COASTAL PROCESSES AND SHORELINE CHANGE: CORNWALL

A synthesis of articles written by coastal scientists from the University of Plymouth



Making Space For Sand Project

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A synthesis of articles written by coastal scientists from the University of Plymouth

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Produced as part of the:
Making Space for Sand Project
led by Cornwall Council

Funded by Defra as part of the £200 million Flood and Coastal Innovation Programmes which is managed by the Environment Agency. The programmes will drive innovation in flood and coastal resilience and adaptation to a changing climate.

Department for Environment Food & Rural Affairs

Environment Agency

Flood and coastal resilience innovation programme

Part of the £200m Flood and coastal innovation programmes

making space for sand

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First Edition

Recommended citation:
Masselink, G., Scott, T. & Konstantinou, A. (Eds.) (2026). *Coastal Processes and Shoreline Change in Cornwall: A synthesis of articles written by coastal scientists from the University of Plymouth*. Plymouth: University of Plymouth for the Making Space for Sand Project. https://doi.org/10.24382/1adp-rv12.

Foreword



Tom de la Rosa

FCRM Adaptation and Resilience Manager, Environment Agency

“Coastal adaptation is one of the defining challenges of our time. Across the country, we know that communities are already experiencing the effects of rising sea levels, coastal erosion and more frequent extreme weather. Meeting these challenges requires more than good science alone; it demands collaboration, innovation and a shared commitment to turning knowledge into action.

Making Space for Sand is a powerful example of what can be achieved when research is connected directly to the needs of communities. Cornwall Council, Plymouth University and all the partners have risen to the challenge of bringing together scientific excellence and practical coastal adaptation, ensuring that knowledge is not only generated, but applied where it can make the greatest difference.

This work has been supported through wider investment in flood and coastal resilience innovation, creating the opportunity to test new ideas, strengthen evidence and explore different approaches to adaptation. However, programmes alone do not create change. The success of this work has been built on the partnerships behind it: researchers, practitioners, local authorities, communities and organisations working together towards a shared goal. It is these relationships that have transformed research into meaningful outcomes.

The result is a body of work that is both inspiring and practical. It provides vital evidence to help guide decisions today, while offering direction and hope for the challenges of tomorrow. The research is grounded in high-quality science, but it is the passion, commitment and determination of the people involved that stands out throughout these pages.

It is a privilege to see this work brought together within the Environment Agency’s Flood and Coastal Innovation Programmes and to reflect on the influence it has already had. The knowledge generated, the partnerships created and the experience gained will leave a lasting legacy, helping to better equip our coastal communities for a changing climate.”



Cllr Loic Rich

Cornwall Council Portfolio Holder for the Environment and Climate Change

"Cornwall's coast is one of our greatest assets. It shapes our identity, underpins our economy, supports internationally important habitats and attracts millions of visitors each year. It is also a dynamic and evolving environment, increasingly influenced by the combined pressures of climate change, sea-level rise and changing storm patterns. Understanding these changes is essential if we are to make informed decisions about the future of our communities, infrastructure and natural environment.

This booklet brings together decades of coastal research undertaken by the University of Plymouth's Coastal Processes Research Group, providing an accessible and practical summary of the science that underpins our understanding of Cornwall's coastline. Importantly, it translates complex research into insights that can support the work of practitioners, decision-makers and communities across Cornwall.

The findings presented here closely align with Cornwall Council's ambitions for a clean and green Cornwall, strong and resilient communities and sustainable economic growth. Our coastline plays a vital role in all these priorities. It supports tourism, livelihoods and biodiversity, while also protecting homes, businesses and infrastructure. As we plan for the future, we must ensure that our decisions are guided by robust evidence and a clear understanding of the processes shaping our coast.

The Making Space for Sand project exemplifies the value of partnership working between researchers, public bodies and local stakeholders. By improving our understanding of coastal change and resilience, it provides the knowledge required to support effective adaptation and long-term stewardship of Cornwall's coastal environment.

I hope this publication serves not only as a valuable reference for coastal practitioners, but also as a reminder of the importance of investing in science, monitoring and collaboration. By working together and drawing upon the best available evidence, we can help ensure that Cornwall's coastline remains resilient, vibrant and productive for generations to come."

Coastal Processes and Shoreline Change: Cornwall

A synthesis of articles written by coastal scientists from the University of Plymouth

Prof. Gerd Masselink

Professor in Coastal Geomorphology at the University of Plymouth

This compendium consists of summaries of 49 scientific papers reporting on shoreline dynamics and coastal processes in South West England, predominantly relating to the coast of Cornwall. These papers have all been published in peer-reviewed scientific journals and have been written over the past two decades by researchers of the Coastal Processes Research Group, University of Plymouth.

The production of this compendium has been made possible through support from the Flood and Coastal Resilience Innovation Programme (FCRIP), which has also contributed to the most recent research presented here and is supporting ongoing research that will continue to expand the evidence base for coastal management in the years ahead.
 This collection of paper summaries is primarily aimed at professionals involved with coastal management.



The book is organised along the following broad subjects:

- **Wave climate**
- **Beaches**
- **Surf zone processes**
- **Coastal dunes**
- **Regional sediment transport processes**
- **Extreme storm impacts**
- **Predicting coastal change**
- **Coastal management**

Each summary consists of a short scientific summary, a description of the context, methodology and results of the research, a key figure from the paper and a practical take-home message. Each summary also contains a QR code that links to the actual scientific paper and most of these can be freely downloaded. If the paper is behind a paywall, a copy can be requested from the authors.

About the book

If we assume the South West Coast Path closely hugs the coast, then the coast of Cornwall is 300 miles long. It has something to offer for everyone: majestic coastal cliffs at Land's End, Cape Cornwall and along most of the Lizard; sweeping sandy beaches with extensive dune systems at Penhale and St Ives Bay; historic fishing harbours, such as Polperro, St Ives, Port Isaac and Boscastle; almost-pristine estuarine river systems of the Gannel, the Fal and the Fowey; salt marshes and tidal flats in the larger estuaries of the Tamar and the Camel; and even a stretch of gravel coast on the south coast of Cornwall between Porthleven and Gunwalloe.

Apart from this variability in coastal landforms, the marine processes that shape the coast also vary greatly. The maximum tidal range, occurring during spring tides when the Moon is full, increases from 4 m at the Tamar estuary in south-east Cornwall, to 8 m in north Cornwall near Bude. Nearshore wave conditions range from almost no waves in the deepest and most secluded embayments, to more than 8 m during storm conditions along most of the exposed coast of north Cornwall. Even larger waves, sometimes in excess of 10 m during the most extreme storms, occur off the coast at the Isles of Scilly, located 30 km southwest of Land's End.

The role of geology in controlling the coastal landforms must also be acknowledged. Apart from the granite at Land's End, the coast of Cornwall is characterised by metamorphic rocks, which are generally sedimentary rocks altered by heat and pressure. The along-coast variability in lithology, hardness and fracturing has been capitalised by marine and terrestrial weathering processes over millions of years, resulting in a myriad of alternating straight coastal stretches, promontories, embayments and river valleys.

While the geographic variability in geology, wave and tide forcing gives rise to the along-coast spatial variability in coastal geomorphology, it is the changes over time in sea level, tides, wave conditions and sediment delivery to the coast that drives the coastal dynamics, i.e., the changes in the coastal landforms over time. These changes operate over various time scales, ranging from slow changes operating over decades to centuries due to sea-level rise, inter-annual to decadal changes due to climatic forcing of the winter wave climate with specific mention of the North Atlantic Oscillation, seasonal cycles of coastal change due to wave variability, dramatic changes that can occur on the coast due to the action of wave and wind storms, and smaller coastal changes over hours due to tidal cycles.

The globally almost unprecedented variability in coastal landforms and processes along the Cornish coast, combined with the dramatic coastal changes that occur over the full range of time scales, makes the coast of Cornwall an ideal natural laboratory for coastal scientists. As a result, the coast has been widely studied. At the same time, the coast is extremely popular with tourists with Cornwall receiving millions of visitors each year, most of which will make the coast their main destination. According to Wikipedia, tourism is responsible for 12% of Cornwall's Gross Domestic Product (GDP), supporting one in five jobs.

The coast of Cornwall is not as vulnerable to climate change as low-lying places like the Netherlands, Maldives or Bangladesh. However, sea-level rise and changes to the storm wave climate do provide a challenge to coastal communities that require adaptation, as the coast is expected to retreat due to sea-level rise. A wide spectrum of adaptation tools are available to mitigate against the adverse impacts of coastal climate change, ranging from constructing sea defences, nature-based solutions, managed realignment and better coastal planning. It is universally acknowledged that a robust understanding of the coastal processes is required to conduct sustainable coastal zone management and identify the most appropriate adaptation strategies and methods.

This compendium aims to make a positive contribution to the general understanding of the coast by communicating the state-of-the-art understanding of the coastal processes in Cornwall based on scientific research. It is based on scientific papers written by academics and scientists of the Coastal Processes Research Group at the University of Plymouth. Each of the contributors have a passion for the coast, both professionally and recreationally, and all use the coast for walking, running, camping, sailing and surfing. Even though this is essentially a scientific description of some of the key coastal processes and dynamics, it is hoped that some of the fascination for the coast shines through this work.

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Chapter 1: Wave climate

Wave climate underpins almost every aspect of coastal change, influencing beach behaviour, cliff erosion, coastal sediment transport and the impacts of storms. Understanding how wave conditions vary over seasonal, annual and decadal timescales is therefore essential for effective coastal planning and management. The papers in this chapter explore the atmospheric drivers that control wave climate in the North Atlantic and around southwest England, introducing new approaches to describing and predicting wave variability. Together, they demonstrate how improved knowledge of wave climate can support coastal monitoring, forecasting and evidence-based decision-making in an era of changing climate.

A new index controlling winter wave activity along the Atlantic coast of Europe: The West Europe Pressure Anomaly.

Castelle, B., Dodet, G., Masselink, G. and Scott, T., 2017.

Key message

A new climate index is developed based on the sea-level pressure gradient (SLP) between Valentia (Ireland) and Santa Cruz de Tenerife (Canary Islands). This new climate index, called the West Europe Pressure Anomaly (WEPA), outscores other leading atmospheric modes (e.g., North Atlantic Oscillation) in explaining the winter wave conditions along the Atlantic coast of Europe. WEPA also captures the 2013/2014 extreme winter that caused widespread coastal erosion and flooding in western Europe.



Take away thought

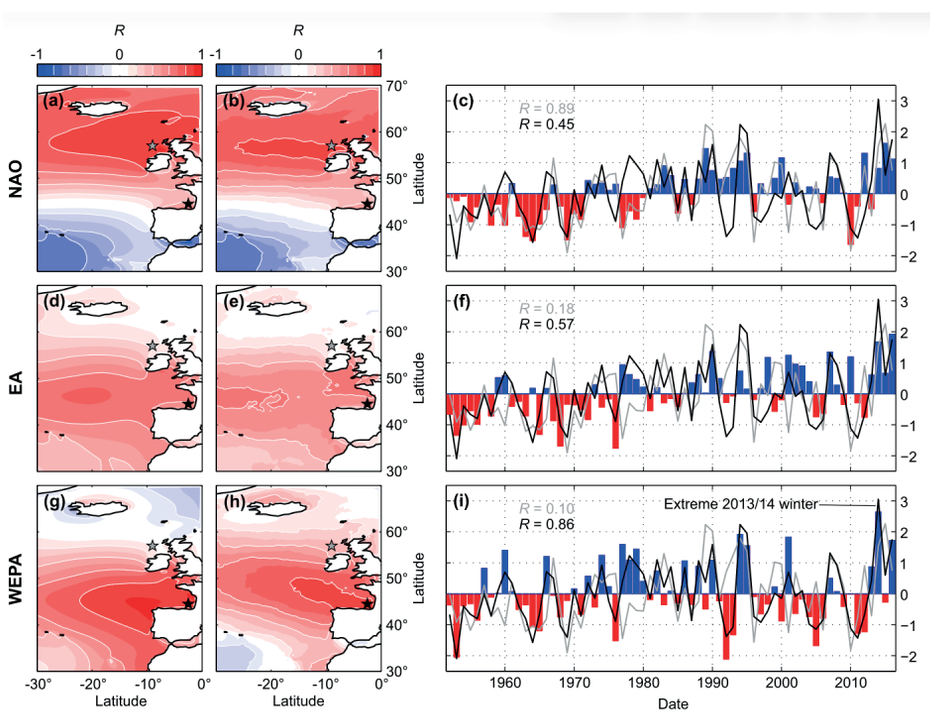
A new climate index, called the West Europe Pressure Anomaly (WEPA) is introduced. The new index is a strong indicator of extreme winter wave conditions along the Atlantic coast of Europe, including for SW England. We have some ability to make season-ahead predictions for WEPA and this can provide coastal managers with an early indication of winters likely to experience enhanced coastal erosion and flooding. This has the potential to improve preparedness for climate-driven coastal hazards.

Summary

Large-scale patterns of atmospheric and oceanic variability on interannual and longer timescales, which are usually characterized in terms of oscillation around the mean, can be explained by teleconnections at the global scale. This variability has a profound influence on temperature, rainfall, storm tracks and storm intensity, and, in turn, on the terrestrial and marine biosphere. Coastal hazards are also strongly affected by large-scale climate patterns. Therefore, winter and extreme coastal wave climate variability is a recent and important topic in climate studies and it becomes increasingly important to link extreme wave energy arriving locally at the coast to large-scale oceanic and atmospheric variability.

The North Atlantic Oscillation (NAO) has long been known to affect climate variability in the Northern Hemisphere and, as a result, the wave climate arriving at the west coast of Europe. The influence of NAO on waves along the Atlantic coast of Europe is particularly strong in the winter months, when storm events are critical to both short- and long-term coastal behaviour. However, while NAO has a major impact on the Atlantic winter wave height in the northern sector (NW of the British Islands), its influence is more subtle at more southern latitudes (UK, France, Spain, and Portugal). In these regions, winter waves are more affected by other leading atmospheric modes in the North Atlantic, namely, the East Atlantic (EA) and Scandinavia (SCAND) patterns. The absence of a climate index specific to the Atlantic coast of Europe and the resulting lack of understanding of the major atmospheric control on winter wave climate along this coast is considered a major drawback. A striking example is the winter 2013/2014, which was characterized by extreme winter wave activity and sea level events along the Atlantic coast of Europe, but was not captured by any of the above mentioned climate indices.

In this paper a new sea-level pressure climate index was developed that acts as a primary control on winter waves along the Atlantic coast of Europe. The index is reverse-engineered from the end product, namely, the winter wave height along the west coast of Europe as large wave heights are the primary cause of coastal hazards. The new index is called the West Europe Pressure Anomaly (WEPA) and is based on the sea-level pressure (SLP) gradient between the stations Valentia (Ireland) and Santa Cruz de Tenerife (Canary Islands). WEPA explains between 40% and 90% of the observed winter-averaged wave height variability from southern Ireland down to Portugal, where all the other indices explain at best 40%. The positive phase of this climate index reflects an intensified latitudinal SLP gradient in the NE Atlantic, between Ireland and Canary Islands, driving increased W-SW winds around 45˚N that funnel high-energy waves toward western Europe together with deep low-pressure systems passing over the UK. The highest value for WEPA since 1953 occurred during the 2013/14 winter.



