in the attempt to reduce erosive/flooding processes’ impacts on natural and urbanized coasts. Several recent investigations [27,28] have identified dunes as one of the most relevant coastal ecosystems as a natural defense able to reduce flood sensitivity/vulnerability and hence, dunes’ maintenance/emplacement has been considered as an effective coastal protection measure included among possible “Disaster Risk Reduction” (DRR) strategies in several European directives [28–32]. In fact, dune ridges protect large sections of low-lying coasts against flooding during extreme storms [9,33,34], and hence, lateral dune continuity and level of fragmentation are extremely relevant [35–38].

This paper is the first one that deals with the characterization and evolution of all dune systems along the Mediterranean coast of Andalusia (South of Spain), and this is a first step to assess their great ecological value, sensitivity and relevance in coastal flood protection. Different dune types have been mapped as well as their level of fragmentation (by means of a new index proposed in this paper) and present human occupation and evolution from 1977 to 2016. Results obtained are of relevance to enhance the general database on dune characteristics along the Mediterranean coast of Andalusia and the possibility of use ecosystem-based solutions in coastal protection along with, or instead of, traditional engineering approaches [27,28].

2. Study Area

Located in South Spain, the Mediterranean coast of Andalusia administratively belongs to the provinces of Cádiz, Málaga, Granada and Almería (Figure 1). It has a prevailing rectilinear E-W outline, with two NE-SW easterly facing sectors, i.e., the Gibraltar Strait and the Almería easternmost coastal sector (Figure 1). It is a micro-tidal environment (tidal range < 20 cm) with a total length of ca. 546 km, including rocky sectors (ca. 195 km) and intermediate to reflective beaches (ca. 350 km) [39], usually composed of medium to coarse dark sands and/or pebbles. Dune systems, which have a total length of ca. 76 km, are especially observed along the provinces of Cádiz and Almería (Figures 1 and 2) [25,40,41].

The Betic Range, a tectonically active mountain chain that, at places, reaches relevant elevations higher than 2200 m above sea level (m a.s.l.) close to the coast, determines coastal orography and morphology, forming cliffs, embayments and promontories. Several small coastal plains are especially extended at the mouth of short rivers and *ramblas* (seasonal streams) draining the chain, the most important being the Guadiaro, Guadalhorce, Guadalfeo, Adra and Andarax rivers (Figures 1 and 2). In the past decades, river basin regulation plans devoted to water management for tourist and agricultural purposes have enhanced the construction of dams and reservoirs that have reduced sediment supplies to the coast and have promoted coastal retreat in most deltas [39,42–44].

Large coastal towns are Málaga (>500,000 inhabitants), Almería (ca. 200,000 inhabitants) and the tourist towns along the western part of Costa del Sol area, namely Marbella (150,000 inhabitants), Fuengirola (80,000) and Torremolinos (70,000). Málaga is the province that has experienced the most important coastal occupation, in particular due to the construction of structures related to national and international tourism [45]. Main commercial ports are located at Almería, Algeciras, Cádiz and Málaga, and several marinas at Costa del Sol [46–48].

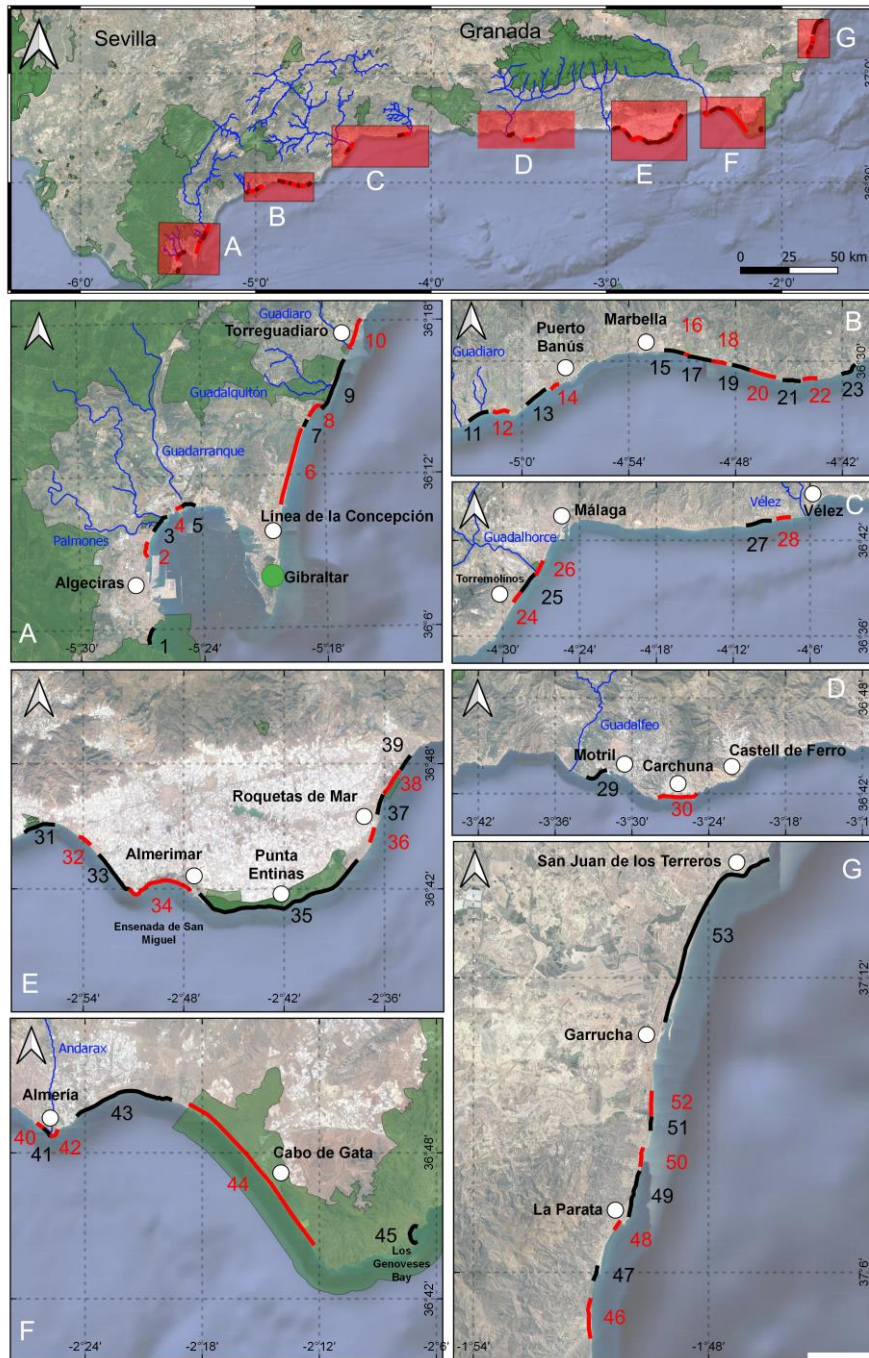


Figure 2. Location of the studied dune systems. Natural protected areas are in green. The capital letters A–G in the main subplot refer to the zoomed areas in the other subplots.

3. Materials and Methods

Aerial orthophotographs dated 1977, 2001 and 2016 (Table 1) were used to map different dune systems, and to quantify their surface evolution, level of fragmentation and the progression of human occupation. Aerial orthophotographs were obtained from the Web Map Services (WMS) of the Open Geospatial Consortium (OGC) of the Andalusia Regional Administration [52].

Table 1. Aerial orthophotos used [52], 2001 and 2016 orthophotos are from Plan Nacional de Ortofotografía Aérea (PNOA).

Year	Scale	Spatial Resolution(m)	Flight
1977	1:5000	0.5	Iryda flight 1977
2001	1:10,000	0.5	PNOA 2001
2016	1:5000	0.25	PNOA 2016

Orthophotographs were elaborated within a GIS project (reference system WGS84–UTM 30N) by means of the ArcMap application from ArcGIS Desktop, Release 10 Redlands, CA: Environmental Systems Research Institute. All dune systems with a minimum longshore seaward front of 100 m in length were mapped, summing a total of ca. 106 km in 1977, including 53 systems (Figure 2). Within each system, three dune environments were mapped according to Sanjaume Saumel and Gracia Prieto [25], who defined, on the base of the most important coastal dune habitats in Spain [53], i.e., (i) embryo and mobile dunes (Type I), (ii) grass-fixed dunes (Type II) and (iii) stabilized dunes (Type III). Coastal dune habitats described at the study area corresponded to the Sites of Community Importance (SCI's) of the European Commission Habitat Directive listed in Table 2.

Table 2. Sites of Community Importance (SCI's) described in the study area and their correspondence with the dune typologies mapped in this work [54].

Sites of Community Importance (SCI's)	Classification
2110—Embryonic shifting dunes	I—Embryo and mobile dunes
2120—Shifting dunes along the shoreline with <i>Ammophila arenaria</i> (“white dunes”)	
2130—Fixed coastal dunes with herbaceous vegetation (“grey dunes”)	II—Grass-fixed dunes
2150—Atlantic decalcified fixed dunes	
2210— <i>Crucianellion maritima</i> fixed beach dunes	
2230— <i>Malcolmietalia</i> dune grasslands	
2240— <i>Brachypodietalia</i> dune grasslands with annuals	III—Stabilized dunes
2250—Coastal dunes with <i>Juniperus</i> spp.	
2260— <i>Cisto-Lavanduletalia</i> dune sclerophyllous scrubs	
2270—Wooded dunes with <i>Pinus pinea</i> and/or <i>Pinus pinaster</i>	

The first group (Type I) comprises embryo and mobile dunes, which are the first band of colonizing vegetation and the first important continuous sandy relief. The second group (Type II) comprises grass-fixed dunes, which develop in a more stable soil and form a more continuous plant cover based on lawns or even some woody plants and bushes. The third group (Type III) comprises the stabilized dunes, is the innermost band of the dune system, and is made up of fully fixed vegetated dunes, with structured and stabilized soils. Its vegetation evolves into forests and a dense and diverse vegetation cover is developed.

The main characteristics used to distinguish between each dune type was the color and vegetation density, so that as systems evolve, color darkens and plant density increases, i.e., embryo and mobile dunes are often called “white” or “yellow” dunes and fixed dunes are called “grey” dunes because of their characteristic color. Díez-Garretas et al. [55], in their study on spatio-temporal changes of coastal ecosystems in Southern Iberian Peninsula (Spain), used a similar classification, taking into account the phytosociological plant communities present at the location studied and the habitat code. They related the habitat code with the ecological units present in their study, including mobile dunes, semi-fixed dunes and stable dunes. Pintó et al. [56] recognized the distinct habitats present in their study area and related them to the sea-to-land ecological gradient and the Habitats of Community Interest. Their classification is more detailed, attending more to morphological than ecological criteria.

The position, evolution and fragmentation of the dune toe position was also reconstructed, and the latter aspect favors dune sensitivity to storms' impacts [40,57–59]. Further, the total surface of each one of the 53 system and dunes' surfaces occupied by human structures/interventions was calculated.

The proxy used to map the dune toe was the seaward dune vegetation line, manually detected by a GIS operator [13,39,48,60–62]. To calculate dune fragmentation, a database was obtained for each dune system containing three shape files: the first file included a polyline of the total length of the dune toe line, the second file included the length of all breaks observed along the dune toe line of each system, and a third file, which was the result of the differences between the two previous shape files. The level of fragmentation was calculated by determining the ratio between the length of all breaks and the whole dune toe length at each dune system and year. These values were normalized according to a constant length of 100 m by dividing the total length of all breaks in the shorefront dune toe (“l”) by the entire length of the dune toe (“L”):

$$F = \frac{l}{L} \quad (1)$$

The F Index is a new index proposed for the first time in this paper vaguely based on the coefficient of infrastructural impact “K” [63]. It was applied along unitary coastal sectors of 100 m in length in order to reduce the importance of dune seaward length. The F Index was calculated for the systems present in all investigated periods (37 out of 53 systems), that is, the dune systems that disappeared in the second period were not taken into account to avoid interpreting a decrease in fragmentation when, in the reality, the entire system was lost. Values of the F Index used to express the fragmentation level were classified into three classes using the Natural Breaks Function [64], from Class 1 (“Null or very low fragmentation”, $0.00 < F < 0.06$), Class 2 (“Medium fragmentation”, $0.06 < F < 0.16$) to Class 3 (“High fragmentation”, $0.16 < F < 0.41$).

4. Results

4.1. Dune Systems’ Distribution and Evolution

Of the 53 dune systems investigated in the Mediterranean coast of Andalusia, 10 belonged to natural protected areas and, from an administrative point of view, 10 were located in Cádiz province, 18 in Málaga, 2 in Granada and 23 in Almería province (Figure 2, Appendix A Table A1). In Cádiz province, dune systems were equally divided between the Algeciras Bay and an exposed, rectilinear shoreline, including both natural and urbanized areas (Figure 2A). In Málaga province, they were mainly located at the westernmost part of the littoral (Figure 2B), and south of the Guadalhorce river mouth and west of the Vélez river delta (Figure 2C). In Granada province, only 2 dune systems were observed, located in an area updrift of the port of Motril and at Carchuna (Figure 2C). In Almería province, 5 systems were located close to delta areas, namely at Adra and, especially, at Andarax river delta (Figure 2E,F), and 8 were located at rectilinear coastal sectors limited by ports, promontories or river deltas (Figure 2E–G). Very developed dune systems were located in the relevant protected area of Punta Entinas-El Sabinar (Figure 2E); meanwhile, several systems were located at the easternmost area of Almería province and the most relevant system was observed in a large pocket beach (Los Genoveses) (Figure 2F,G).

A total of 15 dune systems disappeared from 1977 to 2016, 7 of them located in Málaga, 7 in Almería and 1 in Cádiz provinces. Dune systems’ extension was changing during the periods studied without a clear trend; meanwhile, a clear decrease in size was evident for the three largest dune systems (Appendix A Table A2). Surfaces of “Embryo and mobile dunes” (Type I), “Grass-fixed dunes” (Type II) and “Stabilized dunes” (Type III) were calculated within each one of the 53 dune systems and per each time span considered. The progressive decrease of typologies I and II was observed, meanwhile, “Stabilized dunes” (Type III) recorded a decrease from 1977 to 2001 and a slight increase from 2001 to 2016 (Figure 3).

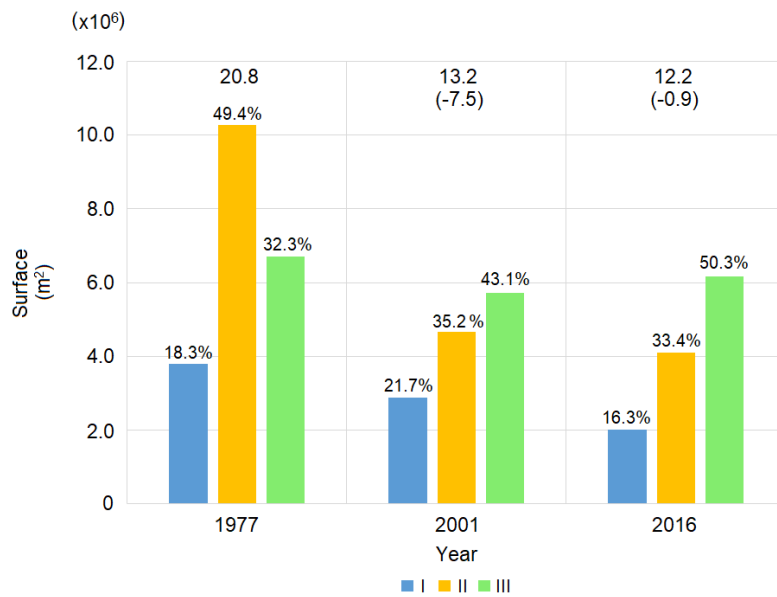


Figure 3. Yearly surface values of each dune typology, i.e., “Embryo and mobile dunes” (Type I), “Grass-fixed dunes” (Type II) and “Stabilized dunes” (Type III). Value on top represents the surface of all dune typologies and in brackets the surface that was lost with respect to the previous year is reported.

The distribution of the different dune typologies within each dune system varied during the studied period (Figure 4). At all provinces (but Cádiz), a reduction of all dune typologies was recorded during the 1977–2001 period; meanwhile, a decrease in all provinces (but Almería) of types I and III and an increase of Type II was recorded in the 2001–2016 period (Figure 4).

