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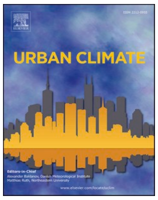

# Nature-based solutions on the coast in face of climate change: The case of Benidorm (Spain)

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ABSTRACT

The increase in anthropic activities and floods of coastal and river origin put the proper functioning of coastal cities at risk. Benidorm (Spain), an international tourist destination, is no exception to the effects of climate change. Maritime storms intensified, with an increase in wave height by 61% in the last 10 years. Likewise, changes in atmospheric circulation patterns have maximized the irregularity and torrentiality of rainfall in the study area, finding that 2 of the 3 years with the highest number of days of daily precipitation >30 mm have occurred in recent years (2017 and 2019). All these changes will accelerate the beach erosion process. Therefore, it was necessary to act, implementing natural solutions that increase the resilience of the coastal city. The innovative construction of a vegetated urban dune parallel to the promenade was proposed to protect it from the 3 m flood level during the most unfavourable maritime storm. The dune must favour the drainage of sea water and be compatible with the recreational activities carried out in its surroundings. The solutions proposed here are a recommendation so that Public Administrations in other parts of the world can design their climate adaptation plans using nature-based solutions.

## 1. Introduction

Coastal erosion is a natural phenomenon that is becoming a growing problem on shorelines around the world (Gracia et al., 2018; Jacob et al., 2021). This problem is the result of multiple factors, and can be classified into those related to anthropic pressure or those related to the maritime climate of the area (sea level rise, greater storm frequency, increase in sea surface temperature, etc.), many of them being stimulated in recent decades by global climate change (Reimann et al., 2018; Toimil et al., 2020).

Anthropogenic activities have been extensively reviewed in the literature (Danladi et al., 2017; Foti et al., 2022). We find actions such as the construction of dams in the river course (Aragonés et al., 2016), massive urban developments in many coastal areas (Pagán et al., 2016) or the construction of dikes and breakwaters to protect the coast from storms (Martin et al., 2021). All this has altered the natural dynamics of the coast as a consequence of the retention of sediments or the lack of erosion of the hydrographic basins, which has generated retreats of the shoreline throughout the world (De Leo et al., 2017; Warrick et al., 2019). Another example of these

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anthropogenic actions is the nourishment of beaches. Any spillage of material can cause impacts on the environment, since it will cause changes in water currents (Truong et al., 2021), turbidity (Chiva et al., 2018) and even the destruction of natural habitats, such as *Posidonia oceanica* meadows (Aragonés et al., 2015).

Changes in wave direction, as well as in their intensity and frequency, are another aspect that influences the evolution of the shoreline (Flor-Blanco et al., 2021; Toledo et al., 2022). The more frequent and intense occurrence of extreme weather events is already a reality. The increase in sea surface temperature has a direct correlation with the potential of cyclones (Mei et al., 2015; Pytharoulis, 2018). In the same way, the deepening of the storms and the increase in wind speed have a consequence in the increase in the level of the storm surge and, therefore, in the risk of flooding in coastal areas (Jisan et al., 2018; Vousdoukas et al., 2016). For all these reasons, it is necessary to continuously monitor the meteorological variables through different instruments with the aim of establishing valid climate projections for any region of the world (Lemos and Rood, 2010; Susmitha and Sowya Bala, 2014).

All these changes become more important in the event that they occur in urban areas. Currently, half of the largest cities on the planet are located on the coast, where almost 40% of the world's population lives (Kummu et al., 2016). Government agencies are forced to provide coastal cities with protection elements against the erosion of their environment. During the last decades, hard defence works have played a very important role in coastal protection (Morris et al., 2020; Schoonees et al., 2019). However, these engineered solutions, such as dikes or breakwaters, are becoming increasingly economical and ecologically unsustainable (Morris et al., 2018). For this reason, it is necessary to broaden the range of coastal protection interventions to more natural ones.

This is where Nature-based Solutions (NbS) arise, which are defined as approaches, actions or processes that use the principles of nature to solve different problems related to territorial and urban management such as adaptation to climate change, management of resources, or the quality of air and the environment (CONAMA, 2022). In the field of coastal protection, multiple options have been proposed to be developed in urban environments, including the management and restoration of green infrastructures (Kabisch et al., 2017). An innovative sand breakwater was proposed for a port built at Lekki in Nigeria (van der Spek et al., 2020). This solution includes a monitoring program to ensure the navigability and continued safety of the sand breakwater, and to counter the retreat of the shoreline downstream of the port through sand feeding. On muddy coastlines, mangrove restoration or bamboo fencing is a sustainable option on eroded shorelines (Dao et al., 2020; Verhagen, 2019). Another alternative is to benefit of the vegetation property in attenuating the strength of the waves, as was done with the plantation of *P. oceanica* seeds in Calabaia Beach to reduce the degradation of the coast (Maiolo et al., 2020). On other occasions, a complete project is proposed that involves the restoration of the riparian

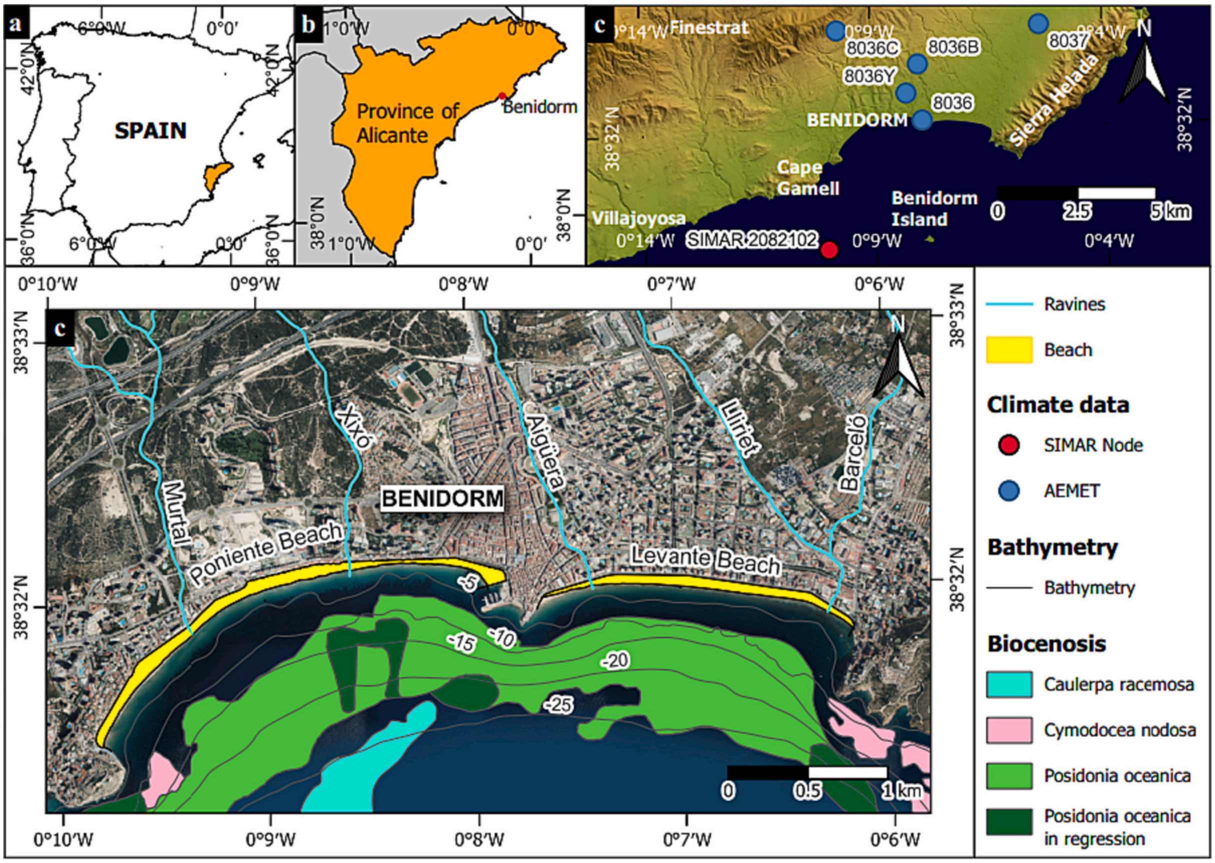

**Fig. 1.** (a) Study area located in Spain and (b) in the province of Alicante, (c) detail of the study area, with SIMAR node and AEMET weather stations, (d) location of Poniente Beach, Levante Beach and the ravines in Benidorm.

vegetation and the mangrove forest, as well as an artificially constructed dune, stabilized with native vegetation and a breakwater (Rivillas-Ospina et al., 2020).