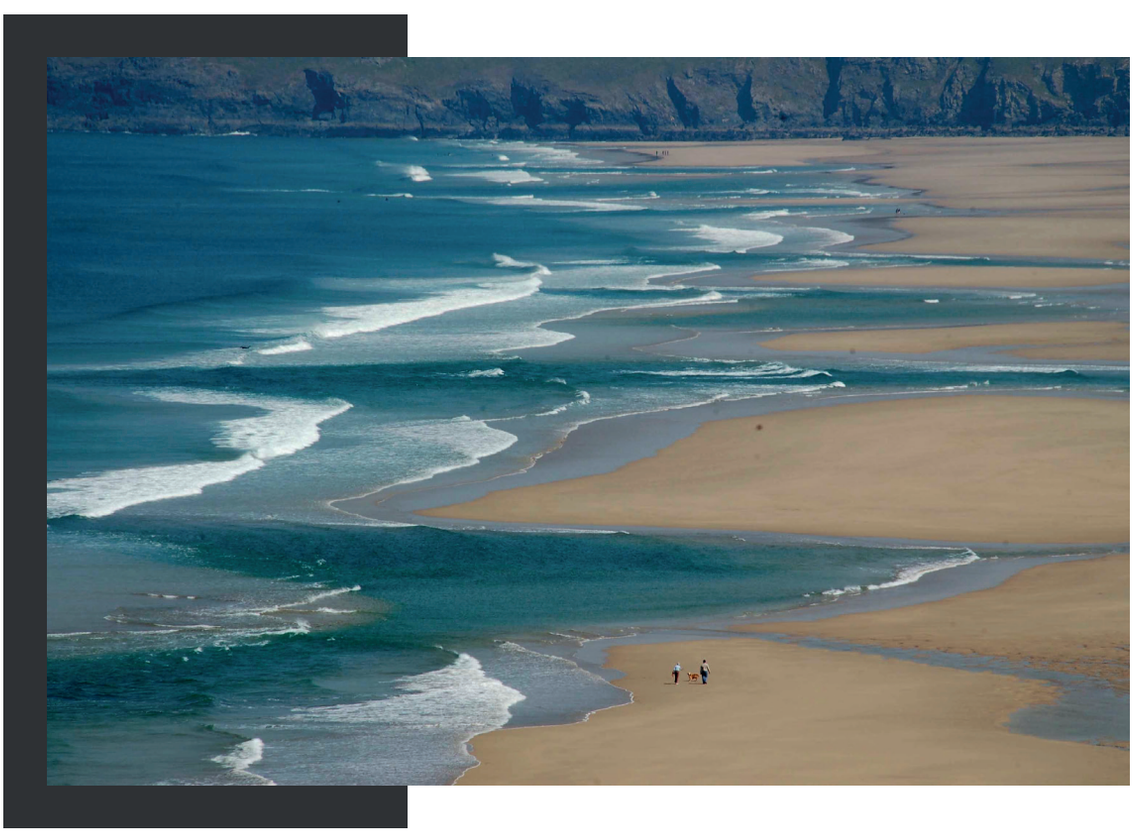
Left panels depict the spatial correlation between modelled winter-averaged significant wave height H_s and winter-averaged climate indices (NAO, EA and WEPA). Panels (a), (d) and (g) represent the winter-averaged H_s, whereas (b), (e) and (f) represent the 95% exceedance H_s. Right panels show time series of the corresponding indices (blue and red bars) with superimposed normalized winter-averaged H_s measured on the west coast of Scotland (grey) and in Gulf of Biscay (black), with corresponding correlation coefficient R. The R values in the right panels represent the correlation between winter wave conditions and winter climate index. For example, R = 0.86 in panel (i) indicates that the winter wave conditions for the Gulf of Biscay are correlated with winter WEPA index with a correlation coefficient of 0.86.

Role of atmospheric indices in describing shoreline variability along the Atlantic coast of Europe.

Masselink, G., Castelle, B., Scott, T. and Konstantinou, A., 2023.

Key message

Winter shoreline change along the Atlantic coast of Europe, including in SW England, is strongly correlated with storm wave forcing, itself related to atmospheric indices (West Europe Pressure Anomaly WEPA and North Atlantic Oscillation NAO). The beach morphology at the start of the winter is also an important factor in determining the winter shoreline response.



Take away thought

The strongest predictor of seasonal shoreline change is wave forcing, which itself is associated with large-scale climate indices, such as NAO and WEPA. However, individual storms, antecedent beach conditions and tidal water levels can substantially alter shoreline response. Climate indices can provide useful context for seasonal coastal risk assessments, but cannot replace site-specific wave and beach monitoring.

Summary

It is generally accepted that beach and shoreline dynamics are a result of changes in the wave conditions. In turn, inter- and intra-annual wave variability is controlled by weather and climate. Two beaches in SW England (sandy Perranporth in north Cornwall and the gravel barrier of Slapton Sands in east Devon), and one beach in SW France (sandy Truc Vert along the Aquitaine coast) have been surveyed every month for more than 15 years. This paper uses these unique datasets to look, for the first time, at the connections between beach dynamics, wave variability and climate along the Atlantic coast of Europe.

Atmospheric indices are numbers that tell us about large-scale weather, and the North Atlantic Oscillation and the West Europe Pressure Anomaly (WEPA) are powerful indices that describe the weather and waves in the north-east Atlantic.

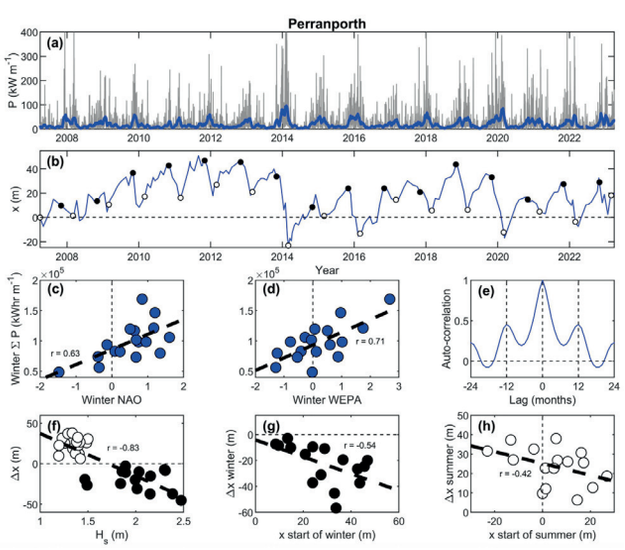
It was found that the winter WEPA index (representing the pressure gradient between the Azores and Ireland during the winter months) is strongly correlated with Atlantic westerly winter waves and beach change for all three study sites. Large positive values for winter WEPA are associated with a strong latitudinal pressure gradient and such conditions are responsible for large winter waves from the Atlantic SW quadrant. In turn, such wave conditions cause shoreline retreat on the exposed north coast of Cornwall and northward longshore sediment transport and clockwise beach rotation along the more sheltered south coast of SW England. It was further found that the winter NAO index (representing the pressure gradient between Spain and Iceland during the winter months) is not significantly correlated with the Atlantic winter waves, but is correlated with easterly storm wave activity. In turn, easterly storm waves cause southward sediment transport and anti-clockwise beach rotation along the more sheltered south coast of SW England.

However, winter wave forcing is not the only factor that controls beach dynamics and there are at least three additional factors that are important in driving shoreline change.

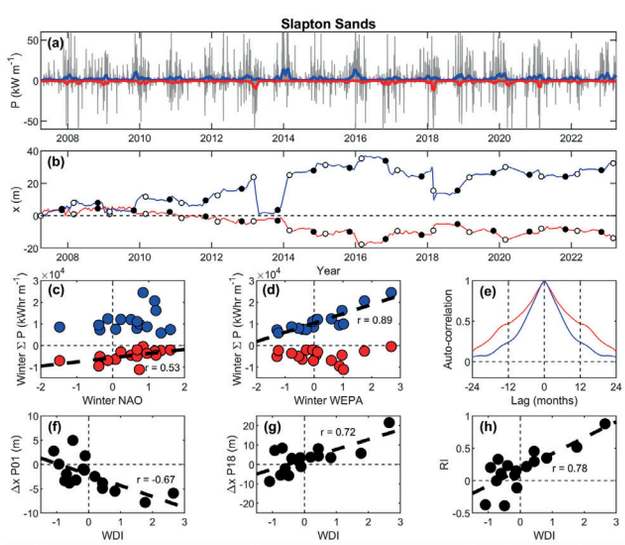
1) Shoreline response is not necessarily the result of sustained storm wave activity over the winter period related to an exceptional atmospheric condition over the winter. Instead, significant shoreline change can also be the result of a single event in an otherwise unremarkable winter.

2) Seasonal beach change along the exposed and cross-shore dominated beaches of Perranporth and Truc Vert depends very much on whether the beach is relatively healthy or depleted of sediment. So, shoreline advance of the beach over the summer months is more pronounced following a winter with severe storms, than after a relatively calm winter.

3) The role of water levels during storm conditions should also be considered as storm impacts are maximized if peak wave conditions coincide with extreme water levels.



Wave conditions and shoreline response for Perranporth, north Cornwall: (a) time series of wave power P (grey line) and 30-day moving average of the wave power (blue line); (b) time series of monthly shoreline position x (0 m ODN) relative to start of the survey period with start of winter (1 December) and summer (1 April) marked by black and white circles, respectively. Note impact of 2013/14 winter.



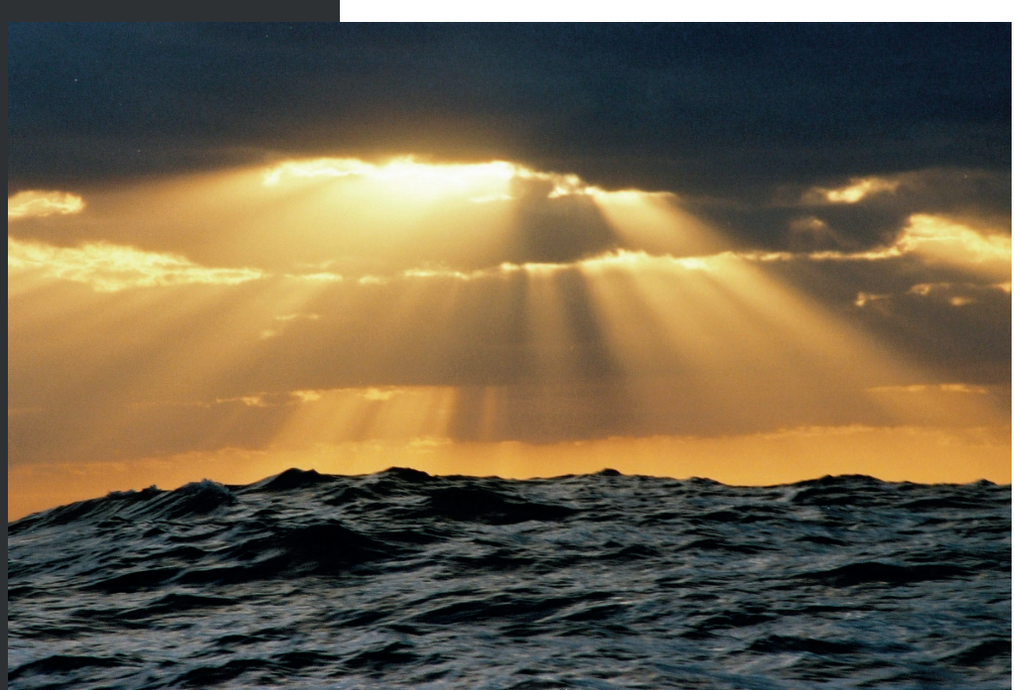
Wave conditions and shoreline response for Slapton Sands, east Devon: (a) time series of wave power P (grey line) and 30-day moving average of southerly (>135°; blue line) and easterly (<135°; red line) wave power; (b) time series of monthly shoreline position x (0 m ODN) at the southern (red) and northern (blue) end of the beach, relative to start of the survey period with start of winter (1 December) and summer (1 April) marked by black and white circles, respectively.

Atmospheric controls and long range predictability of directional waves in the United Kingdom and Ireland.

Scott, T.M., Masselink, G., McCarroll, R.J., Castelle, B., Dodet, G., Saulter, A., Scaife, A. and Dunstone, N., 2021.

Key message

Atmospheric indices are significantly correlated to both the magnitude and direction of inshore wave climate around the UK and Ireland. Over 70% of sites were shown to have directionally bimodal wave climates, and combinations of indices (e.g. NAO, WEPA, SCAND) explained much of this variability, enabling the possibility of skillful prediction of directional wave conditions at seasonal to decadal scales.



Take away thought

Atmospheric indices can be used to predict not only wave height but also wave direction. On many coasts, the balance of opposing wave directions is a key driver of coastal change, particularly beach rotation which is driven by longshore sediment transport processes. Continued advances in seasonal forecasting of these indices may allow coastal change and associated hazards to be anticipated months in advance. This may enable better preparedness and forward planning by providing earlier warning of periods of increased erosion risk.

Summary

Understanding how wave climate varies in space and time is fundamental to predicting coastal evolution and managing coastal risk. While the influence of atmospheric variability on wave energy is well established, the role of climate indices in describing wave direction, particularly in inshore and semi-sheltered environments, has received much less attention. This is important because wave direction strongly influences alongshore sediment transport and coastal morphology.

This paper examined the inshore wave climate at 63 locations around the UK and Ireland using a 37-year hindcast dataset (1980–2017). The study focused on both total wave power and directional variability, and analysed relationships with six major atmospheric indices: NAO, WEPA, SCAND, EA, AO, and EA/WR. Statistical techniques, including correlation analysis, cluster analysis, and multi-linear regression, were used to identify spatial patterns and quantify predictive relationships between atmospheric forcing and wave climate.

The results showed that 73% of sites exhibited directionally bimodal wave climates, meaning that waves commonly approached from two dominant directions. This was particularly evident in semi-sheltered regions such as the English Channel and North Sea, where opposing wave directions relative to the shoreline create strong potential for alongshore sediment transport and shoreline change.

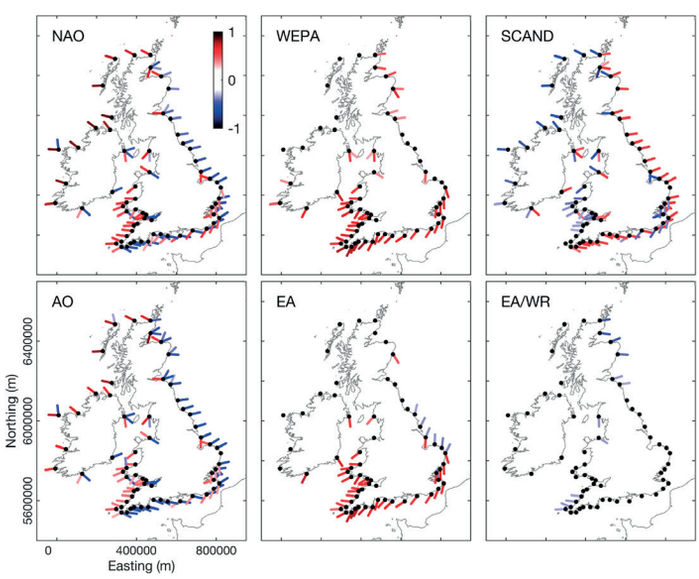
Strong and statistically significant relationships were identified between atmospheric indices and both total and directional wave power. These relationships varied spatially. The NAO was the dominant control along exposed Atlantic coasts, while WEPA and EA were more important in southern regions. The SCAND index played a key role in controlling directional variability, particularly in sheltered and North Sea environments.

A key finding was that different directional wave modes at the same location could be controlled by different atmospheric indices, sometimes with opposing effects. For example, south-westerly waves were often linked to positive WEPA, while easterly waves were associated with negative NAO or positive SCAND. This means that the overall balance of wave direction, and therefore coastal forcing, is governed by the combined effect of multiple atmospheric drivers.

To capture this, the study showed that multi-linear regression models combining multiple indices significantly improved predictive skill compared to single-index approaches, with model performance in the range $R^2 \approx 0.45–0.8$. This demonstrates that directional wave climate can be reconstructed and predicted with useful accuracy using atmospheric data.

The study also identified four spatially coherent coastal regions with distinct wave–climate relationships, reflecting differences in exposure, orientation, and atmospheric forcing. This regionalisation provides a framework for understanding how different parts of the coastline respond to large-scale climate variability.

Finally, the study highlighted the potential for forecasting. Advances in seasonal prediction of atmospheric indices, particularly the NAO, mean that wave direction and energy may be predictable months in advance, offering a new opportunity to anticipate coastal change and manage risk more proactively.



Relationship between winter-averaged NAO, WEPA, SCAND, AO, EA, and EA/WR and directional winter-averaged wave power (local wave directional window of ±20° for each node) for 63 wave nodes (black dots) around the coast of the UK&I (1980–2017). Colors are correlation coefficients (r), only results where p < 0.05 are shown.