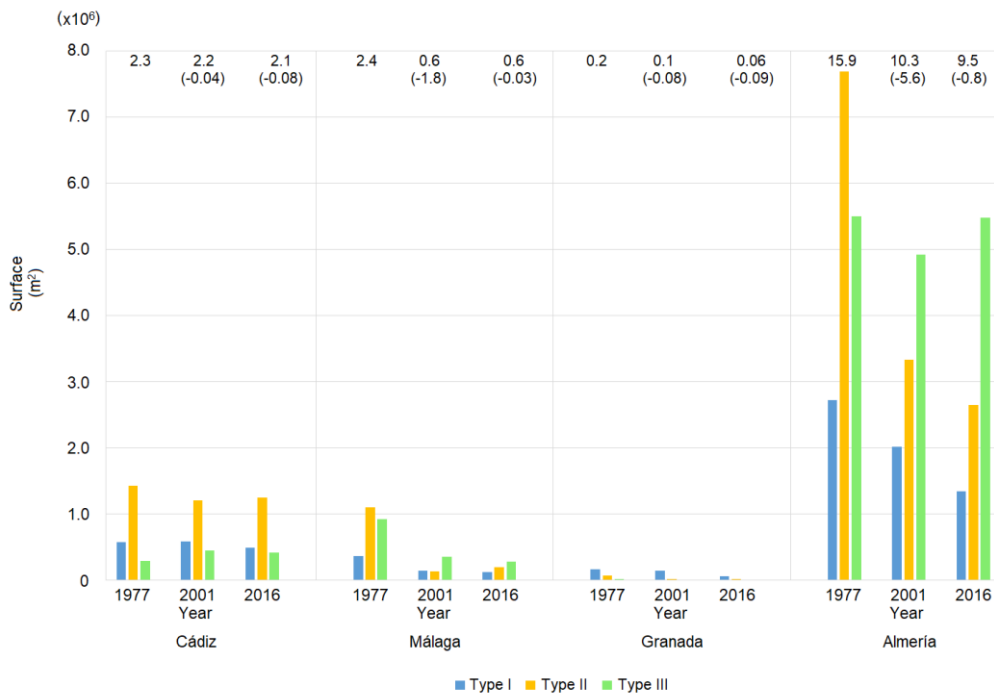


Figure 4. Distribution of dune surface typologies, i.e., “Embryo and mobile dunes” (Type I), “Grass-fixed dunes” (Type II) and “Stabilized dunes” (Type III), by province during the studied periods. The value on top represents the sum of dune surfaces (in m²) and in brackets the value of lost dune surface with respect to the previous year is presented.

The comparison of the total amount of eroded/accreted surfaces recorded in each system for the periods 1977–2001, 2001–2016 and 1977–2016 showed a clear negative balance for 49 systems and a positive one for 4 systems (Figure 3). The dune systems that showed a positive balance were located at Playa del Rinconcillo (System no. 2, 38,884.4 m²), at the Guadarranque (no. 5, 19,262.8 m²) and at the Guadalquitrón (no. 9, 260,531.7 m²) rivers' mouths in Cádiz province (Figure 2A), and in the Albufera de Adra (no. 31, 6708.5 m²), a natural protected area at the Adra river delta (Almería province, Figures 1 and 2E). The most eroded dune systems were located at Ensenada de San Miguel (System no. 34, −557,765.0 m²), Punta Entinas–El Sabinar (no. 35, −4,166,157.9 m²) and Vera (no. 53, −567,841.2 m²) areas, in Almería province.

Comparing the evolution of each system in the 1977–2001 and 2001–2016 periods, it was observed that 3 systems recorded accretion and 23 erosion in both periods, and the others showed different behaviors. Regarding the distribution of these records, the 3 accreting dune systems were located in Cádiz province and most of the dune systems that recorded erosion or disappeared were located in Málaga province, and dunes in Granada province presented erosion for both periods. In Almería province, the systems located in Almería Bay and at the easternmost part of the province presented a negative trend for both periods, and the group located from the Adra river delta to Ensenada de San Miguel presented erosion and then accretion. The two dune systems located at Roquetas de Mar disappeared in 2001–2016 (Figures 2E and 5).

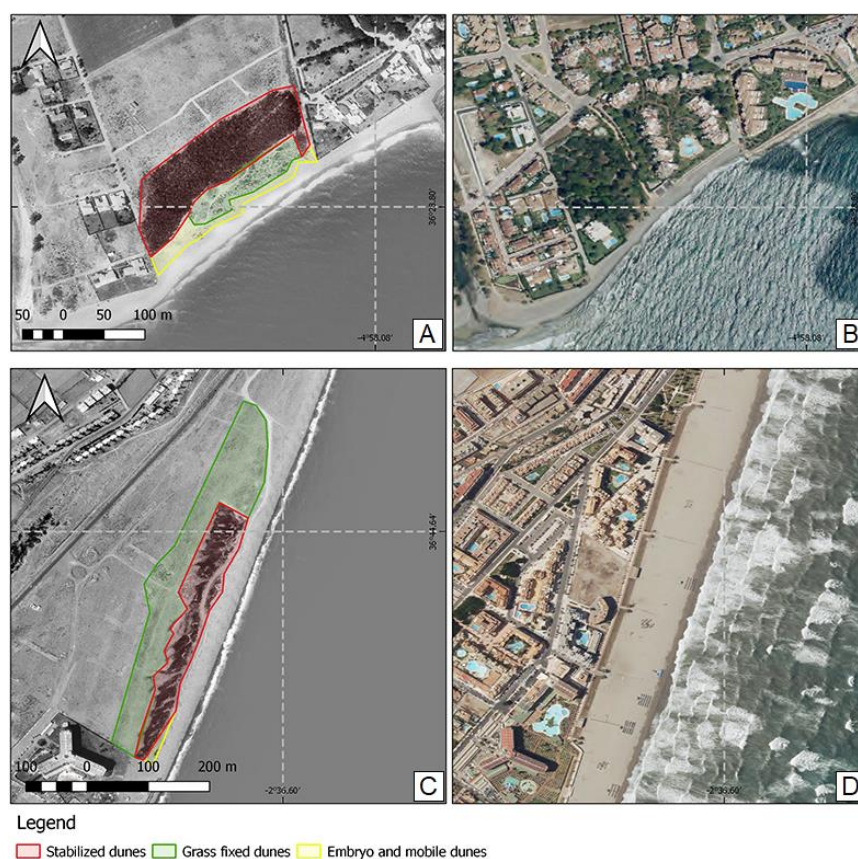


Figure 5. Dune systems urbanized in Málaga and Almería provinces. System no. 14 Playa Nueva Andalucía in 1977 (A) and 2016 (B), and System no. 36 Playa de Roquetas in 1977 (C) and 2016 (D).

4.2. Anthropic Occupation Evolution

Surfaces occupied by human structures/interventions were calculated within each one and per each year of the 53 dune systems (Figure 6). The greatest increase (ca. 2.3×10^6 m²) was observed in the 1977–2001 period.

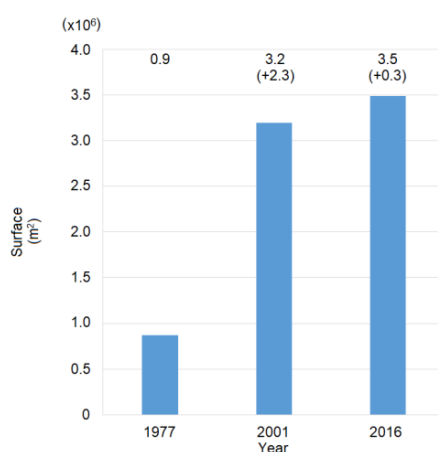


Figure 6. Evolution of the surfaces occupied by anthropic interventions during the studied periods. The number on top of histograms represents the total value of surface occupied, and in brackets shows the increment recorded among successive periods.

Comparing the evolution of human occupation of each system in the 1977–2001 and 2001–2016 periods, it was observed that 21 out of 53 systems presented an increase of human occupation in both periods and 2 systems a decrease due to the removal of small installations (Figure 7). Further, 4 systems recorded an increase in the first period and a decrease in the second due to the urbanization of a part of the dune system, and the removal of small installations, and the opposite was true for 1 system due to coastal erosion problems since the shoreline retreatment forced the removal of human structures (Figure 7).

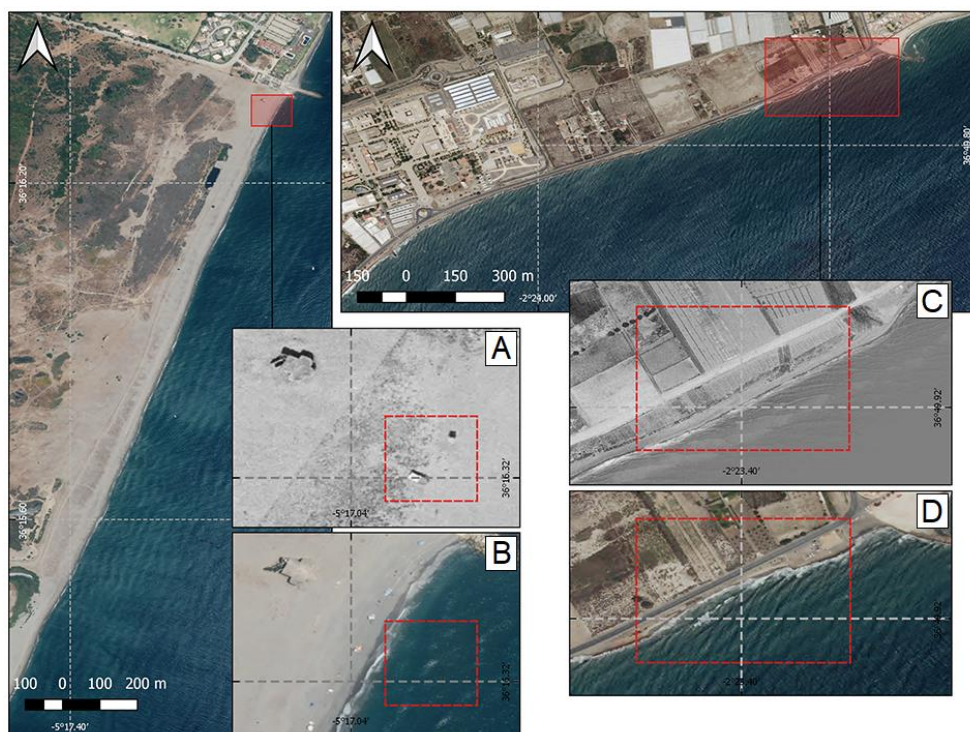


Figure 7. Removal of small constructions in Cádiz and croplands in Almería provinces. System no. 9 Guadalquítón 1977 (A), 2016 (B), with a decrease of the occupation area of 112.90 m² in 1977–2001 and 263.31 m² in 2001–2016. System no. 43 Las Algaidas-Las Marinas in 1977 (C) and 2016 (D), with a decrease of 117.14 m² in 1977–2001 and 184.07 m² in 2001–2016.

At places in System no. 2 Playa del Rinconcillo (in Cádiz province), the increase of dune surface and anthropic occupation was linked to the formation of a new beach at the northern side of the port of Algeciras (Figure 8). Summing up, the decrease of occupation was essentially due to the removal of buildings and was always very small.



Figure 8. System no. 2 Playa del Rinconcillo registered an increase of dune surface of 732.26 m² in 2001–2016. (A) 1977, (B) 2001 and (C) 2016.

4.3. Dune Fragmentation

Analysis of the dune toe fragmentation was carried out for such systems (37 out of 53) that were observed in all investigated periods and a general increase of fragmentation was evident (Figure 9), confirming the trend observed for the evolution of human occupation.

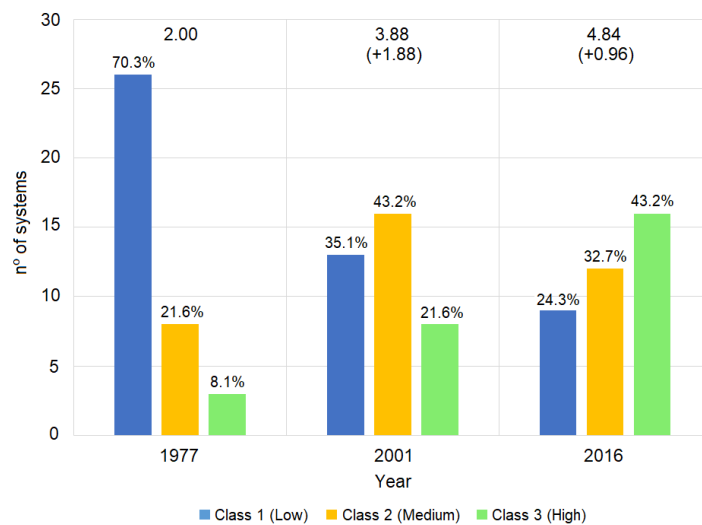


Figure 9. Fragmentation Index. The number on top of histograms represents the total value of fragmentation per year and in brackets is the increment recorded among successive periods.

Considering the 1977–2016 timespan, 23 dune systems presented an increase of fragmentation, 3 systems recorded a decrease (they were located in erosive coastal sectors within natural protected areas) and 11 presented no variations. The two systems that recorded a major increment of fragmentation were Punta del Río (no. 41), in Almería province, and Playa de las Chapas (no. 20), in Málaga province, with an increase of +0.25 and +0.22, respectively. Conversely, the two systems that recorded the major decrease of fragmentation were Playa de Río Real (no. 16) and Playa de la Misericordia (no. 26) in Málaga province, with a decrease of -0.20 and -0.09 , respectively. Comparing the evolution of fragmentation at each dune system in the 1977–2001 and 2001–2016 periods, it was observed that only 7 out of 23 presented an increase of the fragmentation at both periods, in general due to coastal zone urbanization (Figure 10A–C). Only 1 dune system showed a decrease of fragmentation (no. 16) (Figure 10D–F), and 8 presented no variation in both periods.



Figure 10. System no. 20 Playa de las Chapas, in Málaga province, recorded an increase of fragmentation due to the increment of anthropic pressure, changing from (A) Class 1 ($F = 0.003$) in 1977 to (B) Class 2 ($F = 0.12$) in 2001 and to (C) Class 3 ($F = 0.22$) in 2016. System no. 16 Playa de Río Real, in Málaga province, where the modification of the coastal zone and the emplacement of a touristic urbanization produced the destruction of the already fragmented dune system. Remnant dune systems presented a lower Fragmentation Index, changing from (D) Class 3 ($F = 0.20$) in 1977 to (E) Class 2 ($F = 0.15$) in 2001 and to (F) Class 1 ($F = 0.0$) in 2016. Red line represents dune toe position.

Other dune systems presented a different behavior at both periods: 4 systems recorded an increase in the first period and a decrease in the second and the opposite was true for 1 system (Figure 11). In general, the increase in fragmentation occurred along with the increase of urbanization and anthropic

pressure, while the opposite was observed in natural protected areas. At places where systems were already fragmented, their erosion implied a reduction in their fragmentation since: (i) very fragmented sectors often disappeared and the remaining ones presented low fragmentation (Figure 10D–F and Figure 11A,B) and (ii) coastal erosion produced the loss of the most fragmented part of dune toe (Figure 11B,C). An increase of fragmentation in 7 dune systems was due to the increment of erosion processes and/or the formation of pedestrian pathways.

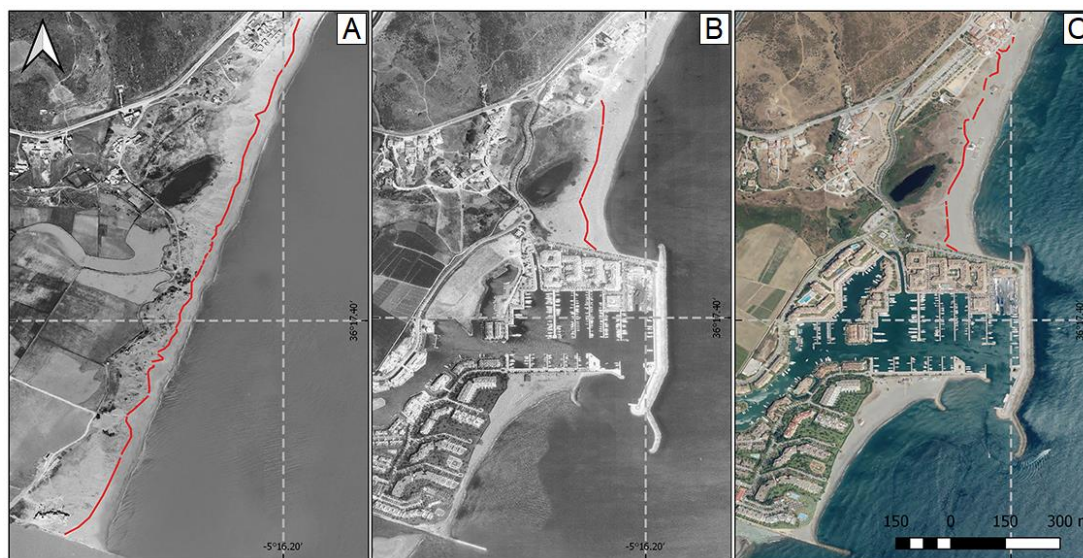


Figure 11. System no. 10 Torreguadiaro (in Cádiz province) recorded a slight decrease of fragmentation in the 1977–2001 period and an increase in the 2001–2016 period due to the reduction of a high fragmented dune sector that was replaced by the port structure. The dune system located in front of the natural protected Torreguadiaro Lagoon was not modified. In the 2001–2016 period, the growth of new dunes at the northern part of the system and the increase of pathways at both sides of it was observed. This resulted in a decrease of fragmentation that changed from (A) Class 1 ($F = 0.08$) in 1977 to (B) Class 2 ($F = 0.03$) in 2001 and an increase of fragmentation to (C) Class 3 ($F = 0.20$) in 2016. Red line represents dune toe position.

5. Discussion

5.1. Erosional Dune Systems

Erosion or complete disappearance of dune systems can be produced by human activities or natural processes [65–67]. Anthropogenic impacts were related to: (i) urban developments, mainly due to the coastal tourist demand, and the associated opening of pathways on dune ridges, which was especially evident in Málaga province (Figure 5) [41,46,48,55,68], (ii) dunes' occupation due to the demand for agricultural uses, as observed at different locations in Andalusia, and reported by References [67,69–73] in other Mediterranean Spanish areas (in Catalonia, [56]) or on the Mediterranean coast of Morocco [74] and (iii) the decrease of sediments' inputs to coastal environments due to the construction of ports and harbors, as observed along the study area by Malvárez et al. [46] and Manno et al. [48], and the reduction of the sedimentary load of rivers due to the construction of dams in river basins, especially in Málaga and Almería provinces [43,46,75], also observed in other Mediterranean rivers, e.g., for the Ebro [76] and the Arno [77] rivers.