The shoreline of Benidorm (Spain), an international benchmark in the tourism sector, is not an exception to the effects of climate change. The city has suffered in recent years a series of storms that have jeopardized the infrastructures located on the coast frontline. The study of maritime storms in the city has already been recorded in the literature (Toledo et al., 2022). However, solutions to contain these effects have not yet been proposed. This research has two main objectives: a) to analyse the coastal resilience of Benidorm city (Spain) against coastal erosion and the effects of maritime storms, which are increasing in recent years due to the effect of climate change in the Mediterranean zone; b) recommend an appropriate Nature-based Solution to address the continuous flooding that occurs, both on the beach berm and on the promenade. Adaptation to climate change requires urgent actions, especially in coastal areas, due to the high degree of vulnerability and exposure they present to the higher frequency of development of extreme weather events predicted in climate models (Cramer et al., 2018; IPCC, 2022). The Spanish Mediterranean coast is the Spanish area that already shows the greatest effects of the warming process and the one that experiences the greatest economic damage from extreme events (Oliva and Olcina, 2022; Torres et al., 2021). Therefore, carrying out this study is an opportunity to promote Nature-Based Solutions for the adaptation of its beaches, which is the main natural resource of its economy (Olcina Cantos and Miró Pérez, 2017).

## 2. Methodology

### *2.1. Study area*

The study area corresponds to the city of Benidorm (Spain), which is located on the eastern coast of the Iberian Peninsula, on the shores of the Mediterranean Sea (Fig. 1a). The city is characterized by a powerful economic activity in the tertiary sector, specifically in tourism. Currently, Benidorm represents a fundamental tourist destination both for the Valencian Community and for the rest of Spain (Femenia-Serra and Ivars-Baidal, 2021), being the third city in Spain by number of hotel beds after Madrid and Barcelona and the most important tourist centre of the Spanish Mediterranean coast (Rico et al., 2020).

Originally a small fishing village, Benidorm is a typical example of the resorts that emerged along the Mediterranean coast in the 1960s during the mass tourism boom that catered mainly to foreign tourists. Within the framework of local urban planning, the authorities planned the categories of land use and buildings and defined growth areas. Specifically, an area of adjacent urban expansion along its shoreline that gave rise to Benidorm's distinctive image of high-density urbanism and high-rise building (Nolasco-Cirugeda et al., 2020).

#### *2.1.1. Physical description*

Part of the city's success is due to the two beaches included in its municipal area: Poniente beach and Levante Beach. Both beaches are characterized by a fine-sized sediment and a unique morphology (length and width). Playa de Poniente is 3 km long and has an average width of 68 m, while Playa de Levante is 2.3 km long and has an average width of 54 m (Toledo et al., 2022). Regarding the sediment size, they have a mean size ($D_{50}$) of 0.28 and 0.25 mm, respectively.

Both beaches are included in a closed littoral system (Fig. 1c), forming a promontory inlet. The orientation of both beaches to the south and the protection provided by the Sierra Helada massif against waves coming from the east (the most frequent direction in this area) means that the impact of storms is less than in other parts of eastern Spain (Amores et al., 2020). The waves in the area are conditioned by Sierra Helada to the east and Punta de Gamell to the west, as well as by the Island of Benidorm (Fig. 1c). *P. oceanica* abounds on the seabed, a marine phanerogam that forms extensive meadows on sandy and rocky bottoms (Blanco-Murillo et al., 2022).

A series of ravines that outline the topography of the city flow into the study beaches (Fig. 1d). The high degree of urbanization in the area due to the transformation of land use has modified the course of the ravines (Table 1). By paving and burying the pipelines, the hydrological and hydraulic behaviour of the basins has been changed, generating more risks, such as the increase in flow speed.

The continuous erosion caused by the waves and by the discharge from the ravines has caused many feeding actions to be carried out on the two beaches. The most important was the one carried out in the eastern sector of Playa de Poniente in 1991, where an artificial contribution of 710,847 $m^3$ was made, which made it possible to increase the beach width to 100 m. However, the excessive dumping of sand buried the present *P. oceanica*, destabilizing the beach profile and losing beach surface up to the current width of 30 m (Aragonés et al., 2015).

The study area is located in a microtidal zone, where oscillations due to atmospheric pressure are more important than the tides themselves. Astronomical tides reach a maximum value of 0.3 m, while storm surges can reach values of up to 0.45 m (Ecolevante, 2006).

**Table 1**
Temporal evolution of CORINE Land Cover in the Benidorm catchment areas.

| | 1990 | 2000 | 2006 | 2012 | 2018 |
|---|---|---|---|---|---|
| **Agricultural area** | 32.24% | 22.24% | 22.24% | 9.87% | 9.87% |
| **Artificial surface** | 25.77% | 37.64% | 37.64% | 41.21% | 41.21% |
| **Natural environments** | 41.99% | 40.12% | 40.12% | 48.92% | 48.92% |
| **TOTAL** | 100.00% | 100.00% | 100.00% | 100.00% | 100.00% |

### 2.1.2. *Natural hazard in Benidorm*

Benidorm city has a Mediterranean climate. This climate stands out for a regime of mild temperatures in winter (10 °C on average) and high temperatures in summer (25 °C on average), and for a low annual rainfall, of the order of 400–450 mm. However, this precipitation tends to be concentrated on a few days a year, especially during the autumn. During this season, deep low-pressure systems tend to form, associated with the presence of a 'cold drop' in height. The 'cold drops' have the potential to cause heavy rains and storm surges simultaneously, as demonstrated by the storm 'Gloria' of January 2020 on the Spanish Mediterranean coasts (Amores et al., 2020).

The appearance of one or several of these meteorological elements simultaneously can cause substantial damage to coastal infrastructures (Bevacqua et al., 2017). These natural hazards and their consequences have been recorded over time for Benidorm city (Tros De Ilarduya and Fernández, 2013). The Benidorm promenade is subject to frequent flooding. Those of a maritime nature are striking, where sea water floods the entire beach berm and the waves hit the wall of the promenade, causing overflows (Fig. 2a-b). In bays flanked by promontories, as is the case in Benidorm, water levels can rise more than in open areas (McInnes et al., 2003).

Pluvial floods are caused by large rainfall discharged in a short space of time. The high intensity that rainfall can reach often generates large floods in ravines that can overflow and cause flooding in the city (Fig. 2c). Many of these situations are caused by a deficient catchment system, causing the flow velocity to increase and eroding the beach berm once it drains on the beach (Fig. 2d-e).

## 2.2. *Study of climatic phenomena*

### 2.2.1. *Waves*

Wave data (height, period and wave direction) were provided by Puertos del Estado, based on SIMAR series (data simulated from

**Fig. 2.** (a-b) State of Levante Beach during 'Gloria' storm in January 2020 in which the waves hit the promenade, (c) Floods in the centre of Benidorm on 11 November 2022, (d-e) Damage caused to Levante Beach by the storm on 18 September 2022. Source: UA Climatology Laboratory.

numerical models). This is hourly data collected over 65 years, during the period 1958–2022.

For this work, the SIMAR Node 2,082,102 database (0.167° W, 38.500° N), located about 5 km south of the study area, was used (Fig. 1c). The data from this locality were processed by CAROL v1.0 software (developed by IH-Cantabria), obtaining for each of the study periods the wave height $H_{s,12}$ (wave height with a 0.137% probability of be exceeded), and their corresponding periods, directions and probabilities of occurrence. Wave diffraction was not considered given the low influence that the island has on the change of direction of the wavefront, since it only eliminates 5% of the waves on the beaches of Benidorm (Fig. 3).

Finally, a key point was the analysis of storms. This study was carried out from the SIMAR Node records. There is no universally accepted climate definition for the term "storm". In our study, it was considered storm when a significant wave height of 1.35 m was exceeded for Poniente Beach and 1.15 m for Levante Beach (corresponding to the 95th percentile) for a minimum period of 6 consecutive hours and with a delimitation of at least 24 h without exceeding said threshold (Harley et al., 2014; Valiente et al., 2019). This study focused on the average duration of the maritime storm, and its maximum height.

