



Maintaining a way of life for São Miguel Island (the Azores archipelago, Portugal): An assessment of coastal processes and protection

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HIGHLIGHTS

- Assessed coastal vulnerability and engineering benefits for São Miguel Small Island
- Suggested statistically significant sea level trend (2.5mmyr^{-1}) from 1978 to 2007
- Generated regional wave statistics using Ponta Delgada wind record (1998 to 2011)
- Found circa 60% of Island's population reside within 1km of the sea
- Showed case studies where coastal engineering preserved Azorean lifestyle

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ABSTRACT

Traditional hard engineering structures and recently emerging soft engineering alternatives have been employed to protect vulnerable coastlines. Despite negative publicity, they have ensured community survival where socio-economic benefits outweigh adverse impacts. This is especially true for Small Islands (SI) where increasing sea levels and storm intensities threaten already limited land availability. This paper presents coastal vulnerability in São Miguel Island (the Azores SI archipelago) and considers SI issues with regard to coastal land loss. Regional wave statistics using 1998 to 2011 wind record showed: periods ranging from 7 to 13 s (circa 83%); wave heights between 1 and 3 m (circa 60%); and increasing trends in westerly ($p = 0.473$), easterly ($p = 0.632$) and south-easterly ($p = 0.932$) waves. Sea level analyses between 1978 and 2007 indicated a statistically significant rising trend ($2.5 \pm 0.4 \text{ mm yr}^{-1}$; $p = 0.000$), while between 1996 and 2007 it was $3.3 \pm 1.5 \text{ mm yr}^{-1}$ ($p = 0.025$), agreeing with other global sea level studies. Based on 2001 and 2008 population data and using zonal statistics, circa 60% of the Island's population was found to reside within 1 km of the sea and the percentage of total population was linearly correlated with distance from the shoreline ($r^2 = 99\%$). Three case studies show hard coastal engineering solutions preserved Azorean coastal lifestyle and had little or no observed negative impacts on their environs. Although hard engineering is likely to remain a valuable and feasible coastal protection option, an inventory of São Miguel's population distribution, surf breaks, bathymetry and coastal erosion rates showed the potential of using multifunctional artificial reefs as a soft engineering solution. These offshore submerged breakwaters offer coastal protection while providing additional benefits such as surfing amenity and beach widening. Consequently, findings of this work can inform other SI communities.

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1. Introduction

The coastal zone is dynamic and shaped by natural forces and/or human activities. Despite covering only circa 20% of the Earth's surface (World Ocean Review, 2010), more than 45% of world's population live and work within the coastal strip with 75% of megacities (>10 million population) situated on coastlines. Consequently, coastal areas are the most densely populated regions and since historic

times have been vital to human civilization. The six major realms of coastal human activity identified by Ketchum (1972) were residency and recreation; industrial and commercial; waste disposal; agricultural, aquaculture and fishing; conservation; military and strategic, and these are still valid today. Many developed coastal areas are vulnerable to erosion and inundation, caused by winds, waves, sea levels and storms. However, no protection would be needed if not for human occupation and activities on the coast. To protect vulnerable shorelines, coastal engineering such as traditional hard structures and more recent emerging soft engineering alternatives have been employed. For that reason, coastal engineering has been critical to the survival of many coastal communities, particularly those located close to or below mean high water level, e.g. Venice, and many of which would have been lost if not for coastal protection measures.

Van Rijn (2011) and others have argued that engineering projects designed to mitigate erosion contribute to adverse effects at nearby coastal locations. However, Phillips and Jones (2006) contended that beach management and sea defences can generally be justified on socio-economic grounds for communities depending on the beach, even though in some cases these may cause accelerated erosion further along the coastline. The problem for Small Islands (SI) is more critical, as they are particularly vulnerable to the effects of climate variability in the form of sea level rise and increased intensity of storms, consequences which could significantly impact on way of life. Thus, this research assesses coastal engineering's role in maintaining a way of life on São Miguel Island, the Azores archipelago, Portugal (Fig. 1). It considers coastal hazards, processes and current protection measures, developing new knowledge on local sea level rise and wave climate. It assesses hard engineering measures that provide net positive benefits for Azorean coastal residents, and reflects on the significance of SI specific social perception with respect to residency and coastal land loss. It also suggests a soft engineering alternative for the Azores by introducing multifunctional artificial reef (MFAR) as a coastal protection option

with surf amenity. This paper therefore provides a counter perspective to engineering negative publicity by showing the value and positive contributions of coastal engineering to local communities, particularly for SI.

2. Physical background

The Azores, a Portuguese autonomous region, is a SI archipelago located in the North Atlantic circa 1500 km from Lisbon and circa 3900 km from the east coast of North America (Fig. 1a). Due to their geographical distribution, they are divided into three groups: the Western Group (Flores and Corvo), the Central Group (Pico, Faial, São Jorge, Graciosa and Terceira) and the Eastern Group (São Miguel and Santa Maria) (Fig. 1b). The nine islands of volcanic origin are approximately aligned WNW–ESE, with steep submarine slopes rising from a 2000 m deep plateau, and there is an absence of shallow shelves (Fig. 1c). In total, they occupy a land area of 2333 km² with a population of 246,772, according to the 2011 census (INE, 2011). Despite its small land area, the Azores archipelago encompasses an Exclusive Economic Zone (EEZ) of circa 984,300 km² (Borges et al., 2009), and subject to recent Portuguese claims to the Commission on the Limits of the Continental Shelf (CLCS) to extend its continental shelf limits, the potential of a larger jurisdictional area (CLCS, 2010).

The Azores has high-energy wave climate where both sea and swell contribute to coastal energy caused by extensive fetch length in the surrounding ocean (Borges et al., 2002). Tides are semidiurnal with a yearly average and maximum spring tidal range of 0.75 to 1 m and 1.3 m, respectively (Andrade et al., 2006). The diverse Azores coastline ranges from low to high plunging cliffs, bluffs, pocket beaches, dunes and lagoons. The steep submarine slopes and absence of shallow shelves produce localised patterns of wave shoaling, refraction and diffraction, and as these processes take place they simultaneously produce breaking waves, especially during storms. This leads to coastal fragmentation and

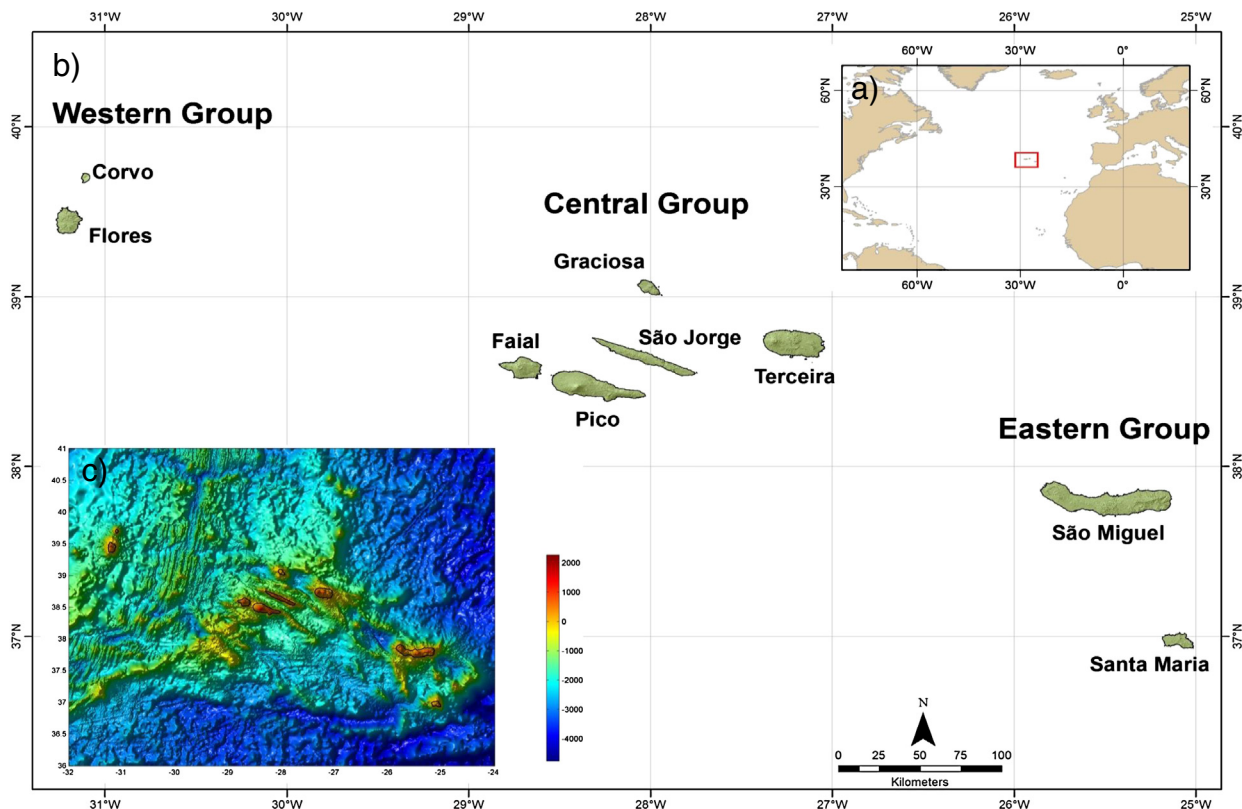


Fig. 1. Study area: a) Azorean Islands (bordered red) in relation to North Atlantic Ocean; b) Azores archipelago and c) bathymetric map of the Azores (Smith and Sandwell, 1997).

a number of dynamic cells, limited by virtually impermeable lateral boundaries in terms of alongshore sediment movement with residual west to east longshore drift (Borges et al., 2002; Borges, 2003). With the narrow coastal fringe being one of the few land areas that offers settlement potential and Azoreans' strong dependency on the sea for livelihoods, communication and trade, despite extreme hazards most Island populations and economic activities are clustered in the coastal zone.