Among natural processes, there are the impacts of chronic erosion processes and of extreme storms, the impacts of which are often enhanced by climatic change-related processes, e.g., an increase of storm intensity and frequency and Sea Level Rise [11,35,37,67,78–83]. Specifically, for the studied area, storm characterization was described by Guisado et al. [42] and Molina et al. [50]; meanwhile, it seems that Sea Level Rise is not relevant at the studied area [84–86].

Of the 53 dune systems studied, all but 4 recorded a reduction of their surface, or even disappeared, and this was especially evident where the systems were affected by hard human interventions [41,55,68–73] and, secondarily, by shoreline erosion [71,87,88]. The greatest loss of dune surface was recorded in the 1977–2001 period due to the massive urban occupation of coastal areas, although in the 2001–2016 period, a decrease in the loss of dunes' surfaces was observed because the main causes of their destruction recorded in the previous period partially ceased. Cases of disappearance due to urban occupation were still observed, especially in Málaga province [41], but the anthropic pressure derived from the tourist use of beaches and the decrease in river contributions were not so evident as in the 1977–2001 period [46,68–73].

The loss of dune surface was at places and times linked to the progressive fragmentation of the dune toe (i.e., the increase of dune discontinuity), which is a factor that has to be considered in order to estimate coastal and dune vulnerability [40,57–59] since a fragmented dune system is more vulnerable to temporary flooding and hence, it is less effective against storm surges [35,40,58,59,89–91]. In this study, the most fragmented (and hence susceptible sectors) were observed at the west side of the Andarax river delta in Almería province (no. 41, Figures 1 and 2), which was the most fragmented dune system located in a natural area (Appendix A Table A2) and the system at Las Chapas beach in Málaga province (no. 20, Figures 1, 2 and 10), located in a strongly developed urban area.

At almost all sectors, dunes' fragmentation was mainly due to the opening of pathways and to their progressive expansion due to marine- and wind-induced erosion processes, as also observed by Gracia et al. [40], Pintó et al. [56], Rangel-Buitrago and Anfuso [58] and Rizzo et al. [59]. Due to the accuracy of the orthophotos used in this study, dune discontinuities caused by overwash processes were only detected at few places (Figure 12). Such processes were distinguished from other types of fragmentation due to the absence of vegetation at the areas presenting the characteristic shape of a washover fan; meanwhile, pathways showed narrow rectilinear shapes.

Summing up, the majority of the dune systems that showed an aerial decrease were affected by anthropic factors, highlighting the importance of urban and agricultural occupations that were very relevant in Málaga and Almería administrative districts.

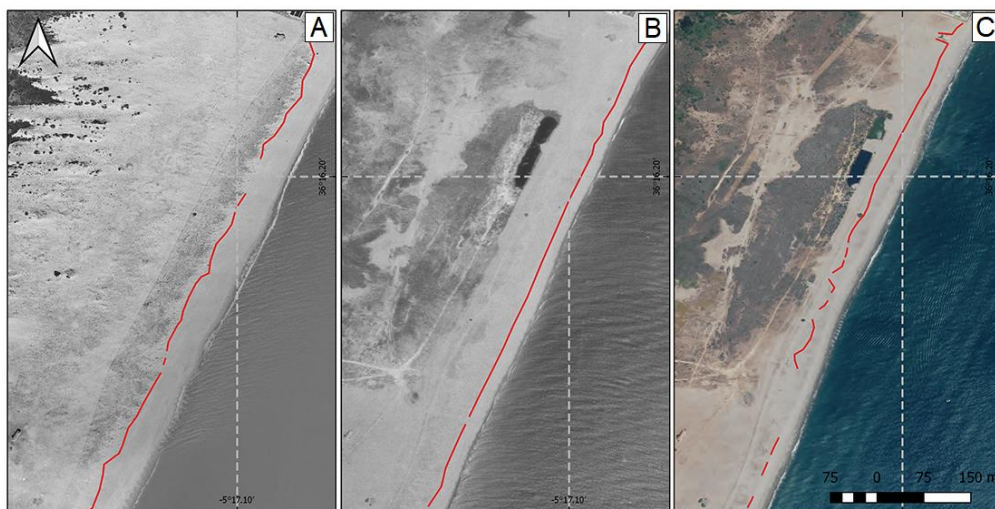


Figure 12. Details of the central area of System no. 9 Guadalquítón (Cádiz province), where washover fans and pathways were observed. Red line represents dune toe position. (A) 1977, (B) 2001 and (C) 2016.

5.2. Accretional Dune Systems

Conditions for dune formation and development were discussed by a large number of authors who agree that the temporal variation of the sedimentary contribution and the wind regimes are the most important factors controlling the beach–dune system relationship [65,92–95].

The increase of systems located in the Bay of Algeciras (Figure 2A) was associated with the sedimentation processes recorded in such beaches [96] that receive the sediment supplies of the Palmones and Guadalranque rivers [73]. Such beaches are located next to two large coastal protection structures that promote sedimentation processes. In the case of the system observed at El Rinconcillo in 2001, it began to form after the expansion of the port of Algeciras (Figure 8). Instead, systems at Guadalquítón and Albufera de Adra (Figure 2) were located in areas that registered an important erosion [39,96] and a significant human occupation linked to urban development in the case of Guadalquítón and intense agricultural occupation in Albufera de Adra. The Guadalquítón dune system recorded the highest increase during the 1977–2001 period, and it was due to the degradation of the vegetation that facilitated the inland dune migration. The formation of large mobile dunes in this area was also due to strong east winds (Figure 1), especially on the east-facing beaches [73]. In the case of the Albufera de Adra system, an important loss of dune surface in the 1977–2001 period was caused by shoreline erosion and the significant anthropic pressure (intense agricultural activities) [39,43,96]; however, the sedimentation produced at the north side of the system [39,96] supported the development of mobile dunes.

5.3. Dune Types' Evolution

Several dune systems studied in this paper were described by different authors [41,55,68–73,87,88], but none of them provided a description of all dune systems along the whole Mediterranean coast of Andalusia.

Unlike tidal-influenced coasts, in which the sedimentary contribution can be obtained through periodic exposure of the intertidal plain, on micro-tidal coasts such as the Mediterranean one, the beach itself is the main source of sedimentary contribution to the dune systems. In addition, when the beaches are composed of gravels, as is the case of many beaches of Málaga and Almería, it is more difficult to ascertain the source of sandy sediment necessary for the dune systems, so the rivers become the main sediment suppliers of the system [72]. As stated before, river systems at the Mediterranean coast of Andalusia are mostly short or seasonal streams and, in general, provide a coarse grain size on the beaches. Further, the accentuated relief observed nearby the coast and the presence of reflective beaches represent great limitations for the development of coastal dunes [72].

Further points to be taken into consideration are the intensity and direction of predominant winds that, to be effective in dune formation, should be shore normal. Due to their coastal orientation, which is normal to predominant winds, the provinces of Cadiz (especially) and Almeria constitute areas favorable for dune formation. According to Bardají et al. [72] and Gracia et al. [73], the central part of the Andalusia coastline is parallel to predominant winds that give rise to a relevant longshore transport that supplies different dune systems, e.g., at Artola-Cabopino [72,88].

Analyzing the evolution of each dune typology is of relevance since each typology represents a clear evolution state from Embryo and mobile dunes (Type I) to Stabilized dunes (Type III) [65,92]. The increment over the 1977–2016 period of the Stabilized dunes (Type III) (Figure 3) was due to the progressive evolution of Grass-fixed dunes (Type II), a natural process described by Hesp [65,92].

Surface variations of the different types of dunes' systems were relatively homogeneous (Figure 4). With the exception of the province of Cádiz, the rest of the provinces showed a decrease of the three types of dunes in the first period and, in the second period, a decrease of types I and III and an increase of Type II in all provinces except Almería. The general decrease recorded in the period 1977–2001 was mainly due to urban occupation, intensive agricultural exploitation and the extraction of sand—such activities were not regulated until the approval of the Coastal Law in 1988 [41,46,47,55,68–73]. Dune destruction was especially evident in Málaga and Almería provinces, where entire dune systems disappeared: in Málaga province, a total surface of 1,766,711 m² was lost, of which ca. 1×10^6 m² were Type II dunes and ca. 600,000 m² were Type III dunes, and in Almería, ca. 56,300,000 m² of dune surface was lost, of which ca. 4,360,000 m² were Type II dunes. Some examples of papers that quantified the loss of dune surfaces in specific areas were by Viciano Martínez-Lage [71], who

quantified a loss of 262 ha of dunes in Punta Entinas–El Sabinar, in Almería province, due to sand extractions, or Gómez Zotano [41], who quantified a reduction of 44.5% of the dune surface in Saladillo area, in Málaga province, during the 1956–2007 period.

The increase, in the 2001–2016 period, of the Type II in Málaga province was linked to the degradation of Type III dunes, especially evident in an area west of Marbella (Figure 2B) that was greatly impacted by urban developments, a quite common trend in Málaga province [41,46,47]. The increase of Type III in Almería was due to the stabilization of Type II dunes, especially in the area from Albufera de Adra to Almerimar and at Cabo de Gata (Figure 2E,F), which are areas where the shoreline is stable [39]. Overall, in Cádiz province, a slight increase of Type III was observed, and the other dunes' types recorded small variations (Figure 4). Such behavior was due to the low human pressure, the stable or even accreting conditions of the area [39,96] and the action of strong east winds (Figure 1) that favored dunes' growth and mobility [73].

6. Conclusions

This study analyzed the evolution of the dune systems along the Mediterranean coast of Andalusia, focusing on their characterization, level of fragmentation and anthropic occupation, for the 1977–2001 and 2001–2016 periods. Within a GIS project, there were 53 dune systems mapped that summed a total length of ca. 106 km in 1977 and ca. 76 km in 2001 and 2016.

Of the 53 dune systems, all but 4 recorded a reduction of their surface, or even disappeared, and this was especially evident in 1977–2001 when dune systems were affected by hard human interventions, such as the emplacement of buildings and touristic constructions, especially at Málaga province, and agricultural expansion at Almería province, and secondarily, at places by shoreline erosion processes.

Dunes' loss was at places and times linked to the progressive fragmentation of the dune toe, mainly due to the opening of pathways and to their progressive expansion due to marine- and wind-induced erosion processes. An increase of dunes' surface was observed in both natural and anthropic areas in Cádiz and Almería provinces, in accreting and stable beaches, usually on the updrift side of ports or due to strong east winds on the east-facing beaches.

Concerning the evolution of the Embryo and mobile dunes (Type I), Grass-fixed dunes (Type II) and Stabilized dunes (Type III), most of the provinces showed a decrease of the three types of dunes in the 1977–2001 period and, in the 2001–2016 period, a decrease of types I and III and an increase of Type II in all provinces. The increase of Type II dunes was linked to the degradation of Type III, observed in the 2001–2016 period at very anthropized areas; meanwhile, an increase of Type III was observed in stable and accreting areas.

Results obtained could be used to enhance the general database on dune characteristics along the Mediterranean coast of Andalusia and the possibility of utilizing ecosystem-based solutions in coastal protection, along with, or instead of, measures based on traditional engineering approaches. The methodology used in this study could be applied in other locations with a similar database.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Name and protection typology of each dune system and balance for the entire studied period.

System No.	Name	Protection	1977–2016		
			Dune Surface (m ²)	Occupation (m ²)	Fragmentation
1	Playa de Getares	Estrecho ⁽¹⁾	−70,477.70	41,768.39	0.16
2	Playa del Rinconcillo		38,884.38	732.26	
3	Marismas del Río Palmones	Marismas del Río Palmones ⁽²⁾	−47,670.51	3352.14	0.12
4	Guadarranque W		−59,167.52	57,534.25	
5	Guadarranque E		19,262.80	2136.58	0.22
6	La Línea de la Concepción		−102,603.90	30,682.41	0.04
7	La Alcaidesa S		−3796.38	3967.45	0.03
8	La Alcaidesa N		−14,072.90	20.88	0.17
9	Guadalquítón		260,531.70	−376.21	0.09
10	Torreguadiaro	Laguna de Torreguadiaro ⁽³⁾	−145,337.38	89,006.50	0.11
11	Playa del Saladillo W		−65,592.18	25,389.60	0.15
12	Playa del Saladillo E		−52,295.06	37,351.43	0.01
13	Playa de San Pedro de Alcántara		−97,452.20	28,411.01	
14	Playa Nueva Andalucía		−29,702.08	26,131.94	
15	Playa del Pinillo		−27,738.26	9490.44	0.06
16	Playa de Río Real		−16,322.02	3643.28	−0.20
17	Playa de los Monteros		−373,156.19	355,081.76	0.14
18	Playa del Alcate		−49,725.72	32,996.16	0.16
19	Playa Real de Zaragoza		−200,549.55	41,358.39	0.10
20	Playa de las Chapas		−171,835.74	152,819.73	0.22
21	Playa de Artola	Dunas de Artola ⁽⁴⁾	−21,575.89	5068.88	0.16
22	Cabopino-Calahonda		0.00	0.00	
23	Torrenueva - Mijas		−64,545.36	64,344.35	
24	Playa de Canuela - Torremolinos		−44,014.67	970.12	
25	Playa de San Julián		−412,157.55	2085.54	0.10
26	Playa de la Misericordia	Desembocadura del Guadalhorce ⁽²⁾	−98,481.69	84,116.14	−0.09
27	Arroyo de los Íberos		−54,160.94	90.78	
28	El Hornillo		−19,501.79	2698.63	
29	Playa del Poniente - Motril		−59,813.96	15,990.88	0.05
30	Carchuna		−115,558.06	38,433.86	0.00
31	Albufera de Adra	Albufera de Adra ⁽⁵⁾	6708.50	0.00	−0.01
32	Playa de Balerma N		−17,100.05	994.82	0.01
33	Playa de Balerma S		−294,158.23	260,649.68	0.10
34	Ensenada de San Miguel		−557,765.03	259,966.94	0.06
35	Punta Entinas-El Sabinar	Punta Entinas – El Sabinar ^(2,5)	−4,166,157.86	239,842.20	0.03
36	Playa de Roquetas S		−65,618.01	32,255.48	
37	Playa de Roquetas N		−36,963.45	66.72	
38	Playa de los Bajos	Arrecife Barrera de Posidonia ⁽⁴⁾	−18,995.79	408.82	−0.07
39	Playa Urbanización de Aguadulce		−14,309.26	5344.12	
40	Playa Ciudad Luminosa		−11,118.95	3916.61	

Table A1. Cont.

System No.	Name	Protection	1977–2016		
			Dune Surface (m ²)	Occupation (m ²)	Fragmentation
41	Punta del Río W		−2429.22	0.00	0.25
42	Punta del Río E		−8830.07	0.00	0.16
43	Las Algaidas-Las Marinas		−109,308.76	−1102.88	0.01
44	Cabo de Gata	Cabo de Gata-Nijar ⁽¹⁾	−395,189.20	404,678.11	0.14
45	Los Genoveses	Cabo de Gata-Nijar ⁽¹⁾	−31,645.57	−40.32	0.12
46	Playa de Bolmayor		−27,747.41	−301.21	0.04
47	Playa Venta del Bancal		−11,300.77	3577.15	0.08
48	Playa Cueva del Lobo		−11,748.40	4166.26	
49	El Cantal		−35,578.88	15,662.30	0.02
50	Playa del Descargador		−15,373.75	3011.05	
51	Playa de Rumina		−12,937.51	41.41	
52	Playa Marina de la Torre		−29,181.18	365.40	0.00
53	Vera		−567,841.25	233,429.88	0.10

Typologies of protection: ⁽¹⁾ Natural Park, ⁽²⁾ Natural Site, ⁽³⁾ Special Plan for the Protection of the Physical Environment, ⁽⁴⁾ Natural Monument, ⁽⁵⁾ Natural Reserve. Fragmentation index was not calculated for periods where the dune system disappeared.

Table A2. Results obtained at each dune system.