### 2.2.2. Precipitation

Rainfall data (daily precipitation, hourly precipitation and maximum hourly intensity) have been provided by Agencia Estatal de Meteorología (AEMET). For this work, data from various meteorological stations have been used (Fig. 1c), since the period of operation of these has not been continuous over time. The characteristics of the stations used are attached in Table 2 below:

For the analysis of rainstorms, only days with a daily rainfall >30 mm have been considered, due to the limited availability of hourly data. On the other hand, only hourly maximum intensity data is provided from 2005, since only station 8036Y has hourly data. Based on this information, the different rain parameters are analysed (number of days with $P > 30$ mm, maximum daily precipitation and maximum hourly intensity) in different periods of time (month, weather seasons, years and decades) to know their evolution throughout time.

## 2.3. Flood level calculation

This section determines the flood level as the maximum sea level in the beach profile under the action of the most unfavourable storm produced in the study area since records are available. The estimation of the flood level was made as the combined action of the Storm Surge (SS), the Astronomical Tide (AT), and the run-up ($R_{u,2\%}$). For the calculation of the run-up, the formulation of section 5.2.2 and 5.4.6 proposed in EurOtop was used (Van der Meer et al., 2018).

$$\frac{R_{u2\%}}{H_{m0}} = 1,00 \cdot \gamma_f \cdot \gamma_\beta \cdot \left(4 - \frac{1,5}{\sqrt{\gamma_b \cdot \xi_{m-1,0}}}\right) \tag{1}$$

For a maximum value approach, run-up is expressed as in Eq. 1: where $R_{u2\%}$ is the wave run-up height exceeded by 2% of the

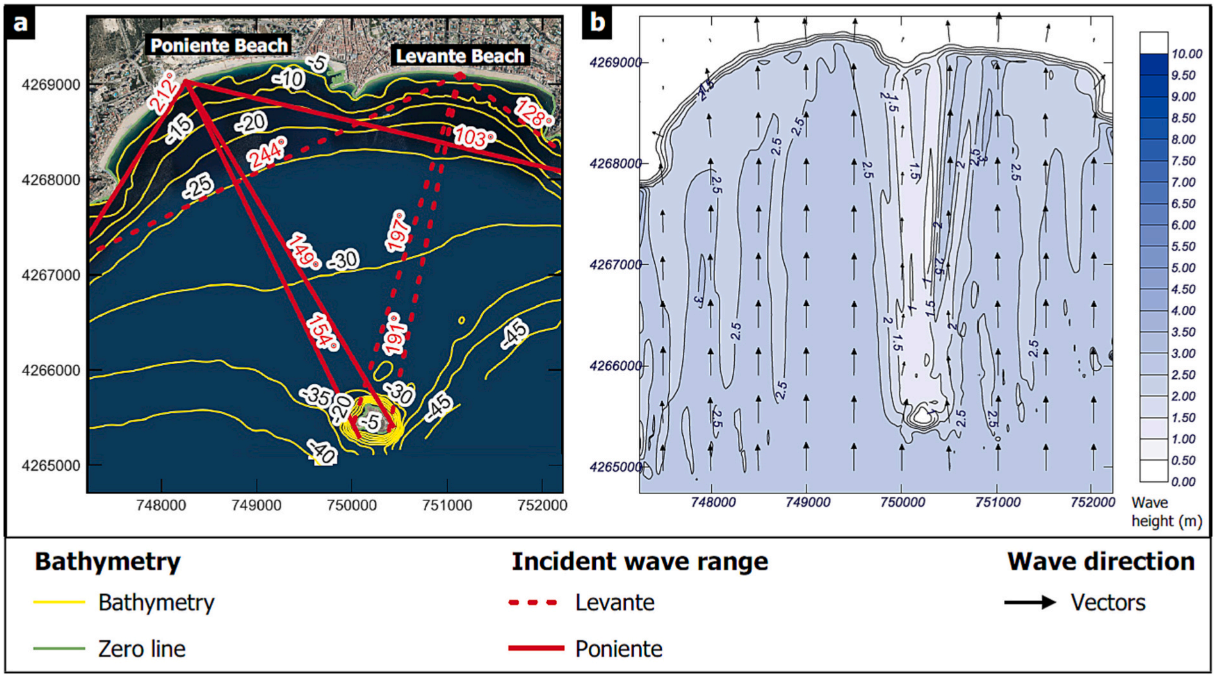

**Fig. 3.** (a) Bathymetry and incident wave range in the study area, (b) Distribution of wave height and wave direction for the most unfavourable storm. Source: SMC (González et al., 2007).

**Table 2**
Characteristics of the AEMET weather stations in Benidorm.

| Code | Name | Start date | End date | Series | Next series | UTM X | UTM Y |
|---|---|---|---|---|---|---|---|
| 8036 | BENIDORM | 1972 | 1981 | 1972–1972 | 1980–1981 | 749,964 | 4,269,170 |
| 8036B | BENIDORM (AQUAGEST) | 1996 | 2022 | 2000–2003 | 2009–2022 | 749,812 | 4,270,925 |
| 8036Y | BENIDORM (PARC LES FOIETES) | 2005 | 2022 | 2011–2019 | 2020–2022 | 749,453 | 4,270,018 |
| 8037 | BENIDORM MEDIA LEGUA | 1954 | 1968 | 1955–1957 | 1959–1961 | 753,601 | 4,272,186 |
| 8036C | BENIDORM-TERRA MITICA | 2002 | 2003 | 2002–2002 | 2002–2003 | 747,260 | 4,271,956 |

incoming waves (m), $\gamma_b$ is the influence factor for a berm (−), $\gamma_f$ is the influence factor for roughness elements on a slope (−), $\gamma_\beta$ is the influence factor for oblique wave attack (−) and $\xi_{m-1,0}$ is the breaker parameter (−).

Sea level data (astronomical tide and storm surge) have been obtained through the Gandía Tide Gauge, from the Puertos del Estado Tide Gauge Network (REMPOR). Located in the Port of Gandía (0° 9′ 5“ W, 38° 59’ 43” N). This data point is the closest to the study area. This is hourly data collected over 15 years, over the period 2007–2022. The Storm Surge, a random variable caused by atmospheric pressure and wind, is estimated as a residual or difference between the starting data (total sea level) and the Astronomical Tide, a deterministic variable resolved by harmonics analysis (Tapia et al., 2016).

### 2.4. Hydrological study

The objective of this section consists in the elaboration of a basic hydrological study in order to identify the hydrological flow of the different basins that flow into Poniente and Levante beaches (Benidorm). To carry out this analysis, the HEC-HMS hydrological modelling program has been used, which is designed to simulate the precipitation-runoff processes of dendritic drainage basins. The analysis of the catchment basins and the main flows has been carried out using the ArcMap 10.6 software. Data on elevation, land use, hydrography, sub-basins, and permeability were collected (Table 3).

The data used to calculate the design precipitation have been obtained from the AEMET 8036Y – Benidorm weather station (Parc Les Foietes), as can be seen in Fig. 1c. An analysis of maximum rainfall has been carried out using the Gumbel function, an adjustment function required by Highway Instruction 5.2-IC (de Fomento, 2019). For this, a design rainfall of 24 h duration has been taken using the alternating block method with a time interval of half an hour ($\Delta t = 0.5$ h). This calculation has been made for different return periods (50, 100 and 500 years). To determine the time of concentration, the Témez model for rural basins has been used (MOPU, 1987).

The infiltration method used has been the Runoff Curve Number (CN) method developed by the Natural Resources Conservation Service - USDA (formerly SCS), widely used in predicting the approximate amount of runoff from a given rainfall event. It is mainly based on soil properties, land use and hydrological conditions (Ajmal et al., 2015). GIS was used to map the Curve Number (CN). In this study, the classification proposed by the Spanish Highway Instruction 5.2-IC (de Fomento, 2019) was used, which depends on i) the slope of the study area classified into two groups (<3% or greater than or equal to at 3%), ii) hydrological group of the soil (four categories based on infiltration speed: A, B, C and D) and iii) the use of the soil. The transformation method used has been that of the SCS Unit Hydrograph, in which a unit hydrograph is defined by first establishing a percentage of 37.5% of the unit runoff that occurs before the maximum flow (Natural Resources Conservation Service, 2007).

