

Wave-driven storm impacts on Scotland's sedimentary barriers intensify with climate change

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ABSTRACT

Beaches and dunes form vital natural barriers, protecting coastal communities from extreme sea levels. To support coastal management, a geomorphologically-informed understanding of how barriers may be impacted by storm-induced coastal hazards is essential. While storm wave runup can contribute significantly to local extreme sea levels and drive dramatic short- and near-term morphological change to sedimentary coasts, it remains only partly characterised in existing national and regional assessments. This study investigates wave-driven storm impacts at large spatial scales (100–1000 km), at a resolution sufficient to inform local decision making. Using higher resolution national and European datasets, established empirical parameterisations and a simplified barrier morphological evolution model, we predict extreme wave runup and storm impacts on Scotland's wave-dominated sedimentary coasts, at 50 m alongshore resolution. We consider a synthetic storm comprised of 25-year return levels of tides and storm surge, and the 1% exceedance of wave height and period, and predict storm impacts for the present-day, mid- and end-century, under RCP4.5 and RCP8.5. Results show that wave runup contributes on average 38% to extreme sea levels, and over 50% in the most exposed locations under present conditions. Nationally, 416 km (65% of the assessed coast) experience barrier erosion during the synthetic storm event, while 72 km (11%) and 27 km (4%) undergo overwash and inundation, respectively. By 2100 the predicted length of inundated coast approximately doubles to 46 km (7%) under RCP4.5, and 59 km (9%) under RCP8.5. Results reveal strong sub-national variability in storm impacts, identifying clear hotspots with the potential for erosion-enhanced flooding.

1. Introduction

Coasts provide a wealth of ecosystem services and continue to be socially and economically important places for human settlement. Despite exposure to multiple and often compounding hazards, including storm surges, extreme waves and rising sea levels (Luijendijk et al., 2018; Nicholls, 2018), coastal populations have grown rapidly, and it is estimated that 898 million people currently live in the low elevation coastal zone (Reimann et al., 2023). Of these, over 130 million people live in rural locations, where natural barriers like beaches and dunes provide vital coastal protection to communities and assets (MacManus et al., 2021). However, as sea level rise accelerates this century,

extreme sea levels and storm waves are expected to reach further inland, potentially compromising the protection provided by natural barriers (Ranasinghe, 2016; Toimil et al., 2023). In this context, European and Scottish adaptation policies call for an increased understanding of present and future extreme sea levels to inform coastal management and proactive adaptation planning (EU Floods Directive (Directive 2007/60/EC), Third UK Climate Change Risk Assessment Technical Report: Summary for Scotland (Committee on Climate Change, 2021), Scotland's National Flood Resilience Strategy (Scottish Government, 2024)).

Nature-based solutions (NbS) for coastal adaptation feature in national (Scottish Government, 2024) and international (European Commission, 2021) adaptation policy as potentially important

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mechanisms to achieve multiple policy goals of risk reduction, societal wellbeing and ecosystem restoration (Cohen-Shacham et al., 2019). However, despite large efforts to upscale NbS (Bridges et al., 2021; Tritinger et al., 2024; van Eekelen et al., 2020) they remain under-utilised due to uncertainties in where to target solutions, and how ecosystems will evolve with climate change (Seddon et al., 2020). As storms play an important role in both the short- and long-term evolution of coastal ecosystems (Masselink and van Heteren, 2014), better understanding of storm-driven extreme sea levels is also essential for evaluating the suitability of adaptation measures that incorporate coastal NbS.

Valuable first-order insights into storm-driven extreme sea levels are provided by recent global- and continental-scale studies (Chaigneau et al., 2024; Jevrejeva et al., 2023; Kirezci et al., 2020; Rueda et al., 2017; Taherkhani et al., 2020; Voudoukas et al., 2018). However, a lack of spatial resolution means that these studies cannot yet inform adaptation planning at the sub-national scale. Furthermore, these studies only partially consider storm wave contributions via wave setup, as wave runup cannot be meaningfully estimated from current low-resolution global topographic data. Storm wave runup can however contribute over 50% to extreme sea levels along exposed coasts, and drive both coastal flooding and morphological changes to beaches and dunes (Stockdon et al., 2023). There is thus a need for national-scale information on coastal storm hydrodynamics that includes wave runup, at a spatial resolution that can inform regional and local adaptation planning. In Scotland, wave runup contributions are considered by statutory organisations for some sectors of the coast, but whole-coast flood risk assessments currently only include SLR, tides and storm surge (Scottish Environment Protection Agency (SEPA), 2023), and similar data gaps exist in other parts of Europe. However, the increased availability of high-resolution digital elevation models and coastal wave forcing derived from regional climate models now enable the prediction of storm wave runup at finer scales, creating an opportunity to address this knowledge gap and improve predictions of storm hydrodynamics in national assessments.

To include wave runup in storm hydrodynamics, methods vary in complexity and computational expense. At the high end, process-based numerical models like XBeach (Roelvink et al., 2009) can provide detailed and accurate estimates of storm wave runup and beach morphological change at the local scale, usually for individual storm events (Simmons et al., 2019). Limitations such as site-specific calibration requirements, computational cost and the need for high-resolution and up to date topo-bathymetry data have so far prevented the use of XBeach at larger spatial and temporal scales. While recent studies have coupled XBeach with long-term shoreline evolution models (Lemos et al., 2024a; Toimil et al., 2023) and artificial neural networks (Athanasίου et al., 2022) to address the spatio-temporal limitation, large computational and data requirements remain, and thus the application of process-based numerical models in national-scale storm impact assessments is not yet feasible.

Alternatively, empirical parameterisations of wave runup are computationally simple, avoid site-specific calibration, and allow wave contributions to be estimated from readily available wave forcing data and national digital elevation models. Substantial effort has been made in recent decades to develop empirical parameterisations (see reviews in Gomes da Silva et al. (2020) and Poate et al. (2016)), and despite lacking the accuracy of numerical models, empirical parameterisations can provide valuable first-order insights for storm wave runup at regional and national scales (Stockdon et al., 2023; Turner et al., 2024). The runup equation proposed by Stockdon et al. (2006) has been widely tested and used along wave-dominated sandy beaches, and remains a method of choice due to its low data requirements and high accuracy (Brodie et al., 2025; Costas et al., 2020; Gomes da Silva et al., 2020; Hovenga et al., 2021; Viavattene et al., 2018). Runup parameterisations have also been developed specifically for pure gravel (Poate et al., 2016) and composite sand and gravel beaches (Blenkinsopp et al., 2022), to

reflect the different hydro-morphodynamic behaviour of these beaches under storm conditions, and to extend the utility of empirical parameterisations in storm impact assessments to different beach typologies.

The role of extreme wave runup in storm hazards is often conceptualised via the storm impact scale proposed by Sallenger (2000). This assesses erosion and flood hazard to natural coastal barriers by integrating hydrodynamic forcing and barrier morphological parameters to identify distinct storm regimes, associated with different morphological consequences for the barriers (Leaman et al., 2021; Stockdon et al., 2023). Future storm impacts can be assessed with the storm impact scale framework, provided data on future hydrodynamic forcing and barrier morphology are available. For the former, mid- and end-century projections of SLR, tides, storm surge and wave climate are readily available in national and regional datasets. However, meaningful estimates of future natural barrier morphology are more problematic, especially at larger spatial scales, due to the complex and site-specific drivers of beach and dune evolution (Masselink and van Heteren, 2014; Ranasinghe, 2016). Studies that do adjust barriers for sea level rise in future storm impact predictions use the Bruun rule, or modified versions of it, to translate the beach profile landward and upward as a first-order estimate of barrier evolution (Hallin et al., 2025; Lemos et al., 2024a; Toimil et al., 2023). Limitations of the Bruun rule are however widely acknowledged (Cooper et al., 2020; Cooper and Pilkey, 2004), creating an opportunity to consider an alternative first-order conceptual model of multi-decadal barrier evolution with which to predict future storm impacts.

The aim of this research is to provide Scotland's first national storm impact assessment that includes wave runup, for the present day and different climate scenarios this century. To this end, we consider the following objectives:

- 1) Using higher resolution national and regional datasets and simple empirical parameterisations, predict extreme wave runup and storm impacts for all of Scotland's wave-dominated sand and gravel coasts, at a resolution of 50 m alongshore.
- 2) Using future forcing conditions and a first-order conceptual model of multi-decadal barrier evolution, model storm impacts under climate scenarios RCP4.5 and RCP8.5 for the mid- and end-century.
- 3) Evaluate the relative contributions of different hydrodynamic components to extreme water levels and how these are likely to change in the future.
- 4) Explore the potential for these national storm impact predictions to inform sub-national coastal risk assessments, and practical adaptation planning.

By providing a nationally consistent dataset on coastal storm hydrodynamics that includes wave contributions, this research will contribute to the evidence base for strategic coastal adaptation planning and inform coastal risk assessments, alongside existing research on coastal erosion (www.DynamicCoast.com/ccs).

2. Methods

2.1. Study area

Scotland's coast is 21,684 km long (Ordnance Survey, 2024a), complex and varied, with a heavily indented configuration on the Atlantic coast, and linear stretches along the North Sea. Sediment varies from fine sand to cobbles, and barriers range from large beach and dune systems to pure gravel berms. The storm wave climate also varies from west to east, with the west coast and islands facing large Atlantic storm systems with mean winter offshore significant wave heights of 5–7 m, predominantly from the south-west, while the east coast faces mean winter offshore significant wave heights of 2–3 m, with a larger directional spread. Despite the less energetic wave climate, Scotland's east coast can experience large storm surges and coastal flooding from

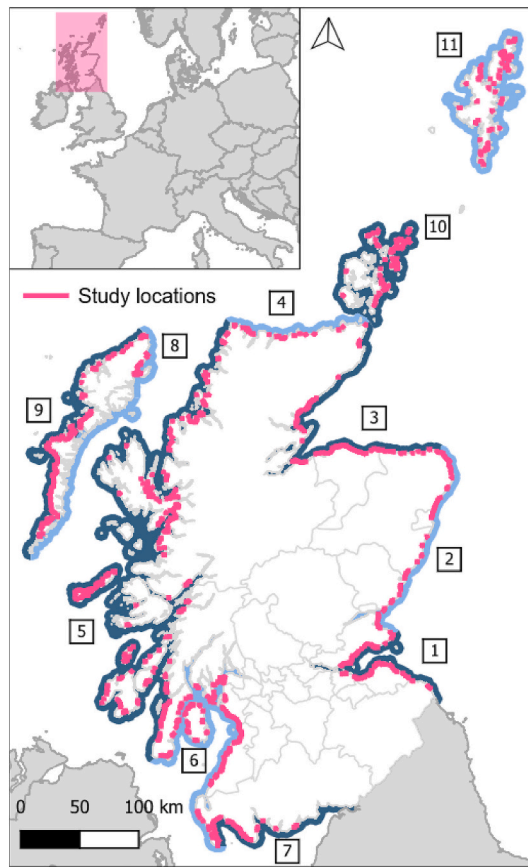


Fig. 1. Distribution of the study locations along the coast of Scotland, with identification of the coastal sedimentary cell extents (numbered) used to report results at the sub-national level.

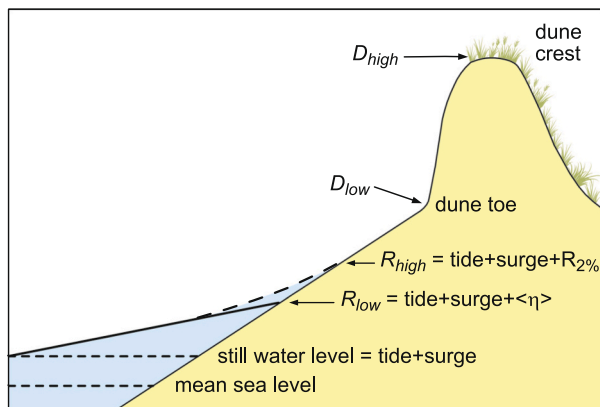


Fig. 2. Definition sketch of the Storm Impact Scale (SIS) model of Sallenger (2000), illustrating R_{low} , R_{high} , D_{low} and D_{high} and the Swash regime. Parameters $R_{2\%}$ and $\langle \eta \rangle$ represent extreme wave runup and setup, respectively. Still water level represents the sum of tide and storm surge elevations. Figure adapted from Stockdon et al. (2007) and Masselink and van Heteren (2014).

extratropical cyclones crossing the North Sea, especially when storm peaks coincide with high spring tides. Tidal regimes around Scotland range from micro- to macro-tidal, with the mean spring tidal range around the coast between 4 and 5 m, peaking at 7–8 m in the Solway Firth (Moffat et al., 2021). Relative sea level rise (SLR) around the Scottish coast is slightly lower than the UK average, as increases in mean sea level are partially offset by glacio-isostatic adjustment (Rennie and

Hansom, 2011). Nonetheless, between 0.3 and 0.9 m of SLR is predicted in Edinburgh by 2100 under a high emissions future, and maximum SLR of 1.2 m is predicted for Shetland (Palmer et al., 2018). An estimated 41% of Scotland's 5.5 million residents live within 5 km of the coast, with 68% of the coastal population concentrated in a small number of urban centres (Hastings and Ferrier, 2010). The remaining 32% are dispersed around Scotland's extensive rural coast in small towns, agricultural areas, and remote and sparsely populated areas, where beaches and dunes are an important first line of defence between the sea and coastal communities and assets. Nationally, an estimated £20 billion of road, rail and residential property lie within 50 m of the coast (Rennie et al., 2021). Of this, £5 billion are fronted by engineered defences, and £14.5 billion are located behind natural defences that include beaches and dunes (Rennie et al., 2021).

In this work, storm impacts were assessed for all beaches found on the wave-dominated sedimentary coasts of Scotland (Fig. 1). This includes open-coast sand, gravel and composite sand/gravel beaches where wave action, as opposed to tidal inundation, is the primary hydrodynamic driver of coastal morphological change and storm impacts. At the sub-national level, results were organised according to coastal sedimentary cells to align with existing national assessments of coastal change and erosion hazards (www.DynamicCoast.com/ccs).