Chapter 2:
Surf zone processes

The surf zone is one of the most dynamic parts of the coastal environment, where waves, currents and water levels interact to shape the shoreline and influence public safety. Understanding these processes is essential for managing beaches, predicting coastal hazards and improving public safety. The papers in this chapter examine the behaviour of waves and currents in the surf zone, including rip currents, infragravity waves and wave transformation across rocky shores, alongside research that translates this knowledge into practical tools for hazard assessment and beach safety management. Together, they demonstrate how coastal process research can directly inform safer and more effective coastal management.

Observations of nearshore infragravity wave dynamics under high energy swell and wind-wave conditions.

Inch, K., Davidson, M., Masselink, G. and Russell, P., 2017.

Key message

Infragravity waves with periods ranging from 30 s to several minutes can dominate the water motion close to shore on low sloping sandy beaches and play a key role in beach and dune erosion. Infragravity wave heights of up to 1 m were measured close to shore and their height is roughly 20% of the ocean wave height.



Take away thought

Infragravity waves are a complex surf zone phenomenon and difficult to observe, visualise and model. Nevertheless, they dominate runup, dune erosion and overwash during extreme storm events. Their influence therefore should be considered when modelling storm impacts and designing coastal interventions, such as beach nourishment and dune restoration. Disregarding the role of infragravity waves results in an underestimation of storm impacts.

Summary

Infragravity waves, or long waves, are waves with long periods (typically 30 seconds to several minutes) that can make up a significant proportion of the total wave energy in the surf zone. Unlike sea-swell waves, which lose their energy in the surf zone through breaking, the height of infragravity waves increases shoreward from several centimetres in deep water to over 1 metre close to shore. The height of the infragravity waves in the surf zone, or at the shoreline as runup, increases with the offshore wave height. This means that infragravity waves are most energetic during storm conditions. As a result, infragravity waves play an important role in beach and dune erosion.

This paper describes a unique data set collected on the sandy beach of Perranporth, north Cornwall, to specifically investigate the importance, generation and behaviour of infragravity waves. A two-week field experiment was conducted during which wave and water-level data were collected using pressure sensors deployed at 15 locations across the intertidal beach, from the top of the beach to spring low tide level. Offshore wave conditions were recorded by the Perranporth directional wave buoy. A range of wave conditions were experienced during the experiment, with offshore wave heights between 0.4 m and 4 m.

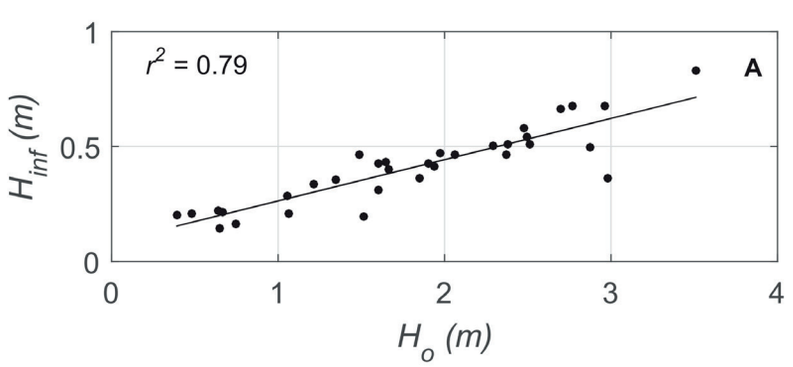
Infragravity waves were recorded under all wave conditions, but were found to be most pronounced under energetic wave conditions. The height of the infragravity waves across the surf zone and at the shoreline was found to be strongly and positively correlated with the offshore wave height, but a more accurate prediction was obtained by using the offshore wave power. This means that infragravity waves are more energetic under swell than wind-wave conditions.

The generation and behaviour of the infragravity waves was investigated by looking at how these waves travel through the surf zone by comparing the data from the different pressure sensors deployed across the beach. The wave signal inside the surf zone was also related to waves outside the surf zone, specifically by looking at wave groups, often referred to as surf beat. It was found that infragravity waves originate from outside the surf zone and are linked to the wave groups. When the ocean waves break at the edge of the surf zone and the wave groups are destroyed, the infragravity wave is then 'released' and travels on its own through the surf zone towards the beach.

As the infragravity wave approaches the shoreline, it increases in height, very much like a swell wave does just before breaking. At the shoreline, the infragravity wave runs up the beach and loses some of its energy through friction and infiltration. However, a significant amount of infragravity wave energy also bounces (reflects) off the beach and travels out to the sea. The interaction between the incoming and outgoing infragravity wave can set up a standing wave motion across the surf zone.



Sand anchors were used to install 15 wave sensors across the full width of Perranporth beach.



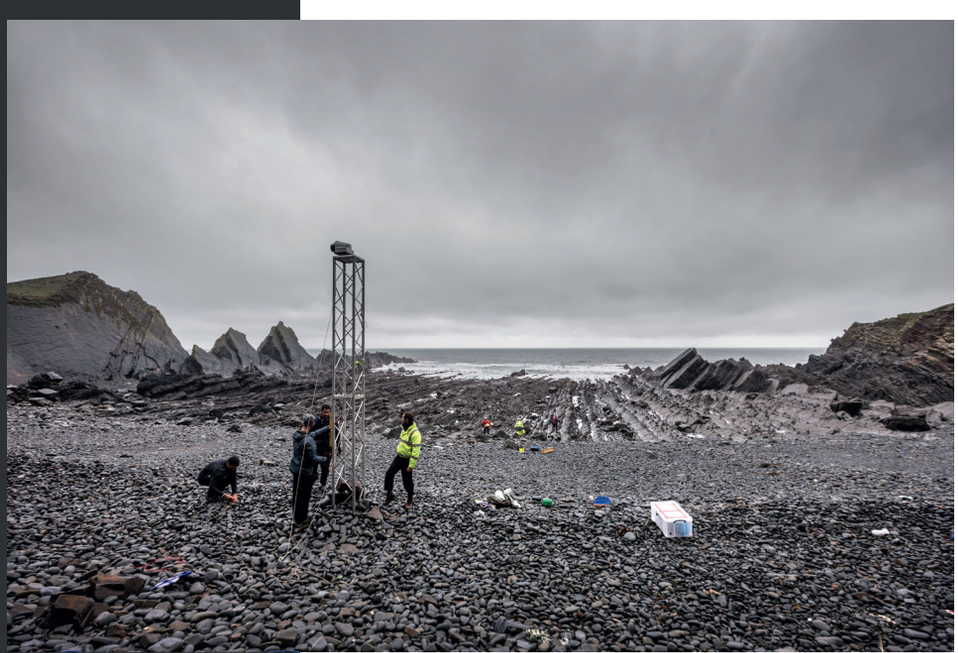
The height of the infragravity waves H_{inf} averaged across the surf zone plotted as a function of the offshore wave height H_o. The data show that the infragravity wave height is roughly 20% of the offshore wave height. The strength of the relationship between H_{inf} and H_o is represented by the correlation coefficient r^2.

The role of bed roughness in wave transformation across sloping rock shore platforms

Poate, T., Masselink, G., Austin, M. J., Dickson, M. and McCall, R., 2018.

Key message

Wave transformation across sloping rock shore platforms is largely controlled by wave breaking rather than frictional energy losses. Extensive field data reveal that wave heights in the surf zone are ‘saturated’ and strongly influenced by tides, with consistent behaviour across platforms despite major differences in bed roughness. Frictional effects from roughness are generally negligible for short waves in the surf zone and only become important on very rough, flat platforms under small-wave conditions.



Take away thought

Rocky shore platforms are less protective than they appear. During storms, wave energy is reduced mainly by surf-zone breaking, not by platform roughness, and standard beach wave models are generally suitable for rocky coasts. During storms, substantial wave energy can still reach cliffs and infrastructure, especially during high tidal levels. Tides thus strongly influence the impact of storm waves, and hazard and erosion assessments should focus on storm timing and water levels, rather than assuming that the presence of a rocky shore platforms provide adequate coastal protection.

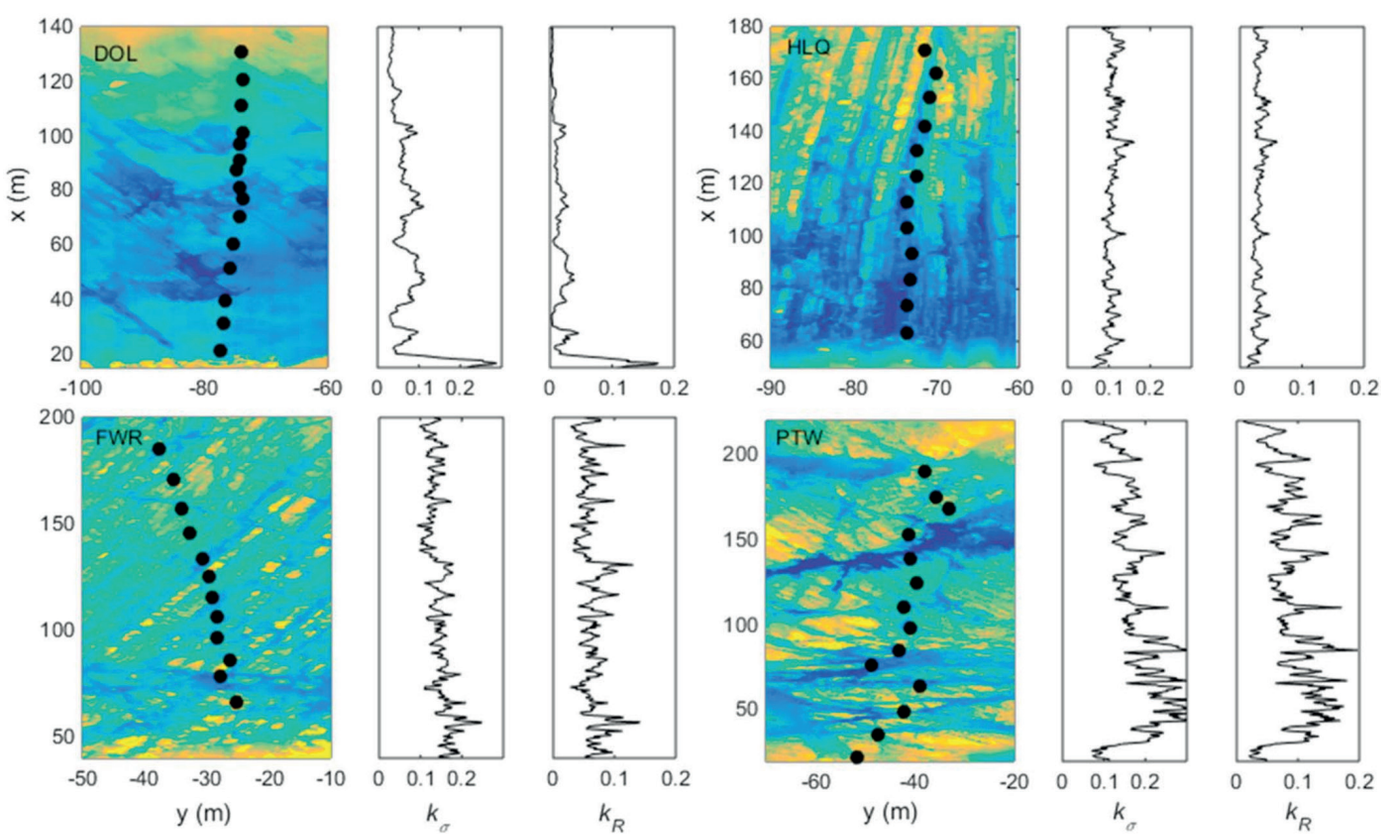
Summary

This paper investigates how waves transform across sloping rock shore platforms, focusing on the role of bed roughness in controlling wave energy dissipation. Using extensive field measurements from five sites with varying roughness, gradients, and wave conditions, combined with numerical modelling, the study provides one of the most comprehensive datasets for rocky coasts.

Results show that as waves propagate across platforms, incident wave energy is dissipated and wave shapes become increasingly skewed and asymmetric, while infragravity wave energy grows toward the shore. Waves in the surf zone are 'saturated', which means that their height is controlled by the water depth which, in turn, is modulated by the tide. Despite large differences in platform roughness, wave transformation patterns are broadly similar across sites, indicating that bed roughness does not significantly influence short-wave behaviour in the surf zone.

Model simulations support these observations, demonstrating that wave breaking is the dominant mechanism of energy dissipation, whereas friction plays a minor role. Frictional effects become important only on very rough, relatively flat platforms and mainly under low-energy wave conditions outside the surf zone. Attempts to parameterize friction using roughness-based drag coefficients show large variability and do not improve model performance, suggesting that simple roughness metrics are insufficient to represent frictional processes accurately.

Overall, the study concludes that wave transformation on rock shore platforms behaves similarly to sandy beaches, with wave breaking controlling surf zone dynamics. This has important implications for coastal geomorphology, indicating that wave-driven erosion processes may be less sensitive to platform roughness than previously assumed.



Detrended digital elevation maps of four rocky platforms, DOL = Doolin (Ireland); HLQ = Hartland Quay (Cornwall); FWR = Freshwater West (Wales); and PTW = Portwrinkle (Cornwall). Yellow and blue in the colour plots represent, respectively, high and low relief on the rock platform. DOL and PTW represent the smoothest and roughest rock platform, respectively. The locations of pressure sensors are shown as black circles. The vertical black plots adjacent to each surface show the alongshore average bed roughness as a function of standard deviation k_σ rugosity k_R.

Rip current prediction: development, validation, and evaluation of an operational tool.

Austin, M.J., Scott, T.M., Russell, P.E. and Masselink, G., 2012.

Key message

Rip currents on macrotidal beaches were shown to be highly dynamic, with their location controlled by beach morphology and their strength controlled by changing patterns of wave breaking as tides move the surf zone across the beach. By combining field observations, numerical modelling and lifeguard incident records, the study developed and validated an operational rip current prediction tool capable of identifying periods of elevated hazard and supporting beach safety management.



Take away thought

Rip current hazard cannot be reliably assessed using regional wave conditions alone, but combining wave forecasts with tidal conditions and local beach morphology can identify periods of elevated hazard, support lifeguard deployment and improve public warnings. Such combined approach based on local conditions provides a more robust basis for beach risk assessments than regional forecasts alone, and can form the foundation for operational rip current forecasting systems.

Summary

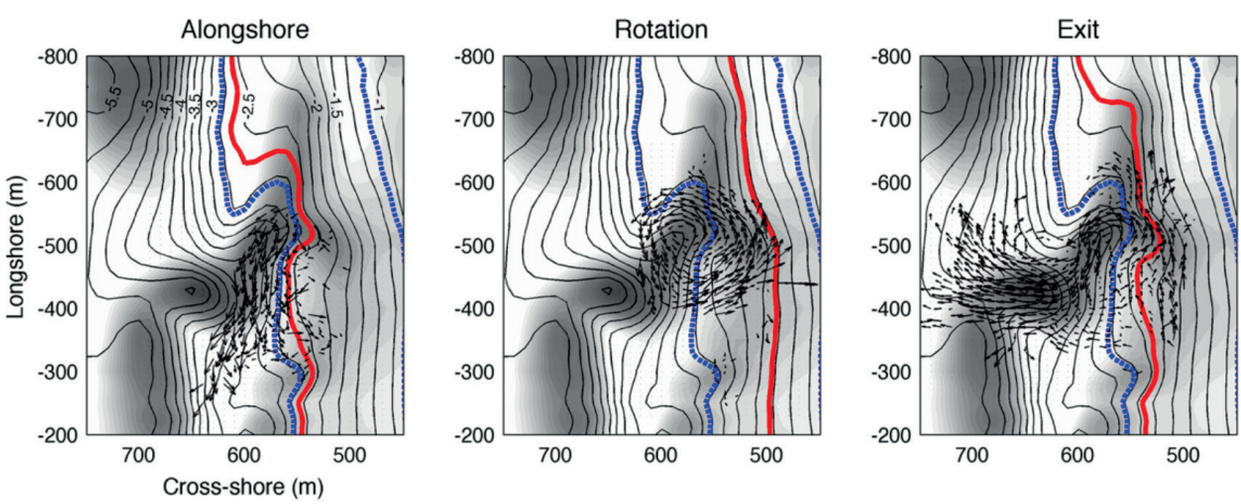
Rip currents are the greatest natural hazard to beach users on wave-dominated coasts and are responsible for most surf rescues on many beaches worldwide. Although previous studies have shown that rip current activity is influenced by waves, tides and beach morphology, forecasting systems generally relied on regional wave conditions and did not account for the site-specific characteristics that control where and when hazardous currents develop. Improving local predictions is therefore an important step towards reducing drowning risk and supporting operational beach management.