3. Methodology

3.1. Wave data

Long-term historic wave buoy data for São Miguel Island is not available. However, between 2005 and 2007, six wave buoys were installed in the Azores: Flores; Terceira; Faial/Pico; Graciosa; São Miguel and Santa Maria (Esteves et al., 2009), their locations and depths are shown in Fig. 2. Hence, longer-term wave data between March 1998 and December 2011 was generated using daily wind data measured at Ponta Delgada airport, located on the south coast of São Miguel (data retrieved from Wunderground, 2012). Inland wind speed data needs to be adjusted for generally higher speeds that occur over the sea (Sorensen, 2006) as inland values could be as much as 20% lower than corresponding sea measurements (Simm et al., 1996). The 1984 Shore Protection Manual (U.S. Army Coastal Engineering Research Center) recommended a parametric method based on the Joint North Sea Wave Project (SPM-JONSWAP) spectrum for deep water wave prediction thereby replacing the previously recommended SMB method (see Sorensen, 2006). In the case of São Miguel Island, exposed to a wide open coast, an estimated worst-case scenario fetch of 1600 km was used (Duck, 2011).

Adjusted wind speed (W_A) is given by:

$$W_A = 0.71W^{1.23} \quad (1)$$

where W_A = adjusted wind speed (m s^{-1}) and W = original recorded inland wind speed m s^{-1} .

Significant wave height is determined from:

$$H_{mo} = \left[0.0016 \left(gF/W_A^2 \right)^{0.5} \right] \left(W_A^2/g \right) \quad (2)$$

where H_{mo} = significant wave height (m), F = fetch length (m).

Wave period is determined from:

$$T_p = \left[0.286 \left(gF/W_A^2 \right)^{0.33} \right] \left(W_A/g \right) \quad (3)$$

where T_p = peak wave period (s).

3.2. Sea level data

Ponta Delgada has sea level records from two different tide gauges located at 37.7333 N 25.667 W: between 1978 and 1991 an analogue float and well tide gauge; and between 1996 and 2007, a digital aquatrack acoustic tide gauge (UHSLC, 2009). As a result, there are data gaps in the record from July 1991 to 1995 inclusive. To illustrate the tide gauge record, a 24-hr sea level record from 13th July 2013 is shown in Fig. 3 (using data retrieved from UNESCO-IOC, 2013). As there was no published long-term sea level trend for the Azores, a 30-year (July 1978 to May 2007) revised local reference (RLR) monthly tide gauge record for Ponta Delgada was retrieved from the Permanent Service for Mean Sea Level (PSMSL; Woodworth and Player, 2003).

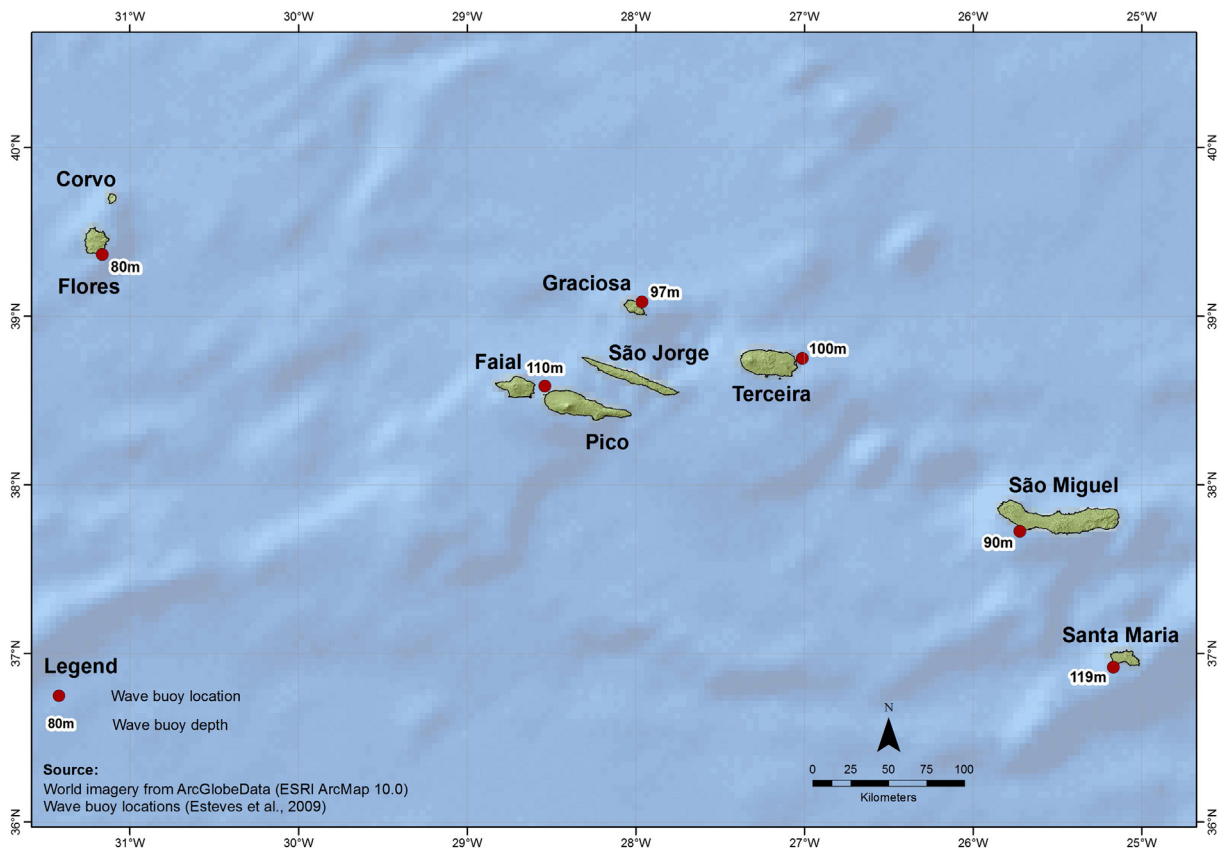


Fig. 2. Wave buoy locations in the Azores.
(Wave buoy locations obtained from Esteves et al., 2009.)

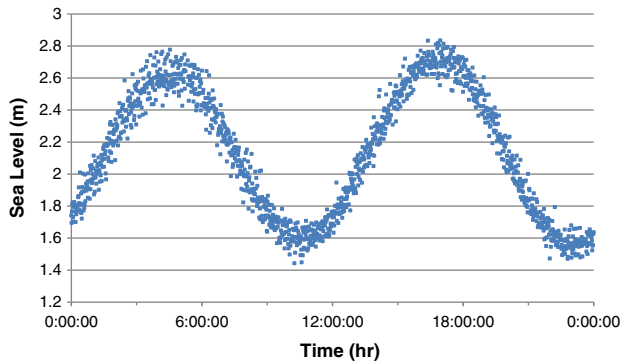


Fig. 3. 24-hr tide gauge record at Ponta Delgada station on 13th July 2013. (Using data retrieved from UNESCO-IOC, 2013.)

Based on the monthly tide gauge record, Table 1 shows the annual minimum, maximum and average PSMSL RLR mean sea level data.

3.3. Coastal assessment: human pressure and coastal engineering

An understanding of coastal settlement is needed to inform future protection requirements. Population distribution data are usually released in areal aggregate format and commonly spatially displayed as choropleth maps. However, these representations do not reflect the inherent spatially heterogeneous population distribution. Thus, from a planning and management perspective, dasymetric mapping using areal interpolated census data and population weighting factors provide a more useful representation abstract of population distribution reality (e.g. Holt et al., 2004; Langford, 2007; Su et al., 2010). Consequently to inform coastal zone management, an estimation of coastal population distribution for São Miguel Island, was generated using dasymetric mapping by applying a building distribution weighting factor.

Table 1

Annual minimum, maximum and average PSMSL RLR mean sea levels for Ponta Delgada (using monthly data retrieved from PSMSL, 2013).