2.2. Storm forcing

2.2.1. Synthetic storm forcing

Synthetic storm forcing was defined by extreme total water levels (TWL), computed as the sum of extreme still water levels (ESL, the combined maxima of astronomical tides and storm surge), and extreme wave runup ($R_{2\%}$, the 2% exceedance of wave runup, calculated as the sum of wave setup and swash) (Stockdon et al., 2023; Turner et al., 2024; Vousdoukas et al., 2018). To define the synthetic storm, an event-based storyline approach was used. Event-based storylines are often used to analyse and communicate the impacts of extreme weather and climate events, with a focus on plausibility rather than probability of occurrence (Celedón et al., 2023; Romero-Martin et al., 2024; Fernández-Montblanc et al., 2020). Here, the aim was to characterise an energetic but likely storm event. Thus, present-day ESL were characterised by 25-year return levels of tide and storm surge (Met Office Hadley Centre, 2023), and $R_{2\%}$ was estimated with the empirical parametrisations in Appendix B, using the 99th percentile offshore significant wave height (H_{s99}) and peak wave period (T_{p99}) from the “Ocean surface wave indicators for the European coast” dataset (Copernicus Climate Change Service, 2020). The representativeness of the 99th percentile wave climate around the Scottish coast was evaluated and reported in Supplementary material S1. Note that as the combination of 25-year ESL and 99th percentile wave climate does not represent a formally defined joint-probability event, results should not be interpreted as formal exceedance probabilities, but instead as representative of the largest storm of the year coinciding with a high spring tide.

2.2.2. Future storm scenarios

Future storm impacts were assessed using two IPCC AR5 Representative Concentration Pathway scenarios. Firstly, the intermediate emissions trajectory RCP4.5, where greenhouse gas emissions stabilise and begin to decrease after 2040, and secondly the high emissions trajectory RCP8.5, where greenhouse gas emissions continue to increase throughout this century, commonly referred to as “business as usual”. These climate scenarios have been widely considered for the mid- and end-21st century (e.g. by Vousdoukas et al. (2018), Kirezci et al. (2020), Hurst et al. (2021), Toimil et al. (2023) and Marino et al. (2025)). For each climate scenario, future ESL elevations were obtained by adding the 95th percentile SLR to the present-day 25-year ESL return levels (Met Office Hadley Centre, 2023). This assumes that tidal elevations and skew surge extremes in Scotland will remain the same throughout this century, with changes expected to be dominated by increases in mean

sea level (Palmer et al., 2018). Future wave runup and setup elevations were computed with H_{59} and T_{p99} from the 2041–2070 modelling epoch for mid-century predictions, and the 2071–2100 epoch for end-century predictions (Copernicus Climate Change Service, 2020). These future wave climates have been modelled for AR5 scenarios RCP4.5 and RCP8.5, aligning future ESL and wave climate scenarios used in this assessment. For details of the datasets, please refer to Appendix A.

2.3. Storm impact scale

To provide a conceptual understanding of potential storm impacts related to the estimated extreme TWL, the storm impact scale of Sallenger (2000) was used to identify the storm impact regimes of Swash, Collision, Overwash and Inundation, in order of increasing intensity. Sallenger's conceptual model is widely used to assess storm impacts at larger spatial scales by comparing coastal barrier elevations with extreme total water levels (Leaman et al., 2021; Stockdon et al., 2023; Stockdon et al., 2007; Turner et al., 2024). In this model, R_{low} represents the mean wave-driven water level during the storm and includes the combined effects of mean sea level (MSL), astronomical tides, storm surge and wave setup. R_{high} represents the highest elevation reached by the landward progression of wave runup, and includes MSL, astronomical tides, storm surge and $R_{2\%}$ (Fig. 2).

At the lower end of Sallenger's storm impact scale is the Swash regime, where R_{high} is below the dune toe elevation (D_{low}) (as illustrated in Fig. 2), followed by Collision where R_{high} exceeds D_{low} but not the dune crest elevation (D_{high}). For these regimes, storm erosion of the beach and dune face can be expected. This tends to be followed by post-storm recovery as sediment is reworked by waves and wind onto the beach and dune, although there are considerable complexity and variability in this reworking (Brodie et al., 2025). At the higher end of the storm impact spectrum are the Overwash regime, where R_{high} periodically overtops the dune, and Inundation, where R_{low} exceeds the dune crest elevation, leading to complete barrier inundation by storm waves. For these higher impact regimes, in addition to beach and dune erosion, more significant changes to barrier morphology are expected, including crest lowering and rollover, along with increased flood hazard to the hinterland (Sallenger, 2000). While Sallenger's conceptual model was developed for barrier islands in the Atlantic coast of the USA, it has been used in diverse geographical and morphological settings that include wave- and surge-dominated coasts (e.g., Celedón et al., 2023; Plomaritis et al., 2018; Turner et al., 2024), extending its use from barrier islands to sandy systems in general. Here, we consider the definition of “barrier” according to Masselink and van Heteren (2014), as the key morphological unit of wave-dominated sedimentary coasts, whether composed of sand, pure gravel, or composite sand and gravel. The inclusion of gravel barriers is argued appropriate, as erosion and overwash processes identified by Sallenger's conceptual model also occur in gravel coasts (Masselink and van Heteren, 2014).

2.4. Geospatial framework

2.4.1. Transect definition

The storm impact assessment was implemented within a geospatial framework, where shore-normal transects formed the geospatial unit of analysis (e.g. Hovenga et al. (2021) and Athanasiou et al. (2024)). Transect length and spacing were chosen to balance the need to capture longshore and cross-shore variation in topography with data processing requirements. Transects were generated at 50 m longshore spacing, with centroids on a simplified and smoothed version of the mean high-water springs (MHWS) contour representing the coastline, extending 1 km landward and seaward of the coastline, with the exception of small islands where lengths were reduced to 500 m or 250 m. The analysis included 12,798 transects that cover the entire wave-dominated sedimentary coast of Scotland and correspond to 640 km of coast (~4% of the national coastal edge). This assessment thus excludes the

predominantly rocky coast of Scotland, and the sheltered inner coasts of estuarine and fjord systems.

2.4.2. Profile morphometrics

The geospatial analysis was implemented in Python 3.11 using automated scripting and input data listed in Appendix A. Step 1 extracted each transect's topography profile from the 5 m digital terrain model (DTM), interpolated in a 20 m longshore window to capture variation in longshore barrier morphology. (A comparison of the 5 m national DTM used to derive topographic profiles, with high-resolution LiDAR DTMs available for part of Scotland's coast is provided in Supplementary material S3.) In Step 2, an automated approach to topographic profile analysis yielded each transect's barrier crest and toe morphometrics D_{high} and D_{low} , along with the back barrier toe, following a modified version of an algorithm developed to identify cliff top and cliff toe (Payo et al., 2018). Step 3 extracted each transect's average intertidal slope. Accurate estimates of the intertidal slope are crucial when predicting $R_{2\%}$ via empirical parameterisations (Stockdon et al., 2023). To achieve this in the absence of a complete national topobathymetry dataset, intertidal slope was calculated based on the distance between the MHWS and mean low water springs (MLWS) contours, and assuming a symmetrical tidal excursion with elevation difference between MHWS and MLWS of double the MHWS elevation. Step 4 used proximity analysis to extract the local ESL and deepwater storm wave parameters.

2.4.3. Runup parameterisation

Using the transect's intertidal slope and wave parameters obtained as described above, in Step 5 $R_{2\%}$ and wave setup were estimated with empirical parameterisations listed in Appendix B. These were selected based on existing local data on sediment type and coastal habitats (NatureScot, 2017), which were used to differentiate between sand, composite sand and gravel, and pure gravel beaches in order to select parameterisations appropriate to the local beach typology.

For sandy beaches (70% of the assessed coastal edge), $R_{2\%}$ and setup were estimated with the empirical parameterisations of Stockdon et al. (2006), differentiating between intermediate/reflective beaches (Appendix B, Eqs. B2, B3) and extremely dissipative beaches (Appendix B, Eqs. B4, B5). As these parameterisations were developed for sandy coasts, they are less applicable where wave interaction with a sandy nearshore is limited (e.g. rock-controlled systems) and where wave runup on the beach is interrupted by hard structures. Thus, predominantly rocky coasts and highly engineered coasts were excluded from the assessment. Complex bay environments like the fjords and inner firths of Scotland's west coast, where wave refraction and sheltering affect the propagation of storm waves, were also excluded as they are out of scope for the Stockdon et al. (2006) parameterisation.

For lesser studied gravel beaches that still lack a widely accepted runup parameterisation, equations developed for pure gravel and composite sand and gravel beaches were evaluated before selecting the most appropriate parameterisation for each beach typology (details provided in Supplementary material S2). Based on this analysis, for pure gravel beaches (1.2% of the assessed coastal edge), $R_{2\%}$ and setup were predicted with empirical parameterisations of Poate et al. (2016) (Appendix B, Eq. B6) and Powell (1990) (Appendix B, Eq. B7) respectively. For composite sand and gravel beaches (28% of the assessed coastal edge), Stockdon's equations were found to be more appropriate for this assessment than the recently developed parameterisation for composite beaches, as the latter produced significantly lower $R_{2\%}$ estimates and has not yet been validated under energetic storm conditions (Fig. S4, Table S2). Accordingly, $R_{2\%}$ and setup in composite beaches were estimated with the empirical parameterisations of Stockdon et al. (2006), applying the same exclusions as for sandy beaches, and differentiating between intermediate/reflective beaches (Appendix B, Eqs. B2, B3) and extremely dissipative beaches (Appendix B, Eqs. B4, B5). Finally, in Step 6 R_{low} and R_{high} were calculated and compared with D_{high} and D_{low} to

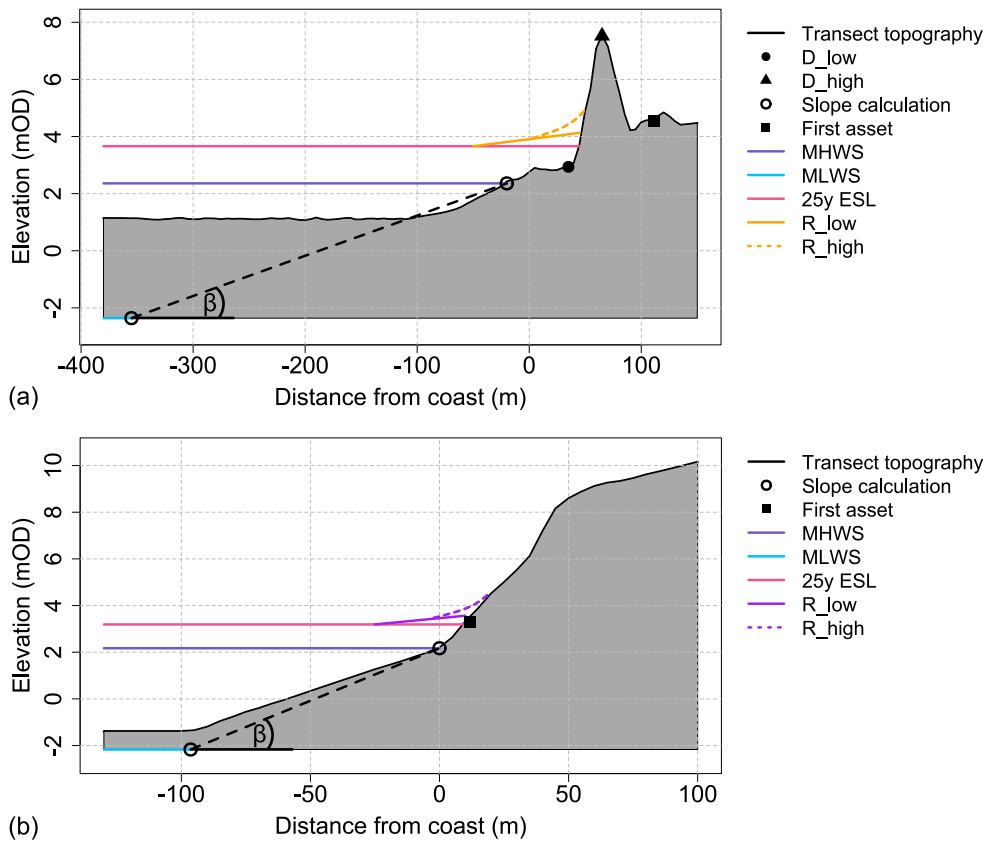


Fig. 3. Storm impact assessment at the transect level, with topography profiles extracted from the 5 m OS Terrain5 digital terrain model (DTM), barrier morphometrics, intertidal slope (β) calculation, asset locations and extreme water levels. MHWS = mean high water springs, MLWS = mean low water springs, 25y ESL = 25-year return level of tides and storm surge. (a) Coastal barrier in the Collision regime. Note how the DTM does not represent the intertidal profile sufficiently, due to data acquisition during high tide. For this reason, the transect intersections with MHWS and MLWS contours, denoted by $\circ$, were used to calculate β , rather than the DTM. (b) No coastal barrier, with first asset (here a road) modelled in the NB_Inundation regime.

Table 1

Storm impact scale for no-barrier (NB) transects. The 5 m boundary between NB_Collision and NB_Swash is somewhat arbitrary, but a precautionary lower threshold for NB_Collision provides a better indication of assets that are not presently at risk of flooding, but that may be at risk in the future.

First asset's distance from coastline (D)	First asset's elevation (E)	No-barrier storm impact
D < 200 m	$E < R_{low}$	NB_Inundation
D < 200 m	$R_{low} < E < R_{high}$	NB_Overwash
D < 200 m	$0 \leq E - R_{high} \leq 5$ m	NB_Collision
D < 200 m	$E - R_{high} > 5$ m	NB_Swash
D > 200 m	n/a	NB_NoAsset

predict the likely storm impact associated with each epoch and climate scenario (example in Fig. 3a).

2.5. Coastal characterisation

In addition to storm impacts, this study characterised the coastal environment landward of the beach, with the aim of informing coastal risk assessment and adaptation planning. Transect-level physical and socio-economic information extracted include the landward distance and elevation of the first property, road and railway line; accommodation space between the coastal edge (MHWS) and first asset; and the average slope and elevation of the hinterland between the back-barrier toe and transect endpoint. Additionally, Overwash and Inundation potential were calculated based on the elevation difference between the barrier crest D_{high} and R_{high} (R_{low}) to indicate how close the barrier is to being overwashed (inundated), respectively. Overwash potential was

first defined by Matias et al. (2012) and can be interpreted in a similar way to the coastal engineering concept of freeboard (Rogers et al., 2010), to provide further insights into barrier vulnerability.

2.6. Coasts without natural barriers

Coastal barriers were considered to exist only seaward of the first asset (road, railway line or property). In some cases, this departed from the geomorphological definition of coastal barriers – e.g. where an asset exists seaward of the foredune, this dune was not considered a barrier, as it is not providing a storm buffer to the asset in question. In these cases, or when no morphological barrier feature could be identified, the transect was classified as a no-barrier transect (Fig. 3b). For no-barrier transects, insights into potential storm impacts to coastal assets were still of interest, and so the first asset elevation (as opposed to D_{high} and D_{low}) were used to conceptualise potential storm impacts (Table 1).