System No.	1977			2001			2016		
	Dune Surface (m ²)	Occupation (m ²)	Fragmentation	Dune Surface (m ²)	Occupation (m ²)	Fragmentation	Dune Surface (m ²)	Occupation (m ²)	Fragmentation
1	144,188.37	9597.20	0.03	77,746.64	51,237.13	0.18	73,710.67	51,365.59	0.19
2	0.00	0.00		12,339.80	0.00		38,884.38	732.26	
3	205,724.64	3178.45	0.23	157,943.70	6516.26	0.31	158,054.13	6530.60	0.36
4	59,167.52	1633.27		0.00	59,167.52		0.00	59,167.52	
5	6316.76	1510.25	0.00	22,658.14	3717.80	0.13	25,579.56	3646.84	0.22
6	684,586.98	2295.32	0.07	719,675.84	3095.54	0.07	581,983.08	32,977.74	0.11
7	5370.58	0.00	0.00	2877.63	0.00	0.00	1574.20	3967.45	0.03
8	31,114.12	70.97	0.03	21,839.17	58.06	0.09	17,041.22	91.85	0.20
9	947,015.74	807.87	0.06	1,167,066.53	694.96	0.02	1,207,547.44	431.65	0.15
10	194,657.12	504.84	0.08	51,787.89	89,372.03	0.04	49,319.73	89,511.34	0.19
11	78,121.80	273.30	0.04	18,609.35	25,662.89	0.08	12,529.62	25,662.89	0.18
12	82,690.38	0.00	0.04	40,109.17	37,351.43	0.05	30,395.32	37,351.43	0.05
13	97,452.20	6377.47		36,487.89	22,027.47		0.00	34,788.48	
14	29,702.08	0.00		0.00	26,131.94		0.00	26,131.94	
15	39,444.19	0.00	0.04	21,835.12	5905.71	0.17	11,705.93	9490.44	0.10
16	19,307.50	0.00	0.20	2956.27	3643.28	0.15	2985.49	3643.28	0.00
17	412,867.48	0.00	0.03	38,602.94	348,097.72	0.12	39,711.29	355,081.76	0.17
18	67,942.45	0.00	0.03	6744.90	32,996.16	0.05	18,216.73	32,996.16	0.19
19	286,323.39	5333.48	0.11	82,951.01	46,657.53	0.15	85,773.84	46,691.87	0.21
20	199,167.71	1830.11	0.00	21,955.35	154,649.83	0.13	27,331.97	154,649.83	0.22
21	306,301.24	6506.44	0.00	246,613.13	11,448.04	0.22	284,725.35	11,575.32	0.16
22	0.00	0.00		4837.91	0.00		0.00	0.00	
23	64,545.36	201.01		0.00	64,545.36		0.00	64,545.36	
24	44,014.67	2722.12		0.00	3692.24		0.00	3692.24	
25	430,219.96	799.40	0.10	33,563.96	797.38	0.16	18,062.41	2884.93	0.20
26	153,324.54	0.00	0.11	63,109.77	84,116.14	0.02	54,842.86	84,116.14	0.02
27	54,160.94	635.79		0.00	726.58		0.00	726.58	
28	19,501.79	0.00		0.00	2698.63		0.00	2698.63	
29	68,178.56	1102.48	0.10	8705.37	17,108.96	0.29	8364.60	17,093.36	0.15

Table A2. Cont.

System No.	1977			2001			2016		
	Dune Surface (m ²)	Occupation (m ²)	Fragmentation	Dune Surface (m ²)	Occupation (m ²)	Fragmentation	Dune Surface (m ²)	Occupation (m ²)	Fragmentation
30	165,721.54	115.73	0.04	142,747.51	38,473.11	0.01	50,163.48	38,549.59	0.04
31	21,286.91	0.00	0.04	8193.76	0.00	0.05	27,995.40	0.00	0.03
32	27,651.90	39.11	0.05	9352.84	826.33	0.07	10,551.85	1033.93	0.05
33	440,474.93	701.17	0.01	125,373.21	257,051.80	0.09	146,316.70	261,350.84	0.11
34	806,346.40	5696.20	0.03	199,426.12	264,867.83	0.09	248,581.37	265,663.15	0.10
35	9,389,288.69	653,813.65	0.03	6,030,071.83	895,307.46	0.03	5,223,130.83	893,655.85	0.06
36	65,618.01	0.00		0.00	32,255.48		0.00	32,255.48	
37	36,963.45	0.00		0.00	66.72		0.00	66.72	
38	36,092.39	218.00	0.08	30,662.57	311.90	0.05	17,096.59	626.82	0.01
39	14,309.26	0.00		4399.52	3429.40		0.00	5344.12	
40	11,118.95	1182.32		0.00	5098.93		0.00	5098.93	
41	17,274.33	0.00	0.08	9693.33	0.00	0.10	14,845.11	0.00	0.08
42	16,891.37	0.00	0.03	13,529.19	0.00	0.08	8061.30	0.00	0.16
43	582,481.36	15,199.95	0.05	477,646.62	10,837.79	0.12	473,172.60	14,097.07	0.17
44	3,305,029.98	118,675.34	0.03	2,950,549.49	321,804.73	0.11	2,909,840.78	523,353.44	0.07
45	231,633.59	95.61	0.05	198,067.08	55.29	0.12	199,988.03	55.29	0.17
46	42,559.55	561.69	0.03	17,828.63	444.56	0.11	14,812.14	260.48	0.07
47	13,831.67	0.00	0.00	1729.15	3496.24	0.00	2530.90	3577.15	0.08
48	11,748.40	0.00		6694.07	697.64		0.00	4166.26	
49	45,547.32	4386.12	0.05	9285.69	15,269.76	0.01	9968.44	20,048.42	0.07
50	15,373.75	165.32		2855.83	1601.84		0.00	3176.38	
51	12,937.51	1214.63		4958.36	2923.88		0.00	1256.04	
52	29,896.87	0.00	0.00	11,900.67	365.40	0.06	715.69	365.40	0.00
53	722,709.90	21,902.89	0.03	152,125.47	240,022.68	0.06	154,868.65	255,332.76	0.13

Fragmentation index was not calculated for periods where the dune system disappeared.

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Anexo IV

Publicación IV. A Methodological Approach to Determine Sound Response Modalities to Coastal Erosion Processes in Mediterranean Andalusia (Spain).

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Article

A Methodological Approach to Determine Sound Response Modalities to Coastal Erosion Processes in Mediterranean Andalusia (Spain)

Rosa Molina ¹, Giorgio Manno ², Carlo Lo Re ², Giorgio Anfuso ^{1,*} and Giuseppe Ciralo ²

¹ Department of Earth Sciences, Faculty of Marine and Environmental Sciences, University of Cádiz, Polígono del Río San Pedro s/n, 11510 Puerto Real, Spain; molina.gil@gmail.com

² Department of Engineering, University of Palermo, Viale delle Scienze, Bd. 8, 90128 Palermo, Italy; giorgio.manno@unipa.it (G.M.); carlo.lore@unipa.it (C.L.R.); giuseppe.ciraolo@unipa.it (G.C.)

* Correspondence: giorgio.anfuso@uca.es; Tel.: +34-956-016167

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Abstract: Human occupation along coastal areas has been greatly increasing in recent decades and, in many places, human activities and infrastructures are threatened by erosion processes that can produce relevant economic and human losses. In order to reduce such impacts and design sound management strategies, which can range from the “no action” to the “protection” option, coastal managers need to know the intrinsic coastal sensitivity and the potential vulnerability and value of land uses. In this paper, in a first step, coastal sensitivity was determined by calculating the following: (i) the spatial distribution at the coast of the wave forcing obtained by using the ERA5 wave dataset and defined as the energy associated with the 50-year return period storm. Two storm conditions were considered, that is, one for the eastern and one for the western parts of the Andalusia Mediterranean coast, respectively, characterized by a height of 8.64–7.86 m and 4.85–4.68 m and (ii) the existence of a buffer zone, namely the dry beach width expressed as a multiple of the 20-year predicted shoreline position that was calculated using a dataset of aerial photographs covering a time span from 1956 to 2016. Coastal sensitivity values were divided into five classes with class 1 indicating the lowest sensitivity (i.e., the presence of a wide buffer zone associated with low wave energy flux values) and class 5 the highest sensitivity (i.e., a narrow buffer zone associated with very high wave energy flux values). In a second step, land uses were obtained from the official Land Use Map of the Andalusia Region, based on the results of the “Coordination of Information on the Environment” (CORINE) European Project. Such uses were divided into five classes from class 1 including natural areas (typologies “A” and “B” of the CORINE Project) to class 5 including very capital land uses (typologies “E1” and “E2”). In a third step, information concerning coastal sensitivity and land uses was crossed to determine the best mitigation strategies to cope with erosion processes. The “no action” option was observed at the westernmost area of Cádiz Province and at some areas from the west coast of Almería Province, where both coastal sensitivity and land use classes show low values; the “adaptation” option was recorded along more than one half of the coast studied, essentially at natural areas with high sensitivity and at urbanized areas with low sensitivity; and the “protection” option was observed especially at some areas from the center and eastern part of Málaga Province and at the easternmost areas of Almería Province, where both coastal sensitivity and land use classes presented high values.

Keywords: coastal trend; wave energy; beach width; land use; mitigation

1. Introduction

Ocean coastlines are highly dynamic and changing environments since they show great temporal and spatial variability in response to the action of different and complex coastal processes essentially linked to waves and currents [1]. Often, beach erosion/accretion cycles are recorded at an inter-annual time scale and are related to seasonal wave climate variations due to temporal and spatial distributions of high latitude storms and hurricanes/typhoons [2–6]. Erosion is observed after storm events, at high latitudes recorded during winter months, but beach recovery takes place during fair weather conditions, which is known as “seasonal” beach behavior [7,8]. In this case, erosion processes represent a threat since they can locally menace human structures/activities, but the following natural beach recovery guaranties the reformation of a wide beach and its associated protection function and tourist use.

Different is the case in which coastal erosion is the result of a long, decadal trend [9–11] due to the impact of large storms and tsunamis [12–14], sea level rise, and variations in sediment supply, which is linked to river contributions and longshore and cross-shore current supplies. River contributions are linked to variations in rainfalls, changes in land use (e.g., soil erosion increases when forests and grasslands are converted into farm fields and pastures) and the construction of dams and the channelization of river banks [15,16]. Longshore and cross-shore supplies record variations because of changes in wave climate and current pathways [17,18] or the accumulation updrift of human structures (e.g., ports, groins, etc. [16]). In this case, erosion processes produce important retreat (with no or partial associated recovery) at natural places reflected by overwash and/or beach and dune erosion [11], and damages at the location of human activities or infrastructures in urbanized coastal sectors [9], that is, storms become natural hazards [19].

In order to reduce such impacts and associated economic and human losses, coastal managers need to know the following: (i) the sensitivity of natural coastal sectors, which is related to wave energy, beach characteristics/evolution, and sea level trend [20,21] as well as (ii) the potential vulnerability and economic value of the urbanized sectors [9,22].

Wave energy characteristics, especially the spatial and temporal distributions and the periodicity of most energetic events, are the forcing agents that drive morphological beach changes and determine erosive/accumulation processes [23,24] that also depend on beach dynamics and characteristics (i.e., beach morphodynamic state, width, presence of dune ridges, etc. [9]).

Human activity and infrastructure vulnerability depend on the distance from the shoreline and their typology [9,25]. Following different criteria, vulnerability maps have been obtained for numerous coastal areas around the world through the use of computer-assisted multivariate analysis, numerical models, and Geographical Information Systems (GIS), with pioneer investigations carried out by Gornitz [26] and Gornitz et al. [27] in the USA, by Cooper and McLaughlin [28], McLaughlin et al. [22], and the Committee on Climate Change [29] in UK, and by Dodds et al [30] in Malta and Mallorca.

Once coastal sensitivity/vulnerability is determined, the next step for coastal managers is to decide which are the most appropriate mitigation strategies that include “do nothing”, “adaptation”, and “protection” [31,32]. Do nothing is the “no action” option (i.e., the decision to not defend properties at risk and/or the abandonment of the current defense line). Adaptation includes accommodation (i.e., the modification of human infrastructures and land uses; e.g., an agricultural area may be replaced by a salt marsh) and relocation (i.e., the landward displacement of human activities/uses). Protection is the “hold the line” option (i.e., the defense and maintenance of the current shoreline position using hard armoring structures or beach nourishment [29]). The selection of the sound management strategy is based on the knowledge of the erosion processes (magnitudes and causes) and funding/legislation (The Shoreline Management Guide, http://www.euroSION.org/project/euroSION_en.pdf, accessed on 3 November 2019). Economic considerations are based on a cost–benefit analysis approach [23] or on action/reaction criteria [9].

The present paper presents a methodological approximation to determine coastal sensitivity and sound response actions to long-term erosion processes that affect sandy sectors along the Mediterranean coast of Andalusia (Spain), an area that records an important flow of tourists

associated with the “Sun, Sea, and Sand (3S) market” [30], which represents a relevant economic resource for the region.

In a first step, coastal sensitivity was determined by calculating the spatial distribution of wave forcing and the existence of a buffer zone, namely the dry beach width expressed as a multiple of the 20-year predicted shoreline position. In a second step, land uses were obtained from the official web page of the Regional Administration of Andalusia. In a third step, coastal sensitivity was related to land uses in order to determine the best mitigation strategies to cope with erosion processes. The methodology proposed in this paper represents a valuable tool for coastal managers at a regional scale and can be easily applied in different coastal areas around the world where basic information on the delineated parameters is available. Once information is obtained at the regional scale, further studies and investigations can be devoted to determine best adaptation options and specific defense methods at a small spatial scale. In this paper, sea level change has not been taken into account because this investigation is devoted to determine human infrastructure vulnerability and sound response options in the next few decades, that is, at a time span for which sea level variations are usually not relevant according to Komar [1].

2. Study Area

The Mediterranean coast of Andalusia, located in SW Spain, extends from the Gibraltar Strait to the Murcia Region, with a length of ca. 546 km (ca. 196 km composed of cliffed and ca. 350 km of sand sectors) administratively belonging to the provinces of Cádiz, Málaga, Granada, and Almería. It has an E-W prevailing rectilinear outline with two NE-SW oriented and easterly facing sectors, that is, at the Almería and Gibraltar areas (Figure 1).

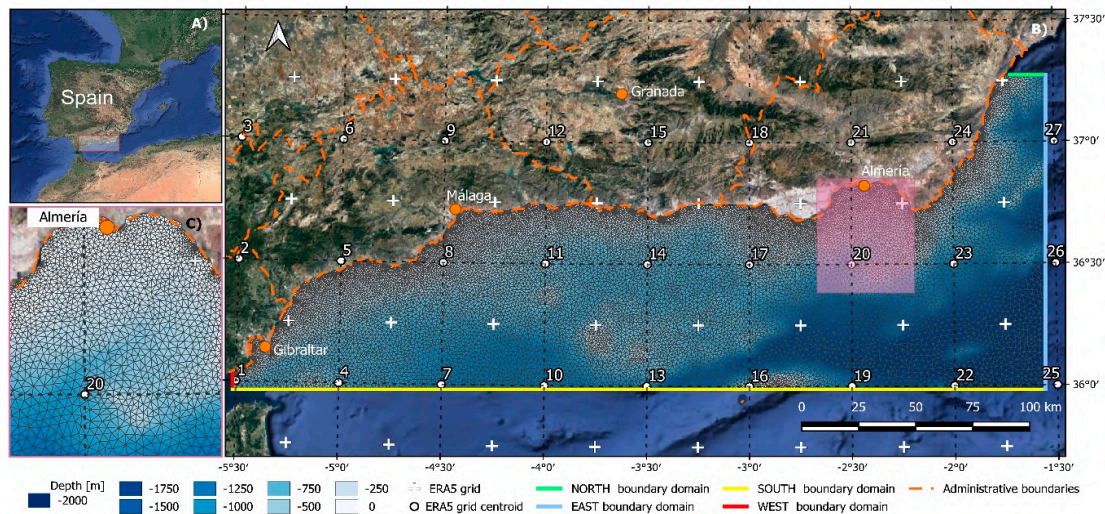


Figure 1. (A) General view of the numerical domain area used in this paper. (B) Numerical domain and triangular mesh sides; white dots represent the ERA5 data grid points and white crosses represent the corner of each grid. (C) Detail of the Delaunay triangulation used for the Gulf of Almería.

The Betic Range, a tectonically active mountain chain that reaches high elevations close to the coast, strongly controls coastal orography. The Guadiaro, Guadalhorce, Guadalfeo, Adra, and Andarax are the most important rivers and “ramblas” (a seasonal stream), draining the chain and favoring the formation of small coastal plains developed at the foot of the chain. Especially under episodic heavy rainfalls, linked to the semiarid climate, fluvial sands and gravels are transported by rivers and ramblas to the coast, constituting important sediment supplies to the beach system. River basin regulation plans in the last decades have brought the construction of dams and reservoirs that have significantly limited sediment supplies to the coast, thereby exacerbating coastal retreat, especially at many deltas [33–36].

Beaches, which usually show medium to coarse dark sands and/or pebbles and intermediate to reflective morphodynamic states, are found along the provinces of Cádiz, Málaga, and Granada [33,37]. Meanwhile, more dissipative beaches, composed of fine/medium quartz rich sand, are observed in Almeria Province [38,39]. Beaches are often interrupted by rocky sectors and headlands that give rise to pocket beaches (“calas”) of different sizes and relevant scenic value [38].

The coastal area is a micro-tidal semidiurnal environment (tidal range < 20 cm) [33] exposed to winds blowing from SE to SW with minimum and maximum velocities ranging from 0.4 to 9.0 m/s. The Gibraltar Strait area is affected by eastern storms, whereas the Málaga and Almeria areas are exposed both to western and eastern storms [40]. The predominance of wave climate shows a seasonal trend with storm events essentially recorded during November–March, that is, the winter season [40,41]. The prevailing littoral drift, linked to both coastal orientation and predominantly easterly winds and associated storm waves, is westward directed [40,41]. An opposite littoral drift, observed at specific places, is associated with sea and swell waves entering from the Gibraltar Strait [33,40].

From an administrative point of view, the coast belongs to the provinces of Cadiz, Malaga, Granada, and Almeria, with the large coastal towns of Malaga (with >500,000 inhabitants), Almeria (with ca. 200,000 inhabitants), and the tourist towns along the western part of Costa del Sol area, namely Marbella (with 150,000 inhabitants), Fuengirola (80,000), and Torremolinos (70,000). According to DGPC [42], coastal uses along Andalusia, expressed in percentage, include tourist/recreational uses (41.1%, which are especially observed in Malaga Province), natural (4.7%, essentially at Almeria and Cadiz provinces), port/commercial (2.5%, with main commercial ports located at Almeria, Algeciras, Cadiz, and Malaga and several marinas at Costa del Sol), industrial (2.3%), and fishing (0.9); the remaining coast has no defined use.