This study developed and evaluated an operational rip current forecasting tool for Perranporth Beach, Cornwall, a macrotidal beach characterised by low-tide bar and rip morphology. Extensive field measurements collected over 87 tidal cycles included current meters, GPS-tracked drifters, video observations and repeated beach surveys. These observations were used to characterise rip current behaviour and validate a numerical hydrodynamic model (XBeach) driven by operational wave forecasts. Model outputs describing rip current speed and circulation were then converted into daily hazard ratings and compared with lifeguard incident records.

The study showed that rip current behaviour was controlled by the interaction between beach morphology, waves and tidal water level. The morphology determined where rip currents formed, while the movement of the surf zone across the beach with the tide controlled when they became active.

Three characteristic circulation modes were identified. Under moderate wave conditions, rip currents either recirculated water within the surf zone or transported it offshore beyond the breaker zone. During more energetic conditions, however, strong alongshore currents became dominant and offshore exits became less common. These changing circulation patterns demonstrated that hazard depends not only on rip current strength but also on how water moves through the surf zone.

The calibrated model successfully reproduced the observed circulation patterns and provided realistic predictions of rip current behaviour. When compared with lifeguard records, 64% of recorded incidents occurred during forecasted high-risk conditions and the remainder during medium-risk conditions, with no incidents associated with low-risk forecasts. The study demonstrated that combining detailed knowledge of local beach morphology with operational wave forecasts can provide reliable predictions of bathing hazard and translate coastal process science into an effective operational decision-support tool for beach safety management.



Example mean drifter circulations from Perranporth field experiments associated with alongshore (left), rotation (middle) and exit (right) dominated deployments. Mean circulation patterns are 10 m × 10 m binned mean velocities (arrow length is proportional to drifter speed), bathymetric contours (Δ0.25 m), daily low water elevations (bold red line), MLWN and MLWS (dashed blue lines) and background is linearly de-trended residual rip channel morphology.

Controls on macrotidal rip current circulation and hazard.

Scott, T., Masselink, G., Austin, M.J. and Russell, P.E., 2014.

Key message

Rip current hazard on macrotidal beaches is controlled by the interaction of wave conditions, tides and beach morphology. Using five years of lifeguard incident records and extensive field observations, the study showed that the most dangerous conditions occur around mean low water when moderate swell waves interact with active bar–rip morphology. Hazard is maximised when rip currents are both strong and the circulation pattern is capable of transporting people offshore beyond the surf zone.



Take away thought

The greatest rip current risk often occurs during relatively benign beach conditions rather than during storms, when beach users may be less aware of the danger. Beach safety systems should therefore focus on forecasting the interaction between environmental parameters (waves, tides) with information on low-tide beach morphology, allowing lifeguards to anticipate high-risk periods and target warnings more effectively.

Summary

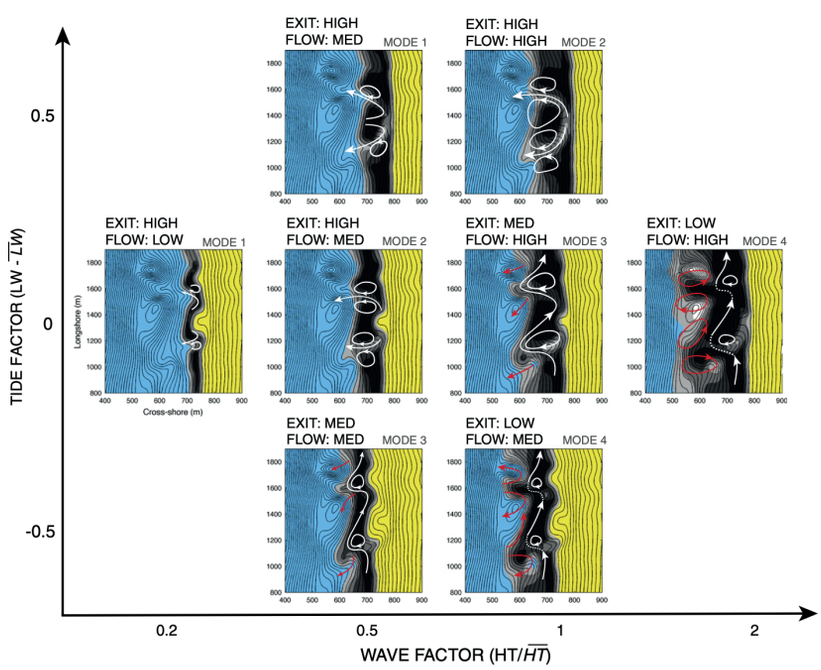
Rip currents are one of the most significant hazards on energetic sandy beaches; yet their behaviour changes continually as waves, tides and beach morphology evolve. While previous studies have established that these factors influence rip currents, the environmental thresholds that distinguish low- and high-risk conditions on macrotidal beaches remained poorly understood. Identifying these controls is essential for improving beach safety and predicting periods of elevated bathing hazard.

This study investigated the environmental controls on rip current behaviour using two complementary datasets. Five years of RNLI lifeguard incident records from twenty beaches across southwest England were analysed to identify the conditions associated with high-risk events. These observations were combined with detailed field measurements collected at Perranporth Beach, Cornwall, where GPS-tracked drifters, beach surveys and hydrodynamic observations were used to examine how rip current circulation changed under different wave and tidal conditions.

The analysis showed that the greatest bathing hazard occurred during moderate swell conditions rather than storms. High-risk incidents were concentrated around mean low water, when well-developed low-tide bar and rip morphology became active. Moderate wave heights, long wave periods, shore-normal wave approach and light winds produced the highest likelihood of dangerous rip currents. The findings demonstrated that dangerous conditions often develop during apparently benign weather rather than during extreme storms.

Field observations identified three distinct rip current circulation modes: (1) rotational circulation within the surf zone; (2) strong alongshore transport; and (3) offshore exits beyond the breaker zone. The balance between these behaviours was controlled by the interaction between wave energy and tidal water level. Maximum hazard occurred when rip currents combined high flow speeds with frequent offshore exits, allowing bathers to be transported rapidly into deeper water. As wave energy increased further, circulation became increasingly dominated by alongshore currents, reducing the frequency of offshore exits despite stronger overall flows. This demonstrated that rip current hazard depends on circulation behaviour, as well as current speed.

The study established quantitative environmental thresholds linking waves, tides and morphology to rip current hazard and showed that these relationships could successfully identify periods of elevated risk across multiple beaches. The results provide a scientific basis for forecasting rip current hazard and improving operational beach safety management on macrotidal coasts.



A conceptual overview of the observed rip dynamics throughout the variation in the wave and tide factor changes. Small and large values for the wave factor refer to less and more energetic wave conditions than average, respectively. Positive and negative values for the tide factor refer to low tide levels above and below the mean low tide level, respectively. The schematic diagrams are supported by hydrodynamic model output generated from XBeach using measured bathymetry from June 2011. White arrows are inner surf zone currents, red arrows are outer surf zone currents. Grey shading is the proportion of wave breaking (dark grey is saturated surf zone). For each diagram, levels for surf zone drifter exit potential ('EXIT') and flow velocity ('FLOW') are given.

Water-level controls on macro-tidal rip currents.

Austin, M. J., Masselink, G., Scott, T. M. and Russell, P. E., 2014.

Key message

Rip currents on macrotidal beaches were shown to be strongly controlled by changing water levels across intertidal bar–rip morphology. Rip activity increased and decreased with the tide as wave breaking migrated across the beach profile, creating spatially variable water surface gradients that drove circulation. Even when feeder channels became inactive at low water, localised pressure gradients around bar ends maintained offshore-directed rip flow.



Take away thought

On beaches characterised by low-tide bar-rip morphology, rip current hazard varies predictably with tidal stage. Specifically, wave breaking on the bar morphology around low tide generates the strongest and most persistent rip currents. Therefore, monitoring and public safety measures on these beaches should focus on the hours around low water, allowing beach safety resources to be targeted most effectively.

Summary

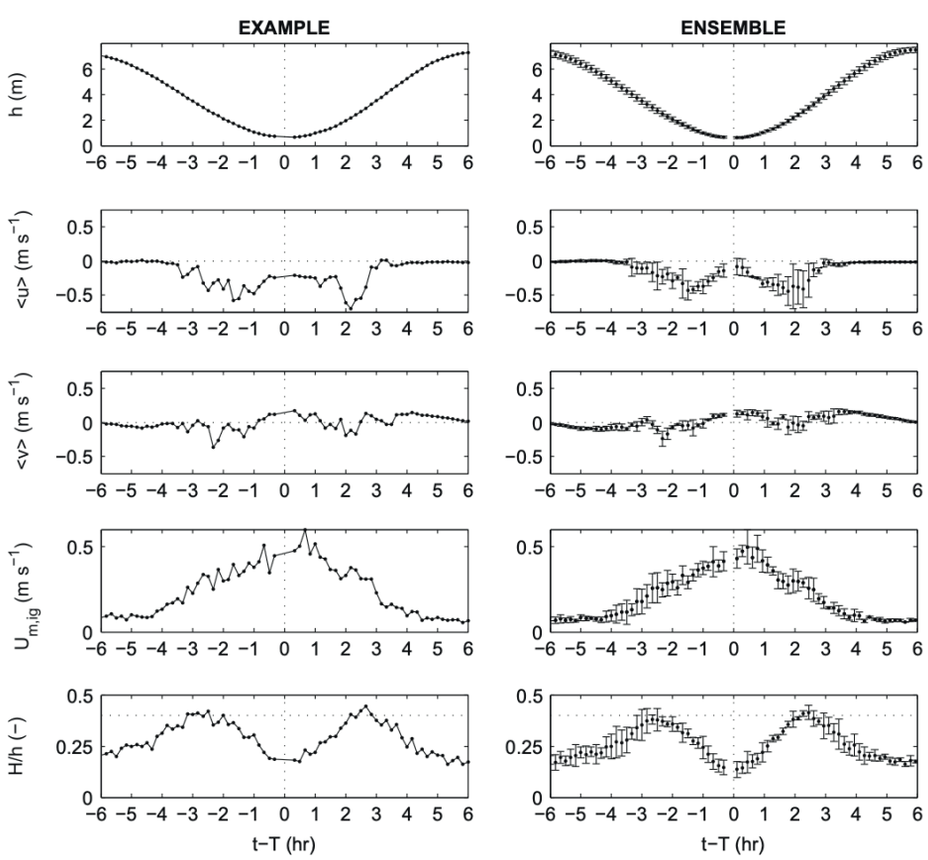
Rip currents are generated by variations in wave breaking that create water-level differences across the surf zone, producing water-surface gradients that drive offshore circulation. Although this process is well understood on microtidal beaches, much less was known about how it operates on macrotidal coasts, where large tidal ranges continually alter beach morphology and the position of the surf zone. Understanding these controls is essential for explaining why rip current activity varies so markedly through the tidal cycle and for improving predictions of beach hazard.

This study investigated the influence of tidal water level on rip current dynamics at Perranporth Beach, Cornwall. Field measurements collected over 32 tidal cycles included current velocities, water levels, wave conditions and GPS-tracked drifters across a well-developed low-tide bar–rip system. These observations were combined with a calibrated XBeach numerical model to quantify wave breaking, water-surface gradients and circulation throughout the tidal cycle.

The results showed that rip current activity was closely linked to the changing position of the surf zone as the tide rose and fell. Rip currents became active several hours either side of low water, reaching their greatest strength around 1.5–2 hours before and after low tide when wave breaking over the intertidal bars generated the strongest water-surface gradients and feeder currents. During this stage, alongshore currents converged into the rip channel and produced rapid offshore-directed flow.

As the tide continued to fall, however, the hydrodynamic behaviour changed. Wave breaking migrated offshore towards the subtidal bar, reducing the strength of the feeder currents that normally supply the rip channel. Rather than disappearing, the rip current remained active because localised water-surface gradients developed around the exposed ends of the intertidal bars, maintaining a narrow offshore jet. This previously unquantified mechanism explained how rip currents can persist even when conventional forcing from alongshore feeder currents is substantially reduced. The numerical model successfully reproduced these changing circulation patterns, confirming the dominant role of tidal water levels in controlling rip current evolution.

The study demonstrated that rip currents on macrotidal beaches evolve through distinct hydrodynamic stages as water levels change, rather than responding uniformly to increasing or decreasing tidal elevation. This provides a process-based explanation for the strong tidal modulation of rip currents observed on many macrotidal coasts and improves understanding of when and why hazardous conditions develop.



Example hydrodynamics collected in the rip channel versus time relative to high tide (t-T). From top: 10-min time-averaged water depth h; cross-shore flow velocity <u>; alongshore flow velocity <v>; cross-shore infragravity velocity amplitude $U_{m,ig}$; and relative wave height H/h. Large and small values for H/h refer to high and low tide, respectively.

Application of multiple linear regression and Bayesian Network approaches to model life risk to beach users in the UK.

Stokes, C., Masselink, G., Revie, M., Scott, T., Purves, D. and Walters, T., 2017.

Key message

Life risk to beach users can be predicted from a combination of physical beach characteristics and patterns of beach use. Using incident records from 113 UK beaches, the study showed that intermediate beach morphology is the strongest contributor to life risk because it is associated with both increased hazard and increased water-user exposure. Statistical models provided a practical framework for identifying beaches where lifeguard services are likely to deliver the greatest benefit.



Take away thought

Beach safety risk is a function of the hazard level and the exposure to that hazard, and is highest on beaches that combine intermediate morphology, high visitor numbers and good accessibility. Risk-based screening tools can provide an effective way to identify locations where lifeguard services, public education and other hazard management measures are likely to have the greatest impact.

Summary

Reducing coastal fatalities requires an understanding of both the hazards present at a beach and the number of people exposed to those hazards. Traditionally, beach safety management has relied heavily on expert assessment and local knowledge, but growing datasets of lifeguard incidents and beach characteristics provide opportunities to develop more objective, evidence-based approaches. For organisations such as the Royal National Lifeboat Institution (RNLI), a key challenge is identifying which beaches are most at risk and therefore most likely to benefit from lifeguard services.

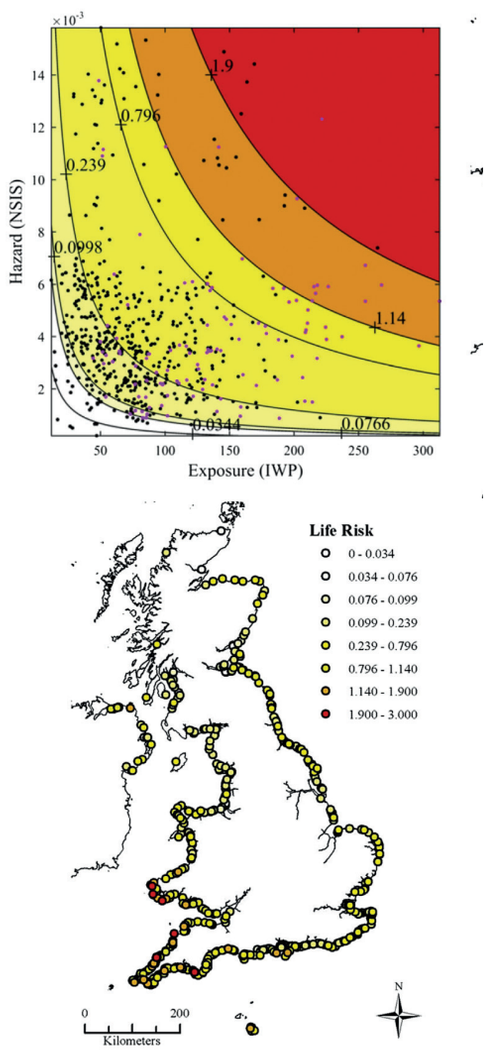
This paper developed and tested statistical models to predict life risk at UK beaches using environmental, geographical and infrastructure variables. Data from 113 lifeguarded beaches were analysed, including incident records, beach user counts, physical beach characteristics and measures of accessibility. Life risk was defined as the product of hazard and exposure, where hazard represented the probability of a severe incident occurring and exposure represented the number of people using the water. Two modelling approaches were evaluated: multiple linear regression (MLR) and Bayesian belief networks (BBN). A total of 77 potential predictor variables were considered, including beach morphology, wave conditions, parking provision, urbanisation and facilities.