2.7. Future barrier morphology

To produce meaningful predictions of future storm impacts, it is important to adjust future barrier morphometrics for SLR. However, barriers on wave-dominated coasts are extremely dynamic landforms, whose evolution is linked with processes and controls that act over a wide range of spatio-temporal scales. Barrier evolution is particularly challenging to predict, as it is driven by both plot-scale processes that determine instantaneous sediment mobilisation and transport, and landscape-scale processes like SLR that operate over decades to centuries (Walker et al., 2017). Due to these challenges of scale and complexity, predictions of multi-decadal national-scale barrier

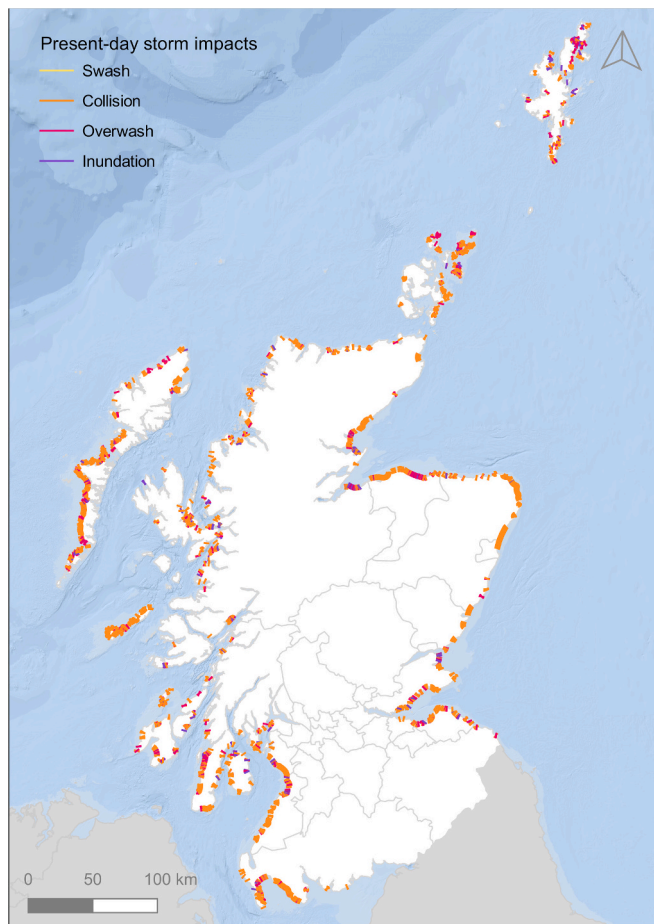


Fig. 4. Predicted present-day storm impacts to natural barriers along Scotland's wave-dominated sedimentary coasts. Basemap: Esri World Ocean Base.

morphological evolution beyond that of the Bruun rule (Bruun, 1988) are generally lacking.

At the landscape scale, barrier evolution – dune building and dune erosion specifically – is driven by aeolian sediment transport, storm impacts and changes in mean sea level (Costas et al., 2020; Walker et al., 2017; Masselink and van Heteren, 2014). There is high certainty that sea level rise will increase extreme water elevations reached during storms (Palmer et al., 2018), thereby increasing storm impacts, i.e. the extents of dune scarping and erosion (Masselink et al., 2022). SLR may also reduce annual dune-building hours when dry-beach conditions are conducive to aeolian transport, thus limiting post-storm foredune recovery (Hovenga et al., 2021). Finally, climate change may increase storm frequency (although there is still a large degree of uncertainty around this (Castelle et al., 2018)), which would further reduce inter-storm recovery periods and affect long-term barrier evolution. Thus, at the landscape scale, dune building and post-storm recovery are likely to be increasingly compromised throughout this century.

At the landform scale, barrier evolution is modulated by the spatial variability in vegetation, moisture interactions, sediment size and, crucially, littoral sediment budget (Walker et al., 2017; Masselink and van Heteren, 2014). The latter determines sediment inputs to the beach, which affect the subaerial beach and barrier morphology. High sediment supply is linked with large barrier volumes and greater storm resilience, while low sediment supply is linked with barrier narrowing

and steepening during storms. Furthermore, a positive sediment budget is likely to result in a wide and gently sloping beach that dissipates wave energy and limits runoff, and facilitates aeolian sediment transport to the dunes in post-storm recovery periods (Masselink and van Heteren, 2014). Littoral sediment budget is thus an important explanatory parameter in long-term barrier evolution.

However, littoral sediment budget is itself complex and site specific, influenced by the local geology, riverine sediment inputs and human interventions that alter longshore sediment transport. Accurate assessments thereof require local studies, and do not yet exist for the extensive national-scale study area of this assessment. To collapse the complexity into a metric that provides an integrated view of the local sediment budget for a given coastal stretch with existing national-scale data, this work used observed historical coastal change over the last 30–40 years as proxy for beach sediment budget (Rennie et al., 2021). In so doing, i) accreting ii) stable and iii) eroding coasts served as a proxy for i) positive ii) neutral and iii) negative beach sediment budgets, with the aim of informing long-term barrier evolution.

Here, a simple conceptual model was developed as an alternative to the Bruun rule, where a relationship between the sediment budget of the beach and foredune results in different modes of foredune development (Psuty, 2008 — details of this conceptual model are provided in Supplementary material S4). Importantly, it is the beach sediment budget that drives the foredune sediment budget, along a continuum from positive to negative beach sediment budgets (Fig. S11). Applying the conceptual model of Psuty (2008) to this study, it was postulated that foredune sediment budgets on historically accreting and stable coasts were sufficiently positive to keep pace with SLR in the near term. However, as SLR accelerates by mid-century, it was argued that dune building would become increasingly compromised due to higher storm-driven TWL elevations and daily tidal elevations that would result in fewer annual dune building hours (Masselink et al., 2022; Hovenga et al., 2021; Costas et al., 2020; Walker et al., 2017), and so barrier crests would not continue to keep pace with SLR towards the end of the century. Thus, barrier crests of historically accreting and stable coasts were maintained at mid-century elevations in end-century storm impact assessments. For barriers on historically eroding coasts, it was postulated that there was insufficient barrier sediment budget to allow crest elevations to keep pace with SLR, and thus crests were maintained at present day elevations in both the mid- and end-century storm impact assessments.

The derivation of a conceptual model for barrier toe evolution was more problematic, due to the widely varying behaviour of barrier toe elevations observed in field studies (Masselink et al., 2022), and the difficulty in separating short-term erosion and rebuilding responses from long-term trends by using field studies with relatively short time-spans (<20 years). As such, we used the classical equilibrium profile concept that assumes a nearshore equilibrium profile comprising entirely of sediment, where, over longer timescales, the nearshore profile adjusts vertically to maintain dynamic equilibrium with mean sea level, leading to a 1:1 increase in barrier toe elevation in line with SLR (Davidson-Arnott, 2005). If a barrier's future toe elevation exceeded its crest elevation (e.g. when crests do not keep pace with SLR in eroding coasts, but toes do keep pace, and SLR exceeded the crest elevation), the future crest elevation was set to equal the toe elevation, and the barrier was flagged as drowning.

Finally, intertidal slopes, an important parameter in the empirical parameterisations, were assumed to remain unchanged in the future. This assumes that the dynamic beach face profile, largely determined by sediment size and local average wave climate, will not change significantly over the course of this century (Bricheno et al., 2025).

This conceptual model necessarily leads to a higher number of

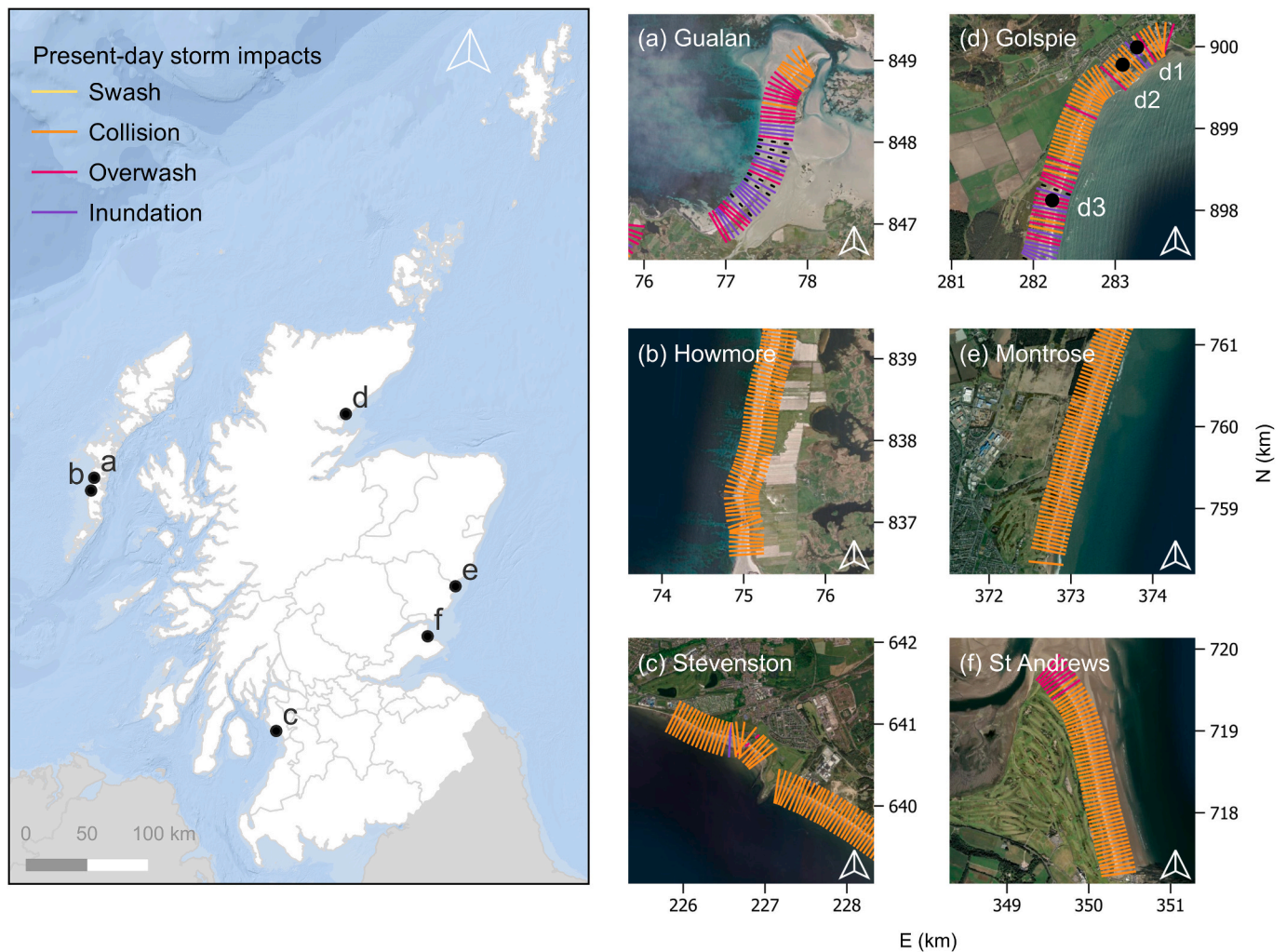


Fig. 5. Storm impact validation locations and predicted present-day storm impacts. Coordinate reference system in subfigures: EPSG 27700. Basemaps: Esri World Ocean Base, Esri World Imagery.

transects modelled in Overwash and Inundation in 2100 than would be the case if crests continued to keep pace with SLR, as in a traditional Bruun rule approach. To test the sensitivity to this assumption, storm impacts under RCP8.5 in 2100 were estimated with all barrier crests increased in line with SLR until 2100 following a Bruun approach, and compared with end-century RCP8.5 predictions of this study. These results are reported in [Section 3.2](#).

2.8. Storm impact validation

Qualitative and semi-quantitative analyses were used to validate present-day storm impact predictions. For the qualitative validation, predicted present-day storm regimes were compared with observations of past storm impacts in the literature, and field observations of large winter storms in the 2023–2025 winter storm seasons for six locations around Scotland's coast ([Fig. 5](#)). Specifically, it was evaluated whether areas of observed storm-driven dune erosion corresponded with Collision predictions, and whether areas of observed storm-driven flooding or barrier breaching corresponded to high impact regime predictions of Overwash and Inundation. Next, in a semi-quantitative approach, predicted R_{high} elevations were compared with observations, obtained from reported storm-driven TWL in the literature, and field observations of extreme TWL during the largest winter storms of 2023–2025, the latter derived via proxy from elevations of dune erosion, debris lines and

barrier breaching. As a final validation step, R_{high} was predicted using the observed wave climate and ESL during the peak of the storm. Comparison with observed R_{high} then allowed the performance of the runoff equation to be evaluated.

3. Results

3.1. Present-day storm impacts

3.1.1. National overview

Storm impacts in Scotland's 640 km of wave-dominated sedimentary coasts show considerable along-coast variation ([Fig. 4](#)). For the present day, a total of 100 m (0.02%) and 416 km (65%) of assessed coast are modelled to experience Swash and Collision as the most severe storm impact, respectively. The majority of natural barriers are thus modelled as effective present-day coastal buffers by eroding during storms and providing flood protection to the hinterland. For the remainder of the coast assessed, 72 km (11%) of natural barriers are predicted to experience Overwash and 27 km (4%) are predicted to experience Inundation as the most severe present-day storm impact, indicating areas where storm-driven coastal flooding of natural barriers is already likely ([Fig. 4](#)).

3.1.2. Validation

Overall, there was excellent agreement between present-day storm impact predictions and observations of barrier erosion, overwash and breaching in the six sites considered (Fig. 5). Observations of dune erosion, consistent with a Collision regime, were prevalent at Howmore, Stevenston, Montrose and St Andrews (Fig. 5b, c, e, f), while observations of spit breaching and significant inland flooding were consistent

with predicted Overwash and Inundation in Gualan (Fig. 5a). Along-shore variation between Collision, Overwash and Inundation was observed for different sectors of Golspie, as predicted for the present-day storm impact regimes (Fig. 5d).

Across the five locations included in the semi-quantitative validation (Table 2), the observed wave climate was more extreme than the synthetic wave climate, indicating that this assessment is not

Table 2
Comparison of predicted and observed total water levels and hydrodynamics during the peak of the storm. Location numbers correspond to labels in Fig. 5. H_s = deepwater wave height, T_p = deepwater peak wave period, ESL = tide + storm surge elevation, $R_{2\%}$ = extreme wave runoff, R_{high} = $ESL + R_{2\%}$.