Annual mean sea level (mm)			
Date	Minimum	Maximum	Average
1978	6863	6981	6912
1979	6782	6991	6911
1980	6830	6951	6886
1981	n/a	n/a	n/a
1982	6903	7006	6948
1983	6859	7051	6921
1984	6844	6966	6884
1985	6844	6979	6918
1986	6748	6996	6899
1987	6820	6973	6886
1988	6886	7035	6974
1989	6847	7031	6935
1990	6792	6947	6879
1991	6824	6883	6855
1992	n/a	n/a	n/a
1993	n/a	n/a	n/a
1994	n/a	n/a	n/a
1995	n/a	n/a	n/a
1996	6884	7011	6959
1997	6850	7034	6932
1998	6814	7013	6929
1999	6924	7026	6967
2000	6891	7007	6941
2001	6846	7056	6949
2002	6867	7094	6946
2003	6873	6997	6938
2004	6895	7075	6962
2005	6963	7090	6998
2006	6897	7085	6990
2007	6823	6940	6896

Current coastal hazard mitigation and adaptation measures in the Azores range from extensive kilometres of seawalls and revetments (e.g. assorted-size rock armour, smooth faced concrete, tetrapods, etc.) to groynes (e.g. Praia da Victoria, Terceira Island; Lombo Gordo, São Miguel Island), detached emerged breakwaters (e.g. Lajes, Pico Island), local small-scale beach nourishment (e.g. Praia da Victoria, Terceira Island; Pocinho, Pico Island; Praia, Graciosa Island), netted cliffs, increased coastal buffer zones to public domain areas, and as a last resort, displacing homes and facilities. These measures are mainly for protection against coastal erosion, storms and flooding and there is a common tendency to only act when faced with an immediate hazard. Hence, coastal engineering measures are generally short-sighted with the aim of alleviating immediate risk, and in most cases, not considering surrounding and environmental consequences. Subsequently, a field survey undertaken in São Miguel Island in 2011 assessed coastal protection measures along the Island shorelines and identified exemplary hard-engineering developments that bring about positive benefits to the local coastal communities. In search for sustainable alternative coastal protection measures that provide socio-economic benefits to the local community, MFAR, a soft-engineering alternative, was considered as an option for the Azores. MFARs are effectively offshore submerged breakwaters that provide coastal protection and benefits such as surfing amenity, beach widening and enhancing marine habitats.

4. Results and analysis

4.1. Winds and waves

In the Azores, tides and tidal currents are minor contributors to coastal morphology and sediment dynamics. With limited land availability, ocean exposure and high-energy wave climates, the Azorean SI are vulnerable to seven generic coastal hazards: sea level change, storms, coastal erosion, tsunamis, landslides, flooding, and seismic activity and volcanoes (Calado et al., 2011). Consequently, coastal management plans indicating high risk zones and corresponding mitigation or adaptation measures have been developed for each Island, as well as a best practice coastal defence manual (IHRH, 2011). Human use can contribute to increased coastal erosion and shoreline vulnerability which subsequently requires implementation of protection measures, e.g. Água d'Alto, São Miguel Island. Recession rates for bluffs are typically 0.20 to 1.00 m yr⁻¹ and 0.05 to 0.10 m yr⁻¹ for rocky coasts (Borges, 2003). Average coastal erosion rates in the north and south are similar, i.e. 0.25 m yr⁻¹ and 0.23 m yr⁻¹ respectively, despite higher wave energies along the north coast (Table 2), i.e. 20% higher mean significant wave height translating to approximately 50% greater wave energy. The geology and geomorphology are similar in the north and south of São Miguel Island, and although southwesterlies are less

Table 2

Offshore hindcast wave climate (1989–1995): north and south coasts of São Miguel Island (Pires, 1995; fide Borges, 2003).

Location	s [σ] (m)	H_{smax} (m)	H_{max6} (m)	Power (kW m ⁻¹)	T_{pot} (s)	V_m (°)
North Coast: (Ponta do Cintrão 37°50.9' N 25°29.5' W) [58 m depth]	1.9 [1.0]	10	19.5	21.6	7.9	333
South Coast: (Ponta Delgada 37°43.4' N 25°40.0' W) [66 m depth]	1.5 [1.0]	11.7	22.2	13.5	6.7	227

s , [σ] – mean and standard deviation of significant wave height (annual average); H_{smax} – maximum significant wave height; H_{max6} – highest wave height occurring in the series; T_{pot} – mean equivalent power period; V_m – mean wave vector.

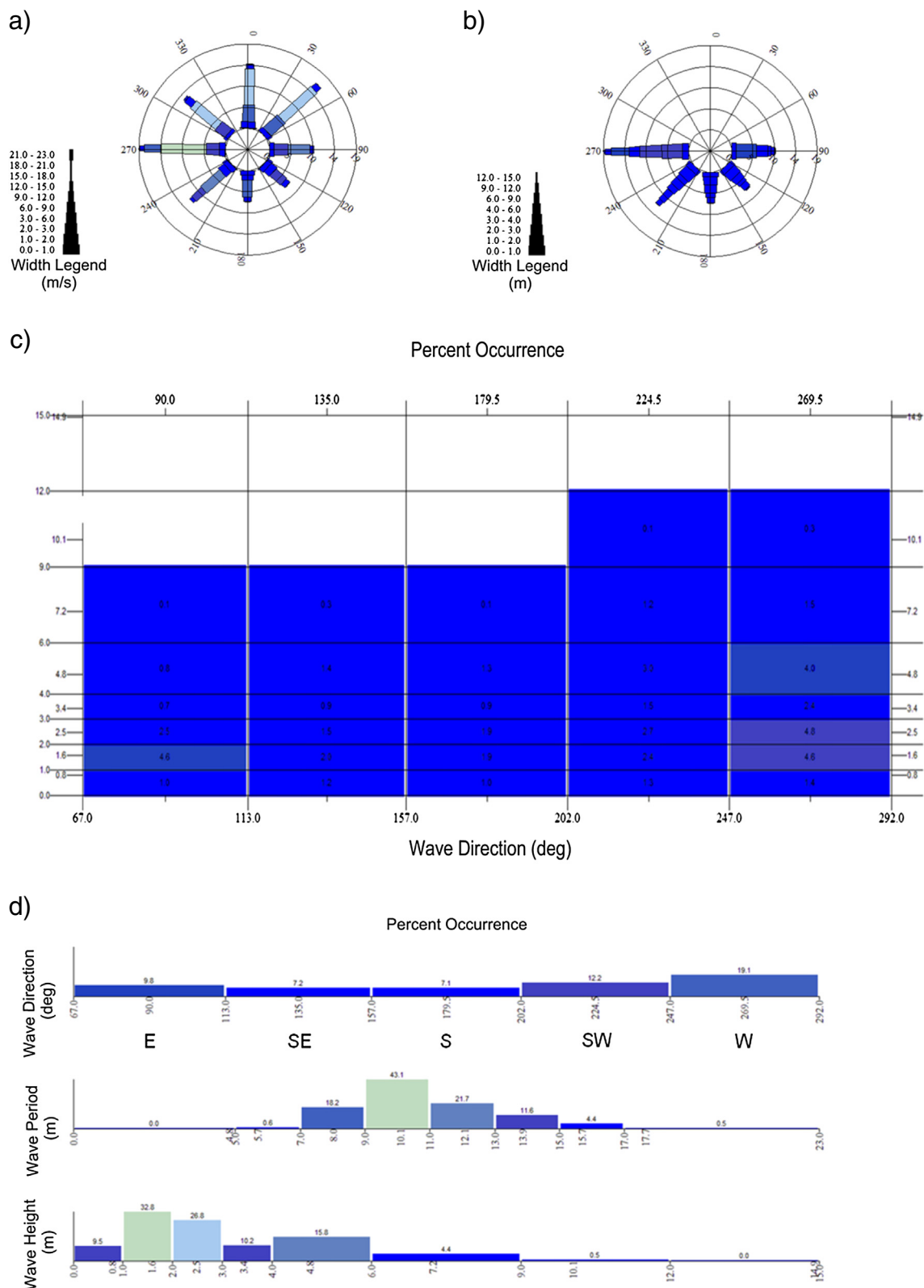


Fig. 4. Illustration of wind and wave statistics: a) wind rose; b) wave rose; c) wave block diagram and d) wave histogram.

frequent, they are more extreme. Consequently, the erosion rates are similar despite different wave energies. Borges (2003) further explained that southwesterly waves typically have more significant effects on scarps and sea cliff erosion processes on this Island. Even though coastal

erosion rates might appear insignificant in comparison to other low-lying regions, for the Azores it represents a reduction of already limited land availability. Following the methodology of Baron (1992), Andrade et al. (1996), and Hickey (1997), Borges (2003) suggested that between

1835 and 1998, characterised by elevated inter-annual and inter-decadal variations, there has been an increase in intensity and frequency (of lesser significance) in Azorean storms over this period. This agrees with Landsea et al.'s (2010) Atlantic basin work for the period 1878 to 2008. However, to determine future trends data needs to be updated and refined as they become available. According to Andrade et al. (2008), an average storm lasts about two days with an estimated frequency of three storms yr^{-1} , while medium intensity storms generally occur four times every five years and extreme storms, once every seven years, usually coinciding with southwesterly waves (Borges, 2003). A medium intensity storm is defined as a storm with moderate to high intensity causing significant damages, while an extreme storm is defined as an extreme event (tropical or extratropical storms; hurricanes) causing devastating damages. Following similar methodologies described by Lamb (1965) and Baron (1992), and tested by Andrade et al. (1996), these definitions were defined according to empirical ranking using historical records, taking into consideration the descriptions and reported damages (Borges and Andrade, 1999 fide Borges, 2003). Storm surge impacts are generally negligible in the Azores because wind build-up is limited due to the exposed nature of the coast and steep submarine slopes (Roger et al., 1982; Carter, 1999). However, for low-lying areas, storm surges in extreme events contribute to coastal inundation: e.g. São Roque prior to coastal protection work, São Miguel Island; Lajes, Pico Island and Fajã de Caldeira, São Jorge Island.