With respect to sea level trend, Criado-Aldeanueva et al. [43] analyzed a 16-year time set of sea level data for the Mediterranean Sea obtained by means of satellite radar images and observed that the most relevant sea level rise took place in the Levantine basin south of Crete with values up to 10 ± 1 mm/year. Some other rising spots were recorded in the Adriatic and Alboran Seas with more moderate positive trends. Tsimplis et al. [44], based on tidal gauge datasets of 10 to 58 years, gave a negative trend at the Gibraltar Strait area (-1.21 m/yr) and a positive trend at Málaga and Almería (4.04 and 0.28 mm/yr, respectively). Lastly, Puertos del Estado [45] presented data on sea level trends based on tidal gauge records including dataset periods ranging from 8 to 25 years. Close to the Gibraltar Strait and at Almeria, sea level trends recorded a negative trend (-0.345 and -0.046 cm/yr, respectively); meanwhile, at Motril and Málaga, they presented a positive one (0.181 and 0.231 cm/yr, respectively).

3. Methodology

For this study, sound mitigation actions to alleviate coastal erosion were proposed by combining coastal sensitivity with land use information (Figure 2). Coastal sensitivity was obtained by combining the main forcing agent, expressed using the longshore distribution of the wave energy flux, with the extent of the buffer zone (i.e., the presence of a beach expressed considering dry beach width as a function of the 20-year predicted shoreline position), and land use was obtained by consulting existing official information, namely the SIOSE Project Land Use Map of the Regional Administration of Andalusia (Spain) (<http://www.juntadeandalucia.es>, accessed on 4 November 2019).

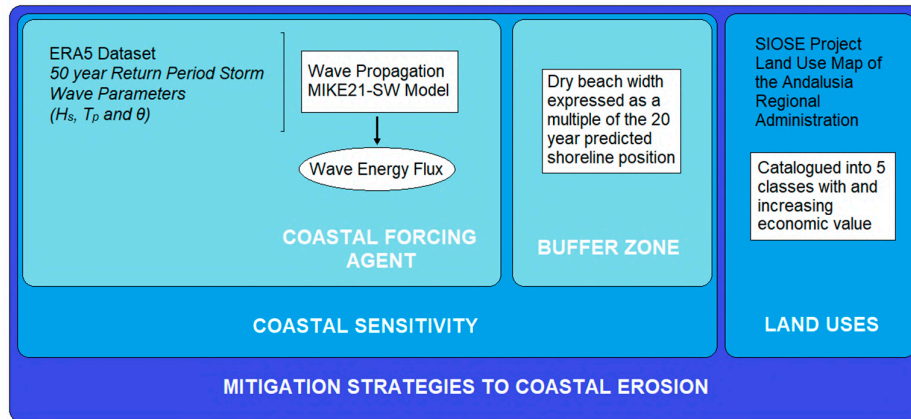


Figure 2. Summary of the methodology used in this work.

3.1. Coastal Forcing

With respect to wave forcing, wave climate analysis was carried out using the ERA5 wave dataset modeled by the European Centre for Medium-range Weather Forecasts ECMWF within the framework of the homonym project, using the WAVE Model (WAM) that is a numerical model based on the energy balance equation able to reconstruct wave climate [46] (<https://www.ecmwf.int>, accessed on 4 November 2019). The data cover the whole Earth on a 30 km grid and has a time interval of 40 years, from 1979 to 2019, which is representative of potential trends of increasing wave height and/or the presence of climate-controlled cycles [6].

This investigation used 27 points among the available grid points from the ERA5 dataset along the Mediterranean coast of Andalusia (Spain, Figure 1). The dataset, analyzed using MATLAB scripts, included the significant wave height (H_s), the peak period (T_p), and the mean wave direction (θ) at each point of the grid. Once the offshore wave parameters were known, a statistical analysis of sea storm (directional and omnidirectional) was carried out. In this paper, each single storm was defined as “a sequence of sea states in which H_s exceeds a fixed threshold h_{crit} , and does not fall below this threshold for a continuous time interval greater than 12 h” [47]. The h_{crit} value was assumed equal to 1.5 m and the linear deep-water wave theory allowed to calculate the storm-associated energy flux [40,47].

The data were divided into 16 main directions; for each direction it was possible to fit the extreme value distribution related to each point of the ERA5 grid. For each direction and for the whole dataset, the best fitting extreme distribution function was chosen among the generalized extreme value (GEV), Gumbel, and Weibull distributions. The goodness of fit of these distributions was assessed using the well-known Kolmogorov–Smirnov test. The result of this analysis was that the GEV distribution had the best fitting performance for all the datasets.

The GEV distribution is a family of continuous probability distributions developed within extreme value theory to combine the Gumbel, Fréchet, and Weibull families, also known as type I, II, and III extreme value distributions. The return period was calculated by the following expression:

$$T_r = \frac{1}{\lambda \cdot P(H_s, \theta)} \quad (1)$$

where λ is the mean number of storms in a year and p is the exceedance probability given by the GEV equation in which the parameters were calculated using the maximum likelihood estimation (MLE) method.

In order to assess storm effects along the service life of coastal structures, a return period of 50 years was used because the aim of the research was focused on mid-term period damages. Only the more representative directions were used to force the model at the boundaries.

The wave propagation from offshore to nearshore was performed using the well-known MIKE21-SW model [48,49]. This model was used with the directionally decoupled parametric

formulation of the wave action balance equation. Moreover, the runs were performed in the non-stationary mode reproducing a storm of 48 h.

The GEBCO 30 arc second bathymetric grid (General Bathymetric Chart of the Ocean) was used to calculate the depth of mesh points [50]. The mesh was created by means of a Delaunay triangulation and the triangle size was determined using a density function taking into account both the local depth and the bottom slope (Figure 1), obtaining a great detail near the coastline. The mesh used in the wave model was made of 30,906 triangular elements and 16,151 nodes. The smallest length of the elements was 14.93 m (near the coastline), and the maximum size was 1988 km in deep water. The smallest and the largest angles of the triangles were ca. 26° and 60°, respectively. The outputs of the numerical model are wave parameters (H_s , T_p , and θ) and the energy flux at each numerical node of the domain. In order to extract the energy flux, all the mesh elements that belonged to the 10 m depth isobath were selected. In order to assess wave effects in the nearshore, the energy flux parameter was used because it takes into account both wave height and length during a storm [51]. The energy flux represents the power of the storm per unit of wavelength.

Following McLaughlin et al. [22] and Rangel-Buitrago and Anfuso [9], the forcing agent, which in this paper is the wave energy flux distribution along the coastline, was divided into five classes by “the natural breaks” function [52] according to its impact on the coast, from “Very Low” (Class 1) to “Very High” (Class 5, Table 1).

Table 1. Classes of wave energy flux (kw/m), the colors are related to the intensity of possible erosion effects.

1	2	3	4	5
Very Low	Low	Medium	High	Very High
0.0–7.65	7.65–15.45	15.45–40.09	40.09–79.75	79.75–146.12

3.2. Buffer Zone Assessment

The dry beach width represents a buffer zone to storm impact and hence it must be taken into consideration in coastal sensitivity determination [9]. Beach slope and elevation are also important factors in beach behavior and coastal protection function, but they presented a great temporal and spatial variability as observed on the Atlantic side of Andalusia [5]. Furthermore, no detailed data are available for the whole length of the coast investigated, hence beach width was used as an indicator of beach protection function. Beach width was considered as the distance between the most recent available shoreline and the landward limit of the beach, coinciding with the dune foot or human structures (promenades, seawalls, etc.). Both lines (i.e., shoreline and landward beach limit) were mapped on the most recent available aerial photos, namely the 2016 orthophotographs of the Regional Administration of Andalusia (<http://www.juntadeandalucia.es>, accessed on 25 October 2019). Since dry beach width can have a considerable range from coast to coast, it was expressed as a multiple of the 20-year predicted shoreline position [53], using the methodology proposed by Rangel-Buitrago and Anfuso [9]. This parameter reflects coastal evolution and hence coastal response to erosion processes that is linked to beach characteristics such as beach width, elevation, and slope/morphodynamic state [5]. The 20-year predicted shoreline position represents the area subject to erosion in the next 20 years and is extended landward from the shoreline for a distance equal to 20 times the average, annual erosion rate for the site calculated for medium- (10–60 years) or long-term time spans (>60 years), [54]. In this paper, the 20-year predicted shoreline position was selected as a reliable indicator of future shoreline trends because, according to Leatherman et al. [55], in order to be reliable, the predicted time span has to be less than 1/2 of the total period considered (i.e., 60 years).

Evolution rates are usually available from previous studies and are obtained by means of aerial photographs [56]. Molina et al. [36] used aerial orthophotographs from 1956, 1977, 2001, 2010, and 2016 to reconstruct and quantify shoreline evolution, and these data were used in this paper. The orthophotos were obtained by the Regional Government (Junta de Andalucía, (<http://www.juntadeandalucia.es>, accessed on 25 October 2019), and all information was presented

in the metric Projected Coordinate System WGS84, UTM zones 29 N and 30 N [36]. The five shorelines used were mapped using the ArcMap application from ArcGIS Desktop, Release 10. Redlands, CA: Environmental Systems Research Institute, and the shoreline position was defined as “the water line at the time of the photo” [57,58] because of the micro-tidal nature of the studied coast. Corrections concerning shoreline position were carried out taking into account the photos’ own characteristics and the digitalizing process [59], that is, digitalizing error, accuracy linked to pixel size, ortho-rectification error, image co-registration error as well as shoreline definition and position determination, namely wave run-up and tidal conditions [10,36].

Because of the accuracy of the method used, the evolution of cliffed sectors, which have an overall length of ca. 196 out of 546 km, was not quantified and hence such sectors were considered stable at the scale of this investigation, that is, changes were too small to be detected by means of aerial orthophotographs. Hence, the evolution of a total amount of 284.95 km of beach sectors was obtained by drawing 10,073 shore-normal transects, with a spacing fixed at 25 m [36]. Rates of change between shorelines were computed using the DSAS extension of ArcGIS [60,61] by calculating the weighted linear regression (WLR), which considers all used shorelines.

Hence, according to Rangel-Buitrago and Anfuso [9], the buffer zone (i.e., the dry beach width expressed as a multiple of the 20-year predicted shoreline position) was assessed in correspondence with each one of the 10,073 shore-normal transects and expressed into five classes according to its relative width (Table 2).

Table 2. Buffer zone classes expressed according to the dry beach width and the 20-year predicted shoreline position the color scale indicates the intensity of exposure i.e. a large buffer zone shows a low exposure.

1	2	3	4	5
Very Wide	Wide	Medium	Narrow	Very Narrow
Dry beach width ≥ 5 times the 20-year shoreline position	4 times the 20-year shoreline position	3 times the 20-year shoreline position	2 times the 20-year shoreline position	≤ 1 time the 20-year shoreline position

3.3. Coastal Sensitivity

Coastal sensitivity was obtained by calculating the arithmetic average value of forcing and buffer zone classes and was expressed into five classes. As this study was carried out at a large, regional scale, coastal sensitivity was obtained averaging buffer zone values along 200 m long sectors within each uniform land use unit.

3.4. Land Use

Land use categories, presented in the SIOSE Project Land Use Map of the Andalusia Regional Administration (<http://www.juntadeandalucia.es>, accessed on 4 November 2019), were used in this paper. These categories were based on the results of the European project “Coordination of Information on the Environment” (CORINE, <http://www.eea.europa.eu>, accessed on 12 October 2019) and, in this investigation, were geo-referenced and catalogued into five classes with an increasing economic value from class A to E (Table 3).

Table 3. Land use economic value according to the Land Use Map of the Andalusia Regional Administration. Codes of land uses (i.e., “A”, “B”, “C1”, “C2”, “D2”) are those used by the “Coordination of Information on the Environment” (CORINE) Project.

A	B	C	D	E
Very Low	Low	Medium	High	Very High
Open spaces with little or no vegetation (A) Scrub and/or herbaceous vegetation	Forests (C1) Wetlands and water	Agricultural areas (D2) Artificial, non-agricultural	Discontinuous urban fabric (D1)	Continuous urban fabric (E1) Industrial, commercial, and transport units and mine, dump,

3.5. Mitigation Strategies to Coastal Erosion

According to Pranzini et al. [31] and Williams et al. [32], there are several mitigation or response strategies to counteract coastal erosion processes that range from “do nothing” and “adaptation” to “protection”. In this paper, three main options were considered: (1), “no action” (i.e., no action is required because coastal area has land uses of low economic value that are at null or low risk); (2) “adaptation”, which includes “accommodation” (i.e., the modification of existing infrastructures and/or the change in land use) and “relocation” (i.e., the landward movement of infrastructures); and (3) “protection” (i.e., the establishment of hard structures as groins, breakwaters, etc., as well as the execution of nourishment works, when land use at risk is of great economic value).

4. Results

4.1. Wave Forcing

The open boundary of the domain, divided into four segments, namely North, East, South, and West, was used to force the model (Figure 1). For each of these boundary segments, a point from the ERA5 re-analysis grid, namely No. 1, 13, 26, and 27, was chosen. For each ERA5 prediction point, directional roses of significant wave height were extracted (Figure 2). Only two main directions (i.e., ENE and WSW) recorded a significantly large number of storms (Figure 3, Table 4). Hence, the H_s wave height, considering a storm with a 50-year return period, was calculated at each point and for each direction (Table 4).

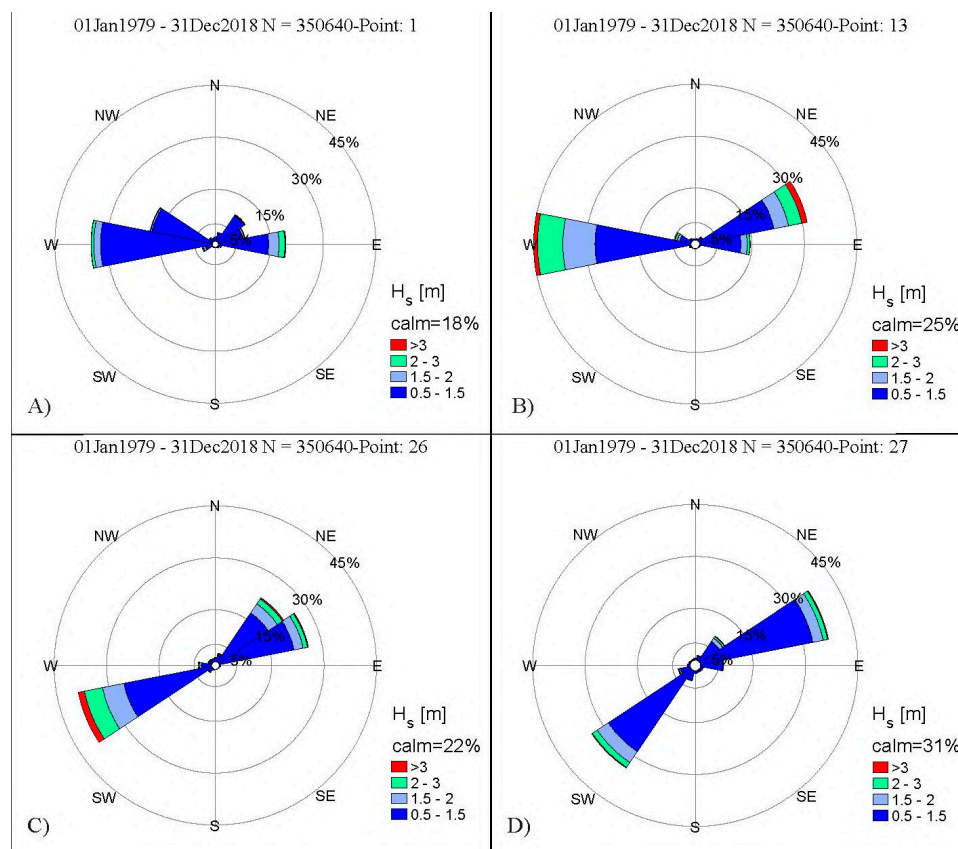


Figure 3. Significant wave height roses obtained considering the time span from 1 January 1979 to 31 December 2018 for ERA5 point nos. 1 (A), 13 (B), 26 (C), and 27 (D).

The significant wave height value (H_s) with a 50-year return period was calculated, for each point and for each direction of approximation (Table 4).

Table 4. H_s and T_p wave parameters in the lateral boundary of the numerical domain for $T_r = 50$ years.

Points	Coordinates	θ (°)	Cardinal Points	H_s (m)	T_p (s)
1	36° N 5°30' E	247.5	WSW	4.68	9.14
13	36° N 3°30' E	247.5	WSW	4.85	6.44
26	36°30' N 1°30' E	67.5	ENE	8.64	9.36
27	37° N 1°30' E	67.5	ENE	7.86	10.25

Using the wave parameters presented in Table 4, two storm conditions were propagated. Significant wave height distribution at the end of the simulation processes was shown for two storms approaching from ENE and WSW (Figure 4A,B). Combining significant wave height and the associated peak period, the wave power distribution per unit of wavelength (i.e., the energy flux) was obtained for the whole domain and presented for the Andalusia coastline (Figure 5).

The division of the energy flux values into classes was carried out by means of the quantile method that divided classes so that the total number of data in each class was the same.