Finally, the characteristics of the considered scenario are defined:

- It has been considered that there is no retention of rainwater by the treetops due to the significant scarcity of these in the study area.
- The precipitation that can be retained in small superficial retentions, to infiltrate or evaporate later, has also been considered zero.
- Initial abstraction (mm) has not been considered, since it has little influence on the outlet flow.
- A delay time ($T_{lag}$) of 40% of the concentration time of the basin has been considered.
- Finally, the base flow method has not been considered, since in none of the channels that cross the city of Benidorm there is a continuous base flow prior to the rainy episode.

**Table 3**
Type, date, format, resolution and source of data used in this study.

| Data type | Date | Format | Resolution | Source |
|---|---|---|---|---|
| Digital Elevation Model | 2016 | Raster | 2 m/pixel | IGN<br>https://centrodedescargas.cnig.es/ |
| Land uses | 2018 | Vectorial | 1:100.000 | CORINE<br>https://land.copernicus.eu/en/products |
| Hydrography | 2007 | Vectorial | 1:25.000 | IGN<br>https://centrodedescargas.cnig.es/ |
| Sub-basins | 2013 | Vectorial | 1:25.000 | DGA-CEDEX<br>https://aps.chj.es/down/html/descargas.html |
| Permeability | 2015 | Vectorial | 1:200.000 | IGME<br>https://mapas.igme.es/ |

## 3. Results

### 3.1. Study of climatic phenomena

In both Poniente Beach and Levante Beach, a large increase in $H_{s,12}$ was detected in the period 2013–2022 for almost all incoming directions (Fig. 4). The cases of waves coming from the west (SSW, SW, WSW) stood out. The SSW swell at Poniente Beach increased its wave height by 44% in the last period compared to the previous one (2.13 m vs. 3.06 m), while at Levante Beach the wave height for SSW directions, SW and WSW increased by 18%, 38% and 31%, respectively. Waves originating from the west also increased with respect to incident waves for the period 2013–2022 compared to the period 1993–2002. Through a linear regression analysis, we can know the influence of climate change in Benidorm. A growing trend in wave height can be seen on both beaches, especially in Levante, where the average wave height has experienced an increase of 62% in the last 50 years. At Poniente Beach, the frequency of SSW wave direction increased by 11%, while the frequency of ESE and S decreased. Likewise, an increase of 13% could be observed for Levante Beach and 4% for the SSW and SW directions, respectively, while 15% is lost in the S direction.

In addition, the incoming storms on Poniente and Levante beaches since 1958 were analysed (Fig. 5). Poniente Beach presented a similar average duration, but a higher wave height of the storms, compared to Levante Beach. In Poniente, it has remained relatively stable between 15 and 25 h due to storms until 2005, where from that year a slight downward trend is observed, marking a minimum of 10 h in 2007. In the case of Levante, there is greater instability in the average duration and, therefore, a greater number of peaks. However, this small decrease observed in the trend of the average duration on both beaches was not reflected in the same way in the storm $H_{max}$. As in the $H_{s,12}$ study, $H_{max}$ has shown a significant increase since the 1960s on both beaches, especially in the last 15 years, with a maximum of 3.58 m in 2017 on Poniente Beach (Fig. 5b) and 3.31 m in 2018 on Levante Beach (Fig. 5d). A more detailed study

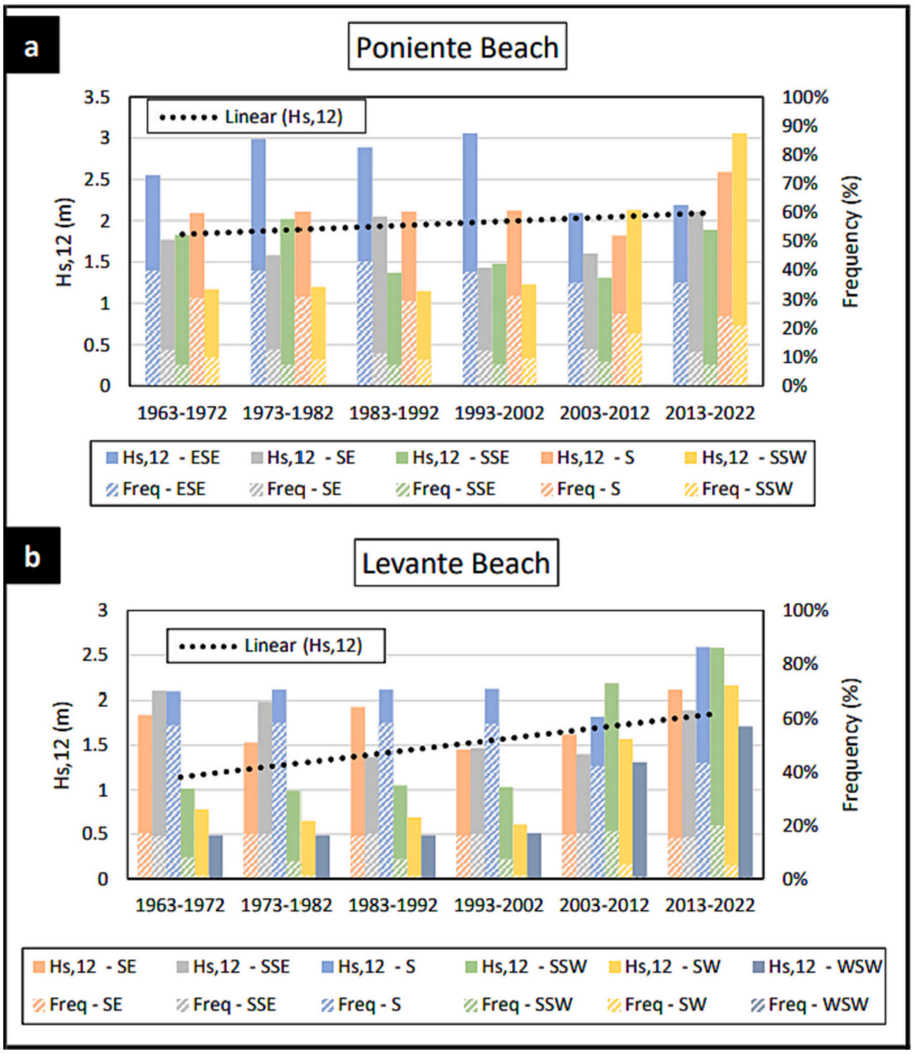

**Fig. 4.** Wave height ($H_{s,12}$) and frequency for each direction and period in (a) Poniente Beach and (b) Levante Beach.