Regional wave statistics were generated within the Nearshore Evolution Modeling System (NEMOS), a set of codes that operates as a system to simulate beach evolution in response to imposed wave conditions, and is a module within the CEDAS software programme. Using wind data from Ponta Delgada, NEMOS generated a wind rose for the period 1998 to 2011 (Fig. 4a). This showed that predominant winds emanate from southwest to northeast. However, recorded northwesterly through northeasterly winds included overland winds due to the wind station location (south coast), and therefore were not fully representative of North Atlantic wave patterns from these directions. Subsequently, a wave rose was generated showing waves from west through southwest to east (Fig. 4b). Results show that predominant waves emanate from the west and southwest, while the block diagram (Fig. 4c) indicates that these waves make up circa 31% of the wave record. The majority of wave periods (circa 83%) range from 7 to 13 s, while most wave heights approaching the shore range between 1 and 3 m (circa 60%, Fig. 4d). Predominant wave directions find agreement with Esteves et al. (2009) who used data between 2005 and 2008 for São Miguel Island's wave buoy, although they indicated a lack of data from northwest through north to east due to location (Fig. 2). Pires (1995) who used a third generation numerical wind-wave hindcast model MAR3G to map north and south coast offshore wave climates (cf WAMDI Group, 1988 and Pires, 1993) found predominant northwesterly waves in the north and predominant southwesterly waves in the south (Table 2). The two locations selected for this model were

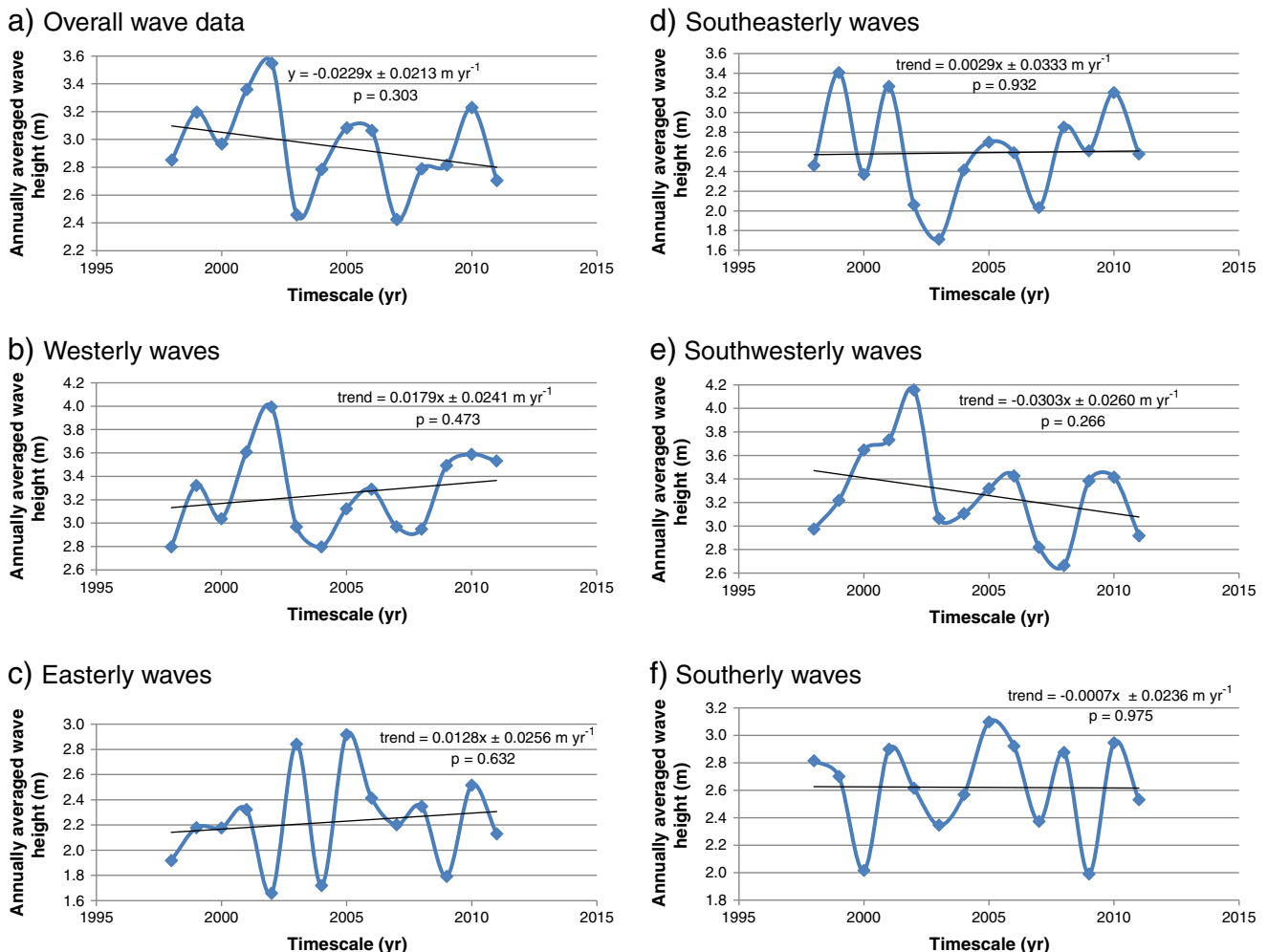


Fig. 5. Temporal annually averaged wave height trends between 1998 and 2011: a) overall; b) westerly; c) easterly; d) southeasterly; e) southwesterly and f) southerly.

based on the following criteria: 1) sufficiently far from the shoreline to minimise bottom morphology effects on incident waves, thus conserving regional phenomenon; 2) close enough to the Island to ensure sheltering effects were considered, thus conserving north and south coast wave exposure asymmetries.

To assess temporal changes in overall wave climate, wave height regression analysis between 1998 and 2011 (Fig. 5a), showed a falling trend and further evaluation of its significance gave: trend = $-0.0229x \pm 0.0213 \text{ m yr}^{-1}$ ($p = 0.303$). With the exception of dominant westerly waves and sub-dominant easterly and southeasterly waves (Figs. 5b, c and d), similar downward trends were seen when southwesterly and southerly waves were considered separately. Trendline analyses gave: southwesterly waves (trend = $-0.0303x \pm 0.0260 \text{ m yr}^{-1}$) and southerly waves (trend = $-0.0007x \pm 0.0236 \text{ m yr}^{-1}$) with p values 0.266 and 0.975, respectively (Figs. 5e and f). Results for westerly, easterly and southeasterly waves indicated increasing trends given by $0.0179x \pm 0.0241 \text{ m yr}^{-1}$ ($p = 0.473$), $0.0128x \pm 0.0260 \text{ m yr}^{-1}$ ($p = 0.632$) and $0.0029 \pm 0.0333 \text{ m yr}^{-1}$ ($p = 0.932$), respectively. Taking into account standard error, only southwesterly waves showed consistent downward trends (Fig. 5e). More data are needed to update and refine these trends as they become available to provide trends with higher confidence. However, the decreasing

southwesterly and southerly wave trends at Ponta Delgada agree with Thomas et al.'s (2010) results over a similar time period at Tenby, South Wales (UK) and Phillips et al.'s (2013) work in the Bristol Channel (UK), while the increasing westerly, easterly and southeasterly trends

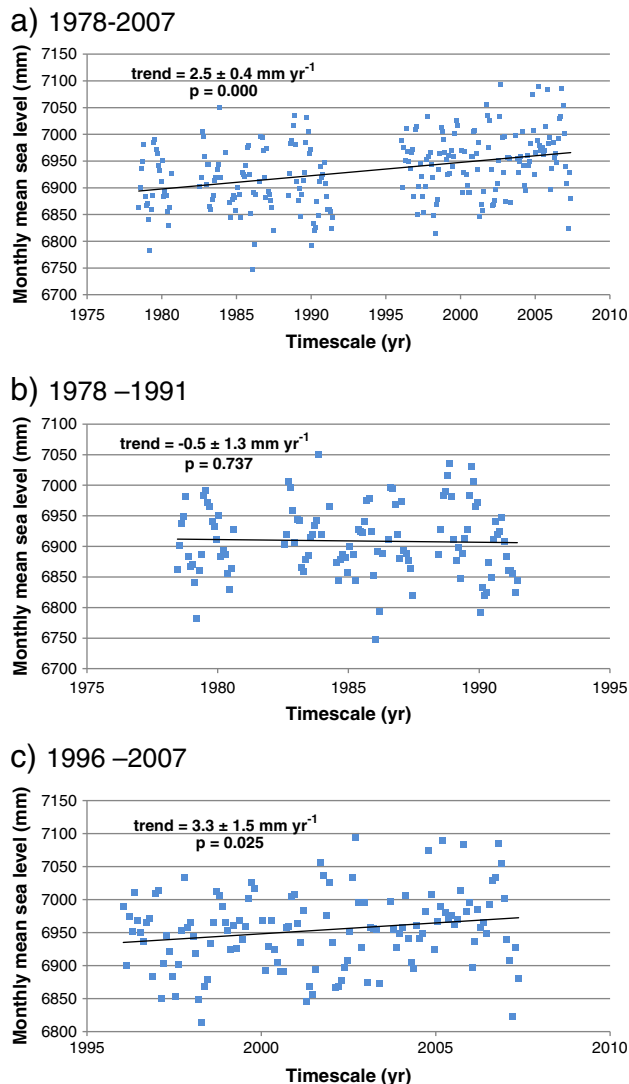


Fig. 6. Mean Sea Level trends from Ponta Delgada tide gauges: a) 1978–2007; b) 1978–1991 and c) 1996–2007. (Using monthly data retrieved from PSMSL, 2013.)