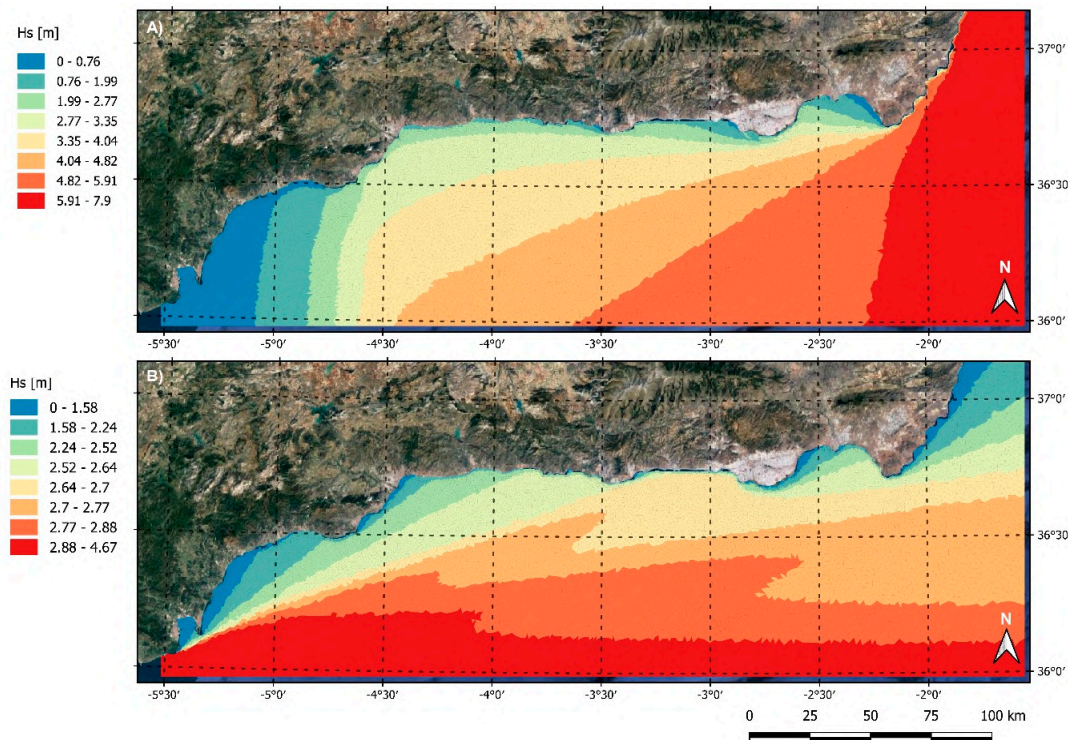


Figure 4. Significant wave height obtained by the numerical model run. (A) Offshore boundary conditions: mean wave direction = 67.5° ENE and wave height return period = 50 years. (B) Mean wave direction = 247.5° ENE and wave height return period = 50 years. Wave height values were divided into 8 intensity classes using the quantile method.

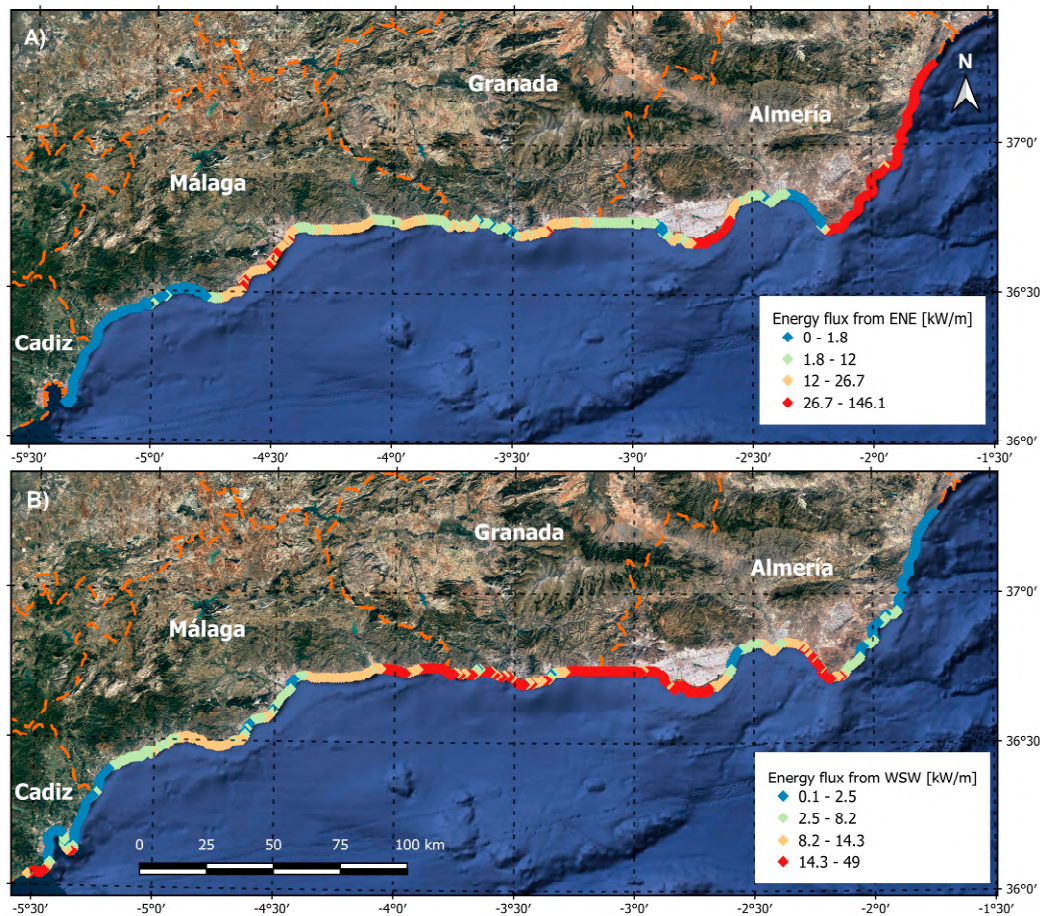


Figure 5. Energy flux distribution along the Andalusia coastline. Offshore boundary conditions: (A) mean wave direction = 67.5° ENE and wave height return period = 50 years (Figure 4A); (B) mean wave direction = 247.5° WSW and wave height return period = 50 years (Figure 4B).

4.2. Buffer Zone

In this study, dry beach widths ranged from 101.46 m at El Zabal (Cadiz Province) to 3.91 m at Los Genoveses beach (Almeria Province). Mean values of dry beach width expressed as a multiple of the 20-year predicted shoreline position showed the prevalence of class 1, that is, of a dry beach width ≥ 5 times the 20-year predicted shoreline position, along 52.8% of the coast.

4.3. Coastal Sensivity

Considering the total amount of transects studied, the most frequent class was 2 (29.63% of the coastal length, or 2985 transects), followed by classes 3 (23.19%, 2336 transects), 1 (22.60%, 2277 transects), and 4 (18.64%, 1878 transects). Class 5 represented only 5.93% of the area studied or 597 transects (Figure 6).

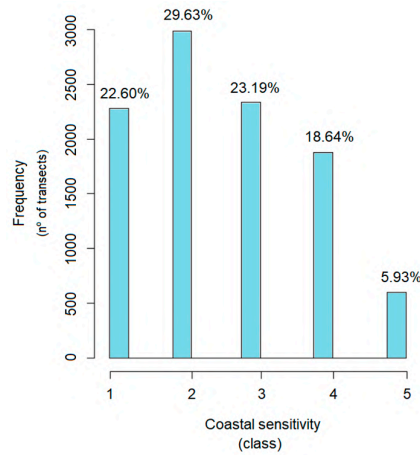


Figure 6. Frequency of coastal sensitivity classes.

The highest values of sensitivity were recorded at the easternmost coast of Almería Province (Los Genoveses beach, and Carboneras, La Parata, and Garrucha areas) likely due to the great exposure to wave energy (Figure 4) and the intermediate/narrow values of dry beach width. The areas with lower sensitivity values were located in the westernmost area of Andalusia, namely at Cádiz Province, from La Línea de la Concepción to Torreguadiaro, essentially because of the very low energetic conditions of this coastal sector (Figure 5) and the presence of relatively large buffer zones. The Costa del Sol area (Málaga Province), from Fuengirola to Málaga, showed low sensitivity related to low and very low energy levels (Figure 5) and the presence of a relatively wide buffer zone observed in correspondence with coastal protection structures that favored, together with the accomplishment of nourishment works [10], the formation of a stable, wide beach.

4.4. Mitigation or Response Strategies

The three main recommended response strategies to counteract coastal erosion processes were obtained by combining coastal sensitivity classes and land uses (Table 5) and are presented in Figure 7. In the case in which a coastal area with a low economic value (e.g., agricultural areas, etc., in Table 3, corresponding to land use classes “A” and “B” in Table 5) presented low sensitivity (i.e., classes 1 to 3 in Table 5), the area was not considered at risk and hence no action was required. In the case in which a coastal area with a very relevant economic value (i.e., extended urban and industrial areas, etc., in Table 3, corresponding to land use classes “D” and “E”) presented high sensitivity (i.e., classes 4 and 5), the area was considered at the highest risk and hence protection measures were mandatory. All situations in between the two mentioned cases were considered at a medium level of risk and hence likely needed some kind of action; further studies are required in order to decide the necessary sound actions depending on the specific typology of the menaced infrastructure and level of sensitivity.

Table 5. Combination of coastal sensitivity and land uses to obtain the response strategies. Blue color corresponds to the “no action” option, yellow corresponds to the “adaptation” option, and red corresponds to the “protection” option.

		Land Use				
		A	B	C	D	E
Coastal Sensitivity	1	1A	1B	1C	1D	1E
	2	2A	2B	2C	2D	2E
	3	3A	3B	3C	3D	3E
	4	4A	4B	4C	4D	4E
	5	5A	5B	5C	5D	5E

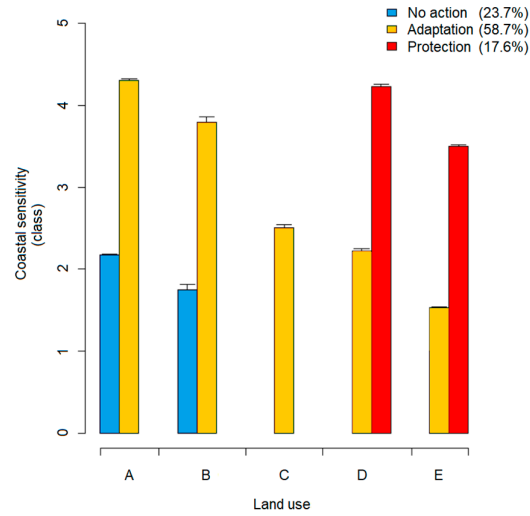
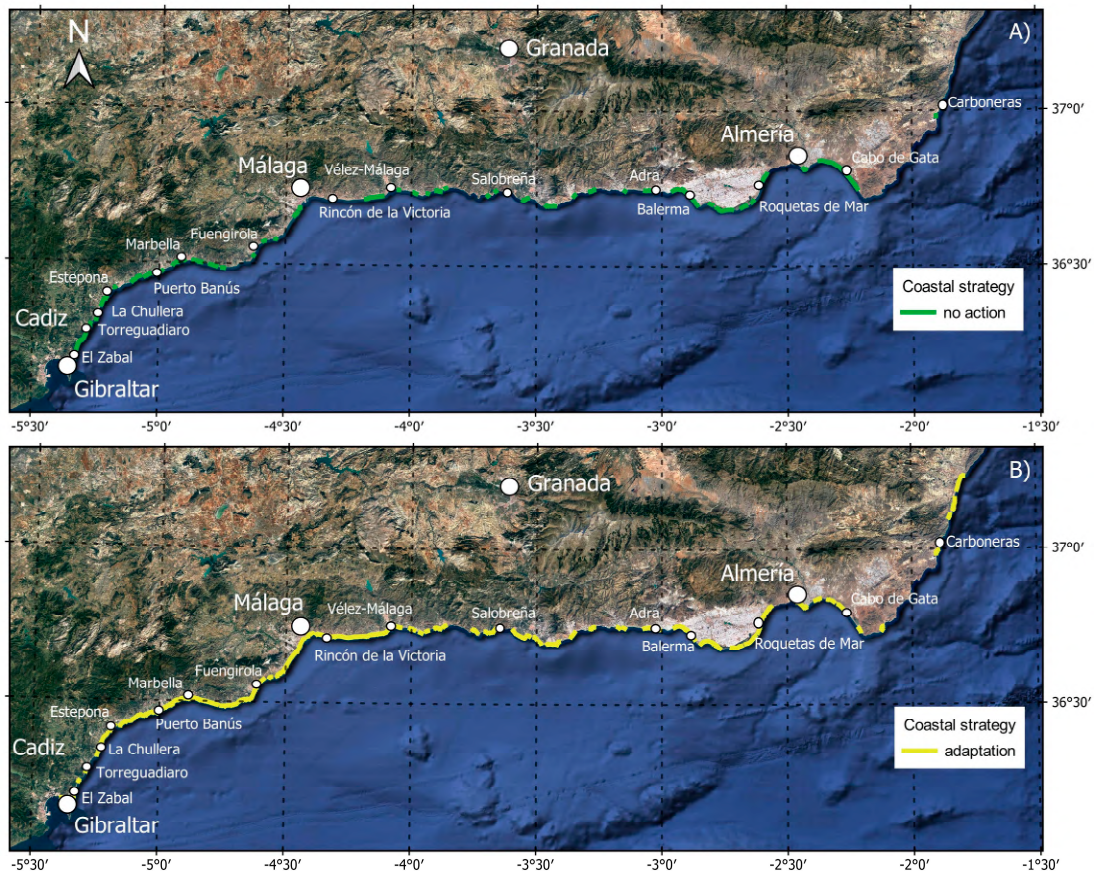


Figure 7. Response strategies resulting from the combination of coastal sensitivity and land use classes. Error bars are also presented. Percentages indicate the total amount of coastline classified within each response option.

The most common response strategy was “adaptation” (58.7%) followed by the “no action” (23.7%) and the “protection” (17.6%) options (Figure 8).



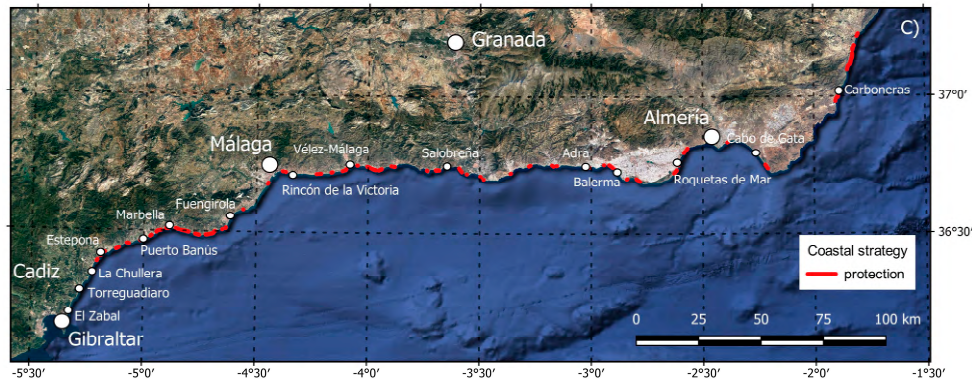


Figure 8. Distribution of response strategies: “do nothing” (A), “adaptation” (B), and “protection” (C).

5. Discussion

5.1. Wave Forcing

Rangel-Buitrago and Anfuso [9] considered wave height, storm surge, degree of littoral exposition to wave fronts [62], and tidal range [63] as forcing agents, following several investigations on storm-induced erosion [8,11,24,64–67]. In this paper, it was not possible to calculate the storm surge, and the tidal range was uniform along the area investigated; therefore, the forcing agent was represented by the wave energy flux distribution along the coast associated with very energetic conditions (i.e., a storm with a return period of 50 years). Wave energy flux distribution adequately represents forcing agents since it is the output of a wave propagation process and hence reflects several cumulative factors determining the way in which wave energy is distributed along the coastline (e.g., the degree of littoral exposure and the local bathymetric characteristics). Bathymetric conditions regulate wave shoaling and dissipation that, within coastal orientation, determine the level of exposure to the most energetic approaching wave directions (Figure 5), for example, the prevalence of longshore or shore-normal transport are very relevant in beach and dune erosion [68]. Storm waves approaching from the ENE direction predominantly affect the easternmost area of the Mediterranean coast of Andalusia from Cabo de Gata to the administrative limit of the Region, as seen in Figure 3. The rest of the coast is essentially exposed to storm waves approaching from WSW. The central area of the studied coast is characterized by the alternation of westerly and easterly waves and winds, as observed for the Costa del Sol [33,69,70], which agrees with the wave forcing shown in Figure 4 and the medium/high values of energy flux shown in Figure 5.

5.2. Buffer Zone Characteristics

A wide dry beach represents an efficient buffer zone to storm erosion processes, but this parameter is often considered in a subjective way. In several regional and local studies, coastal sensitivity was often expressed by means of absolute values of coastal erosion rates [68,71,72], making difficult the use and application of a unique methodology since erosion rates range considerably from place to place [9,36,66]. Hence, since the dry beach protection function is strongly related to its width and local erosion recorded rates, the dry beach width was considered in this paper as a multiple of the 20-year predicted shoreline position. This methodology is thus objective and applicable to different areas where similar data are available.