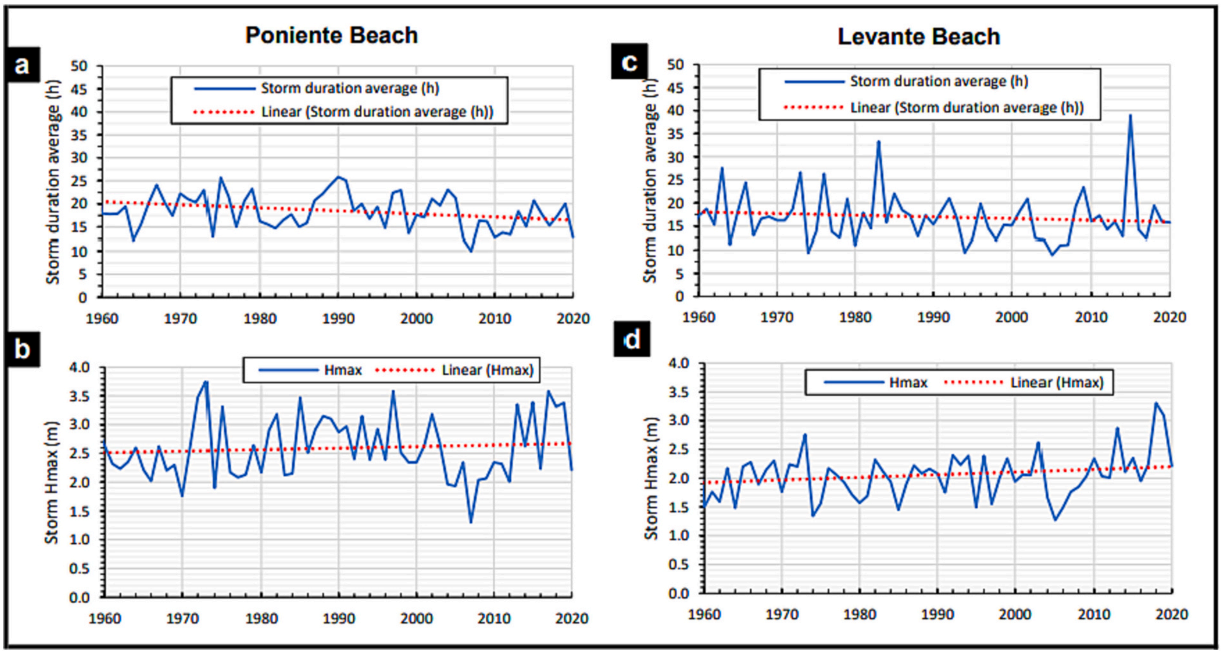

**Fig. 5.** Evolution of storms in the study area: (a) Storm duration average in Poniente, (b) Storm $H_{max}$ in Poniente, (c) Storm duration average in Poniente, (d) Storm $H_{max}$ in Levante.

of storms in the study area was carried out by (Toledo et al., 2022).

Finally, the evolution of the main wave parameters on the two beaches of Benidorm has been studied (Table 4). As previously mentioned, the significant wave height has suffered a significant increase in the period 2013–2022 in both locations, with Levante Beach standing out with an increase of 14% compared to the previous period. The periods, both average and peak, have not shown major changes over time, with rises and falls in the last two analysed periods. However, the average wave direction stands out among all, with a significant clockwise rotation since the period 1983–1992. Since then, the waves have rotated 7.2° at Poniente Beach and 5.3° at Levante Beach.

The behaviour of the precipitation variables in Benidorm city was also studied. First, the number of days per year in which a daily rainfall of 30 mm is exceeded was analysed (Fig. 6a). This value is highly variable given the Mediterranean climate in which the Benidorm is located with irregular rainfall over time. However, the three years with the highest records have already occurred in the 21st century, 7 days with daily precipitation >30 mm in 2007 and 6 days in 2017 and 2019. Despite this, the trend over time remains stable on 2 days per year. Grouping the years by periods of 5 years (lustrum) and by season, the characteristic irregularity of the Benidorm climate is once again observed, where in periods of 5 contiguous years the number of days with $P > 30$ mm can double or halve with relative frequency (Fig. 6b). An example of this is the 5 days with P > 30 mm in the 1998–2002 period, going to 12 days in 2003–2007 and subsequently dropping to 7 days in the 2008–2012 period. The five-year period with more days of precipitation >30 mm occurs in the last period analysed (2018–2022) with up to 15 days. The days with the highest precipitation accumulate in the autumn period, concentrating more than half of these in many cases. In addition, there is a slight increase in this type of rain in spring, becoming in the last 15 years the second season with the highest number of days with P > 30 mm, surpassing winter. Next, maximum daily precipitation per year is analysed (Fig. 6c). Once again, an increase in precipitation can be seen in the last years analysed. 7 of the 8 years in which the maximum daily rainfall exceeds 75 mm have occurred since 1996, which determines a significant change in the current climate, making it more torrential (Olcina, 2020). The year with the highest daily rainfall occurred in 1997 with 136.5 mm. In

**Table 4**
Evolution of wave parameters in Poniente Beach and Levante Beach: significant wave height ($H_{m,0}$), average period ($T_m$), peak period ($T_p$), average wave direction (AWD).

| | Poniente Beach | | | | Levante Beach | | | |
|---|---|---|---|---|---|---|---|---|
| | $H_{m,0}$ (m) | $T_m$ (s) | $T_p$ (s) | AWD (°) | $H_{m,0}$ (m) | $T_m$ (s) | $T_p$ (s) | AWD (°) |
| **1963–1972** | 0.525 | 3.684 | 5.225 | 147.85 | 0.461 | 3.462 | 5.064 | 173.00 |
| **1973–1982** | 0.508 | 3.669 | 5.178 | 147.65 | 0.441 | 3.448 | 5.032 | 172.67 |
| **1983–1992** | 0.519 | 3.687 | 5.194 | 145.86 | 0.434 | 3.434 | 5.002 | 172.84 |
| **1993–2002** | 0.527 | 3.651 | 5.197 | 148.00 | 0.454 | 3.416 | 5.028 | 173.09 |
| **2003–2012** | 0.512 | 3.356 | 5.038 | 151.68 | 0.477 | 3.135 | 4.932 | 176.85 |
| **2013–2022** | 0.568 | 3.551 | 5.429 | 153.02 | 0.546 | 3.319 | 5.317 | 178.12 |

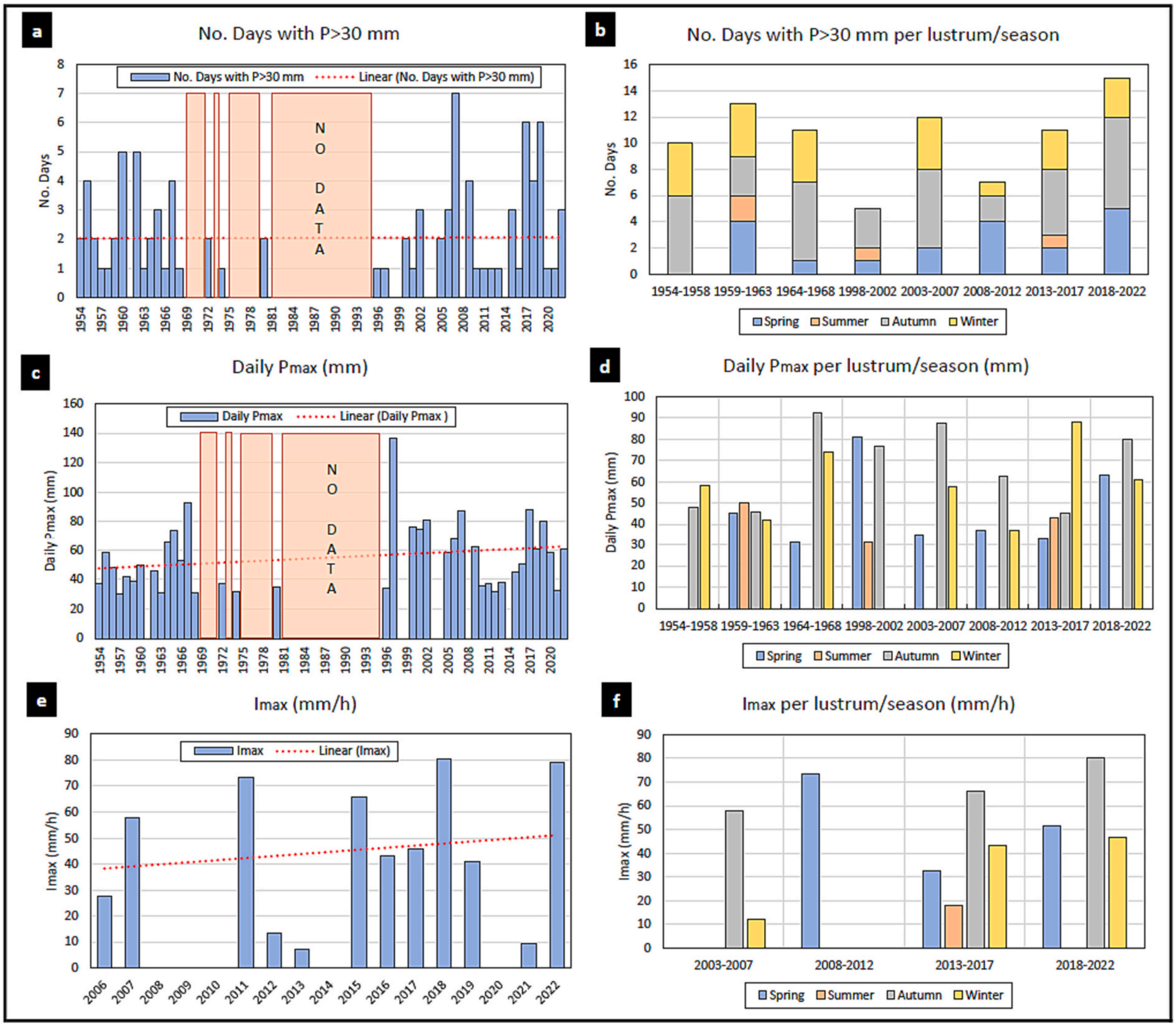

**Fig. 6.** (a) No. days with precipitation >30 mm, (b) No. days with precipitation >30 mm per lustrum/season, (c) Maximum daily precipitation (mm), (d) Maximum daily precipitation per lustrum/season (mm), (e) Maximum hourly intensity (mm/h), (f) Maximum hourly intensity per lustrum/season.