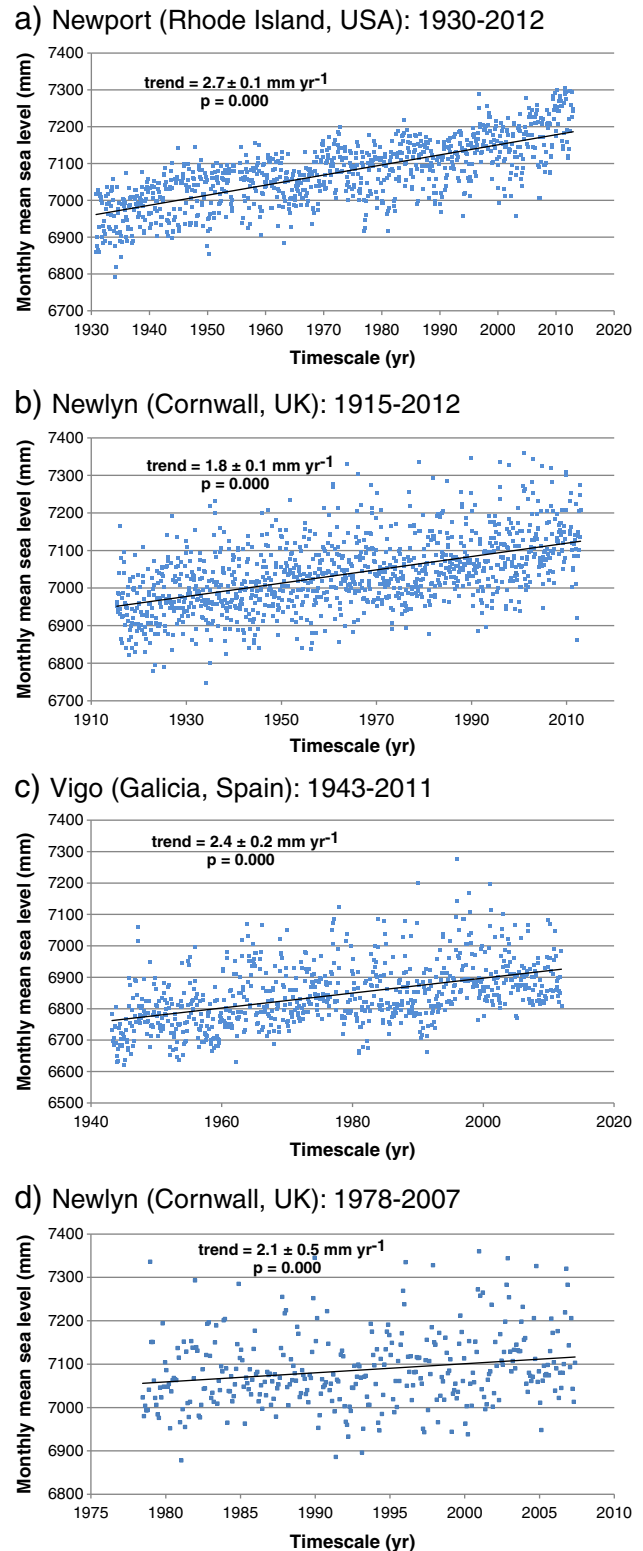


Fig. 7. Mean sea level (revised local reference) trends at North Atlantic tide gauge locations: a) Newport (Rhode Island, USA) tide gauge from 1930 to 2012; b) Newlyn (Cornwall, UK) tide gauge from 1915 to 2012; c) Vigo (Galicia, Spain) tide gauge from 1943 to 2011 and d) Newlyn (Cornwall, UK) tide gauge from 1978 to 2007. (Using monthly data retrieved from PSMSL, 2013.)

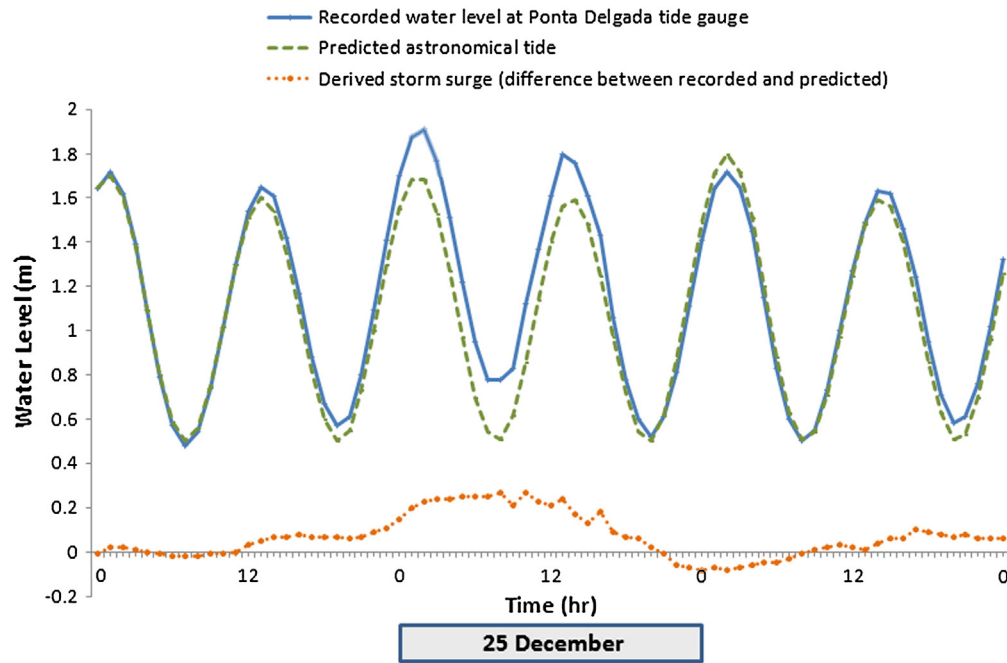


Fig. 8. Derived storm surge in 1996 Christmas day storm at São Miguel Island. (Tide gauge data provided by Portuguese Hydrographic Institute.)

agree with Bertin et al.'s (2013) long-term findings over the 20th century for the North Atlantic Ocean and Allan and Komar's (2006) work on the west coast of the United States. Correlations with these other scientific studies give added validity to the newly derived Azorean results.

4.2. Sea level trends

Ponta Delgada tide gauge data between June 1978 and May 2007 was subsequently analysed to determine changes in mean sea level. Consideration of the entire dataset suggested with 99% confidence, a statistically significant rising sea level trend given by: trend = $2.5 \pm 0.4 \text{ mm yr}^{-1}$ ($p = 0.000$; Fig. 6a). However, when evaluating datasets individually for each tidal gauge, results showed a statistically insignificant decreasing mean sea level trend between 1978 and 1991 given by:

trend = $-0.5 \pm 1.3 \text{ mm yr}^{-1}$ ($p = 0.737$; Fig. 6b) followed by a statistically significant rising trend between 1996 and 2007, given by trend = $3.3 \pm 1.5 \text{ mm yr}^{-1}$ ($p = 0.025$; Fig. 6c), showing that either missing data between July 1991 and 1995 inclusive or change of tide gauge could have influenced results. While tectonic movement is important, there have been no studies on this relative sea level rise component in the Azores. Consequently, at this time tectonic movement signals cannot be assessed.

Consequently to assess their validity, Ponta Delgada results were compared with other North Atlantic locations. Douglas (2001) argued that long datasets were needed to give confidence in sea level trends and subsequently, long-term tidal gauge records between: 1930 and 2012 for Newport (Rhode Island, USA); 1915 and 2012 for Newlyn (Cornwall, UK); and 1943 and 2011 for Vigo (Galicia, Spain), using PSMsL (2013) data were analysed. Sea level analyses at these locations

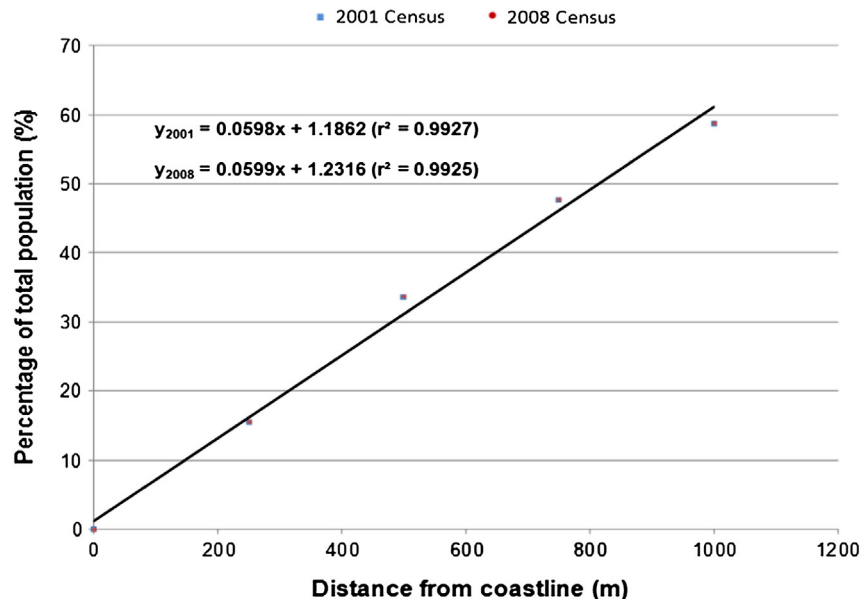


Fig. 9. Estimated population from coastline to 1 km inland using dasymetric mapping and 2001 and 2008 population data from SREA (2003) and INE (2009).