The results showed that intermediate beach morphology was the most important predictor of life risk. Beaches with intermediate morphology were associated with higher hazard levels because they commonly contain rip currents and other dynamic surf-zone features. At the same time, these beaches attracted larger numbers of water-users, likely because they provide favourable conditions for activities such as surfing. This combination of high hazard and high exposure made intermediate beaches consistently more risky than reflective or dissipative beach types.

Both modelling approaches identified several additional controls on hazard and exposure. Hazard tended to be lower at beaches with slipways and in more urbanised areas, possibly reflecting differences in beach type and greater public familiarity with local coastal conditions. Exposure increased at beaches with larger car parking areas, designated bathing water status and enclosed embayment settings. These factors were interpreted as indicators of accessibility, attractiveness and concentration of beach users.

The multiple linear regression model outperformed the Bayesian network in predictive skill, explaining approximately 48% of the observed variation in life risk and demonstrating a strong ability to rank beaches according to risk. The Bayesian network explained less variance but provided additional insight into the relationships between variables and offered advantages when dealing with incomplete datasets. Both approaches successfully identified beaches with elevated risk and demonstrated the value of combining environmental and social factors when assessing beach safety.

A key outcome of the study was the development of national-scale risk maps showing where high hazard and high exposure coincide. These maps provided a practical decision-support tool for the RNLI, allowing beaches to be prioritised for further assessment and potential lifeguard provision. The work demonstrated that beach safety risk can be quantified systematically and that relatively simple physical indicators can provide valuable information on likely life risk.



Top panel: hazard predictions plotted against exposure predictions for 618 UK beaches where predictor data were available. Contours show lines of equal life risk at (from bottom left to top right) the 1, 5, 10, 50, 90 95, and 99 percentile levels. Bottom panel: life risk predictions for the 618 beaches, plotted at their location in the UK. Most beaches with a large life risk are found in SW England.

A 15-year partnership between UK coastal scientists and the international beach lifeguard community.

Scott, T., Masselink, G., Stokes, C., Poate, T., Wooler, A. and Instance, S., 2022.

Key message

A sustained partnership between coastal scientists and the international lifeguard community demonstrated how applied coastal research can improve beach safety. Over 15 years, collaborative research advanced understanding of beach hazards, rip currents and life risk, while delivering practical tools for risk assessment, forecasting and public safety. The study highlights how co-designed research can translate scientific knowledge into measurable societal benefit and support reductions in coastal drowning.



Take away thought

Effective beach safety strategies can be developed through long-term partnerships between practitioners and researchers. Combining operational experience with scientific evidence supports the development of operational forecasting tools, improves hazard assessments, helps target beach safety resources more effectively and strengthens public safety messaging. This collaborative approach provides a framework for integrating research into routine coastal management and operational decision-making.

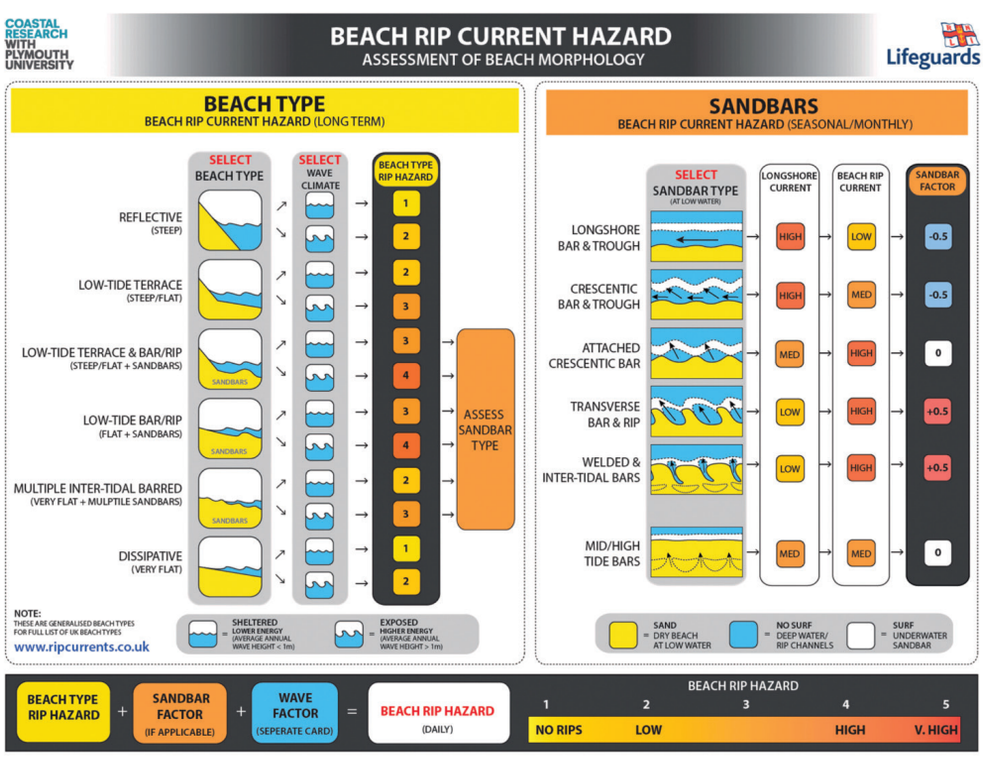
Summary

Reducing drowning on beaches requires more than understanding coastal processes; it also depends on translating scientific knowledge into practical tools that support decision-making. While lifeguard organisations have traditionally relied on professional experience to assess beach hazards, increasing emphasis has been placed on evidence-based approaches that improve risk assessment, resource allocation and public safety. This paper reflects on how a sustained collaboration between coastal scientists and the lifeguarding community successfully bridged the gap between research and operational practice over a fifteen-year period.

The paper reviews a programme of collaborative research undertaken between the University of Plymouth, the Royal National Lifeboat Institution (RNLI) and international beach safety organisations. Beginning in 2006, the partnership addressed a series of operational challenges identified by lifeguard managers, including understanding beach hazards, improving rip current prediction, developing objective beach risk assessments and forecasting periods of elevated bathing risk. Rather than presenting new research, the paper synthesises the scientific advances, operational tools and wider societal impacts that emerged from this long-term collaboration.

The review demonstrates how fundamental coastal process research directly influenced beach safety management. Early work established that rip currents were responsible for the majority of incidents on UK beaches and led to the development of the UK Beach Safety Assessment Model and a national beach classification system. Subsequent field studies and numerical modelling improved understanding of rip current behaviour, showing how waves, tides and beach morphology combine to control hazard. These advances underpinned the development of operational rip current forecasting systems, quantitative beach life-risk models and evidence-based approaches for prioritising lifeguard resources. The research also expanded internationally, supporting beach safety management in countries including New Zealand and South Africa.

A central theme of the paper is that scientific impact was achieved because research questions were co-developed with practitioners. Continuous engagement between researchers and end-users ensured that scientific outputs addressed operational needs and were translated into practical guidance, forecasting tools and policy development. The authors identify sustained collaboration, knowledge exchange and long-term relationships as essential ingredients for achieving meaningful societal impact, demonstrating that coastal science can make tangible contributions to reducing drowning risk when developed alongside those responsible for managing beach safety.



Example of one of the beach hazard training posters created for lifeguard training

New insights into combined surf zone, embayment and estuarine bathing hazards.

Stokes, C., Poate, T., Masselink, G., Scott, T. and Instance, S., 2024.

Key message

Estuary mouth beaches can present bathing hazards that exceed those associated with conventional rip currents. By combining field observations and numerical modelling, this study showed that interactions between estuarine discharge, embayment circulation and wave-driven rip currents can generate flows exceeding 1.5 m/s and frequently produce flows that exit the surf zone. A forecasting framework was developed that successfully hindcast past incidents and provides a basis for operational hazard prediction at estuary mouth beaches.



Take away thought

Estuary mouth beaches represent a distinct hazard environment in comparison to open-coast beaches. Consider estuarine discharge, tidal stage and channel position alongside wave conditions when assessing risk, and consider developing forecasting tools on high-value/risk beaches to identify periods when combined estuarine and water-driven surf zone currents can rapidly transport bathers into deeper water.

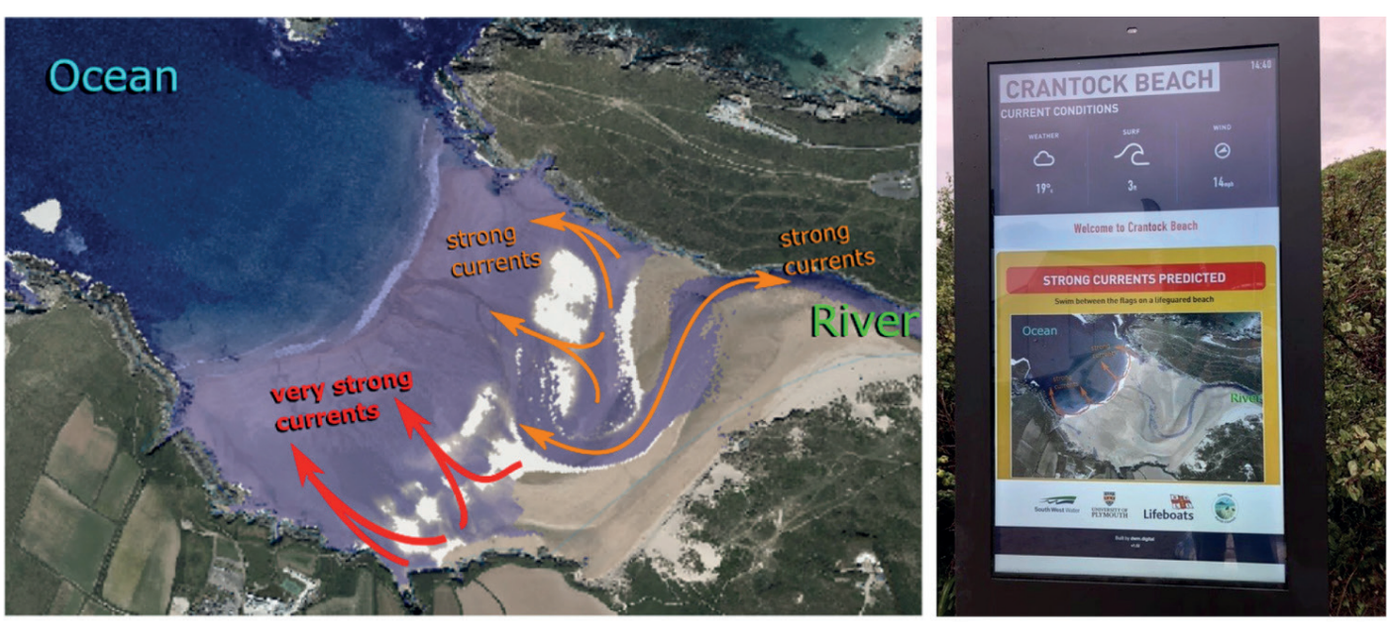
Summary

Rip currents are widely recognised as the principal cause of surf rescues and drowning incidents on wave-dominated beaches. However, around a quarter of designated bathing beaches in the UK also contain a river or estuary, where tidal discharge creates additional currents that interact with surf zone circulation. Although estuary flows are known to exceed the speed of many rip currents, their influence on bathing hazard has received little scientific attention. Existing beach classification and hazard assessment approaches also largely ignore the presence of estuary mouths, leaving an important gap in understanding and beach safety management.

This study investigated the interaction between estuarine discharge, waves and beach morphology at Crantock Beach, Cornwall, an embayed, macrotidal beach intersected by the Gannel Estuary. The research combined field measurements of waves, currents and GPS-tracked drifters with detailed topographic surveys and a calibrated XBeach hydrodynamic model. Numerical simulations were then used to examine surf zone circulation under a wide range of wave and tidal conditions and to develop the first operational forecasting system for bathing hazards at an estuary mouth beach.

The study demonstrated that bathing hazard is controlled by the interaction of three distinct processes: (1) wave-driven surf zone circulation; (2) embayment boundary rip currents; and (3) estuarine discharge. During low water, circulation resembled that of a typical embayed beach, with boundary rip currents dominating the hazard. As the tide rose, however, the ebb-tidal delta and estuary channels became increasingly important, directing strong ebb flows across the beach and into the surf zone. These estuarine currents frequently connected with boundary rip currents to produce complex circulation patterns capable of rapidly transporting bathers offshore. Peak flow velocities exceeded 1.5 m/s, around 50% stronger than those typically reported for rip currents, while more than 60% of simulated bathers exited the surf zone during the most hazardous conditions. Unlike conventional rip-current beaches, where the greatest hazard commonly occurs around low tide, the highest risk at Crantock often developed during the upper half of the tidal cycle when estuarine discharge was strongest.

The research also showed that, despite continual changes in river channel position and beach morphology, the dominant hazard patterns remained sufficiently predictable to support operational forecasting. By combining wave forecasts, tidal conditions and estuary morphology, the authors developed a practical hazard look-up system that successfully reproduced the timing and severity of previous bathing incidents. The study demonstrated that estuary mouth beaches represent a distinct class of coastal hazard and require dedicated assessment and forecasting approaches beyond those used for conventional rip-current beaches.



In the left panel is an example of simplified beach hazard information derived from simulated drifter patterns. In the right panel is an operational digital bathing hazard sign at Crantock Beach next to a key beach access point showing dynamic hazard predictions for the next hour. Aerial imagery courtesy of National Network of Regional Coastal Monitoring Programmes of England, © 2024 NNRCMP.