Loc	A. Field observation	B. Synthetic forcing				C. Observed forcing, storm peak		
	Observed R_{high} (mOD)	H_s (m), T_p (s), ESL (mOD)	Predicted $R_{2\%}$ (m)	Predicted R_{high} (mOD)		H_s (m), T_p (s), ESL (mOD)	Predicted $R_{2\%}$ (m)	Predicted R_{high} (mOD)
b	2.5–3.5	8.8, 17.6, 3.0	2.8	5.8		14.7, 20.0, −1.4	4.1	2.7
c	3.7–4.0	2.5, 9.1, 3.3	0.8	4.1		4.2, 10.0, 2.7	1.1	3.8
d1	>3.8	3.1, 12.5, 3.1	1.2	4.3		5.0, 12.5, 2.2	1.5	3.7
d2	5.2–5.6	3.1, 12.5, 3.1	1.5	4.6		5.0, 12.5, 2.2	1.5	3.7
d3	>3.3–4.0	3.1, 12.5, 3.1	1.5	4.6		5.0, 12.5, 2.2	1.5	3.7

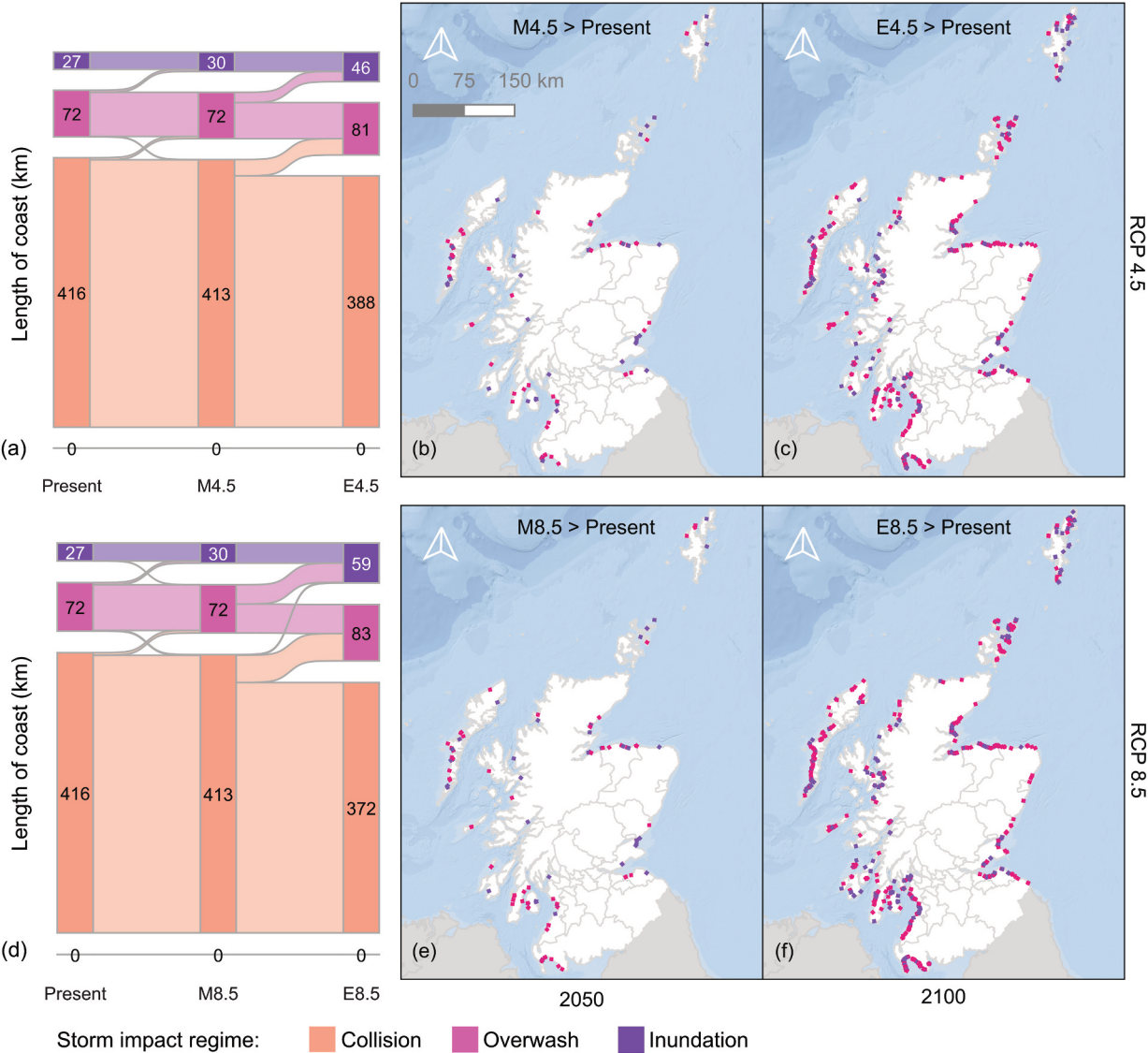


Fig. 6. Total length of Scotland's wave-dominated sedimentary coast in each storm regime, assessed for natural barriers. Flows from the present day to mid-century (M) and end-century (E), for (a) RCP4.5 (4.5) and (d) RCP8.5 (8.5). Locations with more severe impacts than the present day for (b) mid-century RCP4.5, (c) end-century RCP4.5, (e) mid-century RCP8.5, (f) end-century RCP8.5. Basemap: Esri World Ocean Base.

Table 3

Total length of coast in each storm impact regime for the present day, 2050 and 2100, considering an intermediate (RCP4.5) and high (RCP8.5) emissions scenario. Percentage of coast assessed in brackets. Results for coasts with natural barriers. Final column shows predictions when using a traditional Bruun approach to adjust barrier elevations for sea level rise.

Storm impact regime	Present day	2050 (RCP4.5 and RCP8.5)	2100 (RCP4.5)	2100 (RCP8.5)	2100 (RCP8.5) Bruun
Swash	100 m (0.02%)	100 m (0.02%)	100 m (0.02%)	100 m (0.02%)	100 m (0.02%)
Collision	416 km (65%)	413 km (65%)	388 km (61%)	372 km (58%)	418 km (81%)
Overwash	72 km (11%)	72 km (11%)	81 km (13%)	83 km (13%)	70 km (14%)
Inundation	27 km (4%)	30 km (5%)	46 km (7%)	59 km (9%)	26 km (5%)

overestimating the wave climate in the choice of synthetic storm. The impact of this difference in wave climate on predictions of $R_{2\%}$ was relatively small, exceeding 0.3 m only in location b in the exposed Outer Hebrides (Table 2). In comparison, tide and storm surge elevations during the peak of the storm were found to play a critical role in predicted total water levels, with good agreement between predicted and observed R_{high} where the storm peak coincided with high tide (as modelled) in locations c, d1 and d3, and overprediction of R_{high} where the storm peak coincided with low tide in location b (Table 2 columns A and B). Finally, estimating R_{high} with the observed forcing conditions, thus isolating the performance of the runup equation, showed very good agreement with observed R_{high} in locations b, c, d1 and d3 (Table 2 columns A and C). For location d2, a local stretch of coast enforced with rock armour on the back beach, R_{high} was underpredicted (3.7 m) when compared to observations of wave-thrown debris (5.2–5.6 m), indicating that the empirical parameterisations used in this study, developed for natural beaches, are likely unsuitable in human-modified coasts. Please refer to Supplementary material S5 for more details about the validation of present-day storm impacts.

3.2. Future storm impacts

By 2050, differences in predicted storm impacts between the scenarios considered are limited, with an upward shift in storm impacts for a total of ~3 km of coastal barriers for both RCP4.5 (Fig. 6a, b) and

RCP8.5 (Fig. 6d, e). By 2100, differences between scenarios are more pronounced, with substantial increases in the total length of coast predicted to experience Overwash and Inundation, both for RCP4.5 (Fig. 6a, c) and RCP8.5 (Fig. 6d, f). The largest predicted increase in 2100 is in the Inundation regime, with the total length of inundated coast approximately doubling by 2100, regardless of emissions scenario (Fig. 6a, d, Table 3).

To test the sensitivity of future predictions to the chosen model of barrier evolution, results were compared with those predicted following a traditional Bruun approach (Bruun, 1988). It was found that the Bruun approach yielded 418 km of coast in Collision, 70 km in Overwash and 26 km in Inundation under RCP8.5 in 2100 (details in Supplementary material S4). Storm impact predictions using a traditional Bruun approach are thus less severe than the RCP8.5 2100 predictions from this study, and in fact very similar to present-day predictions (Table 3). This is considered in Section 4.3 of the discussion.

Patterns of storm impact regime upshift were also predicted for transects without natural barriers (125 km of coast). For the present day, in the absence of natural barriers an estimated 14 km (2.1%) and 10 km (1.5%) of coast assessed have coastal assets vulnerable to Overwash and Inundation, respectively (Fig. 7). Here too, there are limited differences between emissions scenarios by 2050, with an additional 2–3 km of coast predicted to have assets vulnerable to Inundation under RCP4.5 (Fig. 7a) and RCP8.5 (Fig. 7b). By the end of the century, 18 km (21 km) of no-barrier transects have coastal assets predicted to experience Inundation as the most severe storm impact under RCP4.5 (RCP 8.5). As for transects with natural barriers, this represents a near doubling of inundated coast compared to the present day, regardless of emissions scenario.

3.3. Sub-national storm impacts

To analyse results at the sub-national level, storm impacts were grouped according to coastal sedimentary cells, as used by other national-scale coastal assessments in Scotland (Rennie et al., 2021). Here we present results for natural barriers for the present day and the end-century under RCP8.5 scenario. Results for all scenarios, including no-barrier storm impacts, are provided in Supplementary material S6.

Coastal cells vary in length and coastal type (Ramsay and Brampton, 2000), and accordingly there are large differences in the contributions of individual coastal cells to the assessment. For example, cells 3, 5 and 9 contain the longest stretches of sedimentary coast and each contributed 90–130 km to the coast assessed, while cells 4 and 8 have predominantly

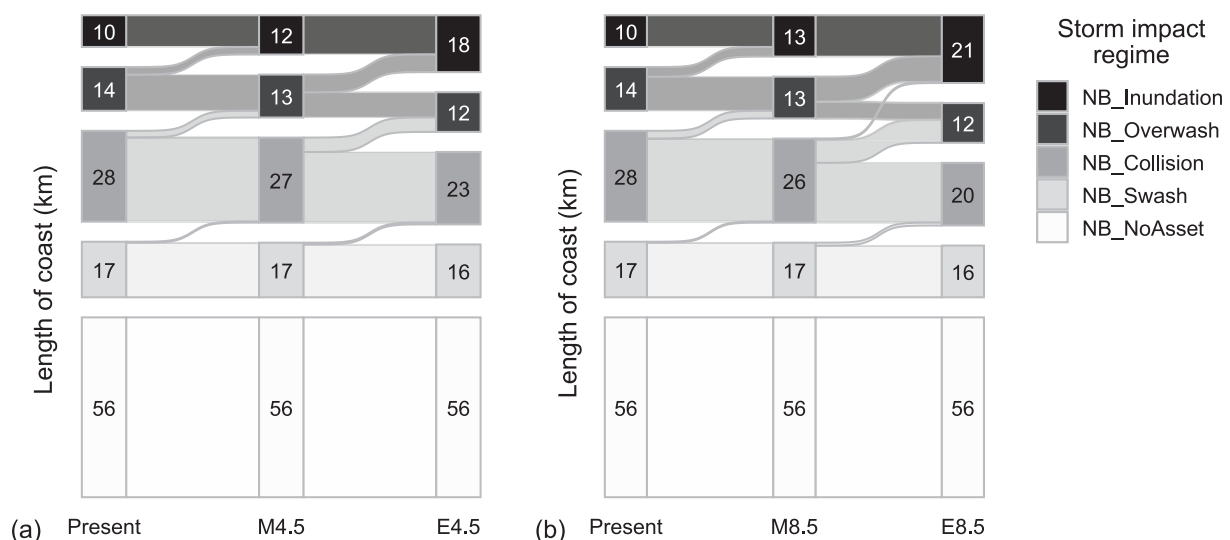


Fig. 7. Total length of Scotland's wave-dominated sedimentary coast in each storm impact regime, assessed for coasts without natural barriers. Flows from the present day to mid-century (M) and end-century (E), for (a) RCP4.5 (4.5) and (b) RCP8.5 (8.5). The different no-barrier storm impact regimes are defined in Table 1.

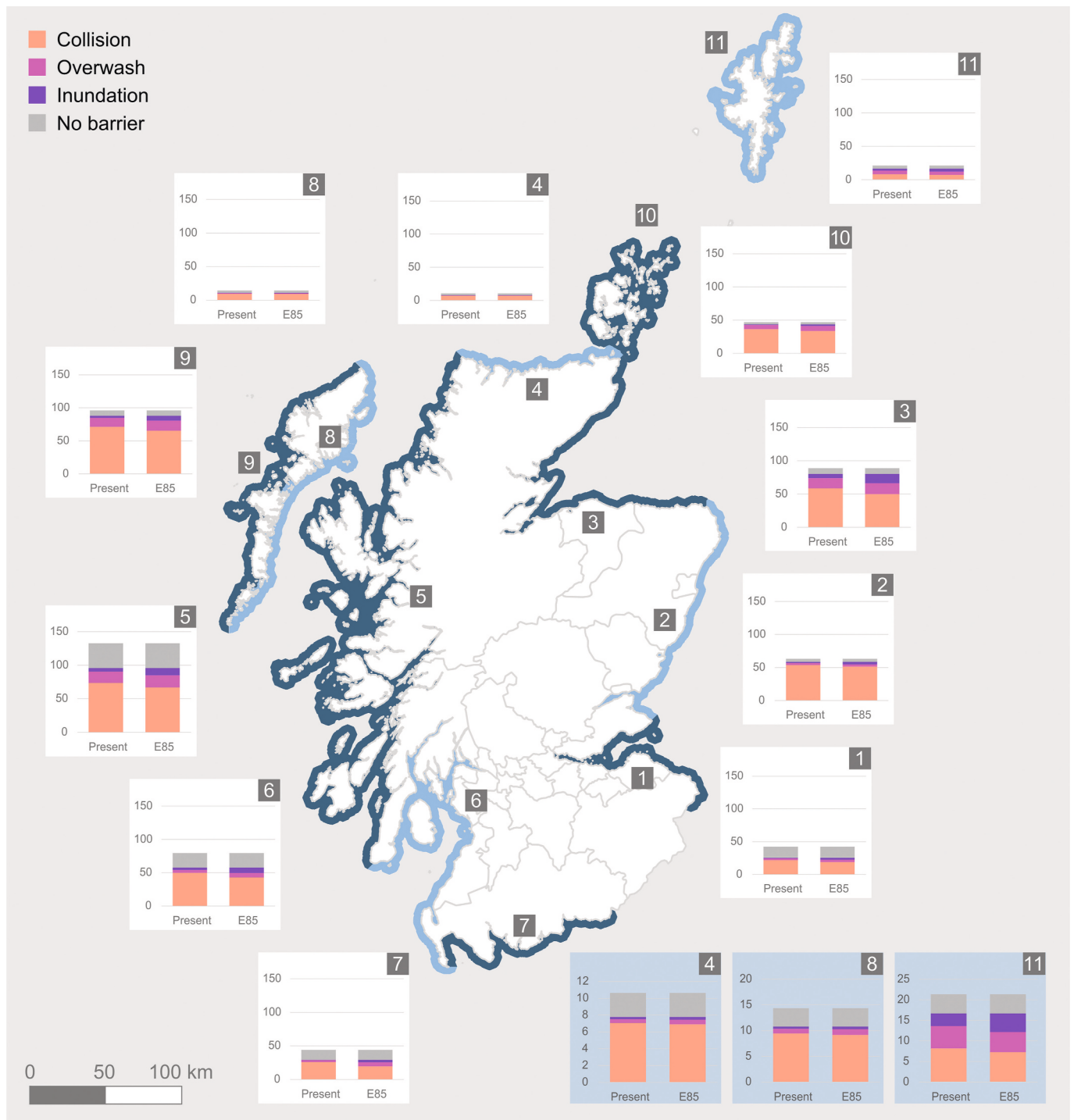


Fig. 8. Length of coast (km) in each storm regime per coastal cell (numbered) for Scotland's wave-dominated sedimentary coasts. Results for the present day and end-century RCP8.5 (E85). Bar charts share a common y-axis scale to illustrate regional variation. Cells 4, 8 and 11 are duplicated in insets in the bottom right corner with smaller y-axes to show information not readable on the common y-axis.

rocky coasts and made only minor contributions (11–14 km). This regional variation is illustrated by the height of the bar charts in Fig. 8 that show the length of coast included in the assessment in each coastal cell, plotted on the same vertical axis. In addition to this spectrum of coastal typologies, there are gradients in storm exposure around the coast, all of which contribute to considerable variation in storm impacts between coastal cells.