showed with 99% confidence, statistically significant rising trends, i.e. Newport: trend = $2.7 \pm 0.1 \text{ mm yr}^{-1}$ ($p = 0.000$; Fig. 7a); Newlyn: trend = $1.8 \pm 0.1 \text{ mm yr}^{-1}$ ($p = 0.000$; Fig. 7b); and Vigo: trend = $2.4 \pm 0.2 \text{ mm yr}^{-1}$ ($p = 0.000$; Fig. 7c). Because Newlyn had the longest tidal record, a further analysis was undertaken to establish the sea level trend between 1978 and 2007, the same time period as for Ponta Delgada. Results showed rising sea levels of similar magnitude ($2.1 \pm 0.5 \text{ mm yr}^{-1}$; $p = 0.000$; Fig. 7d) which gives further confidence in Ponta Delgada trends. Results for Ponta Delgada also agree with other findings, e.g. Antunes (2011), Nicholls and Cazenave (2010) and Phillips and Crisp (2010) and with the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report's global average sea level rise rates of circa 1.8 mm yr^{-1} (1.3 to 2.3) between 1961 and 2003 and circa 3.1 mm yr^{-1} (2.4 to 3.8) from 1993 to 2003 (IPCC, 2007). Hence, Ponta Delgada's 30 year trend ($2.5 \pm 0.4 \text{ mm yr}^{-1}$; $p = 0.000$; Fig. 6a) has been validated by analysis and comparison with other locations and predictions.

While anthropogenic pressure is likely to increase in São Miguel, rising sea level trends and wave energies will amplify storm effects resulting in more frequent flooding and coastal erosion, threatening larger populations. Although isolated storm surges and tides alone have not previously been threats, the compounded effects of high spring tidal range, coastal storm and storm surge could cause major damage, as was the case in the 1996 Christmas Day storm. It lasted over a day and produced 130 km hr^{-1} SW winds with circa 12 m high waves, and caused an estimated €50 million in damages (Borges and Andrade, 1999). A storm surge of 0.27 m was estimated from the difference between predicted astronomical tide and recorded Ponta Delgada

sea levels (Portuguese Hydrographic Institute, Fig. 8), while field measurements indicated up to 0.6 m at some locations (Borges, 2003). Therefore, in order to sustain and protect local residents' way of life in vulnerable areas, particularly low-lying areas, these observations suggest that coastal protection is going to play an important future role. Although observed storms and sea level trends do not provide an absolute future prediction, coastal planning needs to be more flexible and adaptive to allow incorporation of new findings.

4.3. Coastal engineering: positive benefits to coastal communities in São Miguel Island

With increasing sea level trends and wave energy, the protection of coastal populations is going to become even more important. Based on 2001 and 2008 population data (SREA, 2003; INE, 2009) and using zonal statistics to determine the population in each specified coastal buffer zone, circa 60% of the Island's population was found to reside within 1 km of the coastline (Fig. 9). Interestingly, the percentage of total population in both 2001 and 2008 censuses were shown to be linearly correlated with distance from the shoreline up to 1 km ($r^2 = 99\%$). Commercial and tourism infrastructure dominates the Island's developed coastal frontage. Consequently, residence densities increase with distance from the shoreline, explaining the linear relationship.

The coastal assessment field survey around São Miguel Island selected three exemplary case studies in the Island that demonstrated how coastal engineering helps to maintain the way of life in some Azorean coastal communities: Ribeira Grande; Villa Franca; and São Roque (Fig. 10). Each of these locations has cultural significance. Comparing

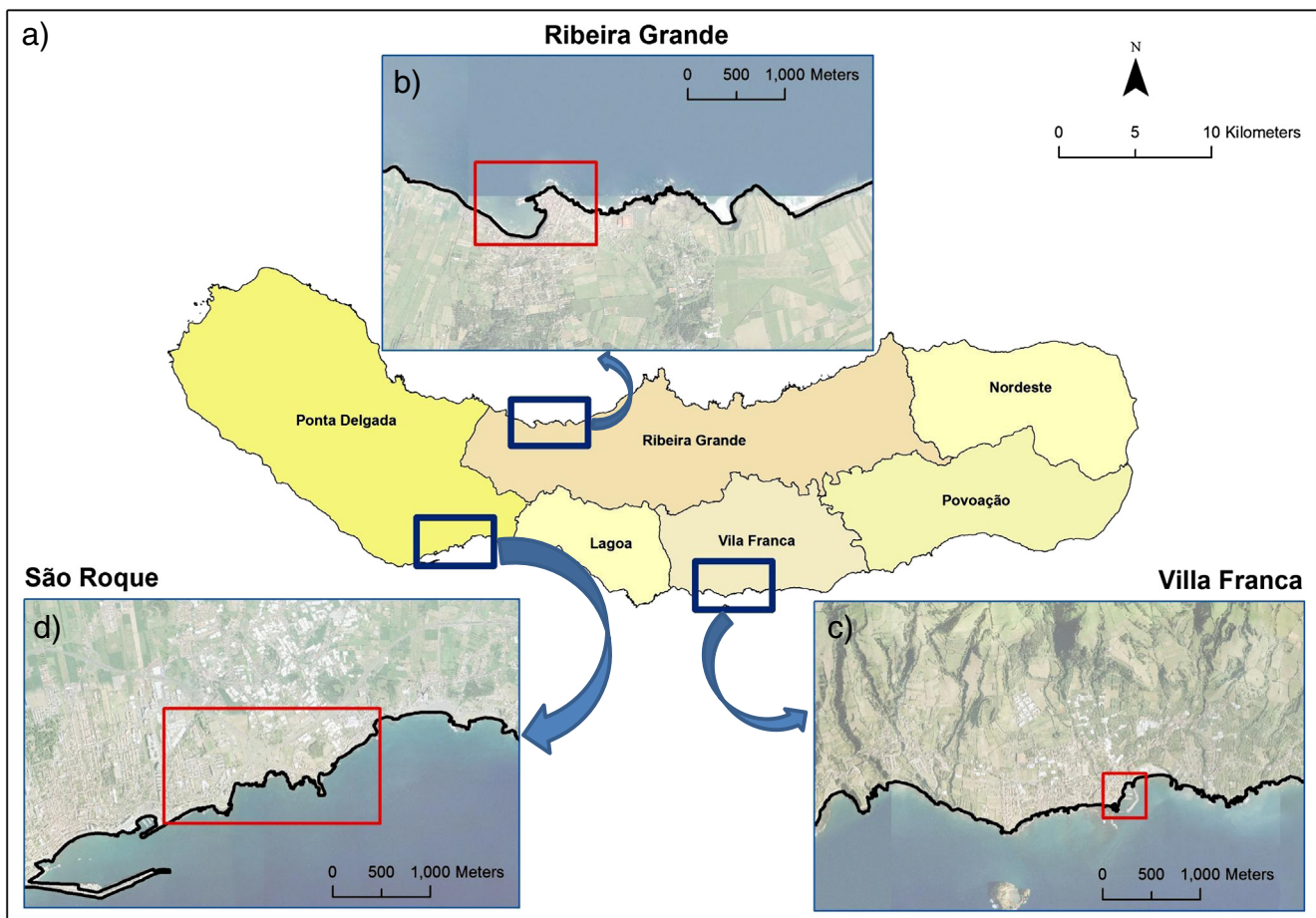


Fig. 10. Study area: a) map of São Miguel Island; b) Ribeira Grande; c) Villa Franca; d) São Roque.

population data in 1991 and 2011 does not indicate significant population changes in these cases. Hence, changing drivers with respect to population expectations, tourism growth and increased wealth are the main motivating factors to these coastal engineering measures.

4.3.1. Ribeira Grande

Ribeira Grande, located in the northern part of the island, is the second largest city in São Miguel Island with 3968 residents (INE, 2011). Dominant swells come from NW with a maximum significant wave height of 10 m (Borges, 2003). The presence of gravel storm deposits, mainly huge boulders in some sandy beaches, demonstrates the northern coast's high wave energy. A public bathing area, managed by the municipality, provides access for a minimal fee to a swimming pool, a small sandy pocket beach and basic bathing area facilities. An emerged breakwater was constructed in 2005 at the eastern end to protect the small recreational quay. It was extended downdrift to protect the public road at risk to coastal erosion due to concentrations of wave energy on hitting the shore (Borges, 2002; Fig. 11a). In this case, the breakwater changed but did not destroy the existing surf wave, as the take-off spot moved and surf quality depends on the shifting sand banks. It protected the small recreational quay and coastline without any observed negative downdrift impacts. Additionally, local littoral drift sediments trapped by the breakwater formed a small pocket beach (Fig. 11b). However the breakwater is also responsible for periodically reducing the pocket beach's width and volume under certain wave conditions. For example, the breakwater refracts NE swell towards the beach causing scouring and sediment loss during storms. Sediments are not naturally re-deposited onto the beach during summer accretion, resulting in some retreat and lowering, as indicated by exposed rocks and walls on each side of the beach observed in the field survey

undertaken in 2011 (Fig. 11c and d). As sediments are likely to be trapped in the inshore bar system, periodic dredging and beach nourishment using these sediments could help recover and maintain this beach.