Chapter 3: Beaches

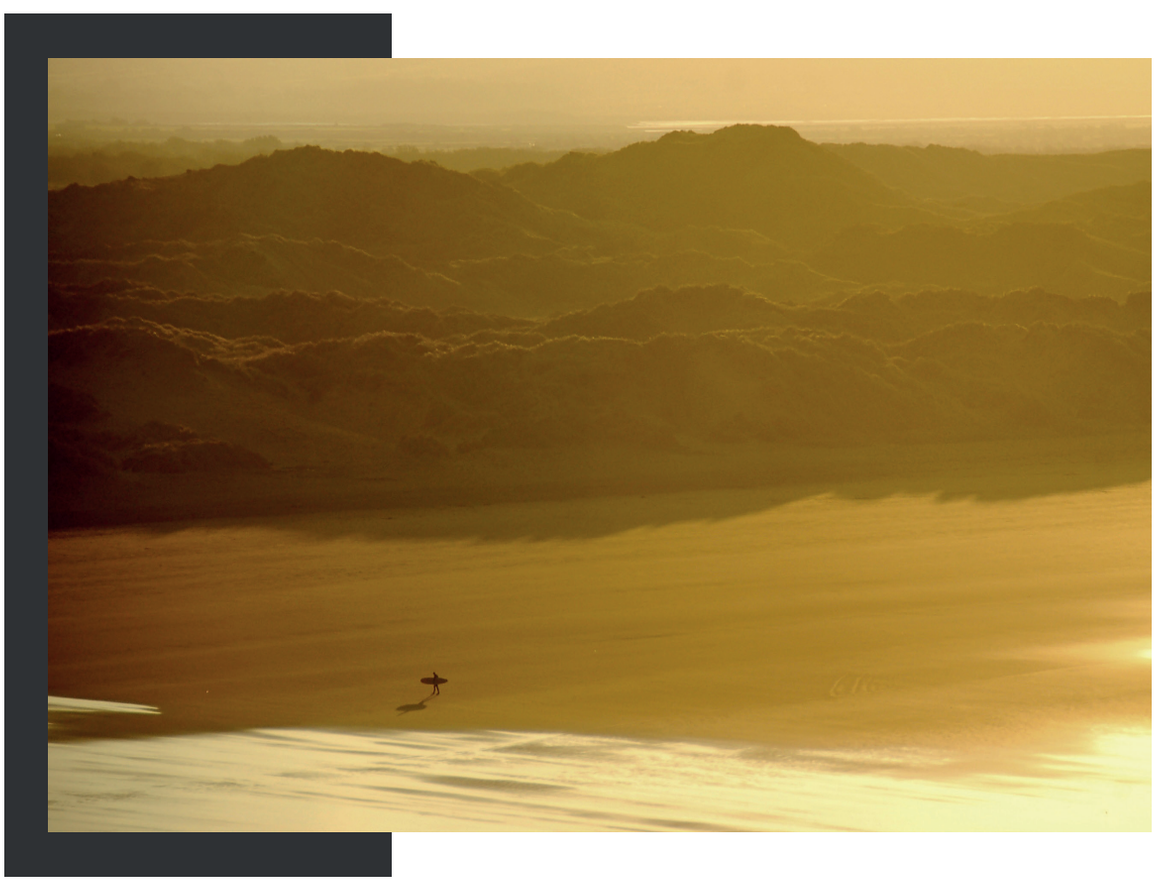
Beaches are dynamic environments that continually adjust to changing waves, tides and sediment supply. Their behaviour influences the impacts of coastal erosion, flooding, habitat condition and the performance of coastal protection measures, making an understanding of beach dynamics fundamental to effective coastal management. The papers in this chapter examine how beaches can be classified and monitored, how they respond to storms and longer-term environmental variability, and the processes that control their evolution across a range of coastal settings. Together, they demonstrate how scientific observations and new monitoring techniques can improve the understanding and management of coastal change.

Morphodynamic characteristics and classification of beaches in England and Wales.

Scott, T., Masselink, G. and Russell, P.E., 2011.

Key message

A new national-scale classification of beaches in England and Wales was developed using morphology, sediment characteristics, and hydrodynamic conditions.
The study identified distinct beach types, introduced an absolute wave energy threshold separating low- and high-energy environments, and provided a practical, hazard-based framework for assessing beach behaviour and coastal risk.



Take away thought

Beach type provides a useful first-order indicator of coastal hazard to support consistent risk assessment across different beaches. A UK-wide beach classification framework is proposed that distinguishes fundamentally different hazard environments. This framework provides an important context for managers to recognise where different monitoring, risk assessment and beach safety approaches may be required. However, local beach conditions and knowledge remain essential for site-specific management decisions.

Summary

Beach morphology varies in response to waves, tides, sediment size, and geological setting, and these controlling mechanisms have led to the development of simplified classification models that link beach type to environmental forcing. Most existing models were developed in specific regions, particularly Australia, and their applicability to more complex coastal settings, such as those found in England and Wales, remained uncertain.

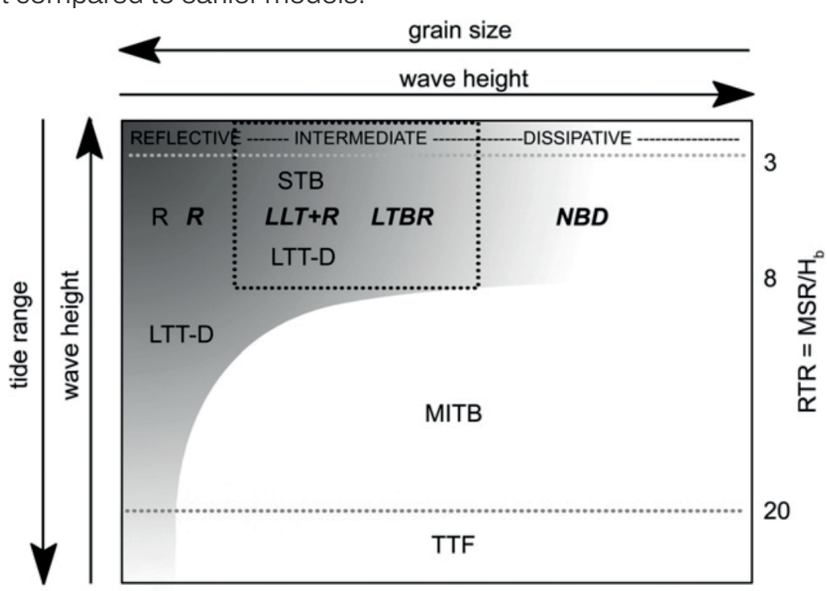
This paper presents the first national-scale analysis of beach morphology in England and Wales using a comprehensive dataset of morphological, sedimentological, and hydrodynamic characteristics. Statistical techniques, including cluster analysis, were used to objectively group beaches into types based on similarities in their physical properties. The approach allowed the identification of dominant morphodynamic beach types without imposing predefined categories and was designed to support practical applications, particularly in relation to beach hazard assessment.

The results showed that beaches in England and Wales could be grouped into a number of distinct morphodynamic types. A key finding was the identification of an absolute wave energy threshold separating low-energy and high-energy beach types, providing a clear distinction between fundamentally different coastal environments, especially those with and without rip currents. This represented an important development compared to earlier models.

The classification also demonstrated the strong influence of both wave exposure and tidal range on beach morphology. High-energy, exposed coasts were associated with dissipative beach states, characterised by wide, low-gradient profiles and active bar systems, while more sheltered or lower-energy environments exhibited more reflective or intermediate characteristics. The large tidal range around the UK modified these relationships, leading to differences from classifications developed in microtidal environments.

Although distinct beach types were identified, the study deliberately avoided imposing rigid boundaries between them. This recognised the continuous nature of coastal systems and the importance of local controls, such as geology and sediment supply, in modifying beach response. As a result, the classification provided a structured but flexible framework for understanding beach behaviour.

The study concluded that the classification could be used to link beach type to hazard levels, particularly in relation to wave conditions and surf zone processes. By defining beach types in terms of physical controls and behaviour, the model provided a basis for predicting how different beaches may respond to changing conditions and for comparing sites at a national scale.



Conceptual morphodynamic framework for sampled beaches throughout England and Wales. Dark and light shadings indicate a general transition from reflective to dissipative surf zone conditions, respectively. Bold black dashed box indicates region of intermediate beach types where high-energy conditions (P > 3 kW m– 1) are required to support three-dimensional bar formations. Beach types in bold italics exist only in a high-energy wave climate. Relative Tide Range (RTR) is composed of breaking wave height (H_b) and Mean Spring Range (MSR). Beach types are: R = Reflective; STB = Sub Tidal Barred; LLT+R = Low Tide Terrace and Rips; LTT-D = Low Tide Terrace Dissipative; LTBR = Low Tide Bar/Rip; NBD = Non-Barred Dissipative; MITB = Multiple Intertidal Barred; TTF = Transition to Tidal Flats.

Morphodynamic variability of high-energy macrotidal beaches, Cornwall, UK.

Poate, T.G., Masselink, G., Russell, P.E. and Austin, M.J., 2014.

Key message

This study is the detailed characterization of the morphodynamic variability of two high-energy macrotidal beaches on Cornwall's north coast over a three-year period. Despite pronounced seasonal wave climate variability, the beach morphology did not exhibit clear seasonal patterns but was mainly controlled by episodic storm events with sustained energetic waves ($H_s \geq 4$ m). These storms prompt offshore sediment transport from the upper beach to the subtidal bar, reducing three-dimensional (3D) beach complexity.



Take away thought

High-energy macrotidal beaches are shaped more by unpredictable storm events than by predictable seasonal cycles. For managers, this means erosion and recovery should be anticipated based on storm frequency, duration and intensity, and not just explained by winter–summer patterns. The study's conceptual model demonstrates how sediment moves offshore during storms and returns onshore during calmer periods, improving understanding of sediment budgets and helping guide nourishment, protection, and recovery planning.

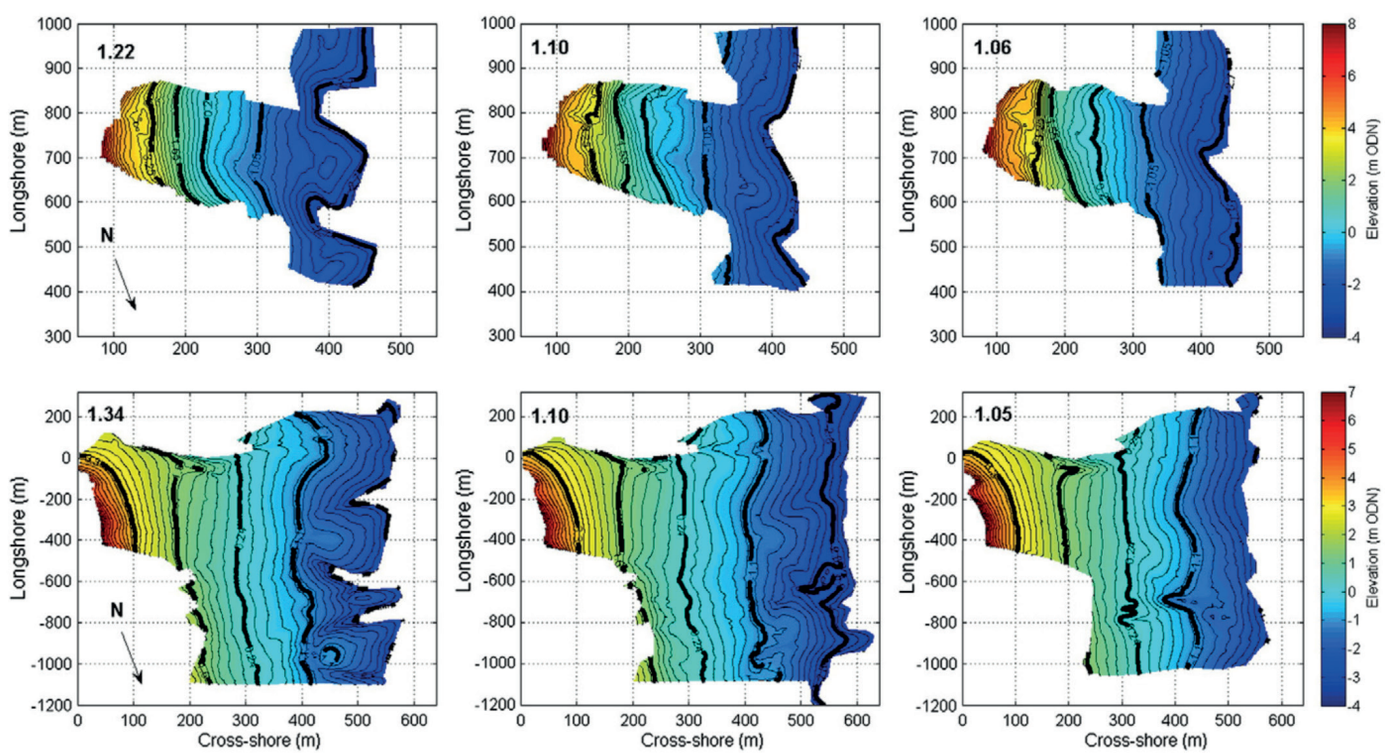
Summary

This paper presents a three-year study of morphodynamic change at two high-energy macrotidal beaches on the north Cornish coast, UK: Perranporth (PPT) and Porthtowan (PTN). The study addresses the lack of long-term 3D morphological data for macrotidal beaches, where large tidal ranges and energetic waves create complex behaviour.

Beach change was tracked at high spatial and temporal resolution using monthly RTK-GPS surveys, wave buoy data, tide gauges and video monitoring. A curvature-based metric was used to quantify beach three-dimensionality and classify morphological states..

A key finding was that these beaches did not follow a simple seasonal cycle despite higher winter waves and calmer summer conditions. Instead, change was mainly driven by episodic storm events (waves >4 m for more than 50 hours). During storms, sediment moved offshore, flattening bar/rip morphology and reducing 3D complexity. Post-storm recovery phases are marked by onshore sediment transport and the redevelopment of complex 3D bar/rip morphology, lasting several months before calmer conditions smooth the landscape.

This created a storm-driven morphodynamic cycle rather than the classic winter/summer cycle seen on smaller tidal beaches. The study highlights that macrotidal beaches have longer recovery times, and provides valuable insights for coastal management, hazard assessment, and morphodynamic modelling.



Sequential 2D morphological evolution. The top panel shows monthly surface plots for Porthtowan from June, July, and August 2008, and the bottom shows Perranporth from January, February, and April 2010. Thick black contours identify MLWS, MLWN, MSL, MHWN and MHWS. The number in the top left of each panel is a 'Curvature Value' which is the ratio of the total contour length (lower beach) and the stright line length, where 1 is straight line and >1 represents an increasingly variable shorline.

Role of wave forcing, storms and NAO in outer bar dynamics on a high-energy, macro-tidal beach.

Masselink, G., Austin, M., Scott, T., Poate, T. and Russell, P., 2014.

Key message

Using a 15-year observational time-series of Perranporth beach, five distinct types of outer bar morphology were identified with the crescentic bar type being the most common. The outer bar on Perranporth has a typical amplitude of 0.5–1 m and a longshore wave length of 600 m. The outer bar system is highly dynamic, migrating offshore and becoming increasingly two-dimensional under energetic wave conditions, and migrating onshore and becoming increasingly three-dimensional under calm wave conditions.



Take away thought

The shape and dynamics of the outer bar system at Perranporth is related to wave forcing which is partly controlled by large-scale climate variability, which can be parameterised by the winter North Atlantic Oscillation (NAO). Recognising these climate-driven patterns provides valuable context for interpreting long-term monitoring data, assessing coastal change, beach hazards and planning management interventions.

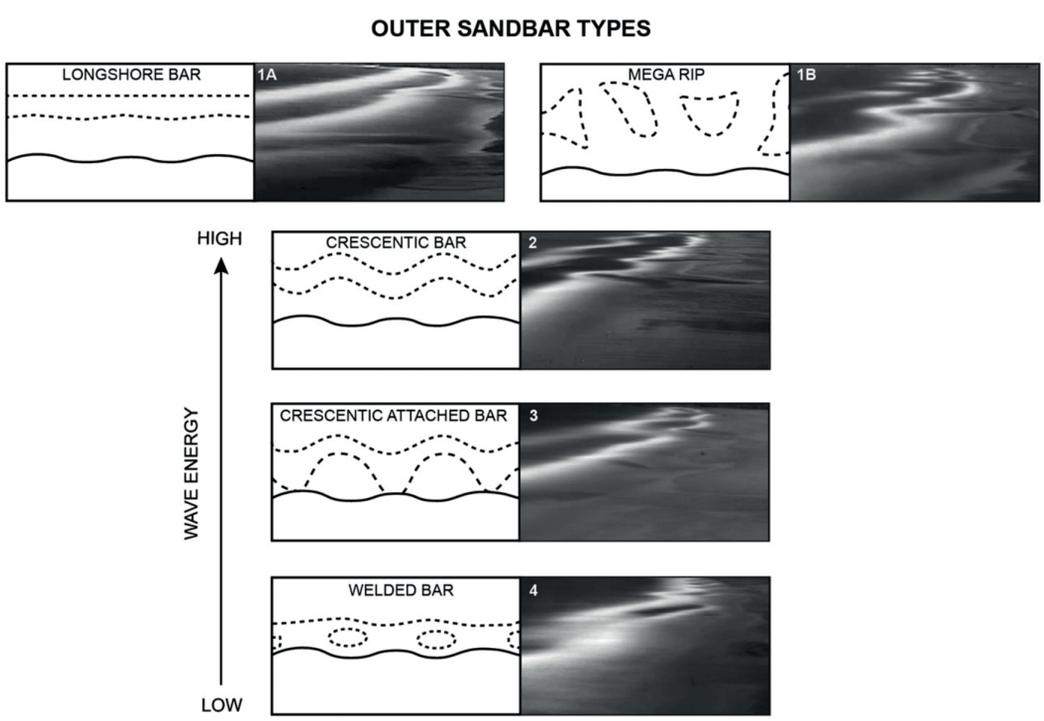
Summary

Energetic sandy beaches commonly possess sub-tidal bar morphology. When a significant tide is present there may also be intertidal bars. Investigating the dynamics of these bar systems is of interest as the bars are often associated with hazardous rip currents; hence, there are implications for beach safety. The bars also represent significant sediment stores and therefore provide natural protection to the upper beach and dune system under energetic wave conditions by providing a focus for wave breaking and wave energy dissipation.