As an example of previous assumptions (i.e., the subjectivity linked to the use of beach width value as an indicator of its effectiveness as buffer zone), the results presented in this paper were compared with data recorded by Molina et al. [36]. Sometimes a wide beach records relevant accretion rates, that is, there is a direct correspondence between beach width and beach accretion trend or a narrow beach is linked to an erosional trend; this was the example of El Zabal (SW part of Cádiz Province), which presented a wide beach up to 101.4 m and belonged to the “very wide”

buffer zone class (“high accretion” class in [36]), and of Los Genoveses beach (eastern part of Almería Province), which was 3.91 m in width and belonged to the “very narrow” buffer zone class (“high erosion” of the classification used in [36]). However, there are many cases in which this premise is not met, for example, at the Natural Park Punta Entinas-El Sabinar (Almería Province) where, even though the beach is very narrow, it belongs to the narrow buffer zone class in this paper and to the “high accretion” class of the classification used in [36]. The opposite is observed at Salobreña and Carboneras that presented 196.8 and 111.6 m of beach width, respectively (“very wide” buffer zone class), but because of the recorded erosion trend, they belonged to the “high erosion” class in Molina et al. [36].

5.3. Land Use

Land use classes broadly coincided with the ones proposed by Rangel-Buitrago and Anfuso [9], McLaughlin et al. [22], and McLaughlin and Cooper [63]. In this paper, in order to have more objective and well-established categories, available data obtained from the official web page of the Andalusia Regional Administration, based on the SIOSE Project that was a continuation of the European Project CORINE, were used. Therefore, the information was compatible with the European land cover and was based on the Hierarchical INSPIRE Land Use Classification System (HILUCS) land use classification from the European Union’s INSPIRE Directive. Such data were easily accessible at the European and Global scales as they have been integrated into the Land Monitoring Service of the Copernicus Programme, the European Union’s Earth Observation Programme.

Further investigations could be focused on obtaining the percentage of urbanized area that has been expressed according to the density of human infrastructures and which broadly corresponds to the “engineered frontage” [73,74], the “coastal construction index” [75], and several sub-indexes (e.g., “settlements”, “roads”, and “railway”) characterized by McLaughlin and Cooper [63].

5.4. Mitigation or Response Strategies

The “no action” option (Figure 8) appeared where both coastal sensitivity and land use classes were low, for example, at natural areas with a wide buffer zone and low/medium coastal forcing values. This was observed at the westernmost area of Cádiz Province (El Zabal Figure 9A, Torreguadiaro, and La Chullera), and at some areas from the west coast of Almería Province (Balerna, San Agustín, Costacabana, and Cabo de Gata). In such areas, no interventions are required on the decadal time scale but caution has to be focused on possible changes of the coastal trend on the large temporal scale due to climatic change-related processes (e.g., changes in storm intensity and sea level rise [26,27,29]), even though this latter process (i.e., sea level rise) seems to be not a problem for these areas [43–45].



Figure 9. Maps of three investigated areas and associated response strategies. (A) El Zabal, close to La Línea de la Concepción (Cádiz Province); (B) Puerto Banús (Málaga Province); and (C) Caleta de Vélez, (Málaga Province). The projection used is the UTM30N, the referencing system is the WGS85, and the coordinates are in meters.

The “adaptation” option (Figure 8) was partially linked to the great level of urbanization and the general erosive behavior of the Andalusia Mediterranean coast, a trend well documented by several authors [10,36,76–80]. Specifically, the adaptation was found to be ideal along more than one half of the studied coast, essentially in two main cases: (1) at natural areas with high sensitivity and (2) at urbanized areas with low sensitivity values. Examples of the former case are the natural area south of Carboneras, some natural areas in La Parata, and the natural area north of Garrucha (East of Almería Province). Examples of the latter case are La Línea de la Concepción (SW part of Cádiz Province), Puerto Banús (Marbella Bay, Málaga Province Figure 9B), and in general the Costa del Sol central and eastern areas (Málaga Province). Furthermore, such areas are recording sea level rise values of a few millimeters per year [43–45], so erosion problems are expected to increase in the next decades. Since this methodology was applied at a large, regional scale, within this research it was not possible to distinguish or propose detailed adaptation strategies according to coastal sensitivity and specific land use distribution/typologies. Hence, further investigations must be carried out at a smaller spatial scale in order to recommend the best adaptation strategies ranging from the “land use change” strategy (i.e., an agricultural area can be transformed into a grazing area [32,81,82]) to the “relocation” strategy (i.e., the landward movement of a coastal road [31], as could be the case of the main Andalusia coastal highway at Mijas and Fuengirola (Málaga Province) and the National coastal road at some sectors of Vélez-Málaga and Adra (Málaga Province)). For other locations, adaptation must be devoted to the modification of existing protection structures, as proposed by Costa and Coello [83], or their abandonment according to the “do nothing” strategy [31]. This could be the case of the Puerto Banús area and many urban beaches at Málaga protected by coastal structures that have been modified several times over the last decades [10]. Such structures need periodic maintenance and/or may require modification (e.g., lowering a breakwater or a groin), thereby reducing their impact on the landscape [38], negative environmental effects [84,85], and dangerous related currents during storms [86]. Hard protection structures can be partially removed

[10] and nourishment projects implemented to enlarge or maintain the dry beach width, thus increasing the beach carrying capacity [87].

The “protection” option (Figure 8) characterized coastal sectors where both coastal sensitivity and land use classes presented high values, that is, at urbanized areas with a narrow buffer zone and medium/high coastal forcing values. This was observed at La Gaspara (SW part of Cádiz Province), Marbella and Mijas (center of Málaga Province), Caleta de Vélez (eastern part of Málaga Province, Figure 9C), and Balerma (east of Almería Gulf) areas that have narrow buffer zones and medium coastal forcing values, as well as at the Carboneras, La Parata, and Garrucha areas (eastern part of Almería Province) that have from medium to narrow buffer zones and high coastal forcing values. In such areas, the implementation of coastal mitigation strategies will be required in future years, and the determination of sound defense modalities is linked to coastal trend, characteristics, and human land uses.

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PLAN DE INVESTIGACIÓN

PLAN DE INVESTIGACIÓN DE TESIS DOCTORAL
R.D. 99/2011

A. MEMORIA DEL PLAN DE INVESTIGACIÓN DE TESIS DOCTORAL

(A cumplimentar por el doctorando)

Apellidos: Molina Gil Nombre: Rosa D.N.I./Pasaporte: 48902745-F Programa de doctorado: 8205 Ciencias y Tecnologías Marinas Escuela de Doctorado: Escuela Internacional de Doctorado en Estudios del Mar (EIDEMAR) Título de la tesis: El litoral mediterráneo andaluz: características, evolución y respuesta frente a los procesos naturales y las actuaciones antrópicas.

Director/es Dr. D. *Giorgio Anfuso Melfi*

Dr. D. *Giorgio Manno*

1 - Resumen

Las zonas litorales son de gran importancia para el desarrollo de los países costeros que concentran en ellas gran parte de su población y actividad económica. Estos dos factores, entre otros, provocan un progresivo e importante deterioro del litoral que, por ende, necesita la realización de actuaciones finalizadas a su protección.

En Europa se han creado protocolos para la conservación de los elementos costeros premiando la protección del litoral como camino hacia la sostenibilidad; ejemplos son la Recomendación 2002/413/CE de 30 de mayo de 2002, relativa a la aplicación de la gestión integrada de las zonas costeras de Europa, y que insta a los Estados miembros a crear programas y políticas enmarcadas en la *Gestión Integrada de las Zonas Costeras* (GIZC), con premisas como aquellas de adoptar un planteamiento estratégico basado en la protección del medio ambiente costero y en la gestión sostenible de los recursos naturales y adoptar medidas de protección costera adecuadas y responsables ecológicamente, entre otras.

En España, tras la aprobación de la Ley de Costas en 1988, y su posterior modificación en 2013 con la aprobación de la Ley de protección y uso sostenible del litoral, se han realizado numerosos trabajos de restauración costera construyendo barreras de protección artificiales que, debido al cruce de intereses políticos, sociales y económicos, no han tenido éxito, provocando el deterioro de las zonas adyacentes que se han visto afectadas por la alteración de la dinámica costera. En especial, entre los ambientes costeros, las dunas forman uno de los elementos más importantes en la protección del litoral, ya que lo protegen de las inundaciones marinas y constituyen un reservorio de arena y, además, albergan hábitats singulares.

El objetivo de investigación de la presente tesis de doctorado es el de evaluar el estado y condiciones actuales de las dunas y playas del tramo litoral mediterráneo de la costa de Andalucía a través de un

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análisis de la evolución de las dunas y la línea de costa, llevado a cabo a partir de cartografía generada en software GIS para el periodo 1956-2016.

2 - Antecedentes y estado actual del tema

Las zonas litorales son de vital importancia para el desarrollo de los países costeros, ya que la mayoría de su población habita en ellas y que éstas además concentran gran parte de su actividad económica, tal y como se expresa en el informe “*Gestión Integrada de las Zonas Costeras en España*” elaborado por Ministerio de Medio Ambiente (2006). La industria del turismo es un factor económico importante en las regiones costeras, ya que no sólo genera empleo sino que también aporta a los países costeros una gran parte de sus ingresos regionales y, por ello, cada año, estos países invierten en mejoras en la calidad de estas áreas recreativas, incluyendo el estado ambiental de las playas (Semeoshenkova y Newton, 2015).

En España, el Estado tiene la competencia sobre las actuaciones en el litoral al pertenecer este espacio al Dominio Público Marítimo Terrestre, correspondiéndole por tanto también la protección, conservación y restauración del mismo. Desde que se aprobó en 1988 la Ley de Costas española, y su posterior modificación con la aprobación de la Ley 2/2013 de protección y uso sostenible del litoral, se han estado sucediendo numerosos trabajos de restauración de zonas costeras con poco éxito, debido a una gestión confusa fruto de los cuantiosos intereses que confluyen en el litoral (Ley de Seoane *et al.*, 2007). A lo largo de la costa se han construido barreras de protección, espigones y otros tipos de obras de ingeniería, con el propósito de mitigar la gran pérdida de arena de las playas, para embellecer aquellas playas de mayor interés turístico o para proteger puertos deportivos de interés económico. Como consecuencia, en las playas donde se encuentran este tipo de estructuras antrópicas existe el riesgo de que se produzcan corrientes peligrosas para los bañistas, pérdida de valor ecológico, de biodiversidad y valor paisajístico y, a menudo, la progresiva adición de estas obras de ingeniería se corresponde con el desarrollo de procesos erosivos aguas abajo de las estructuras (Manno *et al.*, 2016).

Las dunas costeras juegan un papel significativo en las playas no sólo por los hábitats singulares que se desarrollan en ellas, y constituyen reservas de arena de las playas durante episodios extremos (Ley de Seoane *et al.*, 2011). Una de las principales causas de la inestabilidad de las áreas litorales es la eliminación del intercambio de arena dunas-playas junto a la regulación de las cuencas fluviales, además del gran efecto de la construcción de infraestructuras (Cendrero Uceda *et al.*, 2005). Uno de los factores por lo que es imprescindible la protección de los sistemas dunares es su alta vulnerabilidad a los cambios ambientales y a la actividad humana, ya que sólo son necesarios meses o años, o incluso horas, para que se destruya un complejo dunar comparado con las decenas de años que necesita para desarrollarse por completo (Sanjaume Saumell y Gracia Prieto, 2011).

En 1987, la Unión Europea utilizó por primera vez el término “Desarrollo Sostenible” en el *Informe Brundtland* definiéndolo como “*aquel que satisface las necesidades del presente sin comprometer las necesidades de las futuras generaciones*”, mostrando un cambio significativo de actitud frente a la protección del medio ambiente. Respecto a la protección del litoral, en 2002 el Parlamento y el Consejo Europeo promulgaron la Recomendación 2002/413/CE de 30 de mayo de 2002, relativa a la aplicación de la gestión integrada de las zonas costeras en Europa, poniendo de manifiesto su preocupación por la preservación y recuperación de las costas de los Estados miembros, vinculando la gestión integrada de éstas con el concepto de desarrollo sostenible.

Esta recomendación insta a los Estados miembros a crear programas y políticas enmarcadas en la GIZC de forma voluntaria, con premisas como la de adoptar un planteamiento estratégico basado en la protección del medio ambiente costero y en la gestión sostenible de los recursos naturales, reconocer la

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amenaza del cambio climático, adoptar medidas de protección costera adecuadas y responsables ecológicamente, entre otras (Tros-de-Ilarduya, 2008). Con estas premisas se pone de manifiesto la importancia que la Unión Europea le da al término de desarrollo sostenible, señalando que “*las actividades humanas han de ser más respetuosas con el medio, más responsables socialmente, y racionales desde un punto de vista económico*”.

3 - Hipótesis y Objetivos

Dada la importancia que tiene la protección de la costa y el papel tan relevante que asumen los complejos dunares en ésta, se plantea realizar un trabajo de investigación que considere tanto la evolución de las playas como de las dunas del tramo costero mediterráneo de Andalucía.

La hipótesis de la que partimos es que las playas del litoral mediterráneo andaluz se encuentran en un estado de retroceso y los sistemas dunares sufren continuos episodios de erosión y degradado, debido a las condiciones climatológicas adversas y a la presión antrópica.

El objetivo principal de este trabajo es el de evaluar la evolución, el estado y condiciones actuales de las playas y dunas del tramo mediterráneo de la costa de Andalucía a través de un análisis histórico a partir de cartografía generada en *software* GIS (*Geographic Information System*) y un análisis del clima marítimo.

Para ello se plantean tres objetivos:

Objetivo 1: Determinación de la línea de costa (contacto agua-tierra) para el periodo 1956 - 2016 y realización de una cartografía de las dunas (para el periodo 1977 – 2016) de la costa mediterránea andaluza a partir de fotos aéreas e imágenes de satélite a través de un *software* GIS.

Objetivo 2: Análisis de la evolución de las playas y dunas. Esta fase prevé: a) análisis de la evolución de la línea de costa en función de la presencia de estructuras antrópicas (puertos, rompeolas, espigones, etc.); b) análisis de la evolución de las dunas y definición de los cambios dentro de las diferentes unidades geomorfológicas e identificación de la presión antrópica; c) análisis de la energía del oleaje de tormenta a lo largo de la línea de costa.

Objetivo 3: Análisis de los resultados obtenidos en los *objetivos 1 y 2* y evaluación de las tendencias presentes y futuras del estado y condiciones actuales de las playas y dunas estudiadas.

4 - Metodología

En este apartado serán descritos de manera detallada la metodología que se utilizará en los trabajos conducentes a cada objetivo planteado:

4.1 Objetivo 1

Para la realización de la cartografía se utilizará el *software* GIS ArcGIS, usando como base las ortofotografías aéreas disponibles de la costa mediterránea andaluza del periodo comprendido entre 1956 y 2016.

Las ortofotografías se obtendrán a través de los servicios *Web Map Services* (WMS) pertenecientes a los servicios *Open Geospatial Consortium* (OGC) de la Red de Información Ambiental de Andalucía

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(REDIAM) de la Consejería de Agricultura, Ganadería, Pesca y Desarrollo Sostenible (Junta de Andalucía) y del Centro de Descargas del Centro Nacional de Información Geográfica perteneciente al Plan Nacional de Ortofotografía Aérea (PNOA) del Ministerio de Fomento (Gobierno de España).

Las ortofotografías aéreas seleccionadas son:

	Año	Escala	Resolución [m]
Color	2016	1:5.000	0,25
Pancromática	2001	1:10.000	0,50
Pancromática	1977	1:5.000	0,50
Pancromática	1956	1:10.000	1,00

Las ortofotografías aéreas del año 1956 se utilizarán para el análisis de la evolución de la línea de costa (en *objetivo 2*). Debido a la baja calidad de las imágenes no se utilizará para la cartografía de las dunas. En áreas interés, p.e. áreas urbanizadas o muy modificadas en el periodo comprendido entre 1956 y 1977, se cartografiarán las dunas existentes si la calidad de las imágenes lo permite.

Debido a la naturaleza micromareal de la costa mediterránea andaluza, la posición de la línea de costa se establecerá en el límite agua – tierra (Pajak y Leatherman, 2002; Boak y Turner, 2005) y las correcciones se llevarán a cabo teniendo en cuenta las condiciones mareales (σ_{td}) y del run-up (σ_{wr}) de acuerdo a Manno *et al.* (2017).

La precisión de las medidas dependen de la incertidumbre total (σ_T) asociada a la determinación de la posición de cada línea de costa, que depende de las características propias de las imágenes utilizadas y los procesos de digitalización (Moore, 2000) y será calculada a partir de la siguiente relación (Manno *et al.*, 2017):

$$\sigma_T = \sqrt{\sigma_d^2 + \sigma_p^2 + \sigma_r^2 + \sigma_{co}^2 + \sigma_{wr}^2 + \sigma_{td}^2}$$

Donde: σ_T es la incertidumbre total, σ_d es el error de digitalización, σ_p es la precisión relativa al pixel, σ_r es el error de co-registro, descritos en Moore (2000).

Para la realización de los mapas se ha escogido la siguiente leyenda en la que se diferencian las unidades que se describen a continuación:

- Línea de costa;
- Línea de pie de dunas;
- Dunas móviles;
- Dunas fijas con céspedes;
- Dunas estabilizadas.

La definición de los ambientes dunares se ha basado en la clasificación morfo-ecológica descrita en el manual “Las dunas en España” de Sanjaume Saumell y Gracia Prieto (2011) en el que se definen los hábitats dunares costeros más importantes en España.