Areas of more extreme present-day storm impacts include the exposed coasts of cells 3 (Moray Firth), 5 (west coast of Scotland's

mainland) and 9 (west coast of the Outer Hebrides), that contain the longest lengths of coast with natural barriers presently experiencing the higher storm impact regimes of Overwash and Inundation, each impacting between 17 and 22 km of coast. Proportionately, cell 11 (Shetland) has the largest percentage of coast experiencing high impact regimes (40%, with 8.5 km out of 21 km assessed), suggesting that coastal barriers are also considerably exposed to storm impacts, despite the minor contribution to the national totals. In contrast, cell 2 (central east coast of Scotland's mainland) has one of the lowest percentages of

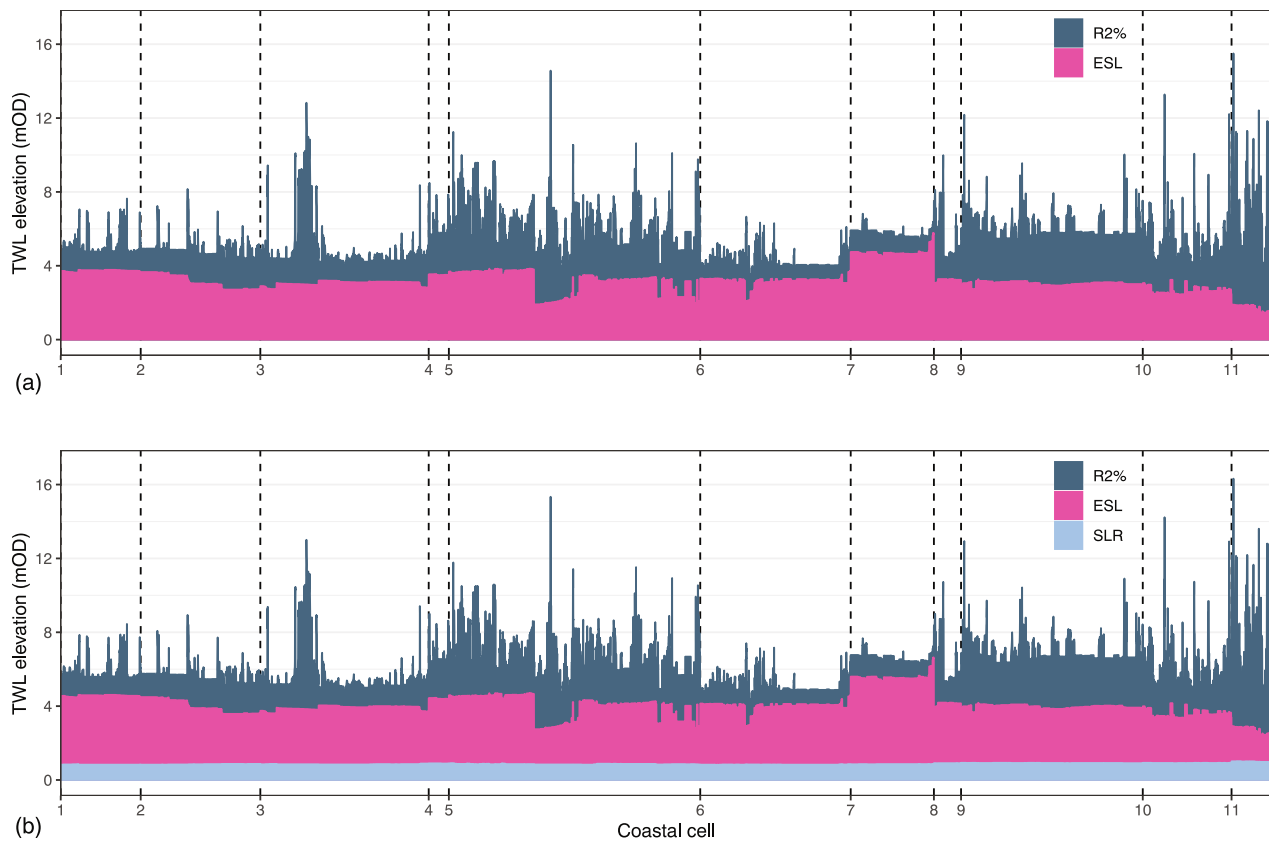


Fig. 9. Storm-driven total water level (TWL) components for Scotland's wave-dominated sedimentary coasts. Results for the whole coast, grouped according to coastal cell. (a) Present day. (b) Scenario RCP8.5 in 2100, with SLR relative to 2020. TWL elevation in meters above ordnance datum (Newlyn). $R_{2\%}$ = extreme wave runup; ESL = extreme still water levels from tides and storm surge; SLR = sea level rise. Coastal cells numbered as in Fig. 8.

present-day high impact regimes (8%, with 5 km out of 63 km assessed), which indicates that the mature beach-dune systems in cell 2 are acting as effective storm buffers (Fig. 8).

The overall increase in the length of coast exposed to high impact regimes towards the end of the century found at the national level is reflected in an increase in Overwash and Inundation in all coastal cells. Patterns of exposure remain the same, with the highest projected future impacts to natural barriers in cells 3, 5 and 9, each with between 23 and 30 km of coast in Overwash or Inundation by 2100. Shetland remains the coastal cell with the largest proportion of coast in high impact regimes. Cell 3 is however predicted to experience the largest increase in storm impact regime, with an additional 8.8 km of coast in Overwash or Inundation by 2100 (Fig. 8).

3.4. Hydrodynamic components of storm forcing

The variation in storm impacts around the coast reflects partly the regional variation in extreme still water levels and wave runup. For example, $R_{2\%}$ can raise the sea surface by 6–8 m above still water levels and account for 50% or more of extreme TWL in parts of cell 3 (Moray Firth), 5 (west coast of Scotland's mainland), 9 (west coast of the Outer Hebrides), 10 (Orkney) and 11 (Shetland). These areas, exposed to intense wave forcing, represent 103 km (16%) of the assessed coast (Fig. 9a). In contrast, the most sheltered coasts are in cells 6 (Irish Sea) and 7 (Solway Firth) where extreme TWL are dominated by tides and storm surge, and $R_{2\%}$ is in the order of 1 m, accounting for ~20% of present-day extreme TWL. These sheltered areas represent 70 km (11%) of the assessed coast (Fig. 9a, Fig. 10). For the remaining 467 km (73%) of coast assessed, $R_{2\%}$ contributes between 20% and 50% to extreme TWL, indicating a significant, albeit not dominant storm wave component. On average, $R_{2\%}$ contributes 38% to overall extreme TWL for the

present day. Towards the end of the century, patterns of exposure around the coast remain the same, with minor changes in predicted wave runup. The most significant change to future TWL elevations is driven by the addition of mean sea level rise (Fig. 9b). By 2100, $R_{2\%}$ is predicted to contribute 32% to overall extreme TWL.

When considering the changes in extreme TWL between the present day and end of century, a mean increase in extreme TWL of 0.84 m is projected under scenario E8.5, with local increases between ~0.4 m and ~1.6 m (Fig. 11a). Changes in TWL components indicate that SLR dominates the increase towards the end of the century with a mean change in ESL of +0.87 m, while $R_{2\%}$ decreases by 0.03 m on average (Fig. 11b). There is local variation in predictions of future $R_{2\%}$ levels (Fig. 11b), with areas where wave runup contributions are expected to increase (parts of cells 9, 10 and 11), decrease (cells 1, 2, 3, 4, 8, parts of cells 5, 10 and 11) and remain at present day levels (majority of cells 5, 6, 7). Changes in future $R_{2\%}$ are driven by changes in future deepwater wave climate (Fig. 11c), which on average are modest, with a mean change of -0.05 m (-0.11 s) for H_{s99} (T_{p99}) by 2100 under RCP8.5. Thus, for most of the coast, only minor changes in $R_{2\%}$ are predicted towards the end of the century.

For 216 transects, representing 1.7% of the coast assessed, absolute changes in $R_{2\%}$ are more pronounced and exceed 0.25 m. Of these, 155 transects (1.2% of the coast assessed) have changes in future $R_{2\%}$ of up to ± 0.5 m, linked with changes in the dynamic wave steepness (represented by the Iribarren number ξ_0 , Eq. B1) which determines whether the intermediate/reflective ($\xi_0 \geq 0.3$, Eq. B2) or ultra-dissipative ($\xi_0 < 0.3$, Eq. B4) extreme wave runup equation for sandy beaches is used (Stockdon et al., 2006). For these 155 transects, when H_{s99} increases and T_{p99} decreases to a degree that switches the beach state to extremely dissipative (o symbols Fig. 11c), future $R_{2\%}$ estimates decrease with Eq. B4. Conversely, when T_{p99} increases and H_{s99} decreases to a degree that

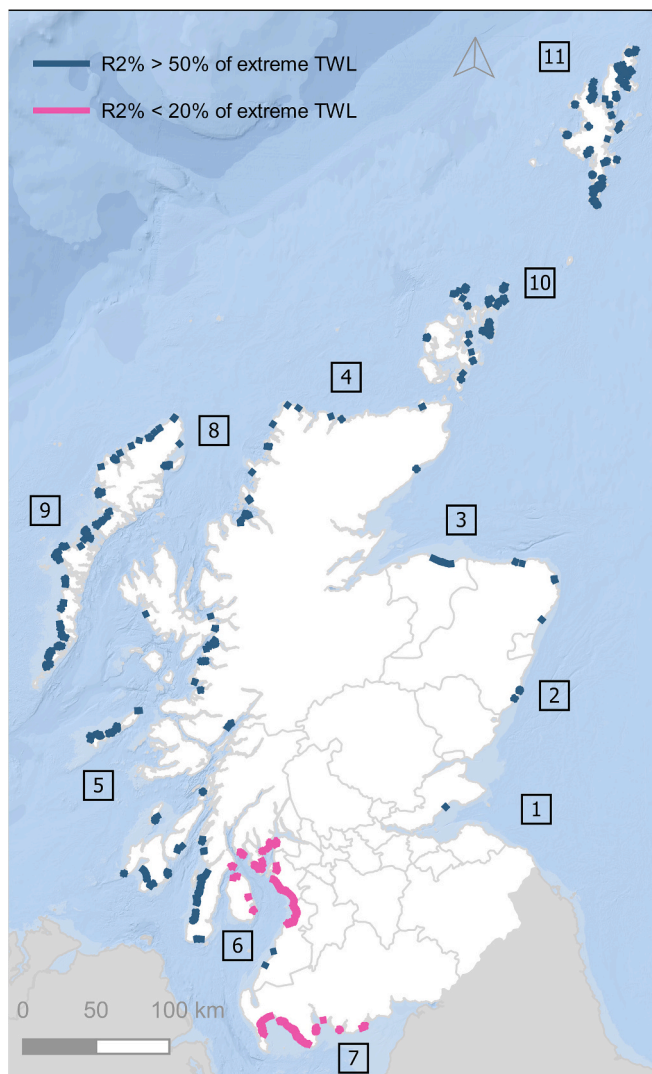


Fig. 10. The spatial distribution of areas where present-day extreme total water levels are dominated by extreme wave runoff (blue) and tides and storm surge (pink). $R_{2\%}$ = extreme wave runoff; TWL = extreme total water level. Coastal cells (numbered) as in Fig. 8. Basemap: Esri World Ocean Base.

switches the beach state to intermediate/reflective (+ symbols Fig. 11c), future $R_{2\%}$ estimates increase with Eq. B2. It is not possible to determine whether this is purely a mathematical artefact of the empirical parameterisation, or whether local changes in future wave climate may indeed cause beaches to change between dissipative and intermediate/reflective conditions and drive larger changes in $R_{2\%}$. However, in 98.8% of the coast assessed, predicted changes in H_{s99} and T_{p99} are not large enough to induce a change in dynamic wave steepness that crosses the $\xi_0 = 0.3$ threshold, and changes in predicted future runoff are exclusively related to changes in H_{s99} and T_{p99} within the same beach state.

4. Discussion

Reflecting on the research objectives outlined in Section 1, the discussion first considers the methodological development of the national-scale assessment (Section 4.1), followed by wave runoff contributions to extreme TWL around the coast (Section 4.2). Next, it considers the prediction of future storm impacts (Section 4.3) and concludes with examples of how this research can be applied in practical adaptation planning (Section 4.4).

4.1. Development of a national-scale storm impact assessment

This work integrated topographic analysis and extreme sea levels that include wave runoff, tides and storm surge, to assess storm impacts for all of Scotland's wave-dominated sand and gravel coasts. In addition to present-day storm impacts, future impacts were considered for two IPCC AR5 climate scenarios RCP4.5 and RCP8.5 in 2050 and 2100. Results show substantial variation in extreme TWL and storm impacts to natural barriers around the coast, adding information at the sub-national to local scale that does not exist in current national and European assessments (Chaigneau et al., 2024; Cotrim et al., 2025; Kirezci et al., 2020; Vousdoukas et al., 2017). Higher resolution predictions at 50 m alongshore were achieved via detailed topographic and hydrodynamic forcing data, intertidal slopes derived at the transect level that capture local longshore variability in the beach, and the use of parametric runoff equations specific to sediment type (sand, composite sand and gravel, or pure gravel) and beach typology (dissipative, intermediate or reflective).