The dynamics of the outer sand bar system on Perranporth on the north Cornish coast was investigated in this paper using a 15-year field dataset of outer bar morphology derived from images obtained from a video monitoring station deployed from the cliff at the southern end of the beach. The visual data set was complemented by GPS-based beach surveys. Based on the video images, five distinct outer bar types were identified: Mega Rip, Longshore Bar, Crescentic Bar, Crescentic Attached Bar and Welded Bar. The most common outer bar type was Crescentic Attached. The outer bar on Perranporth has a typical amplitude of 0.5–1m and a longshore wavelength of 600 m. Changes in outer bar morphology were related to nearshore wave data and it was found that the outer bar types transitioned through distinct states depending on the offshore wave conditions.

An extended duration of energetic wave action was required to bring about a so-called upstate bar transition to the Longshore Bar or Mega Rip state. Once the outer bar reached this state, it remained arrested for a significant amount of time, requiring several months of low wave conditions to induce a so-called downstate transition through Crescentic Attached Bar or Welded Bar. This slow morphological response is explained by extended relaxation times attributed to the large tidal range at the study site where the outer bar morphology is only active for part of the tidal cycle (several hours around low tide). The configuration of the outer bar was related to its position with the upstate bar types associated with a more offshore position, and the downstate bar types associated with a more onshore bar position.

The upstate end-member (Longshore Bar or Mega Rip) was attained sometime during the winter months for 14 out of the 16 years of monitoring; the outer bar remained in the attached to the low tide shoreline (i.e., Welded Bar) over the winter 2005/2006 and 2010/2011. These two winters were characterised by the lowest winter wave conditions and negative winter North Atlantic Oscillation (NAO) indices, suggesting that the winter NAO is correlated with both beach state and nearshore bar configuration. This is the first time that a correlation between NAO and bar morphology has been established.



Schematic overview of defined outer bar states with example time-averaged exposure video images from Perranporth. Inner bar states are not defined.

Classification of beach response to extreme storms.

Burvingt, O., Masselink, G., Russell, P. and Scott, T., 2017.

Key message

Beach response to extreme storms is not uniform, but can be systematically classified into four response types, ranging from large, alongshore-uniform erosion on exposed coasts to rotation-dominated behaviour on sheltered, embayed beaches. These responses are primarily controlled by wave exposure, incident wave angle, and beach geometry.



Take away thought

Even on a regional scale, beach response, and thus coastal vulnerability, is highly site-specific, and is controlled by a combination of wave exposure, angle of wave approach and coastal setting. Exposed beaches tend to experience greater sediment losses and dune erosion, while sheltered or embayed beaches are more likely to undergo alongshore sediment redistribution and beach rotation. This highlights the need for site-specific assessments when evaluating storm impacts and planning coastal management interventions.

Summary

Understanding how beaches respond to extreme storms is critical for coastal management, particularly as storminess may increase under future climate scenarios. Beach response to storms is known to be highly variable, controlled by both hydrodynamic forcing (e.g. wave height, duration, storm sequencing) and site-specific factors such as beach morphology, sediment characteristics, and geological setting. Large-scale studies of coastal change are still limited, and although understanding of how beaches respond to extreme storms has improved, key questions remain. Previous work has shown that the 2013/14 winter storms were the most energetic in decades and caused widespread erosion along the Atlantic coast of Europe. These earlier studies also highlighted strong regional differences in how beaches responded, particularly between cross-shore erosion-dominated systems and beaches exhibiting rotation but were largely based on profile data from a limited number of sites.

This paper builds on that body of work by analysing a much larger dataset (157 beaches) using airborne LiDAR, enabling full spatial assessment of storm-driven morphological change. The aim is to explain why neighbouring beaches subjected to the same storm sequence can respond so differently.

Two key metrics were used: (1) net volumetric change per meter of alongshore beach length (dQnet) , and (2) the longshore variability in response (volume change) represented by the longshore variation index (LVI). These parameters allow both the magnitude and spatial pattern of change to be quantified. The study used cluster analysis, a statistical method that groups data based on the similarity in their characteristics, and identified four distinct storm response types:

Cluster 1 (fully exposed beaches): Large sediment losses (~100 m^3/m) with relatively uniform erosion alongshore, dominated by cross-shore sediment transport.

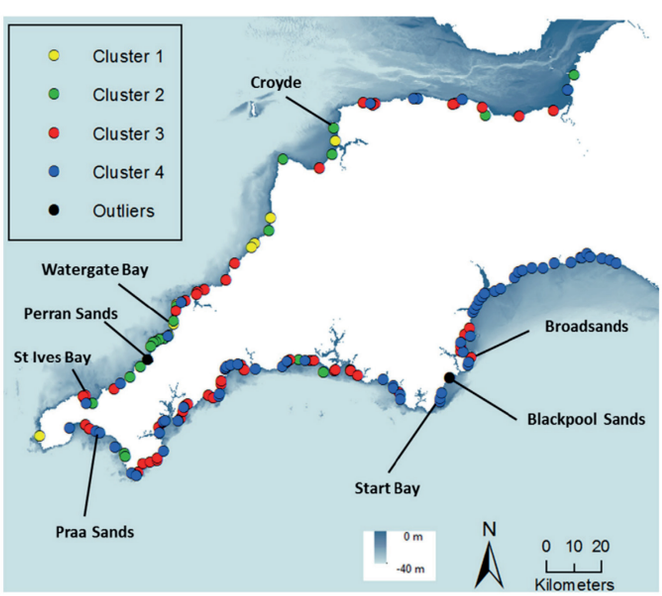
Cluster 2 (semi-exposed beaches): Moderate erosion (~50 m^3/m), still relatively uniform alongshore, with some internal redistribution of sediment across the profile.

Cluster 3 (sheltered short beaches): Limited net change, but highly variable response. Both cross-shore and alongshore processes operate

Cluster 4 (sheltered long beaches): Minimal net volume change but strong alongshore variability. Erosion in one area is offset by accretion elsewhere, reflecting dominant alongshore transport and beach rotation.

The spatial distribution of these response types reflects regional differences in hydrodynamic forcing. North-facing coasts, directly exposed to Atlantic swell, show large, uniform erosion driven by cross-shore processes. In contrast, south-facing coasts, which are more sheltered and subject to oblique wave approach, show rotational behaviour due to strong alongshore sediment transport gradients.

The study further demonstrates that beach geometry (embayment length and shape) is a critical secondary control. Longer embayed beaches are more prone to rotation, while shorter or more constrained systems tend to show mixed but balanced responses, with limited net change. In contrast, more exposed or less constrained beaches typically experience more uniform, cross-shore dominated changes. Local geological controls such as headlands, can modify these patterns and create significant variability between adjacent beaches.



Map showing the 157 beaches of the study coloured according to storm response type (Cluster 1–4).

Satellite-based shoreline detection along high-energy macrotidal coasts and influence of beach state.

Konstantinou, K., Scott, T., Masselink, G., Stokes, C., Conley, D. and Castelle, B., 2023.

Key message

Satellite-derived shoreline position in high-energy, macrotidal environments is strongly controlled by beach morphology and wave action rather than tidal elevation alone. Using 14 years of survey data, the study shows that different beach types require different hydrodynamic corrections, with wave setup and runup being critical on dissipative beaches. Applying appropriate, site-specific corrections significantly improves shoreline accuracy and reduces bias. As a result, satellite shoreline data can reliably reproduce long-term trends, but only when beach state is explicitly accounted for.



Take away thought

Satellite-derived shoreline extraction methods perform differently across coastal settings, with substantially larger errors on exposed, dissipative macrotidal beaches, which are common in Cornwall. Consequently, shoreline extraction accuracy is strongly site-dependent, and the reliability of shoreline datasets depends on the coastal setting. Accounting for local morphology and applying appropriate correction methods improves confidence in shoreline change assessments used for coastal monitoring and management.

Summary

Understanding shoreline change is essential for effective coastal management, yet it remains challenging because it occurs across a wide range of timescales from rapid, storm-driven erosion to longer-term variability linked to wave climate and atmospheric forcing. Capturing these dynamics requires long, consistent datasets, but traditional monitoring methods, although accurate, are spatially limited and rarely extend over multiple decades.

Earth observation provides consistent, repeated measurements over large areas with frequent revisit times, enabling analysis of shoreline change over decadal timescales that traditional surveys seldom capture. As a result, satellite-derived shorelines (SDS) are increasingly used to provide the longer-term perspective needed to understand variability and inform future projections. However, SDS can contain significant uncertainties, particularly in high-energy, macrotidal environments, and their reliability under such conditions is not yet fully understood.

Satellite shoreline detection relies on identifying the land–water interface, but this boundary shifts continuously due to tidal fluctuations and wave action. Consequently, the waterline detected in satellite imagery is highly dynamic and influenced by both morphological change and tide- and wave-driven water-level variations. This study evaluates the accuracy of SDS using a unique 14-year dataset of monthly topographic surveys from two contrasting UK sites: a reflective gravel beach (Slapton) and a dissipative sandy beach (Perranporth). The authors tested several water-level correction methods to better understand how tides and waves influence SDS and to determine the most effective approach for converting the instantaneous waterline into a shoreline position.

The results show that accounting for water level substantially improves SDS accuracy, but the optimal correction depends on beach type. On reflective beaches, shoreline position is primarily controlled by tidal elevation, so tidal correction alone is sufficient. In contrast, on dissipative beaches, wave-driven processes such as setup and runup strongly influence shoreline position and must be included to achieve accurate results. Incorporating both tide and wave effects significantly reduces error and bias in shoreline estimates. A key finding is that knowledge of the beach profile shape is essential, as it underpins the application of water-level corrections. This means that the most effective SDS approach and its achievable accuracy are inherently site-specific.

The study also highlights practical limitations, particularly the reduced availability of usable satellite imagery due to cloud cover, which can hinder the detection of seasonal and interannual variability and affect long-term trend analysis. Overall, the findings demonstrate that satellite-derived shorelines can reliably reproduce observed shoreline trends when appropriate, site-specific corrections are applied.

Optimum SDS extraction strategy for different applications

high — Beach morphology data — low

	REFLECTIVE SITES	DISSIPATIVE SITES	MIXED APPLICATIONS	LARGE SCALE APPLICATIONS
Water level definition	tide	tide + runup	tide + runup	tide + runup
SDW translation	average profile	average profile	average profile	beach slope estimate
Proxy shoreline	MHW	MHWN	MHWN-MHW	AMSL
RMSE	<1.5 pixel	2 pixels <	2 pixels <	12 pixels
Bias	**< 1 pixel (seaward)**	**< 0.5 pixels (landward)**	**≈ 1 pixel**	**7 pixels**

Konstantinou *et al.*, 2023

* pixel = S2 pixel (10 m)

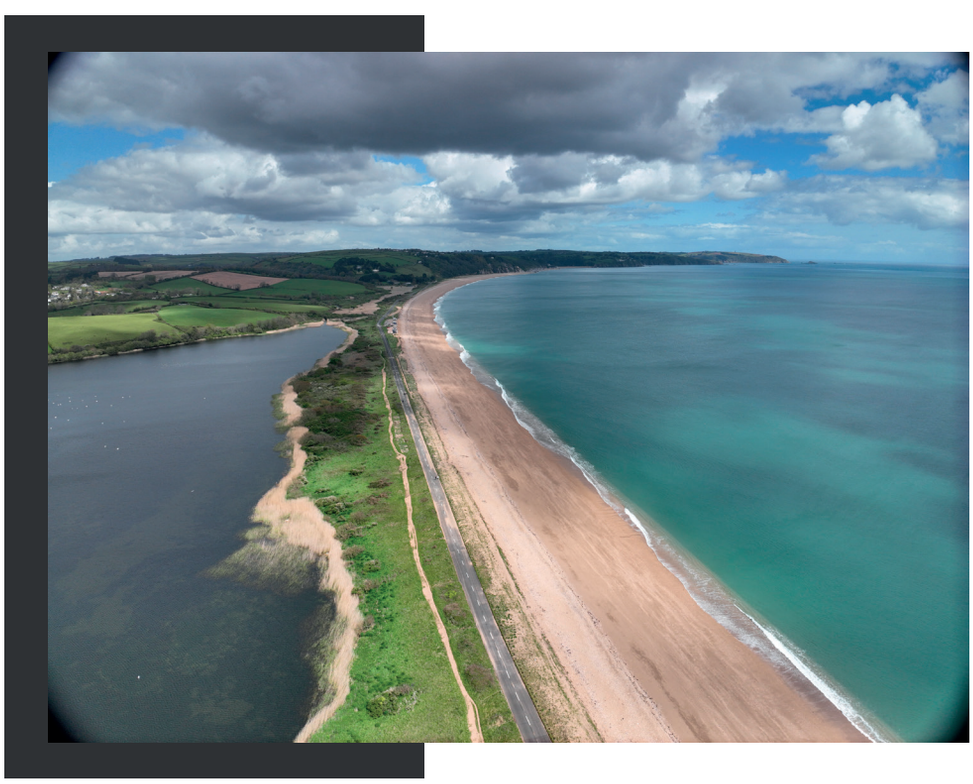
Table summarising the best SDS extraction strategy depending on the type of beach investigated, the scale of the investigation, and the amount of beach morphological information available. The table includes the appropriate water level correction, method for converting the instantaneous land/water boundary into a shoreline (SDW translation), the shoreline proxy to be used for this conversion based on tidal datum (MHW: Mean High Water; MHWN: Mean High Water Neaps; AMSL: Mean Astronomic Sea Level), and the expected accuracy of the SDS (bias or offset and RMSE) in terms of Sentinel 2 (S2) satellite image pixel size (10m) .

Groundwater dynamics in coastal gravel barriers backed by freshwater lagoons and the potential for saline intrusion: Two cases from the UK.

Austin, M.J., Masselink, G., McCall, R.T. and Poate, T., 2013.

Key message

The groundwater table with the Slapton Sands and Loe Bar gravel barriers is highly dynamic and controlled by the ocean tide and energetic waves. The amplitude and phase lag of the tidal signal as it propagates landwards can be used to estimate the hydraulic conductivity of barrier aquifers. Salt water penetrates into the barriers, but the width of the barriers and the high water level of the freshwater lagoons behind them inhibits saline intrusion.



Take away thought

Many gravel barriers are backed by a freshwater lagoon, including Loe Bar in Cornwall and Slapton Sands in Devon. These barriers act as both physical and hydraulic barriers, such that the lagoons are unlikely to experience seawater intrusion, unless the barrier is overwashed or breached. Resilience to saline intrusion depends on the interaction between barrier geometry and lagoon water levels, providing important context for managing barrier-lagoon systems.

Summary

Coastal groundwater systems are complex due to the combined influences of oceanic (waves and tides) oscillations and inland groundwater forcing. They are important for at least two reasons: (1) groundwater discharge from coastal aquifers can transport material (e.g., pollutants) from the land to the sea, often at much higher concentrations than in rivers; and (2) saltwater intrusion, which is the ingress of salt water into coastal aquifers, is becoming increasingly widespread and may pose significant problems for agriculture, drinking water supply and freshwater ecosystems. The key factors controlling these two processes are the gradient of the coastal water table and the hydraulic conductivity of the sediment matrix.