this case, an increase in this parameter is notable, with an upward linear trend of 15 mm in the last 68 years (47 mm in 1954 and 62 mm in 2022). Analysing the maximum daily precipitation by lustrums and by seasons, a common pattern can be seen (Fig. 6d). The maximum rains usually occur during the autumn given the climatic conditions. During the spring, although it has become the second rainiest season, the maximum precipitation is considerably lower than in autumn or winter, with records that rarely exceed 50 mm in one day. Finally, the maximum daily intensity of precipitation was analysed. Given how short the series is, it is difficult to obtain a trend in the behaviour of the rain. However, it can be seen how in recent years there have been higher hourly intensities, such as in 2018 with 80.4 mm/h or in 2022 with 79.2 mm/h (Fig. 6e). Regarding the maximum hourly intensities by lustrum and weather season, it is evident that the highest precipitation intensities occur in autumn given the type of rain that occurs at this time of the year (Fig. 6f). It is striking, comparing the figures of precipitation and maximum intensity, how winter presents maximum daily precipitations higher than spring and close to those of autumn in many cases, however, the intensities are clearly lower.

### 3.2. *Flood level calculation*

The most unfavourable wave conditions in the study area ($H_{m,0} = 2.83$ m, $T_{m,0} = 7.53$ s and SWL = 63 cm) generate a flood level of 1.71 m at Levante Beach. This sea water level covers the entire berm beach surface during the most unfavourable storm in the historical series. However, at specific times the flood level can reach 2.49 m (Fig. 7). The low level of the promenade in some points, of the order of 2.3–2.4 m, causes flooding in part of the promenade, and causing material damage to urban roads and businesses located on the waterfront.

### 3.3. Hydrological study

The process of delimiting basins and obtaining main flows using ArcMap determines that the Lliriet basin is the one with the greatest urbanization, with a curve number of 64.92 (Table 5). In addition, this basin is by far the one with the greatest difference in height, with a difference of almost 800 m in just 11.94 km.

The design rainfall for each return period and basin has been simulated in HEC-HMS (Table 6). The basin with the highest outflow is Lliriet for all return periods. 58.9 $m^3/s$ are reached for a return period of 500 years. This basin, despite not being the largest (the Barceló basin is), has a lower runoff threshold than the rest due to the high level of urbanization in the area (Table 5). Also noteworthy is the high outflow in the l'Aigüera basin. This basin only has an area of 4.53 $km^2$. However, being a fundamentally urban basin and having a short time of concentration, outflows of up to 30 $m^3/s$ are reached for $T = 500$ years.

The hydraulic capacity of the existing drainage pipes must be used to the maximum. To this end, it has been hydraulically proven that the flow circulating through the ravines can be absorbed by the existing pipes once it enters the urban nucleus of the city. The dimensions of the pipes provided by the Benidorm City Council are shown below (Table 7). Only the Murtal drainage system, for all return periods studied, and that of Lliriet, only for T = 500 years, present drainage problems. In the case of Murtal, the hydraulic capacity is very small, so the resulting flow circulates on the surface once the hydraulic section is completed, flooding part of the Poniente Beach promenade.

Finally, the water level that affects the streets has been estimated from the flow that is not conducted by the storm pipes, as the difference between the flow for each return period and the maximum drainage capacity (Table 8). This flow in Murtal varies from 0.18 m for a T = 50 years to 0.34 m for a T = 500 years. As for Lliriet, the maximum draft reaches 0.31 m for the return period of 500 years.

### 3.4. Recommendation of solutions to adopt

The solutions shown in this subsection are solely recommendations of the authors based on the literature reviewed with the aim of addressing the increase in the frequency and intensity of extreme weather events derived from climate change in Benidorm. In no case are they the result of an exhaustive analysis of different solutions based on pre-established criteria.

#### 3.4.1. Urban dune for defence against waves

The design of an urban wave containment dune is proposed on the backshore of the Benidorm beach with the aim of avoiding flooding on the promenade during maritime storms. The sea defence dune should be designed in such a way that the amount of overflow is limited. When the waves flood the beach berm in its entirety, the front slope of the dune will begin to erode, which will eventually add sand to the beach, recovering part of the volume lost during the strong waves. The dune will be destroyed and must be rebuilt once the storm period ends. The proposal is to artificially maintain the sand supply cycle, now interrupted by anthropic actions in the study area. This dune must be vegetated with autochthonous shrub planting to prevent sand mobility when the wind blows with a maritime component (wind from the south).

Since the main function of the dune is to contain the waves, when establishing the design conditions, the design is considered as a vegetated sand dike. For classical dike design, a dike is safe enough when <2% of the waves break over it. The dune height must be sufficient to contain the flood level, but minimizing the visual impact that it may generate on people walking along the promenade. As in *Section 2.3. Flood level calculation*, the flood level has been calculated again (Van der Meer et al., 2018), but this time with the dune design included. The most unfavourable waves generate a flood level of 3 m at its maximum point (Fig. 8). For this reason, the dune crest elevation must be higher than this value, that is, have a maximum height of 3.2 m.

In this research, the urban dune will be built as an 'inverse breakwater'. The core of the dike will be made of a thicker and more permeable material than the armour layer, with the aim of facilitating the outflow of infiltrated water, as well as being a reservoir for the beach itself. Therefore, the dune will be composed of two layers of different size of sediment (Fig. 8). The core will be formed by

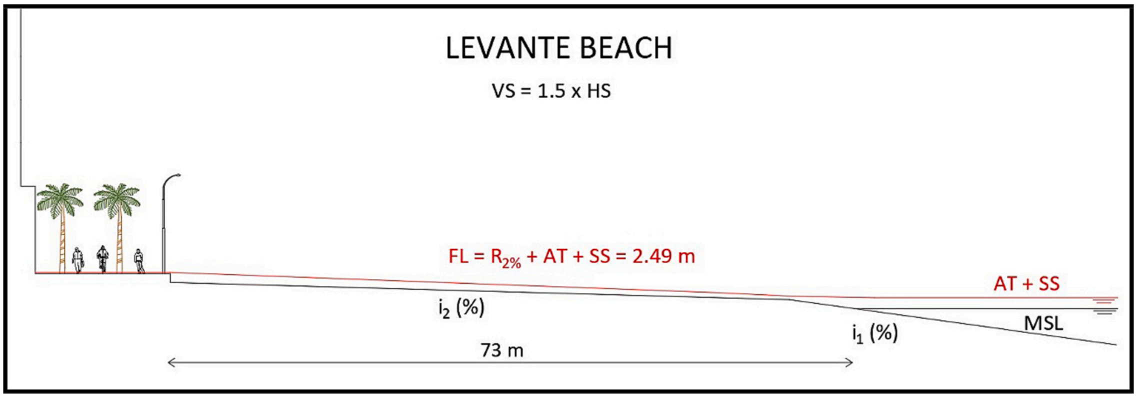

**Fig. 7.** Most unfavourable situation with floods around the promenade.

**Table 5**
Main physical characteristics of the study basins.

| Features/Basin | Murtal | Xixó | Aigüera | Lliriet | Barceló |
|---|---|---|---|---|---|
| **Area (km$^2$)** | 6.62 | 1.26 | 4.53 | 10.74 | 13.10 |
| **X coordinate discharge point (m)** | 747,930.62 | 748,950.97 | 750,460.91 | 751,490.26 | 751,856.15 |
| **Y coordinate discharge point (m)** | 4,268,862.58 | 4,269,270.22 | 4,269,153.91 | 4,269,128.94 | 4,269,074.61 |
| **Curve number** | 54.12 | 58.92 | 59.40 | 64.92 | 46.67 |
| **Runoff threshold** | 42.38 | 34.86 | 34.18 | 27.02 | 57.14 |
| **Main water flow length (km)** | 6.30 | 3.34 | 4.48 | 11.94 | 6.38 |
| **Difference in maximum height of the main water flow (m)** | 332 | 179 | 190 | 798 | 184 |
| **Time of concentration (h)** | 2.13 | 1.31 | 1.71 | 3.30 | 2.41 |