Predictions of $R_{2\%}$ were found not to be highly sensitive to variations in storm wave climate, which is in line with Stockdon et al. (2023) who reported inaccurate estimates of intertidal slope (rather than wave forcing) were the largest source of uncertainty in $R_{2\%}$ predictions. This emphasises the benefit of local intertidal slope estimates used here, over the use of a single intertidal slope value for entire countries or regions in empirical parameterisations of $R_{2\%}$ (e.g., Chaigneau et al., 2024; Kirezci et al., 2020). To assess the impact of potential uncertainty in intertidal slope estimation, present-day $R_{2\%}$ was also determined for a $\pm 10\%$ range in the intertidal slope in each transect (Supplementary material S7). Changes in predicted $R_{2\%}$ were more pronounced in exposed coasts, in steeper intermediate-reflective beaches, and where the beach state is near the threshold of ultra-dissipative to intermediate-reflective conditions. In these sites, uncertainty in intertidal slope estimates have a larger impact on $R_{2\%}$ predictions. However, for 50% of the coast assessed, the beach type remained ultra-dissipative across the $\pm 10\%$ intertidal slope range, resulting in no change in $R_{2\%}$ as the ultra-dissipative parameterisation is independent of beach slope. In these areas, uncertainty in slope estimates has no impact on predicted $R_{2\%}$ elevations.

Validation of present-day storm impact predictions showed good agreement between predicted and observed storm impact regimes for a range of coastal typologies and locations, confirming the representativeness of our choice of synthetic storm of the most energetic winter storm coinciding with a high tide. Validation also confirmed good performance of the empirical parameterisations reported in the literature (Gomes da Silva et al., 2020; Hovenga et al., 2021; Matias et al., 2012), with predicted TWL elevations on natural beaches falling within the ranges observed during recent storm events. A noted exception was an engineered sector of coast where prediction performance was poor. This stretch of coast had been included in the assessment due to the limited amount of rock armour that exists on the back beach, and the mildly sloped sandy beach and nearshore that falls within the scope of the Stockdon et al. (2006) parameterisations. However, results demonstrate that the presence of even a small rock armour served to modify the beach behaviour under storm conditions to the extent that $R_{2\%}$ was under-predicted by approximately 1.5 m, compared to a lesser modified adjacent stretch of coast (Table 2). This emphasises the need for caution in applying empirical parameterisations that were developed for natural beaches, in human modified settings. Nonetheless, this study demonstrates the use of national datasets and simple empirical parameterisations to provide first-order estimates of extreme wave runoff and storm impacts to natural barriers, at a resolution that bridges the gap between global- and local-scale storm impact assessments, in a tiered approach to coastal adaptation planning.

Such a tiered approach is widely acknowledged as an efficient and necessary way in which to tackle coastal adaptation challenges (Brodie et al., 2025; Celedón et al., 2023; Lebbe et al., 2021; Turner et al., 2024;

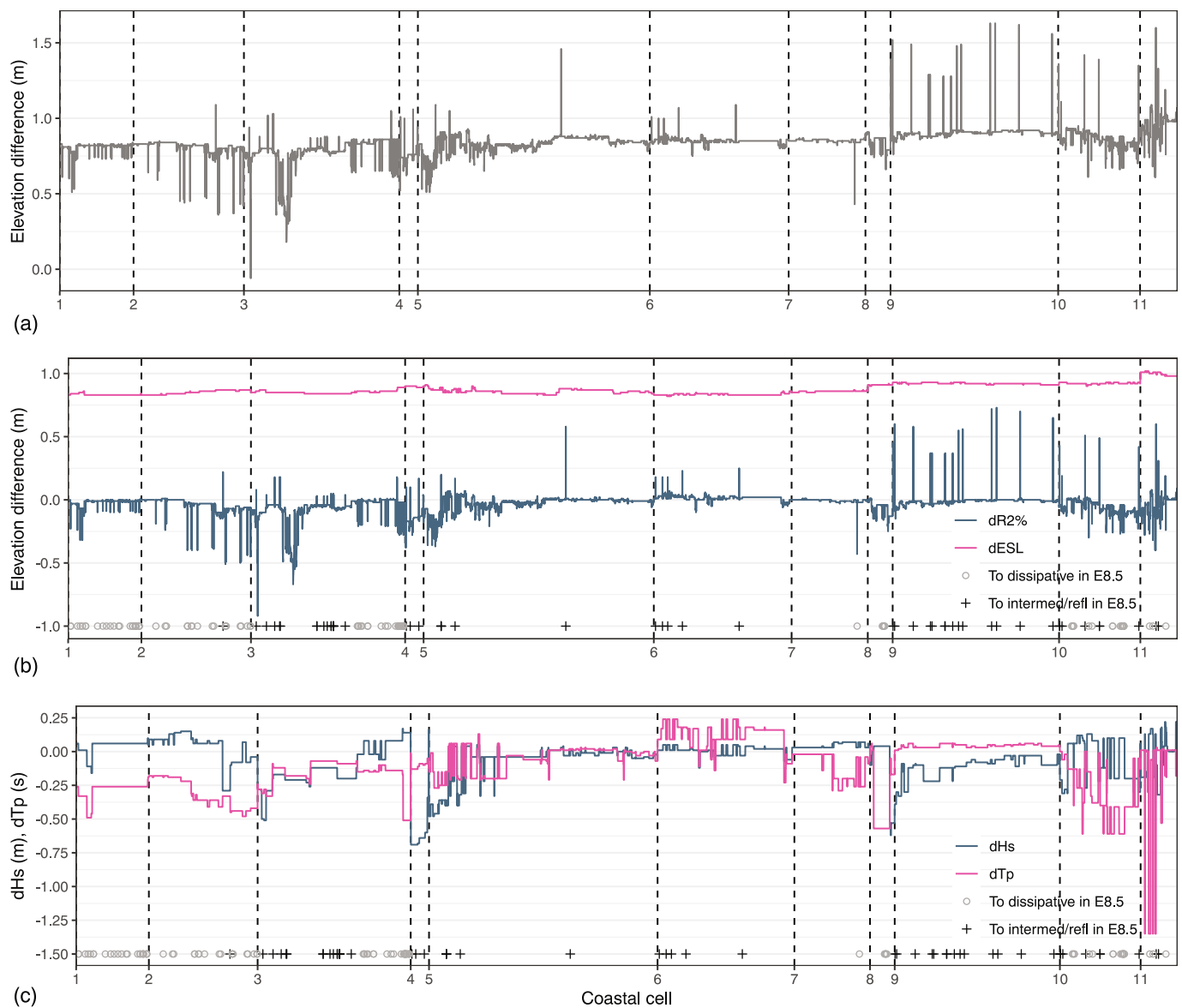


Fig. 11. Change in hydrodynamic components between the present day and end-century RCP8.5 scenario. Results for the whole coast, grouped according to coastal cell. (a) Change in overall extreme total water level (TWL). (b) Change in TWL components. dR2% = change in extreme wave runup, dESL = change in extreme still water levels of tides storm surge and mean sea level. (c) Change in 99th percentile deepwater significant wave height (dH_s) and peak wave period (dTp). Symbols + and o indicate a change of beach state due to changes in future wave climate. Coastal cells (numbered) as in Fig. 8.

Viavattene et al., 2018; Vitousek et al., 2023). However, the national scale of this assessment required simplifications related to methodology and input data, which will be considered next. Methodologically, summing the respective hydrodynamic components to derive extreme total water level neglects possible interactions between waves, storm surge and tides. As highlighted by Vousdoulas et al. (2017), there are potential non-linear effects where interaction between these components could influence storm wave runup. These complexities can be assessed with coupled numerical ocean, atmospheric and wave models, for example COAWST (Hashemi et al., 2014) and CoSMoS (Sembiring et al., 2015) or more recently with ADCIRC-SWAN-XBeach (Jamous and Marsooli, 2026), but high computational costs and short simulation periods make these approaches more suited to operational forecasts linked with specific storm events along specific coastal locations. Another methodological simplification was to not use a probabilistic approach, where probability density functions (PDFs) of each of the hydrodynamic components are combined to derive an overall PDF for extreme TWL (Jevrejeva et al., 2023; Vousdoulas et al., 2017;

Vousdoulas et al., 2018). Studies using a probabilistic approach explicitly consider uncertainty through the relative contributions of each hydrodynamic component both to extreme TWL and the combined uncertainty, and give in-depth understanding of the statistical distribution of extreme water levels. Such an explicit consideration of uncertainty was however outside the scope of this research, for which the aim was to use event-based storylines (e.g., Celedón et al., 2023; Romero-Martin et al., 2024) to identify areas where sedimentary barriers are expected to face greater storm impacts this century, rather than the quantification of the probability of the impacts occurring. Event-based storylines are increasingly used in climate change research and communication to frame hazard and risk, and are particularly useful where multiple hazards coincide, driving deep uncertainty. By presenting scenarios as a plausible, rather than probabilistic, combination of factors (in this study, the coincidence of the largest storm of the year with a high spring tide), event-based storylines align with how people perceive and respond to risk (Shepherd et al., 2018). This approach also aids adaptation planning by allowing coastal managers to work

backward from an identified vulnerability or decision point, linking closely with dynamic adaptation pathways (Haasnoot et al., 2019) that are now widely used in adaptation planning in Scotland (<https://www.dynamiccoast.com/cca>) and elsewhere.

The choices in hydrodynamic forcing also have implications for the key findings. Firstly, extreme still water levels were characterised with 25-year return levels for tides and storm surge. This is similar to the 30-year return levels of Toimil et al. (2023), but not as extreme as the 100-year return levels of Jevrejeva et al. (2023) and Kirezci et al. (2020) who considered low-probability high-impact events. Secondly, the wave data used are derived from the Stand Alone Wave (SAW) model of the European Centre for Medium-Range Weather Forecasts, forced with surface wind from the EURO-CORDEX regional climate model (Copernicus Climate Change Service, 2020). Wave parameters are thus the result of a single model as opposed to an ensemble, with uncertainty related to the predictive skill of this model. Additionally, Castelle et al. (2018) found that the winter wave climate in the Northeast Atlantic has increased in intensity and variability over the last 70 years, but that it is not yet clear whether this is caused by climate change or regional climate oscillations. Such effects are not included in the current regional wave model, and so, if climate change should drive a more extreme future winter wave climate around the coast of Scotland, as suggested by emerging evidence (Bricheno et al., 2025), future extreme wave runup may be underestimated. Nonetheless, SAW outputs were found to compare favourably with the ERA5 benchmark data (Copernicus Climate Change Service, 2020), and it was judged as the best available national-scale projections of the coastal storm wave climate (see also Marino et al., 2025). Finally, in addition to hydrodynamic forcing, storm impacts are also influenced by storm duration and frequency (Kümmerer et al., 2023; Turner et al., 2024), which was not considered in this assessment.

4.2. Wave contributions to extreme total water levels

As found in the US Atlantic coast (Stockdon et al., 2023), in Scotland there are 103 km (16%) of exposed coast where $R_{2\%}$ presently contributes over 50% of extreme TWL. These areas are concentrated in the west coast of the Outer Hebrides and the Scottish mainland (cells 9 and 5), part of the Moray Firth (cell 3), and the islands of Orkney and Shetland (cells 10 and 11), and regularly face intense storm systems from the Atlantic and North Sea extratropical cyclones. While not all coasts are subjected to this intensity in wave forcing, there are nonetheless 570 km (89%) of coast assessed where $R_{2\%}$ presently contributes over 20% of extreme TWL. Omitting extreme wave runup from flood risk assessments could therefore result in significant underpredictions of the actual water levels experienced during storms. Furthermore, even under a high-end SLR projection by 2100, $R_{2\%}$ is expected to contribute on average 32% of extreme TWL for the assessed coast, compared with 38% today. This sustained contribution of wave runup to extreme TWL emphasises the importance of including wave-driven extreme water levels in coastal flood risk assessments.

4.3. Future storm impacts

Storm impacts to natural barriers are predicted to intensify throughout this century, with a small increase in the length of coast experiencing Overwash or Inundation by 2050 both for RCP4.5 and RCP8.5, and more substantial increases in Overwash and Inundation by 2100, with larger increases under RCP8.5 (Table 3). As future storm impacts were obtained by combining future hydrodynamic forcing with future barrier toe and crest elevations, choices surrounding these components are considered next.

4.3.1. Future hydrodynamic forcing

For future extreme still water levels, it was assumed that tide and storm surge elevations will remain unchanged in 2050 and 2100, supported by national projections of no change in storm surge due to

changes in atmospheric storminess during the XXI century (Palmer et al., 2018). Accordingly, future ESL elevations were derived by uplifting present-day 25-year return levels of tide and storm surge by 95th percentile SLR for each climate scenario. As future ESL were uplifted by SLR, the choice of SLR scenario has a direct impact on the predicted future TWL elevations. To explore this effect, a limited sensitivity analysis (detailed in Supplementary material S8) demonstrates that using the 50th instead of 95th percentile SLR for the end-century RCP8.5 scenario results in a median reduction in future TWL of 0.36 m. However, this effect on TWL is an order of magnitude smaller than the effect of tidal elevation during the storm peak, which around Scotland's coast, can lead to a difference of 3 to 4 m of TWL between a high and low spring tide. This indicates that the end-century predictions are representative of an energetic storm coinciding with a high spring tide, and not highly sensitive to a particular SLR scenario.

Furthermore, the propagation of tides and storm surge also depends on water depth, and may thus be influenced by increases in mean sea level. Initial numerical modelling in national marine projections found insubstantial change in storm surge due to SLR, but identified potential spatial variation of tidal elevation changes around Scotland in response to SLR, with increases of up to 10–15% in the Irish sea and decreases of up to 5–10% to the north and west (Palmer et al., 2018). At present, these effects are only indicative, and were not included in this assessment.

Future extreme wave runup elevations were found to resemble present-day levels for most of the coast assessed in this study. As described in Section 3.4, this is due to only minor changes in the projected future deepwater wave climate. With no change in future tides and storm surge, and only minor changes in future wave runup, changes in future extreme TWL are thus dominated by SLR (Chaigneau et al., 2024; Jevrejeva et al., 2023; Kirezci et al., 2020; Vousdoukas et al., 2018; Vousdoukas et al., 2017). This explains the similarity in extreme TWL and storm impacts between RCP4.5 and RCP8.5 in 2050, as there is a difference of only ~4 cm in SLR between these scenarios. Once SLR intensifies towards 2100, differences between RCP4.5 and RCP8.5 are more pronounced, with more extreme impacts predicted under the high-SLR scenario of RCP8.5.