4.3.2. Vila Franca do Campo

Vila Franca do Campo, the first capital of São Miguel Island, was devastated in 1522 by a major earthquake and landslide. With 4085 residents (INE, 2011), Vila Franca do Campo remains an important town well served with a new highway that reduces travel time from Ponta Delgada (the current capital) to 15 min. It is one of the three most important fishing villages in São Miguel Island and is very popular with holidaymakers due to its good nautical facilities and a beautiful natural islet for bathing and snorkelling. Consequently in 2009, an improved and more suitable harbour for local fishermen was built in conjunction with a marina that was constructed in 2001. The SW provides the dominant swell direction in Vila Franca do Campo. However, occasional storms from the SE, although not as strong, sometimes have a bigger impact, partly due to the sheltering effect of the islet to southwesterly storms. Vila Franca do Campo harbour and marina provide safe shelter for fishing and recreational boats (Fig. 12a and b) as it is constructed with antifer cubes and well-protected from storms (Fig. 12c). There is no observed negative downdrift impact on the pocket sandy beach adjacent to the harbour and marina (Fig. 12d). Additionally, it is protected by the harbour and marina from SW swells and partially sheltered from SE swells by the headland east of the beach. Although exposed to southerly swells, this is currently not a major concern. A man-made water park behind the beach and back-beach rock armour placed as a precautionary measure, have not had any negative impacts on the beach, which is in healthy equilibrium with its surroundings.



Fig. 11. Ribeira Grande: a) coastal engineering work at Ribeira Grande; b) pocket beach; c) exposed rocks and left-side wall (arrows) and d) exposed rocks and right-side wall (arrows).

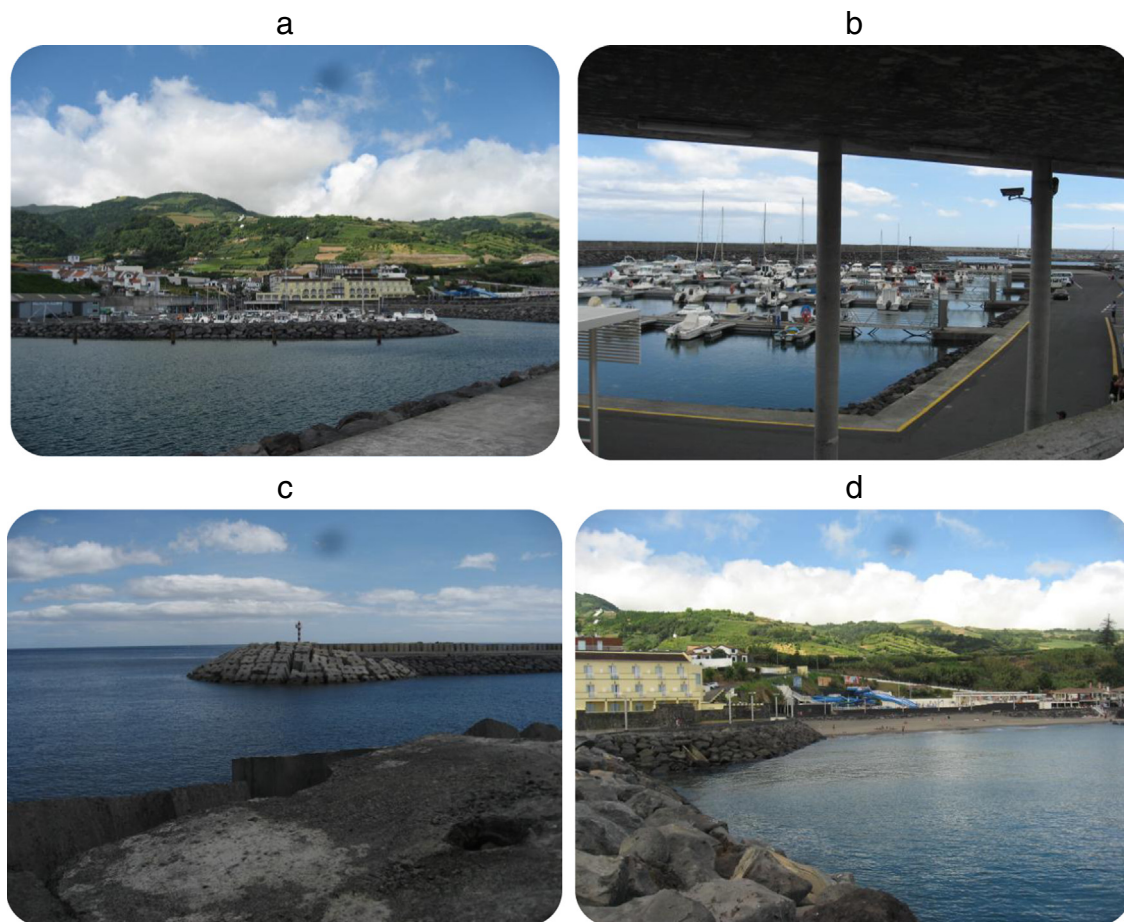


Fig. 12. Villa Franca: a) Villa Franca harbour and marina; b) Villa Franca marina; c) antifer cubes and outer port entrance and d) adjacent pocket downdrift beach.

4.3.3. São Roque

São Roque, with 4932 residents (INE, 2011) is a coastal village located east of Ponta Delgada, the most populated city in São Miguel. In this coastal stretch, both the dominant and prevailing swells come from the SW with a maximum significant wave height of 12 m and therefore, the main coastal hazards are storm inundation and erosion. Homes along this coast used to be flooded during winter storms and extreme events such as the 1996 Christmas Day storm when considerable damage was caused. Some locations experienced severe coastal erosion that resulted in major damage to infrastructure such as the historic fortress (e.g. Fig. 13a and b). A political decision was taken in 2002 to protect the water-front of this village, as well as its cultural heritage. The coastline was

extended seawards and public domain areas were constructed on elevated ground to reduce flooding hazard and act as a buffer zone to protect existing houses and cultural heritage. Almost the entire stretch along this coast is protected by seawalls and/or 3–5 m wide rock armour revetments and additionally in some cases with seaward placed tetrapods to protect houses and cultural heritage (Fig. 14a and b). Five coastal storms, one being an extreme event, have hit the southern coast since major coastal engineering work was carried out in this area, when some road sections and recreational areas were inundated, but not the houses. Inefficient runoff drainage was identified as a major contributory factor in the coastal flooding of two areas. Recently, improvement works have been carried out and a new storm drainage system is being



Fig. 13. São Roque coastal margin in 1997: a) rear aspect of houses and b) erosion near the fortress.



Fig. 14. São Roque coastal defence: a) historic fortress heritage; b) rock armour and boardwalk buffer zone; c) pocket beach at the end of boardwalk and d) church adjacent to pocket beach.

planned to provide adequate and rapid drainage of flooding in future coastal storms.

No negative impacts due to the rock armour have been observed in the sheltered down-drift pocket beach (Fig. 14c). Not protected by rock armour, a seawall constructed >50 years ago to protect the church east of the pocket beach shows signs of under-cutting at its toe (Fig. 14d). The seawall was repaired approximately in 2007 and this major coastal engineering work was carried out by the municipality as the regional government was unable to economically justify its protection. The municipality applied and received funding directly from the EU to protect São Roque (Ecosystema, 2006), and the area has developed into a popular recreational amenity for both locals and tourists, with playgrounds, coastal roads, paved biking/walking boardwalk, trees, benches, parking spaces and access to bathing areas.

To evaluate the viability, challenges, successes and failures of MFARs, a review of nine international installations was undertaken: Burkitt's Reef, Cable Reef and Narrowneck Reef in Australia; Pratte's Reef in USA that was subsequently removed; Mt. Reef and Opunake Reef in New Zealand; Kovalam Reef in India; and Boscombe Reef and Borth Reef in UK. Construction materials are usually rocks and sand-filled geotextile containers, and they are best located in areas with shallow bathymetry and sea-beds ranging from existing natural reef/bedrock to a thin veneer of sand overlying rock. Suitable tidal ranges include micro to meso-tidal with average significant wave heights of <1 m to 2.5 m. Their overall success is controversial and publicity has revolved around failure to deliver surfing expectation. Public opinion on surfing quality often differs from professional assessment by reef designers. Reasons for MFARs not meeting expectations included: running over budget; construction delays; construction not according to design specification; design not having any significant effects on long period swells; deterioration and shifting of geo-containers generating extremely

challenging/dangerous surfing waves; conflicts with local fishermen; and number of surfable days. Based on available information, MFARs perform well where coastal protection is the primary objective, e.g. Narrowneck Reef (Australia), Kovalam Reef (India) and Borth Reef (UK). Narrowneck Reef achieved both coastal protection and surfing objectives, with the former performing better than the latter; while the development of a marine ecosystem on many MFARs appear to be an accompanied positive effect. A comprehensive MFAR feasibility study is currently being undertaken for São Miguel Island, the home of most surfers in the Azores (Ng et al., 2013). To facilitate this study, an inventory of population distribution, accessible surf breaks, regional large-scale bathymetry and coastal erosion rates was produced (Fig. 15).