**Table 6**
Calculated outlet flow for all basins and for all return periods.

| | $Q_{output}$ (m$^3$/s) | | |
|---|---|---|---|
| **Basin name** | **T = 50 years** | ***T*** **= 100 years** | **T = 500 years** |
| **Murtal** | 11 | 15.4 | 27.8 |
| **Xixó** | 4.3 | 5.6 | 9.3 |
| **Aigüera** | 13.5 | 18 | 29.9 |
| **Lliriet** | 30.4 | 38.4 | 58.9 |
| **Barceló** | 8.2 | 13.1 | 28.2 |

**Table 7**
Dimensions and slopes of the pipes when the basins enter the urban area of Benidorm.

| | Dimensions (mm) | Area (m$^2$) | Slope |
|---|---|---|---|
| **Murtal** | Ø4500 GS → 2Ø600 MC | 15.9 → 0.6 | 1.8% → 2.9% |
| **Xixó** | 4ØØ1500x2000 MC | 12 | 5% |
| **Aigüera** | ØØ2300x2600 MC | 6 | 2.1% |
| **Lliriet** | 2ØØ1850x2450 MC | 9.1 | 0.6% |
| **Barceló** | ØØ1700x4450 MC | 7.6 | 0.3% |

GS → Galvanized steel
MC → Mass Concrete
ØØ → Rectangle frame

**Table 8**
Water level produced as a result of the lack of capacity of the drainage pipes.

| | Water level (T = 50 años) (m) | Water level (T = 100 años) (m) | Water level (T = 500 años) (m) |
|---|---|---|---|
| **Murtal** | 0.18 | 0.23 | 0.34 |
| **Lliriet** | – | – | 0.31 |

sand washed from quarry and free of fine sediments, while the armour layer will be covered with the size of the current sand, which according to laboratory tests carried out on the study beaches is 0.27 mm (Toledo et al., 2022).

Gentler slopes generally provide a greater ecological benefit because they do not have stability problems (Verhagen, 2019), but are more expensive due to the larger volume of sand required. A frontal slope of the dune of 25% (1:4) is proposed, with the aim of

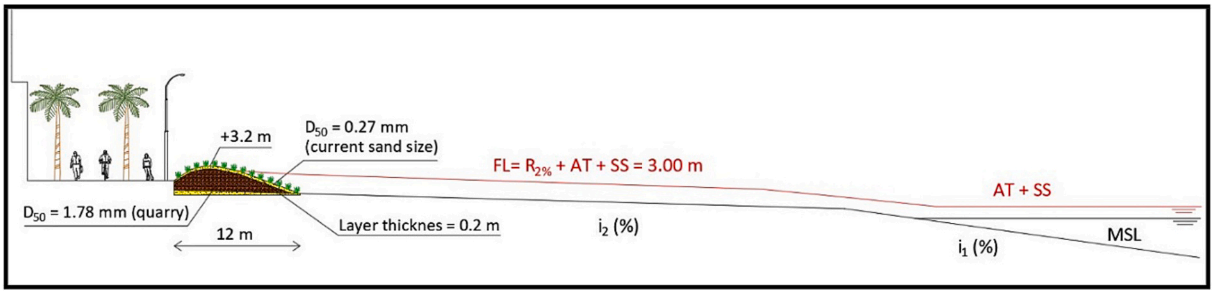

**Fig. 8.** Future situation with the dune protecting the promenade from flooding.

achieving greater stability and minimizing the volume of sand required. Below is a 3D reconstruction of the urban dune of Benidorm (Fig. 9).

### 3.4.2. *Drainage network maintenance*

In case of flooding events, despite the fact that the pipes fulfil hydraulically, it is necessary to review the surface water collection system and properly direct it to the rainwater pipe network. For this, it is recommended to improve the design of inlets, increase their number and distribution along the urban road.

The Benidorm sewage system has a powerful network of large pipes for the evacuation of rainwater. However, rainfall in the study area frequently generates flooding in some localized points of the city, as has been observed through the images and videos collected in the press and social networks (Fig. 2). There are points in the drainage system that prevent all the precipitated water from being collected, even with precipitation that is significantly lower than the design rainfall obtained in this section. Improving the surface water collection system of the city, which currently consists of 6000 storm drains, would make the most of the hydraulic capacity of the existing collectors, especially in Barceló basin.

### 3.4.3. *Channelling of the ravines that flows into the beach*

A more efficient storm drain system would increase the peak flow at the drainage point of the basin, causing greater beach erosion and damage to urban infrastructure. Therefore, solutions must be taken to reduce these effects.

The implementation of a natural channelling solution for the final section of the ravines that drain to the beach is proposed (Fig. 10). Sand defence dikes will be placed on both sides of the drainage in order to channel the flow and prevent other areas of the beach from being eroded, as well as preventing the unbalance of access walkways to the beach and footbaths. These dune ridges, which will be located perpendicular to the shoreline, will have the same technical characteristics as the urban dune proposed in the *Section 3.4.1. Urban dune for defence against waves*.

On the other hand, a cobblestone will be designed at the exit of the ravines that drain to the beach in order to reduce the speed of the flow of the discharged water and with it, the erosion of the beach berm. It will be necessary to lower the ground level to favour the outflow of water towards the sea. The cobblestone will only be exposed when the drainage of the rain runoff occurs, and must be covered by a layer of sand of the existing size on the beach, thus facilitating the passage of bathers in safety conditions.

Finally, to avoid the concatenation of simultaneous flooding events of fluvial and maritime origin, the design of a vertical wall in the upper part of the drains is proposed. This wall will be equipped with a bullnose to contain the overflow that may be produced by the reflection of the waves (Fig. 10c). In times of atmospheric stability, this infrastructure will serve as a long bench for the enjoyment of citizens (Fig. 10d).

## 4. Discussion

Like any coastal place in the world, Benidorm is no exception to the changes that occur in its territory over time. The city has suffered significant anthropogenic pressures, especially as a result of the urbanization process carried out during the 1960s, which caused, for example, changes in land use (waterproofing the land) or channelling of ravines (increased flow speed). This circumstance, together with the construction of maritime infrastructures, such as the Port of Benidorm, causes a decrease in the contribution of sediments to the beaches, causing their erosion (Aragonés et al., 2015; Toledo et al., 2022). The beaches, in addition to their tourist importance, are elements of coastal defence, which protect all the infrastructures (buildings, urban roads…) located on their backside from maritime storms. However, if climate change increases the storm effects, both in frequency and intensity, they will accelerate the eroding process of the beaches.

**Fig. 9.** (a) Urban dune at low points of the promenade, (b) Urban dune where the height of the promenade is sufficient to contain maritime flooding,

**Fig. 10.** (a) General view of the intervention area in Levante Beach, (b) Sand dikes for channelling the ravines, (c) Design of the bullnose seen from the outlet of the drainage pipes, (d) Design of the long bench equipped of a bullnose on the seafront.

In this study, the evolution of waves and sea storms in each of the study beaches has been analysed. The protection offered by Sierra Helada protects the study beaches from easterly storms. However, they present a high risk of deterioration compared to storms coming from the south (Tros De Ilarduya and Fernández, 2013). These are precisely the waves that occur most frequently and have increased their intensity the most during the last 2 periods analysed (Fig. 4). For example, in Poniente Beach, the SSW swell increased its wave height by 44% in the 2013–2022 period compared to the 2003–2012 period (2.13 m vs. 3.06 m), while its frequency increased by 11%. The intensification of storms in the study area, enhanced by climate change, is a pattern that is also detected in other parts of the western Mediterranean (Amarouche et al., 2020; Amarouche and Akpinar, 2021). Despite the fact that the average duration of the storm remains stable or has even decreased in recent years, a greater increase in wave height has been detected, marking a maximum of 3.18 m at Poniente Beach and 2.59 m at Levante Beach (average of the previous 5 years), both in 2019 (Fig. 5). This exceptional situation of maximum regime will be the one that defines the design criteria when proposing solutions to contain the waves and protect the promenade. Therefore, it will be necessary to monitor the evolution of the parameters that define storms (average duration, SPI, $H_{max}$, direction…) and thus obtain trends that allow us to know their behaviour over time.