4.3.2. Future barrier morphology

Future barrier crest elevations were derived using a conceptual model, largely based on that of Psuty (2008), that uses past coastal change observations as a proxy for sediment budget to estimate whether a sedimentary barrier crest will keep pace with SLR. This simple model, applicable at the national scale, is different from other large-scale and long-term studies of storm impacts that either assume stationary coastal profiles (Kirezci et al., 2020) or use derivations of the Bruun rule to translate the shore profile landward and upward with SLR (Lemos et al., 2024b; Toimil et al., 2023). In reality, barrier evolution is highly site specific, depending on factors like local sediment budget, storm frequency, beach orientation, size of the dry beach, vegetation and meteorological factors like rainfall and snow (Brodie et al., 2025; Walker et al., 2017), and is also affected by coastal squeeze (Nicholls, 2018). While modifications to the Bruun rule aim to capture some of these processes (McCarroll et al., 2021), data requirements still rule out application at the national scale. The conceptual barrier evolution model used in this study offers a simple, national-scale approach that incorporates local sediment budget, one of the main drivers in barrier storm recovery and evolution, and the concepts of dune building and dune impact, to estimate vertical barrier evolution as SLR accelerates during the rest of the century.

Observations of present-day foredune evolution by Brodie et al. (2025) correspond with the modes of dune evolution proposed by Psuty (2008) and used in our study, and provide confidence in the processes underpinning the proposed conceptual model. However, uncertainty surrounding future storm climate (Castelle et al., 2018), the amount of SLR that may occur (Palmer et al., 2018) and the important

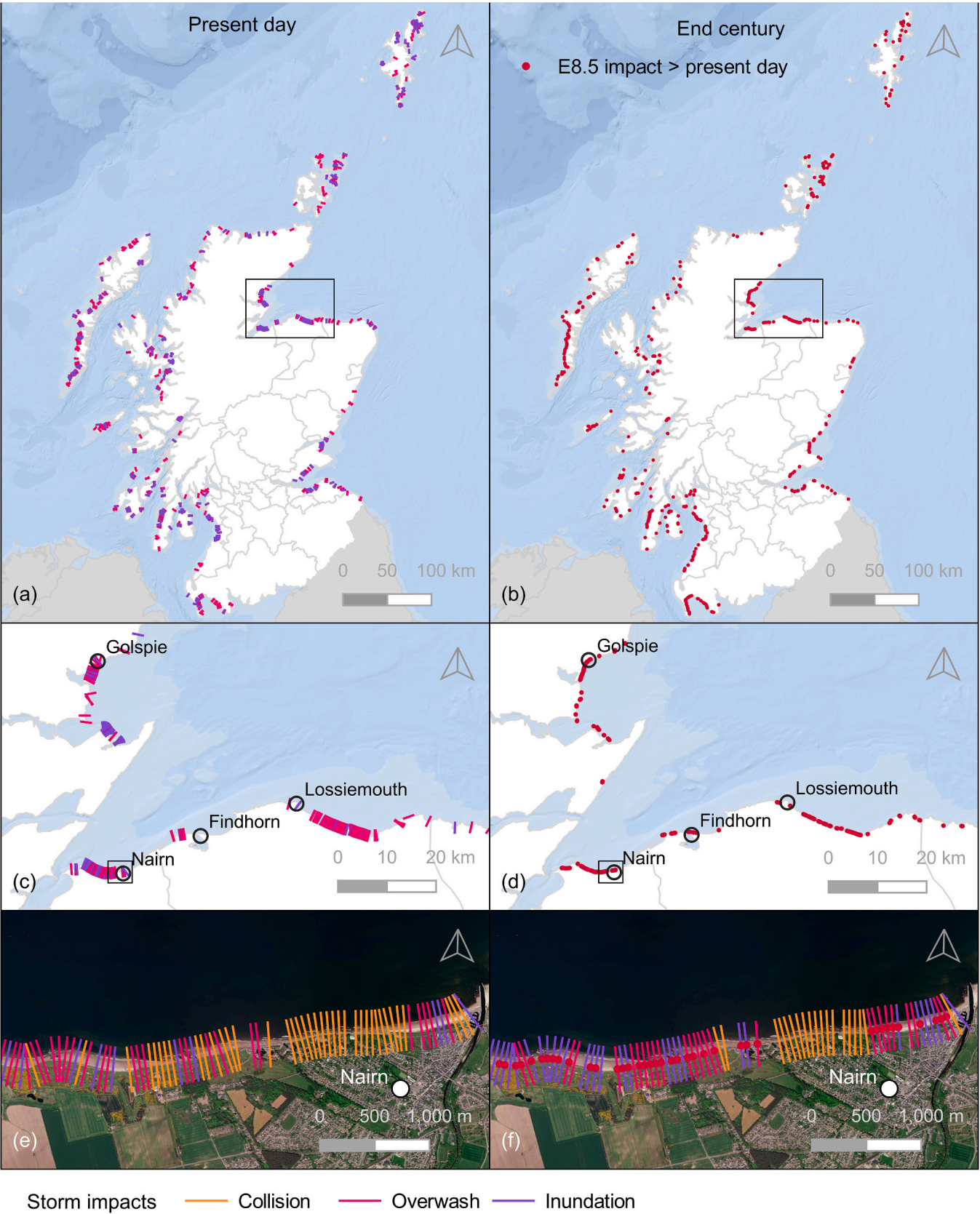


Fig. 12. Present and future storm impact hotspots at the national, regional and local scale. (a) Areas of present-day Overwash and Inundation. (b) Areas where storm impacts are predicted to intensify by 2100 under RCP8.5 (E8.5). (c, d) Regional focus on the Moray Firth highlights coastal settlements facing storm impacts. (e, f) Local focus on the town of Nairn highlights where natural barriers are most vulnerable to present-day storm impacts (e) and where end-century impacts are predicted to intensify (f).
Basemaps: Esri World Ocean Base, Esri World Imagery.

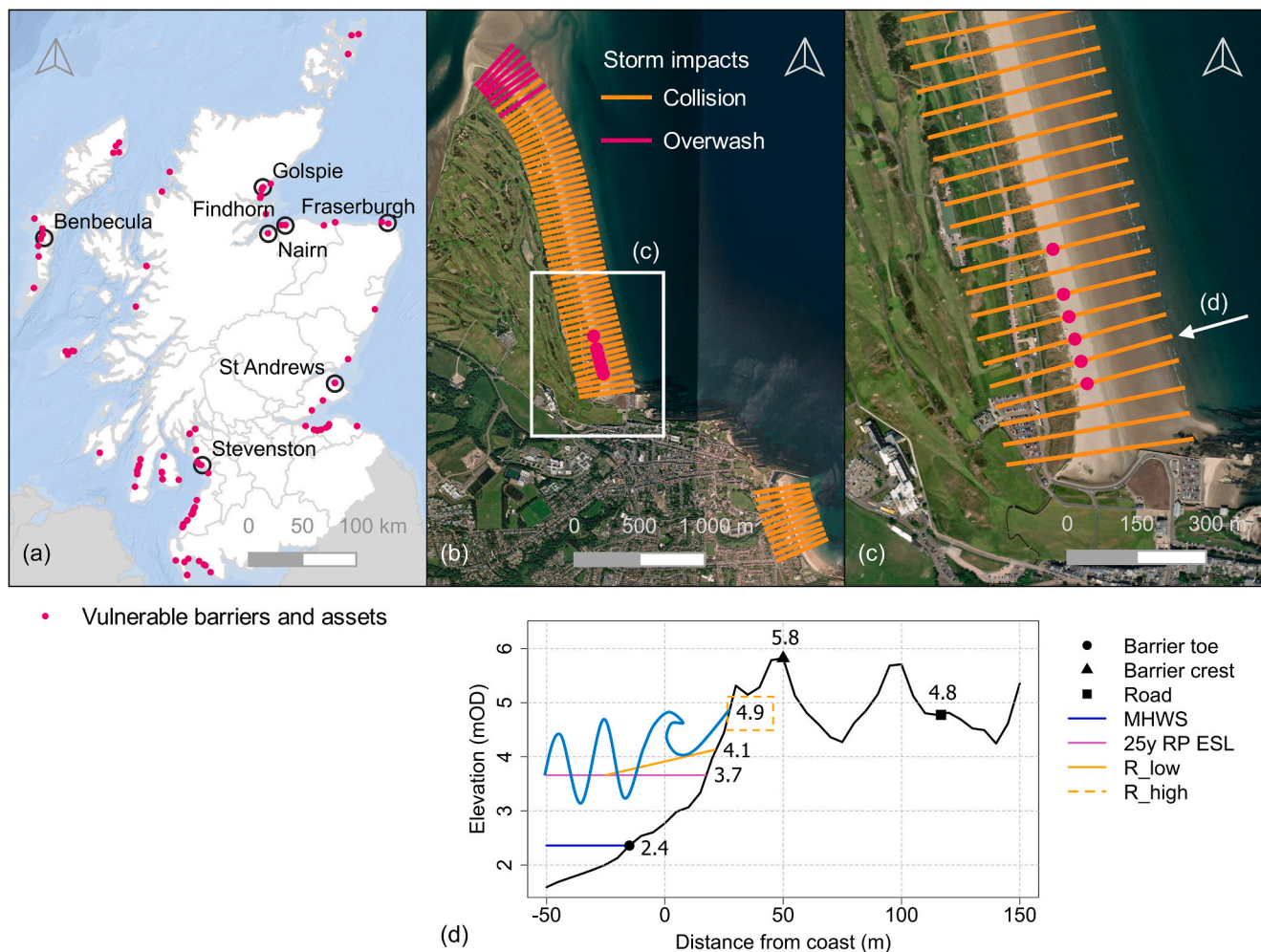


Fig. 13. Integration of storm impacts, asset data and wider coastal characteristics. Vulnerable barriers and assets defined as locations with present-day storm regime of Collision, low-lying assets (elevation <10 mOD) within 200 m of the shoreline, Overwash potential of less than 1 m, and a historically eroding coast. (a) National view. Shetland is excluded as it does not contain any locations in this selection. (b, c) Focus area of St Andrews (Fife) town and golf course: present-day storm regimes and vulnerable barriers and assets. (d) Example transect with interpolated topography profile, dune morphometrics, components of present-day extreme total water level, and first asset location. Elevation values in callouts. MHWS = mean high water springs; 25y RP ESL = 25-year return period of tides and storm surge; R_low = wave setup; R_high = wave runoff.

Basemaps: Esri World Ocean Base, Esri World Imagery.

role of local dune building factors other than the supply limitations considered in Section 2.7 (Masselink and van Heteren, 2014) are large sources of uncertainty in our conceptual model. Given this uncertainty, storm impact predictions were compared with those from a traditional Bruun approach, which is the most widely used alternative conceptual model in large scale temporal and spatial assessments. A sensitivity analysis showed that there is a 9% difference in end-century RCP8.5 storm impact predictions when comparing the above conceptual model of barrier evolution with a traditional Bruun approach, with the Bruun approach yielding 46 km (9%) more coast in Collision, balanced by 13 km (2%) less coast in Overwash and 33 km (7%) less coast in Inundation, compared to our predictions (Table 3). In fact, end-century RCP8.5 predictions using a Bruun approach show very little difference from the present day, with storm impacts predicted to become less severe for ~2 km of coast by 2100. Methodologically, this is because the Bruun approach uplifts all barrier crest elevations in line with SLR, which corresponds to increases in still water levels, as tides and storm surge elevations were assumed to remain unchanged in the future. This leads to zero relative change between still water levels and barrier crest elevations in the Bruun approach. The only factor that can thus alter future storm impacts is a change in wave runoff, which as shown in Section 3.4,

is predicted to show a minor decrease towards the end of the century. This slight decrease in wave runoff by 2100 thus leads to a downshift in storm regime for ~2 km of coast by 2100 compared to the present day, under the Bruun approach. It is argued that this small reduction in storm impacts predicted with a Bruun approach is not plausible, and does not reflect local sediment budgets or likely changes in dune building potential as SLR intensifies. With the alternative model of barrier evolution, this work aims to reflect potential increases in storm impact severity to barriers under large uncertainty. It provides a middle ground between keeping future barrier elevations and present-day values (which does not reflect multi-decadal coastal evolution), and simply increasing all barrier morphometrics in line with SLR, which has been heavily criticised (Cooper and Pilkey, 2004; Cooper et al., 2020).

4.4. Coastal management applications

Here we consider three examples of how research outputs can be used to inform practical adaptation planning as part of a tiered coastal management approach. Where future storm impacts are of interest, the climate scenario of RCP8.5 2100 (E8.5) is used.