La fotointerpretación es la detección, identificación, descripción y evaluación del significado de objetos y patrones en una fotografía (Loelkes *et al.*, 1983). Para facilitar el reconocimiento de las estructuras y unidades existentes en las imágenes y fotografías, se suelen utilizar claves fotointerpretativas como las descritas en el manual “*Land use/land cover and environmental photointerpretation keys*” de Loelkes *et al.* (1983):

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- *Pattern*: se refiere a la forma en la que diferentes objetos se distribuyen y organizan espacialmente en el territorio, pudiéndose así diferenciar, por ejemplo, entre estructuras antrópicas y naturales.
- *Tamaño*: conocer la dimensión absoluta y relativa ayuda a identificar objetos, de forma que se pueda distinguir entre un árbol y un matorral o una casa y una fábrica.
- *Forma*: del mismo modo que el tamaño ayuda a diferenciar entre objetos, la forma de éstos nos ayuda a diferenciar entre objetos antrópicos y naturales de modo que, un objeto hecho por el hombre suele tener formas lineales mientras que los naturales suelen tener formas irregulares.
- *Tono y color*: el color es uno de los parámetros más importantes a la hora de identificar objetos en una imagen.
- *Textura*: se define en función del tamaño de los objetos y la escala de la fotografía. En fotografías de gran escala se reconocen mejor los objetos que en fotografías de escalas menores.
- *Sombra*: la sombra que proyectan los objetos, a menudo ayudan en la identificación de los mismos, ya que nos dan información que en plano no podríamos conocer, sin embargo, también puede obstaculizar la interpretación de los objetos oscureciéndolos en la imagen.
- *Asociación*: se refiere a la asociación de ciertos objetos a algunos lugares, por ejemplo, una fábrica se suele situar a las afueras de una ciudad.

Teniendo en cuenta estas claves, se identifican las unidades geomorfológicas que se quieren analizar, nombradas en la leyenda antes descrita, y se generan los mapas.

4.2 Objetivo 2

Se analizará la evolución de la costa mediterránea andaluza. Para ello, se estudiarán los cambios producidos en la línea de costa, cómo ha variado el cordón dunar y su vegetación, el desarrollo de abanicos de desbordamiento, el efecto de las construcciones antrópicas sobre el tramo costero analizado y las características y energía del oleaje de tormenta.

Para ello se utilizará la cartografía generada en el *objetivo 1* con *software* GIS para hacer una descripción detallada de los cambios observados en los mapas, diferenciando cada unidad estudiada y se realizarán cálculos de áreas y longitudes de las mismas, a través de las aplicaciones del *software* GIS, para complementar el análisis.

El análisis de la línea de costa se realizará a partir del cálculo de las tasas de erosión/acreción calculadas a través de la aplicación *software* DSAS (*Digital Shoreline Analysis System*) de la U.S.G.S. *United States Geological Survey*. Se utilizarán los índices: a) SCE (*Shoreline Change Envelope*) trata la variabilidad de cada transecto calculado teniendo en cuenta el desplazamiento máximo de la línea de costa sin importar las fechas de las mismas; b) NSM (*Net Shoreline Movement*) calcula las distancias entre la línea más antigua y la más reciente para cada transecto; c) WLR (*Weighted Linear Regression*) determina la línea de mejor ajuste dándole mayor peso a los datos más fiables; d) LRR (*Linear Regression Rate*) calcula la regresión lineal a través del método de los mínimos cuadrados; e) EPR (*End Point Rate*) representa el cociente de la distancia del movimiento de la línea y el tiempo transcurrido entre la línea más antigua y la más reciente.

Para el análisis del clima marítimo se estudiarán las características y la energía del oleaje de tormenta a partir de los datos obtenidos para el periodo 1979-2014 del Centro Europeo ECMWF (*European Center Medium Weather Forecast*). Los datos modelados por el modelo Wave Model (WAM) pertenecen al

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proyecto ERA-INTERIM del ECMWF. Estos datos se analizarán mediante un código en el *software* MATLAB que identificará las tormentas más energéticas, es decir, aquellas que son más representativas de los cambios en la dinámica costera.

4.3 Objetivo 3

Con los resultados obtenidos a partir de la fotointerpretación de los mapas realizados, la evolución de la línea de costa y el estudio de las características y energía del oleaje de tormenta de los tramos estudiados, se realizará una evaluación de las tendencias presentes y futuras del estado y condiciones actuales de las playas y dunas estudiadas.

5 - Justificación de recursos disponibles

Para la realización de este trabajo se utilizarán las ortofotografías aéreas y datos de oleaje mencionados en el apartado "metodología" de este texto, *software* GIS y de cálculo.

Con el fin de mejorar las competencias en el ámbito geomorfológico costero, GIS y MATLAB, se prevé una movilidad en *l'Università degli Studi di Palermo* (Italia).

6 - Planificación temporal de trabajo

A continuación se muestra un cuadro con la planificación temporal de la realización de cada objetivo planteado. Durante los cuatro primeros años se desarrollarán los trabajos conducentes a lograr los *objetivos 1 y 2*, y durante el quinto año se desarrollarán los trabajos del *objetivo 3*.

Objetivos	Años Académicos				
	2015-16	2016-17	2017-18	2018-19	2019-20
1					
2					
3					

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M. Tros-de-Ilarduya. El reto de la gestión integrada de las zonas costeras (GIZC) en la Unión Europea. *Boletín de la A.G.E.* 47, 143-156, 2008.

Doctorando: Rosa Molina Gil

Título de la tesis: El litoral mediterráneo andaluz: características, evolución y comportamiento frente a los procesos naturales y las actuaciones antrópicas.

B. INFORME DEL TUTOR Y DE LOS DIRECTORES DE LA TESIS

Informe razonado de valoración de cada uno de los apartados del plan de investigación

Resumen

Describe brevemente el plan de trabajo presentado, valoración positiva.

Antecedentes y estado actual del tema

Se presenta una revisión actualizada de los trabajos existentes, valoración positiva.

Hipótesis y Objetivos

Se presentan unos objetivos razonables, además la candidata ha desarrollado labores parecidas en el marco de su TFM. Valoración positiva.

Metodología

La metodología está bien descrita, además la candidata ha desarrollado labores parecidas en el marco de su TFM. Valoración positiva.

Justificación de recursos disponibles

Se presentan los recursos disponibles, además la candidata ha trabajado con dichas herramientas en el marco de su TFM. Valoración positiva.

Planificación temporal de trabajo

La planificación parece adecuada y razonable a los objetivos que se pretenden alcanzar. Valoración positiva.

Bibliografía

Adecuada y actualizada. Valoración positiva.

Los abajo firmantes, basándose en la valoración de cada uno de los apartados del presente Plan de Investigación de Tesis Doctoral, dan el visto bueno a su contenido para su aprobación por parte de la Comisión Académica del Programa de Doctorado _____

En Cádiz, a 9 de septiembre de 2019

El tutor



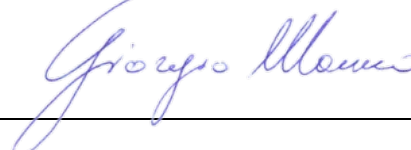
Fdo.: Giorgio Anfuso

El/Los director/es

Fdo.: Giorgio Anfuso



Fdo.: Giorgio Manno



DOCUMENTO DE ACTIVIDADES DE LA
DOCTORANDA

Actividad formativa: 8205B01 Publicaciones o artículos científicos			
Tipo: Obligatoria (mínimo 100.00 h.)		Horas realizadas: 800.00 h.	Actividad superada
Curso	Descripción	Documento justificativo	Horas
2018/19	Copia de la publicación	water-11-00509.pdf	200.00
2018/19	Copia de la publicación	sustainability-11-03539- v2.pdf	200.00
2020/21	Copia de la publicación	2020_Molina_et_al_water.pdf	200.00
2020/21	Copia de la publicación	jmse-08-00154.pdf	200.00

Actividad formativa: 8205B02 Cursos o seminarios de formación para la investigación			
Tipo: Obligatoria (mínimo 100.00 h.)		Horas realizadas: 172.00 h.	Actividad superada
Curso	Descripción	Documento justificativo	Horas
2016/17	Diploma de asistencia al curso	Curso_cambio_climatico_y_humedales_cost...pdf	20.00
2017/18	Diploma de asistencia al curso	48902745F_60199.pdf	20.00
2017/18	Diploma de asistencia al curso	48902745F_77966.pdf	40.00
2018/19	Diploma de asistencia al curso	Seminario_IBERMAR.pdf	10.00
2018/19	Diploma de asistencia al curso	Curso_Beach_Management.pdf	25.00
2018/19	Diploma de asistencia al curso	Curso_DiseA_o_grA_fico_para_investigado...pdf	12.00
2018/19	Diploma de asistencia al curso	IdentificaciA_n_y_gestiA_n_de_riesgos_e...pdf	25.00
2018/19	Diploma de asistencia al curso	L21318_ROSA_MOLINA_GIL_1_.pdf	20.00

Actividad formativa: 8205P04 Movilidad y estancias de investigación			
Tipo: Optativa		Horas realizadas: 600.00 h.	Actividad superada
Curso	Descripción	Documento justificativo	Horas
2017/18	Certificado estancia	certificado_estancia.pdf	300.00
2020/21	Certificado estancia	certificado_estancia_RMG.pdf	300.00

Actividad formativa: 8205P05 Asistencia docente			
Tipo: Optativa		Horas realizadas: 15.00 h.	Actividad superada
Curso	Descripción	Documento justificativo	Horas
2018/19	Informe asistencia docente	inf_colaboracion_docencia_Rosa_Molina.pdf	15.00

Total horas actividades formativas completadas: **1587.00**

Las horas especificadas corresponden a las reconocidas por la Comisión Académica del Programa en el día de la fecha.
El estudiante ha completado todos los requisitos de su plan de estudios para la superación de las actividades formativas.

Cádiz, a 19 de octubre de 2020

INFORME DEL FACTOR DE IMPACTO Y CUARTIL

Las publicaciones de la que consta la tesis doctoral “*El litoral mediterráneo andaluz: características, evolución y respuesta frente a los procesos naturales y las actuaciones antrópicas*” han sido publicadas en revistas incluidas en los tres primeros cuartiles de la relación de revistas del ámbito de la especialidad y referenciadas en la última relación publicada por el Journal Citation Reports (SCI y/o SSCI).

Publicación 1: Molina, R.; Manno, G.; Lo Re, C.; Anfuso, G.; Ciraolo, G. Storm Energy Flux Characterization along the Mediterranean Coast of Andalusia. *Water* **2019**, *11*, 509; doi: 10.3390/w11030509.

Revista: Water

Factor de impacto: 2.544

Categoría: 31/94 (Q2) in 'Water Resources'

Publicación 2: Molina, R.; Anfuso, G.; Manno, G.; Gracia Prieto, F.J. The Mediterranean Coast of Andalusia (Spain): Medium-Term Evolution and Impacts of Coastal Structures. *Sustainability* **2019**, *11*, 3539; doi: 10.3390/su11133539.

Revista: Sustainability

Factor de impacto: 2.576

Categoría: 120/265 (Q2) en 'Environmental Sciences'

Publicación 3: Molina, R.; Manno, G.; Lo Re, C.; Anfuso, G. Dune's systems characterization and evolution in the Andalusia Mediterranean Coast (Spain). *Water* **2020**, *12*, 2094; doi: 10.3390/w12082094.

Revista: Water

Factor de impacto: 2.544

Categoría: 31/94 (Q2) in 'Water Resources'

Publicación 4: Molina, R.; Manno, G.; Lo Re, C.; Anfuso, G.; Ciraolo, G. A Methodological Approach to Determine Sound Response Modalities to Coastal Erosion Processes in Mediterranean Andalusia (Spain). *Journal of Marine Science and Engineering* **2020**, *8*, 154; doi: 10.3390/jmse8030154.

Revista: Journal of Marine Science and Engineering

Factor de impacto: 2.033

Categoría: 31/66 (Q2) in 'Oceanography'

INFORME DE LA CONTRIBUCIÓN DE LA
DOCTORANDA

El grado de contribución de la doctoranda Rosa Molina a las publicaciones de las que consta esta tesis se presenta a continuación:

Publicación 1: Storm Energy Flux Characterization along the Mediterranean Coast of Andalusia.

Búsqueda y descarga de la base de datos de oleaje. Análisis de las características y energía del oleaje de tormenta a partir de los datos obtenidos de la base de datos, clasificación de las tormentas y estimación del periodo de retorno y probabilidad de excedencia de la energía de cada clase de tormenta a través del software utilizado para ello, bajo la supervisión de Carlo Lo Re y Giorgio Manno. Escritura del borrador original de la publicación. El trabajo fue revisado y supervisado por Giorgio Anfuso y Giuseppe Ciralo.

Publicación 2: The Mediterranean Coast of Andalusia (Spain): Medium-Term Evolution and Impacts of Coastal Structures.

Búsqueda y descarga de las fotografías aéreas. Determinación de la línea de costa y cálculo de la incertidumbre asociada a su posición, análisis a través del software utilizado de las tasas de evolución, clasificación y distribución, bajo la supervisión de Giorgio Manno. Escritura del borrador original de la publicación. El trabajo fue revisado y supervisado por Giorgio Anfuso y Francisco Javier Gracia Prieto.

Publicación 3: Dune's systems characterization and evolution in the Andalusia Mediterranean Coast (Spain).

Búsqueda y descarga de las fotografías aéreas y realización de la cartografía de las dunas y definición de los ambientes dunares. Análisis de la evolución de los sistemas dunares y su fragmentación y la ocupación antrópica a través del software utilizado, bajo la supervisión de Giorgio Manno y Carlo Lo Re. Escritura del borrador original de la publicación. El trabajo fue revisado y supervisado por Giorgio Anfuso.

Publicación 4: Methodological Approach to Determine Sand Response Modalities to Coastal Erosion Processes in Mediterranean Andalusia (Spain).

Búsqueda y descarga de las fotografías aéreas y mapas de usos del suelo. Cálculo y análisis de la sensibilidad y clasificación de los usos del suelo a través del software utilizado, bajo la supervisión de Giorgio Manno y Carlo Lo Re. Búsqueda, cálculo y propuesta de aplicación de las estrategias de mitigación, bajo la supervisión de Giorgio Manno y Giorgio Anfuso. Escritura del borrador original de la publicación. El trabajo fue revisado y supervisado por Giorgio Anfuso y Giuseppe Ciralo.

CONFORMIDAD DE LOS AUTORES

**Thesis by compendium of publications.
Document of agreement and resignation of co-authors.**

D. /D^a.: Carlo LO RE

DNI o Passport: CA83730FW co-author of the following publication:

Storm Energy Flux Characterization along the Mediterranean Coast of Andalusia

In accordance with the **Article 23.4** of the **Regulation UCA CG06-2012, June 27, 2012, which regulates the ordinance of doctoral studies at the University of Cádiz (BOUCA No. 208)**.

States his/her approval to the presentation of this publication as a part of the doctoral thesis written by D. /D^a. Rosa Molina Gil, entitled: “El litoral mediterráneo andaluz: características, evolución y respuesta frente a los procesos naturales y las actuaciones antrópicas”

And expresses his/her resignation to present said publication as a part of another doctoral thesis at any other University.

In Palermo, 17 of October, 2020

Signed: Carlo Lo Re

**Thesis by compendium of publications.
Document of agreement and resignation of co-authors.**

D. /D^a.: _____ Giorgio Anfuso _____

DNI o Passport: _____ X1761231Y _____ co-author of the following publication:

Storm Energy Flux Characterization along the Mediterranean Coast of Andalusia

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Signed: Giorgio Anfuso

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D. /D^a.: Giuseppe Ciralo

DNI o Passport: AU3715447 co-author of the following publication:

Storm Energy Flux Characterization along the Mediterranean Coast of Andalusia

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D. /D^a.: Giorgio Manno

DNI o Passport: YA8206489 co-author of the following publication:

Storm Energy Flux Characterization along the Mediterranean Coast of Andalusia

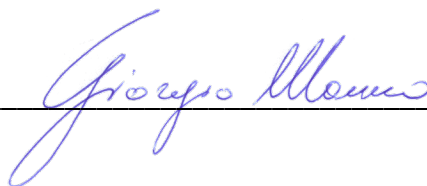
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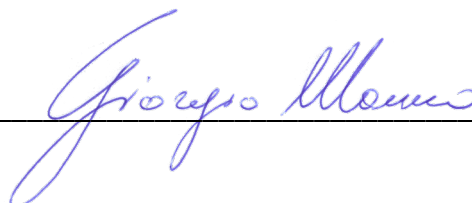
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D. /D^a.: _____ F.J. Gracia Prieto _____

DNI o Passport: 17.156.686-C co-author of the following publication:

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Signed: F. Javier Gracia Prieto

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D. /D^a.: Carlo LO RE

DNI o Passport: CA83730FW co-author of the following publication:

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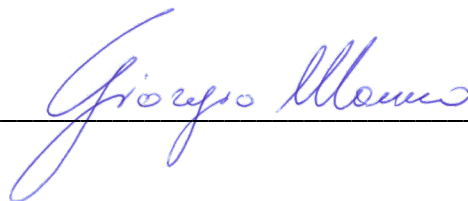
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A Methodological Approach to Determine Sound Response Modalities to Coastal Erosion Processes in Mediterranean Andalusia (Spain)

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