The irregularity of rainfall is a feature that identifies the Mediterranean climate, but this has worsened in recent years, maximizing the extremes (Benabdelouahab et al., 2020; Olcina Cantos, 2021). Two of the three years with the highest number of days with daily rainfall >30 mm have occurred in the last 5 years, with a total of 6 days per year (Fig. 6). On the other hand, in the period 2010–2014 there have not been years in which this type of precipitation has occurred on more than one occasion. In the same way, 7 of the 8 years in which the maximum daily precipitation exceeds 75 mm have occurred since 1996. During the last few years, changes have been detected in the atmospheric circulation that have caused a greater number of detachments of ‘cold drop’, assuming a greater increase in the days with the greatest amount of rain and torrentiality (Olcina, 2020). However, these changes in the jet-stream also increase the possibility of generating more frequent dry periods over time (Morote et al., 2022). This irregularity in the climate is also observed within the annual cycle. The maximum rainfall usually tends to be concentrated during the autumn season in the study area (Fig. 6). However, given the current climate change context, with higher sea temperatures and changes in atmospheric patterns, it is likely that in the future these intense precipitations will also extend beyond autumn, as occurred on 19 January 2017 (winter), when a daily precipitation of 88 mm occurred.

On the other hand, the analysis of the maximum daily intensity of precipitation will give us clues about what type of rain is occurring in each case. Comparing the precipitation and maximum intensity figures, it is striking how winter presents higher daily maximum precipitation than spring and close to autumn in many cases. However, the intensities are clearly lower (Fig. 6f). This fact is a consequence of the different genesis that exists behind the rainy episodes in each season of the year. During winter, the presence of precipitation events linked to weather fronts is more common, with a greater magnitude both in the temporal and spatial framework (Peña-Angulo et al., 2020). In these cases, the maximum intensities are not excessive and can rarely exceed 50 mm/h, but the total accumulated precipitations can be, and the presence of daily accumulated values >60 mm is usual. At the other extreme, precipitation events are linked to convective weather phenomena. These phenomena are much more frequent at the end of summer, when there is a context with a high moisture load (as a consequence of the evaporation produced during the summer period), their spatial extension is usually much smaller compared to weather front processes, and the maximum intensities produced can reach very high values (around 100 mm/h) and present extraordinary spatial heterogeneity, with totally different maximum data at very close points (Maier et al., 2020; Peleg et al., 2018). This last type of rain is the one that commonly causes problems in the rainwater drainage system of cities, causing flooding and increasing erosion in ravines and on beaches, such as the one that occurred on 18 September 2022 in Levante Beach, Benidorm (Fig. 2).

Throughout this study, different solutions have been recommended to deal with the problems of beach erosion and flooding on the shoreline. The construction of a sand dune as a protection element is a solution that has already been proposed in other parts of the world (Rivillas-Ospina et al., 2020; van der Spek et al., 2020). However, the design of a vegetated urban dune is a novel alternative applicable to cities with a risk of coastal flooding in the vicinity of their promenade. The dissipative power of the waves that the dune vegetation possesses would decrease its speed, reducing its erosive capacity (Feagin et al., 2019; Maiolo et al., 2020), in addition to naturalizing the area. The design of the dune must be such that it allows a climate of harmony with the environment in which it is located, but also that it is compatible with the recreational activities that take place around it. The dune ridge must have a sufficient height to contain, or at least limit, the overflow of the waves to its back (Fig. 8), but also to allow a direct view of the beach from the promenade, given the importance of this ecosystem in the city (Fig. 9). The use of 2 sizes of sand is due, on the one hand, to the ease of drainage from the interior of the dune to the sides, and, on the other hand, to the low availability of marine sediment deposits for the extraction of sand, generating environmental problems with it (Dan Gavriletea, 2017).

The Benidorm rainwater pipe system is sufficient to evacuate the outlet flows that occur in the ravines that cross the city in most of the cases studied (Table 6). Despite this, flood events continue to occur in certain areas with lower than design rainfall. The continuous floods of fluvial origin that occur in Benidorm are caused by an insufficient storm drain network, this being a common problem in cities (Nanía-Escobar et al., 2006; Othman et al., 2015). It is recommended to improve the design of the storm drains, increasing their number and distribution. In the latter case, it is also proposed to integrate high-capacity collection elements into the urban landscape (Campisano et al., 2017; Morote, 2017), without ruling out the possibility that water can circulate in a timely manner on the surface. Far from being an impediment, this alternative should be understood as an opportunity to create spaces that can be flood-prone linear green areas, that is, infrastructures that allow recreation for people and, in turn, the transit of water during flood events. Some examples can be found in the Marjal Park in the city of Alicante; or without going any further, in the last section of the Lliriet ravine, once it ends at Levante Beach (Fig. 11).

The images of flooding, both on the beach and inland, and of the damage caused to the shoreline will be repeated more frequently in the current and future context of climate change (Olcina Cantos, 2021; Olcina, 2020). This type of damage will limit the proper functioning of the city, reducing its resilience against future storms. That is why the Public Administrations must design action plans to limit this damage, especially during the prevention stage. Throughout this work, several alternatives have been described to deal with the consequences that these storms may cause. These solutions must be based on nature, that is, they must be in harmony with the ecosystem in which they are going to be implemented, and they must also be sustainable over time (Castelle et al., 2019; Kabisch et al., 2017). Here the particular case of the city of Benidorm (Spain) is presented, with some beaches of natural origin, but in a fully urbanized environment. Despite the local focus, the solution recommended here is fully exportable to any part of the world, especially to those cities whose main economic activity (tourism) depends on the adequate maintenance of the beaches and the shoreline.

**Fig. 11.** High-capacity rainwater harvesting elements integrated into the urban environment, (a) Marjal Park in Alicante, (b) the last section of Lliriet Ravine in Benidorm.

## 5. Conclusions

The coastal regions of the world are part of the most vulnerable ecosystems that exist. The strong urbanization of the territory and extreme weather events driven by climate change put the normal functioning of the cities in these areas at risk. In this study, the danger of coastal and river flooding in the city of Benidorm (Spain) has been analysed, and solutions have been proposed to minimize it, increasing its resilience.

The climate in Benidorm has undergone significant changes. The average duration of maritime storms has remained stable over time. However, these have intensified, with wave heights 60% higher than the previous 10 years. Furthermore, the behaviour of rainfall has worsened, maximizing the extremes: 7 of the 8 years in which the maximum daily rainfall exceeds 75 mm have occurred since 1996.

Thus, the design of a vegetated urban dune on the backshore of the beach is proposed to contain the flood level of 3 m, minimizing overflows on the promenade. To protect the beach from erosion caused by river flooding, the implementation of vegetated sand dikes is proposed to channel the water outflow from the ravines. A cobblestone is laid out to reduce the speed of the flow and the promenade is provided with a bullnose to limit the combined action of fluvial and coastal flooding. In Benidorm there is a problem of collecting rainwater that does not allow the total capacity of the pipes that drain to the beach to be used. In addition to increasing the number and distribution of storm drain, it is planned to integrate high-capacity elements into the urban landscape, such as floodable green spaces.

## Author contribution statement

**Conceptualization**: L. Aragonés conceived the presented idea, the formulation and the general goals and aims of the research.
**Methodology**: I. Toledo designed the methodology of this reseach.
**Software**: I. Toledo was responsible for managing the software used.
**Validation**: I. Toledo and I. López took care of the reproducibility of results.
**Investigation**: I. Toledo carried out the statistical analysis.
**Resources**: I. Toledo collected data from Aemet and Puertos del Estado website.
**Writing - Original Draft**: I. Toledo.
**Writing - Review & Editing**: I. López, J. Olcina and L. Aragonés.
**Visualization**: I. Toledo.
**Supervision**: J.I. Pagán.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

No data was used for the research described in the article.

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