Firstly, outputs of this analysis can be used to gain a strategic

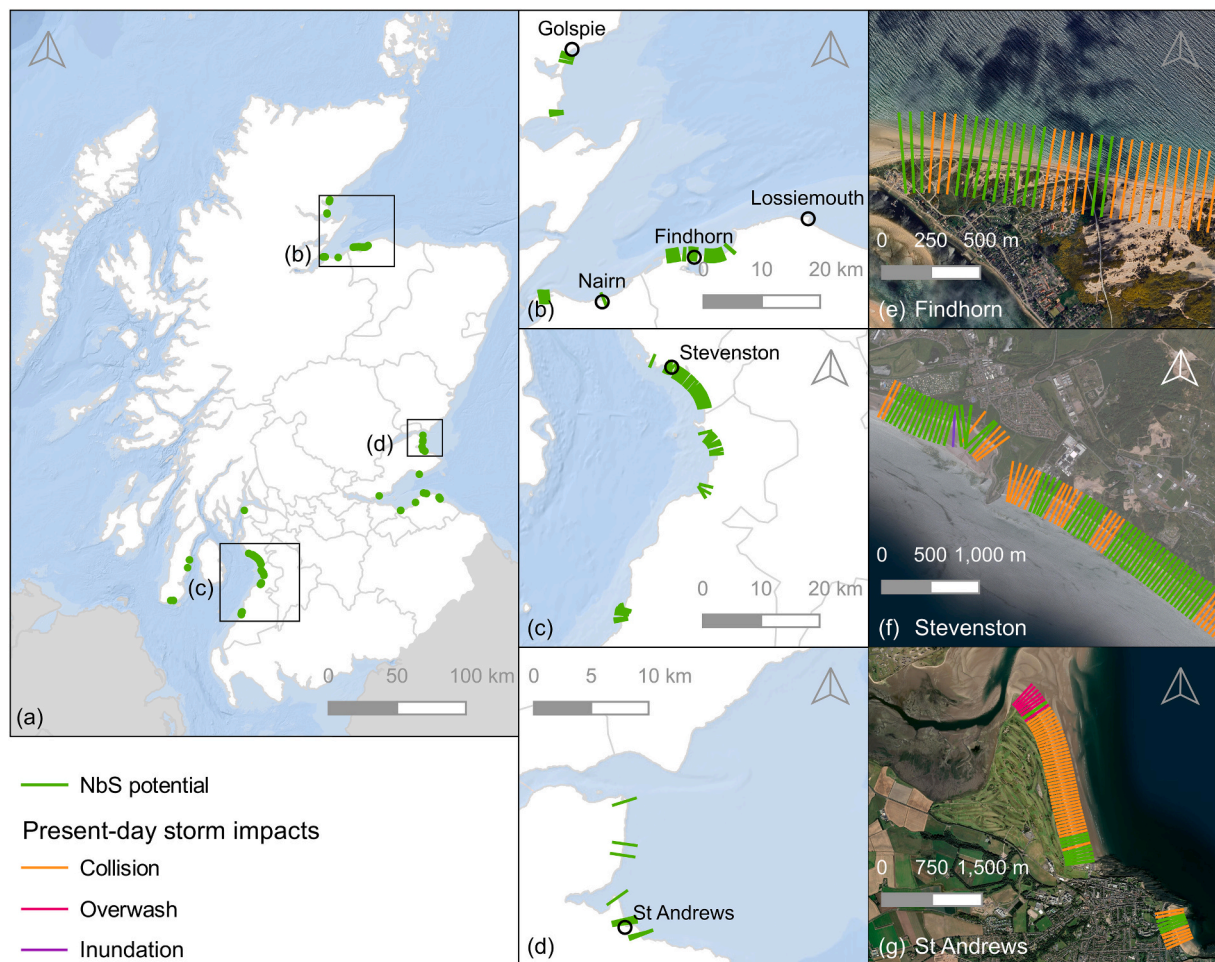


Fig. 14. Areas along Scotland wave-dominated sedimentary coast with potential for working with natural processes as a form of nature-based coastal adaptation (NbS potential). (a) National selection, defined as asset-containing locations (road, property or railway) with natural barriers currently in the Collision regime, with between 100 and 500 m of accommodation space between the coast and first asset, and a low-lying hinterland with mean elevation <10 mOD and mean slope < 3%. Areas exposed to intense wave forcing with $H_{599} > 3.5$ m or $T_{p99} > 14$ s were excluded. Shetland is excluded from the map as it does not contain any locations in this selection. (b, c, d) Areas in Scotland with the greatest concentration of coastal locations with NbS potential. (e, f, g) Regional view of areas with NbS potential, focusing on Findhorn (e), Stevenston (f) and St Andrews (g).

Basemaps: Esri World Ocean Base, Esri World Imagery.

understanding of storm impact hotspots. Nationally, there is a noticeable overlap between areas of present-day concentrations of Overwash or Inundation (Fig. 12a), and areas where storm impacts under scenario E8.5 are expected to intensify (Fig. 12b). As shown in Fig. 8, storm impact hotspots are concentrated in the western Outer Hebrides (cell 9) and the Moray Firth (cell 3), and represent potential high priority areas for coastal adaptation planning. This approach reduces the length of national coast under consideration from the whole coast of ~21,000 km to ~100 km in Fig. 12a. For the Moray Firth, the regional view shows that natural barriers fronting the coastal settlements of Golspie, Nairn, Findhorn and Lossiemouth are vulnerable to both present and future storm impacts (Fig. 12c, d). This can be considered in detail at the local level (Fig. 12e, f), to inform where along the local stretch of coast sedimentary barriers may be most at risk of flooding and erosion, and where to target detailed assessments, for example with numerical modelling (Jamous and Marsooli, 2026).

The next example demonstrates how integration of storm impacts, asset data and wider coastal characteristics can further inform coastal adaptation planning. For the present day, approximately 65% of Scotland's natural barriers are modelled in the Collision regime. The degree to which these barriers provide coastal protection depends both on the presence of coastal assets, and the barrier's morphological response under storm conditions, linked with the overarching trend of coastal

change. While it is not yet possible to accurately predict individual barrier morphological storm response at the national scale, the Overwash potential (OP) parameter, defined in Section 2.5 as the difference in elevation between the barrier crest and R_{high} , indicates how close the barrier is to experiencing Overwash for a given climate scenario, with decreasing positive values as the Overwash regime is approached. OP can thus give an indication of the level of protection against Overwash that a barrier provides. For example, by selecting barriers that are fronting low-lying coastal assets, in present-day Collision, with OP of less than 1 m, and where historic coastal change shows a trend of erosion, it is possible to identify where coastal barriers are currently providing important protection to communities and assets, but where this protection may face increasing pressure in the future (Fig. 13). Such vulnerable locations are found throughout Scotland's coast, but higher concentrations exist in the southwest, northeast and southeast. For example, results for St Andrews (Fig. 13b, c) evidence how a present-day OP of only 0.9 m could accelerate erosion of the foredune, which could put the secondary dune ridge, and ultimately the low-lying road (elevation 4.8 mOD) at risk of flooding (Fig. 13d). Considering a predicted R_{high} of 5.7 mOD under scenario E8.5, along with historic coastal erosion rates of 1 m/year, barriers in this part of the coast are likely to face increasing pressure as climate change intensifies, increasing flood risk to the low-lying assets behind. By considering asset location in

Table A.1
Summary of datasets used in the storm impact assessment.

Dataset	Format	Description	Purpose
Ocean surface wave indicators for Europe (Copernicus Climate Change Service, 2020)	NetCDF	Significant wave height and peak wave period ~11–16 km spacing	Wave component of marine storm forcing for present day, mid-century and end-century epochs
Extreme sea levels (Met Office Hadley Centre, 2023)	Vector	Point data of extreme still water levels (tides + storm surge + sea level rise) ~ 2 km spacing	Still water component of marine storm forcing
OS Terrain5 DTM (OST5) (Ordnance Survey, 2024c)	Raster	UK topographic raster dataset, 5 m resolution, digital terrain model	Subaerial topography profiles and barrier morphometrics
Scotland Phase 5 LiDAR (Scottish Government 2019-2021)	Raster	High resolution topographic dataset, 50 cm resolution, digital terrain model	Uncertainty assessment of OST5 DTM; Subaerial topography profiles in one location where OST5 data was not available
OS MHWS and MLWS (Ordnance Survey, 2024a)	Vector	Mean high and low water springs contours, scale 1:10,000	Intertidal slope calculation
Scotland MHWS elevation (licensed, created by Fitton et al. (2017))	Raster	Mean high water springs elevation, 50 m resolution	Intertidal slope calculation
OS Zoomstack: Road, rail and property (Ordnance Survey, 2024b)	Vector	Geolocation of roads, railways, commercial and residential properties	Coastal characterisation
Habitat map of Scotland (NatureScot, 2017)	Vector	Geolocation of different habitat types	Sand and gravel beaches identification

addition to barrier exposure, this approach can inform where to potentially use beach and dune restoration as a proactive and cost-effective measure to prolong the coastal protection offered by barrier landforms.

The final example illustrates how an integrated view of storm impacts and wider coastal characteristics could be used for scoping of specific adaptation measures. Here we consider areas potentially suitable for working with natural processes as a form of nature-based coastal adaptation, for instance through sediment trapping to promote dune growth, or the removal of pressures like trampling and invasive species to promote natural dune dynamics (hereafter NbS potential) (Bridges et al., 2021). For these types of measures, it may be more challenging in very exposed coasts and areas where barriers regularly face Overwash or Inundation. The physical properties of accommodation space, hinterland slope and hinterland elevation are also important first-order indicators of potential areas where working with natural coastal processes are more likely to succeed. Specifically, lower slopes and elevations are preferable to steep coastal profiles, and larger distances between the coast and first asset are preferable to areas where coastal squeeze will prevent the natural dynamic response of the barrier to storms and sea level rise (Bridges et al., 2021; Groenendijk et al., 2020; Young et al., 2023). Areas without coastal assets, where there is arguably a low priority for intervention, and areas with assets less than 100 m from the coast, where coastal squeeze is already an issue, were excluded. Resulting coasts with NbS potential are concentrated in the southwest (near the town of Stevenston) with 12 km of eligible coast, followed by the northeast (near the towns of Golspie, Findhorn and Lossiemouth), and southeast (in the Firth of Forth and near the Eden Estuary) (Fig. 14a). At the sub-national level, areas of NbS potential are

continuous and distinct from high-impact areas (Fig. 14b–d), indicating potential for different management approaches. At the local scale (Fig. 14e–g), transects with NbS potential are flanked by transects that were ruled out for NbS potential due to assets located either too close to the coast (Fig. 14f, g), or no assets within 500 m of the coast (Fig. 14e to the east). These insights can be used by coastal managers to inform adaptation discussions and further local studies. As in the previous example, the utility of this approach is the rapid and flexible selection of areas of interest, here reducing the national coast under consideration from ~21,000 km to ~20 km.

The above examples illustrate how the utility of the dataset extends beyond that of storm impact assessment, to a geospatial tool that can integrate storm impacts, asset data and physical hinterland characteristics to answer specific management questions across a range of spatial scales. Furthermore, the utility of this approach is verified when six of the seven identified locations (above), are under active consideration by local authorities under their flood and coastal erosion management responsibilities. There are various ongoing projects at these locations, including NbS approaches, in Golspie, Nairn, Findhorn, Lossiemouth, St Andrews, Stevenston (further information at www.DynamicCoast.com/ccca).

5. Conclusion

This work assessed extreme total water levels that include wave runoff, tides and storm surge, and associated storm impacts for all of Scotland's wave-dominated sand and gravel coasts. In addition to present-day storm impacts, future impacts were considered for two IPCC AR5 climate scenarios (RCP4.5 and RCP8.5) in 2050 and 2100. At present, the majority of natural barriers act as vital storm buffers to the hinterland. However, storm impacts are predicted to intensify with SLR, and by 2100 the length of coast inundated by storm waves is predicted to double under both RCP4.5 and RCP8.5. Predictions show that wave runoff is an important component of both present and future extreme TWL, emphasising the need to include wave runoff in flood risk assessments. Results also found substantial TWL variation around the coast at the sub-national to local scale, giving a strategic understanding of extreme wave runoff and storm impact hotspots that cannot yet be provided by global- or regional-scale studies. Wave runoff predictions from this research can be used to explicitly consider wave-driven flood- and erosion risk to the hinterland, by incorporating components of physical and socio-economic exposure and vulnerability.

This work highlights the opportunity for national-scale studies to add an understanding of wave-driven storm impacts, through the use of higher resolution hydrodynamic forcing and topographic data and simple empirical parameterisations. Such information is currently lacking in many countries, especially in data-poor remote or rural locations, but can be readily created with the methods presented here, using the relevant national datasets. This will enable efficient prioritisation of adaptation hotspots and so contribute to the urgent task of proactive and equitable coastal adaptation planning.

Glossary

- Extreme total water level** The total height of the water surface at the coast, resulting from the combined influence of short-term factors like tides, storm surge and waves, alongside long-term sea level rise. Used synonymously with extreme sea level.
- Extreme wave runoff $R_{2\%}$** The 2% exceedance of wave runoff, indicating the most extreme runoff elevations under the given storm conditions.
- Wave runoff** The vertical distance the waterline moves up a beach or structure due to wave action. Composed of wave setup and swash.
- Wave setup η** The quasi-steady, time-averaged elevation of the water surface at the shoreline caused by wave breaking.

Swash The time-varying uprush and backwash of the breaking wave on the beach.

interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Nicola Horsburgh: Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Carlos Loureiro:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization. **Alistair Rennie:** Writing – review & editing, Supervision, Resources, Methodology, Funding acquisition. **Martin Hurst:** Writing – review & editing, Software. **Larissa A. Naylor:** Writing – review & editing, Supervision, Investigation. **Andrew Tyler:** Writing – review & editing, Supervision, Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial

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Appendix A. Input data

The geospatial data processing and analysis were conducted in Python 3.11 using input data from multiple sources listed in Table A.1. For the validation of present-day storm impacts, wave buoy observations of deepwater wave height and period were provided by CEFAS Wavenet (<https://wavenet.cefas.co.uk>), and still water levels from the nearest tide gauge were provided by the British Oceanographic Data Centre (<https://www.bodc.ac.uk>). All data in Table A.1 are openly available, subject to data usage agreement and registration, with the exception of the MHWS elevation raster. For this, Fitton et al. (2017) interpreted the MHWS elevations between standard ports across Scotland using PolTips data licensed by the National Oceanographic Centre (<https://noc-innovations.com/services/tide-prediction-software/coastal-software/>).

Appendix B. Empirical parameterisations

Equation	Variables	Eq.	Source
$\xi_0 = \frac{\beta}{\text{sqrt}\left(\frac{H_0}{L_0}\right)}$	β = intertidal slope $H_0 = H_s$ = deepwater significant wave height T_p = deepwater peak wave period $L_0 = \frac{gT_p^2}{2\pi}$ g = gravitational constant	B1	Battjes (1974)
Intermediate to reflective beaches with $\xi_0 \geq 0.3$: $R_{2\%} = 1.1 \left(0.35\beta_f \text{sqrt}(H_0 L_0) + \frac{\text{sqrt}\left(H_0 L_0 \cdot (0.563\beta_f^2 + 0.004)\right)}{2} \right)$	$R_{2\%}$ = extreme wave runoff β_f = intertidal slope	B2	Stockdon et al. (2006)
$\eta = 0.35\beta_f \text{sqrt}(H_0 L_0)$	η = wave setup	B3	Stockdon et al. (2006)
Extremely dissipative beaches with $\xi_0 \leq 0.3$: $R_{2\%} = 0.043\text{sqrt}(H_0 L_0)$ $\eta = 0.16\text{sqrt}(H_0 L_0)$		B4	Stockdon et al. (2006)
Pure gravel beaches: $R_{2\%} = 0.33\text{sqrt}(\tan\beta) \cdot T_p \cdot H_s$ $\eta = 0.3 \cdot H_0$		B5 B6	Stockdon et al. (2006) Poate et al. (2016)
Composite sand and gravel beaches: $R_{2\%} = 0.19H_0 + 3.11H_{m0}\tan\beta_{\text{berm}} + 0.26$	H_{m0} = spectral significant wave height at the berm toe $\tan\beta_{\text{berm}}$ = slope of the gravel berm	B7 B8	Powell (1990) Blenkinsopp et al. (2022)

Appendix C. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.geomorph.2026.110489>.

Data availability

Data will be made available on request.

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