5. Discussion and conclusions

More future coastal protection measures will be needed with sea level rise and increases in storm intensity, unless coastal communities are relocated inland. The huge costs of protecting the coast often raise controversial questions of whether, and when, to retreat from or defend the coast. However, retreat is very difficult to implement, particularly in SI due to limited land and finances, and surrounding ocean exposure. Social impacts for SI residents who are living with limited land and ocean exposure is generally not given much emphasis, as the loss of land and encroaching sea instils a strong sense of insecurity. In the Azores, the retreat option is also particularly challenging to execute with its narrow coastal fringe being one of the few land areas that offers settlement potential (Andrade et al., 2006; Calado et al., 2011), with an estimated 60% of São Miguel's population living within 1 km of the coastline. Furthermore, although managed retreat has been successfully executed in some communities, e.g. Relva, São Miguel Island, and Lajes,

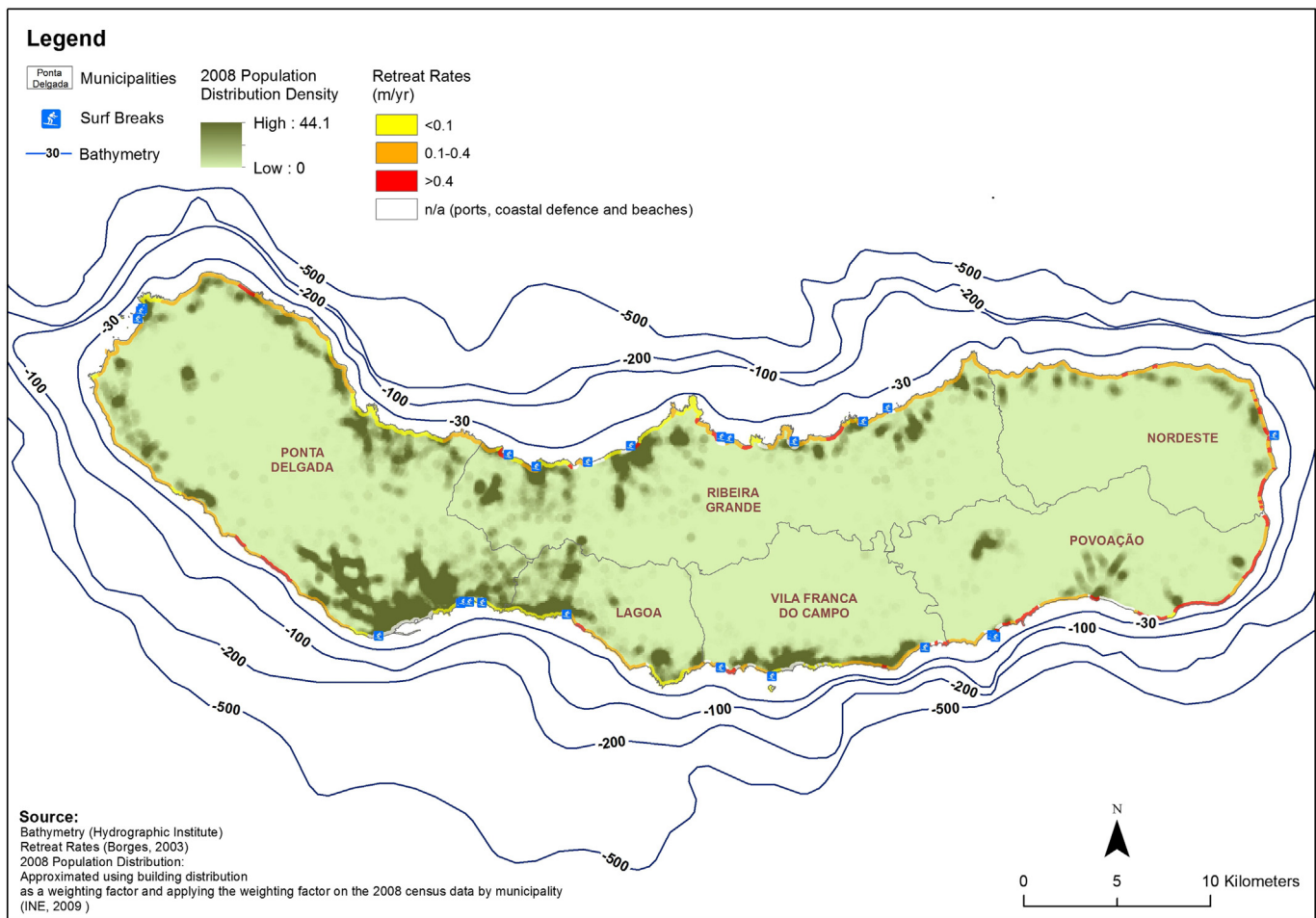


Fig. 15. São Miguel Island: estimated population density; coastal retreat rates; large-scale bathymetry and existing surf breaks.

Pico Island, it is generally difficult in legal systems evolving from Roman law, where private property influences human behaviour.

The case studies showed how coastal engineering preserves Azorean lifestyle with socio-economic benefits such as: protecting cultural heritage; reducing hazard vulnerability; avoiding resident displacement, all of which would have caused major social discontent. There have been benefits, particularly in a SI context, of creating and/or widening pocket beaches, and creating leisure facilities in public domain buffer zones. With relatively few sandy beaches in the Islands, they become even more valuable from a social, cultural and economic perspective. Like all developments, there may be impacts on the environment and surroundings, but in these cases, no significant negative impacts have been observed. Hence, coastal engineering has maintained a way of life for Azorean communities, despite criticisms and negative publicity such as the negative effects of seawalls on beaches (e.g. Pilkey and Wright, 1988) and beach loss along armoured shorelines (e.g. Fletcher et al., 1997). This does not mean that coastal engineering is the optimum solution in all situations, but shows it can have a net positive benefit on the lives of local residents. With continuing human demand and desire to live by the coast, engineering remains a valuable and feasible coastal protection option. However, in all cases a range of options should be analysed and presented to the public before any decision is taken, and should ideally be based on a holistic approach that considers multidisciplinary factors such as environmental impacts and social benefits.

Effective coastal engineering solutions seek to directly address and work with natural coastal processes responsible for the coastal hazard and its effects. Varying extents of ecosystem disturbance is inevitable

for many active shore protection measures. Consequently over the past decade, soft engineering alternatives such as MFARs that work in conjunction with natural processes have been gaining popularity over traditional hard engineering measures. Small-scale MFARs have the potential of providing coastal protection, including widening or stabilizing the beach; improve surfing for short period uni-directional storm waves subject to existing pre-conditioned surfing waves; and provide substrate for marine ecosystem establishment, including fish nursery grounds. With a growing global recognition of surfing amenity value, MFARs could provide the Azores with a soft engineering alternative (Ng et al., 2013). If feasible, MFARs could become another coastal protection option and each location will need to be evaluated for its unique set of coastal and social-economic conditions, taking into consideration climate variability and other impacts.

Ponta Delgada sea level trends between 1978 and 2007 indicated a statistically significant rising trend ($2.5 \pm 0.4 \text{ mm yr}^{-1}$; $p = 0.000$; Fig. 6a). Applying the Brunn (1962, 1983) Rule to this trend suggests a circa 0.25 m yr^{-1} recession rate, similar to the monitored sandy beach retreat rate at Santa Cruz (São Miguel Island). The higher relative sea level rise between 1996 and 2007 of $3.3 \pm 1.5 \text{ mm yr}^{-1}$ (Fig. 6c) suggests that it could be accelerating in line with the 1993 to 2009 global mean sea level rise of $3.3 \pm 0.4 \text{ mm yr}^{-1}$ found by Nicholls and Cazenave (2010). Wave analyses between 1998 and 2011 (Fig. 5) showed an overall downward trend and further evaluation identified that with the exception of dominant westerly waves and sub-dominant easterly and southeasterly waves which increased, falling trends were seen in southwesterly and southerly directions. Most wave periods approaching the shore (circa 83%) ranged from 7 to 13 s,

while circa 60% of wave heights were between 1 and 3 m (Fig. 4). As MFARs perform best in: areas with shallow bathymetry and sea-beds ranging from existing natural reef/bedrock to a thin veneer of sand overlying rock; micro to meso-tidal ranges; and average significant wave heights of <1 m to 2.5 m, this work shows that MFAR is a feasible coastal protection option for São Miguel Island, especially as they have other socio-economic benefits.

Although there is not yet full understanding of sea level rise and there are uncertainties, e.g. limited temporal records and data gaps, results for São Miguel Island show that decision-makers need to give higher priority to sea level rise and climate variability in coastal management and development plans. The potential of accelerated sea level rise also needs to be taken into account in adaptation and mitigation measures. Strategies need to be continually updated and refined as more information becomes available. New Azorean wave buoy data will aid future analyses. Coastal engineering will continue to play an important role in the Azores but a range of solutions, including MFARs, need to be considered and presented to the public before any decision is made. This work will inform other SI coastal management strategies, based on a holistic approach that considers multidisciplinary factors including environmental impacts and socio-economic consequences. With each coastal location having a unique set of conditions and economic needs, the most effective and sustainable engineering solution (hard or soft) will need to be assessed on a case by case basis, taking into consideration climate variability. Subsequently, analyses presented here will help other SI coastal management decision making.

Conflict of interest statement

All authors thereof expressly declare that they have no any actual or potential conflict of interest including any financial, personal or other relationships with other people or organizations within three years of beginning the submitted work that could inappropriately influence, or be perceived to influence the said work.

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