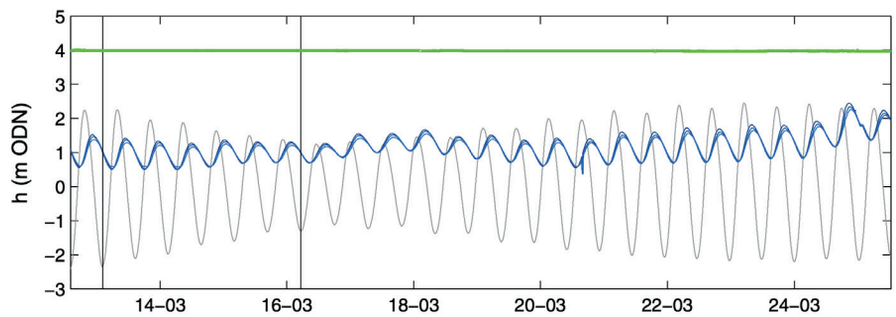
In this paper, a combination of field measurements and relatively simple groundwater modelling is used to study the groundwater dynamics of two gravel barrier system with a freshwater lagoon: Loe Bar in Cornwall and Slapton Sands in Devon. In Loe Bar, the beach groundwater table was measured over a 2-week period at three locations using a pressure sensor deployed in a well, and at Slapton Sands the water table was measured at five locations over a 1-year period. At both locations, the water level in the lagoon and in the ocean was also recorded.

At both sites, the groundwater levels are highly dynamic across the entire width of the barriers, fluctuating at the ocean tidal frequency with a period of just over 12 hours. Large ocean wave events during storms result in a super-elevation of the groundwater across the barrier.

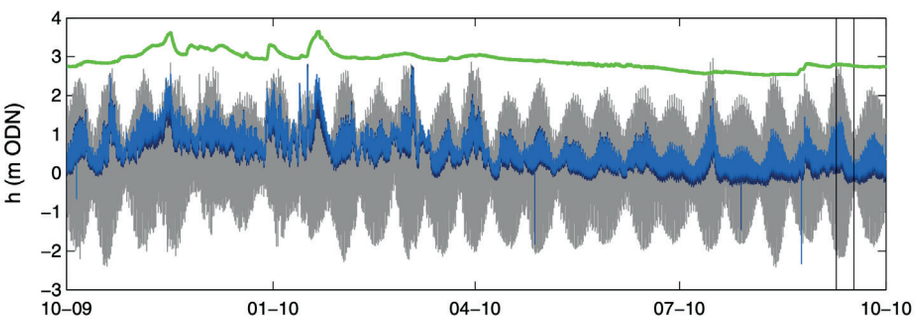
The ocean tidal signal becomes increasingly lagged and dampened as it propagates landwards through the barriers. These properties are used to determine the hydraulic conductivity of the barriers via the one-dimensional unsteady groundwater flow model. The computed value for the hydraulic conductivity was c. 1 cm per second at both field sites, which is highly permeable and typical of fine gravel.

The flow of water through the barrier, referred to as discharge, is principally controlled by the elevation of the lagoon water level. The lagoons are typically 1–2 m higher than the mean high water spring level in the ocean, thus there is a seaward-directed hydraulic gradient and hence discharge. At both barriers, the mean daily discharge is estimated to just over 1000 m^3 per day per unit barrier width. This equates to 15 liters of water flowing from the lagoon into the sea through the barrier every second and along every meter of the barrier.

The potential for saline intrusion into the freshwater lagoons is low. Measurements of the conductivity of the groundwater demonstrated that although salt water penetrates some distance landwards into the barriers (c. 60 m from spring high tide level), the width of the barrier systems and the relatively high water level of the freshwater lagoons inhibit saline intrusion.



Two-week time series of water level data from Loe Bar in Cornwall in 2012: water level recorded in borehole installed in the gravel barrier (blue), the freshwater lagoon (Loe Pool) behind the gravel barrier (green) and the ocean tide (grey). A clear dampened and delayed tidal signal is present in the groundwater, but the lagoon level, which is raised significantly above the ocean high tide level, is constant.



One-year time series of water level data from Slapton Sands in Cornwall from October 2009 to Oct 2010): water level recorded in borehole installed in the gravel barrier (blue), the freshwater lagoon (Slapton Ley) behind the gravel barrier (green) and the ocean tide (grey). The long-term fluctuations in the groundwater are due to wave forcing with elevated groundwater levels due to storm conditions. The fluctuations in the lagoon level are due to rainfall and discharge of rivers into the lagoon. Here, also, the lagoon level is raised significantly above the ocean high tide level.

Chapter 4: Coastal dunes

Coastal dunes form a vital natural buffer for erosion and coastal flooding while also supporting internationally important habitats and landscapes. Their ability to respond to storms, recover and adapt to rising sea levels makes understanding dune behaviour increasingly important for sustainable coastal management. The papers in this chapter investigate the processes that control dune evolution, from short-term erosion during extreme events to long-term responses to sea-level rise and regional-scale prediction of future change. Together, they provide scientific evidence that supports the management, conservation and adaptation of dune systems in a changing climate.

Coastal dune dynamics in embayed settings with sea-level rise – Examples from the exposed and macrotidal north coast of SW England.

Masselink, G., Brooks, S., Poate, T., Stokes, C. and Scott, T., 2022.

Key message

Almost all exposed dune systems along the coast of Cornwall show retreat with a regionally-averaged retreat rate of the dune foot of 0.5 meter per year. A key factor in driving this retreat is the number of hours that waves reach the dune foot. Both sea-level rise and enhanced storminess will increase exposure of the dune foot to energetic wave action and this is expected to accelerate dune retreat rates.



Take away thought

The combination of long-term observations of dune morphological change and wave conditions with dune retreat models can provide useful insights into future dune evolution. For a sea-level rise of 0.6 m by 2100, the models predict c. 40 m of retreat of dunes in SW England, providing an evidence base for long-term coastal adaptation planning.

Summary

Dune systems are present along many low-lying coastlines and are often the first line of defence against the impacts of storms. The dune, foredune and beach are highly dynamic with complex responses to storms depending on the interaction between waves, wind and vegetation. The main impact from storms arises from the difference between the elevation of the dune foot and the so-called 'total water level' (TWL; tide + storm surge + wave run-up). The difference between TWL and the dune foot elevation controls the occurrence and duration of the wetting of the dune base. When dunes are scarped during storms, sediment is deposited on the beach and in nearshore region.

The key objectives of this paper are to: (1) provide a regional overview of the dynamics of 25 coastal dune systems along the embayed, exposed and macrotidal coast of north Cornwall using a combination of topographic survey and LiDAR data; and (2) compare the observed dune behaviour with that hindcasted from simple parametric models and forecast future dune retreat rates due to sea-level rise.

Practically all studied dune systems experienced retreat with a regionally-averaged retreat rate of the dune foot of 0.5 meter per year. The majority of retreat occurred over a small number of especially energetic winters (e.g., the 2013/14 winter). It was found that dune retreat is not automatically linked to dune volumetric change, and many of the retreating dune systems displayed so called 'dune roll-over', characterised by removal of sediment from the dune face and deposition at the dune top.

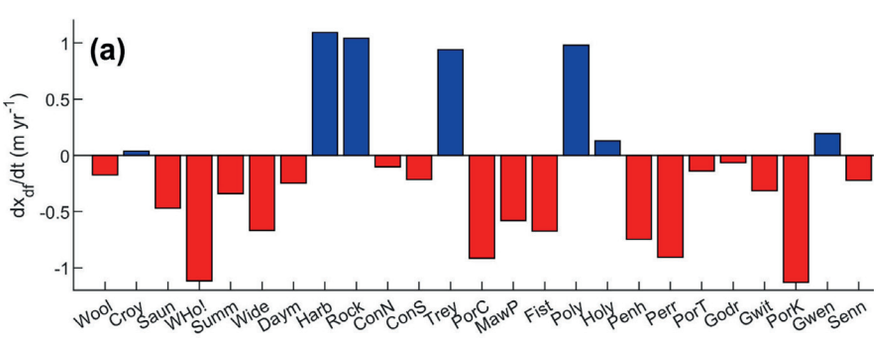
A key factor in driving dune retreat along this coast is the number of hours that (storm) waves reach the dune foot. Along beach-dune systems, both sea-level rise and enhanced storminess will increase exposure of the dune foot to energetic wave action and this is expected to accelerate dune retreat rates in these settings.

Observed dune dynamics were compared with that hindcasted from simple parametric models forced by sea-level rise, including the Bruun Rule. Observed dune retreat rates were 2–3 times larger than predicted, suggesting that the retreat models are inappropriate and/or that sea-level rise in itself may be insufficient to explain the observed retreat and that increased winter storminess may be implicated.

For a sea-level rise of 0.6 m by 2100, the parametric shoreline retreat models predict c. 40 m of dune retreat with a very considerable range in retreat (20–75 m), resulting from uncertainties in model choice and parameterisation. Simply extrapolating the current dune retreat rate also results in c. 40 m of dune retreat by 2100, but this approach ignores the potential acceleration in dune retreat rate due to an increase in the rate of sea-level rise.



Aerial photographs of 18 of the 25 dune sites described in this paper, demonstrating the wide variety in scale and setting. The thick white line in the lower part of the photographs represents a 1-km scale bar.



Bar graph of the rate of dune foot change for all dunes sites over 9–13-year period based on LiDAR data. Negative values (red bars) represent dune retreat and positive values (blue bars) represent dune progradation. Crantock is not included in this figure due to the extreme rate of dune retreat (4.8 meter per year).

Emergent coastal behaviour results in extreme dune erosion decoupled from hydrodynamic forcing.

Hird, S., Stokes, C. and Masselink, G., 2021.

Key message

This study investigates the continuing severe erosion observed at Crantock following the 2013/14 winter, which contrasts with regional recovery patterns. The study combines 11 years of LiDAR, UAV and profile data alongside hydrodynamic analysis and modelling to relate observed dune erosion to changes in beach morphology and river channel position. Findings show that dune erosion occurred as a result of a major shift in the River Gannel channel, which lowered the beach and increased dune vulnerability.



Take away thought

Severe dune erosion is not always directly linked to storm activity and/or sea-level rise. At Crantock, the migration of the River Gannel increased the vulnerability of frontal dunes to wave attack, triggering unexpected and severe erosion. This highlights the importance of considering whole-system interactions in coastal management. Monitoring changes in channel position alongside beach morphology provides important context for assessing emerging erosion risk and informing dune management.

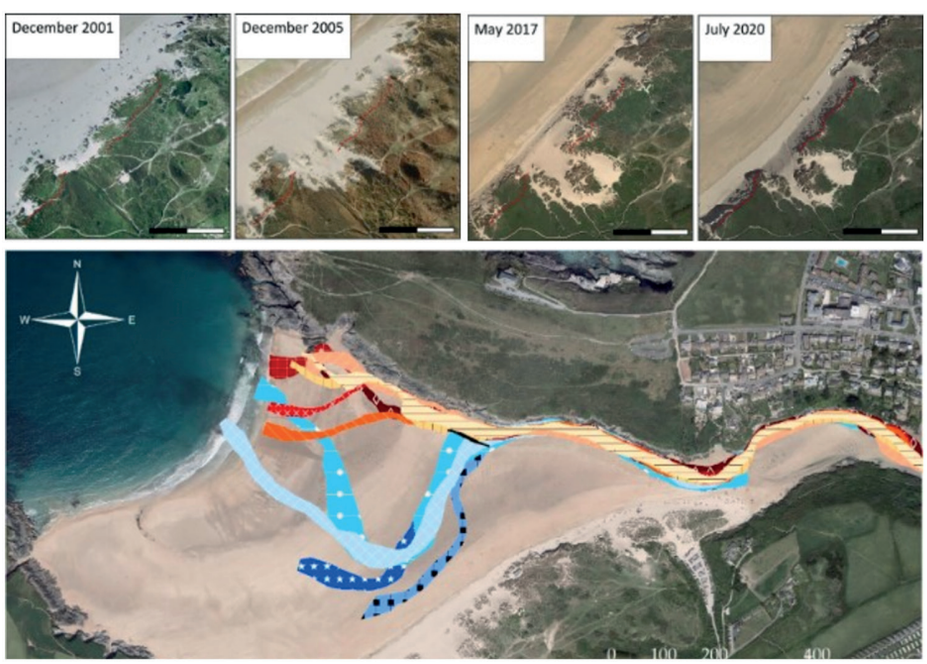
Summary

Coastal dune systems are a critical component of coastal flood defence, but their response to storms is typically interpreted as being driven primarily by hydrodynamic forcing (waves and water levels). Previous studies have demonstrated strong regional coherence in storm-driven erosion during the 2013/14 winter, with beach and dune systems responding in predictable ways to extreme wave conditions as well as recovery patterns. However, there is increasing recognition that coastal systems can exhibit complex and emergent behaviour, where local interactions between processes lead to unexpected or disproportionate morphological responses.

This study investigates an anomalous case at Crantock Beach (north Cornwall, UK), where dune erosion accelerated several years after the 2013/14 storms, in contrast with regional recovery patterns and despite a reduction in storm intensity. Using a combination of LiDAR, UAV surveys, and repeated cross-shore profiles (2008–2019), the study quantifies changes in beach and dune volumes and relates these to hydrodynamic forcing and river channel dynamics. The results show that, unlike nearby exposed beaches that followed expected storm–recovery cycles, Crantock experienced progressive and then rapid dune erosion from 2015 onwards, with the most severe losses occurring between 2016 and 2019, mostly focused at the southern end of the system. Importantly, the timing of these erosion events does not correspond to periods of highest wave energy or water levels, demonstrating a clear decoupling between dune erosion and hydrodynamic forcing.

The primary driver of this behaviour is identified as the migration of the River Gannel channel, which shifted across the beach following degradation of a training wall. This resulted in localised lowering of the intertidal beach in front of the dunes, increasing water depths at the dune toe and allowing greater wave energy to impact the dune face during storms. Numerical modelling (XBeach) confirmed that relatively small changes in beach elevation can significantly increase dune erosion rates, even under similar wave conditions. The study also highlights strong alongshore variability in response, with extreme dune retreat (up to ~27 m between 2008 and 2019) occurring at the southern end of the beach, while areas only a few hundred metres away remained relatively stable. This demonstrates the importance of local controls in governing coastal change at small spatial scales.

Overall, the results show that dune erosion is not solely a function of wave and water level forcing, but can also be influence by estuarine channel dynamics. The Crantock system represents a clear example of emergent coastal behaviour, where interactions between fluvial, coastal, and aeolian processes produce a non-linear and unexpected system response.



Top: Satellite imagery of Crantock dunes from GoogleEarth showing how the dunes have changed between 2001 and 2020. The red dashed lines shows the location of the edge of the vegetation line at the top of the dunes in 2020. Botton: Aerial photograph of Crantock Beach showing the different pathways of the River Gannel from 2008 (red colors) to 2019 (blue colors)

Predicting dune evolution on a regional scale for coastal management.

Brodie, L.M., Stokes, C., Masselink, G., Konsantinou, A., Scott, T. and Poate, T., 2025.

Key message

Coastal dunes across Cornwall do not behave uniformly. Analysis of 31 sites revealed four distinct modes of dune evolution which were not just the expected pattern of erosion and retreat. Half the sites gained volume, rolled over, or advanced, showing that local factors like sediment supply and estuarine dynamics can be more important than sea-level rise in determining how individual dunes evolve.



Take away thought

Coastal dunes are unlikely to respond uniformly to sea-level rise, with vulnerability varying considerably between sites. A staged prediction framework, combining extrapolation of historic shoreline trends in the short-term and application of the Bruun-rule for shoreline prediction in the long term is proposed. More detailed modelling should take place where significant coastal assets are at risk and continued monitoring should be prioritised to update predictions. This framework provides a practical and efficient evidence base for identifying erosion hotspots and supporting coastal adaptation planning.

Summary

Airborne LiDAR surveys (2007–2020) were used to track dune toe position and sediment volume changes at 31 dune sites across Cornwall's north and south coasts. Rates of change varied widely: sediment volume changed by between −12.4 and +5.1 m^3/m/yr, and the dune toe shifted between −3.7 and +1.6 m/yr.

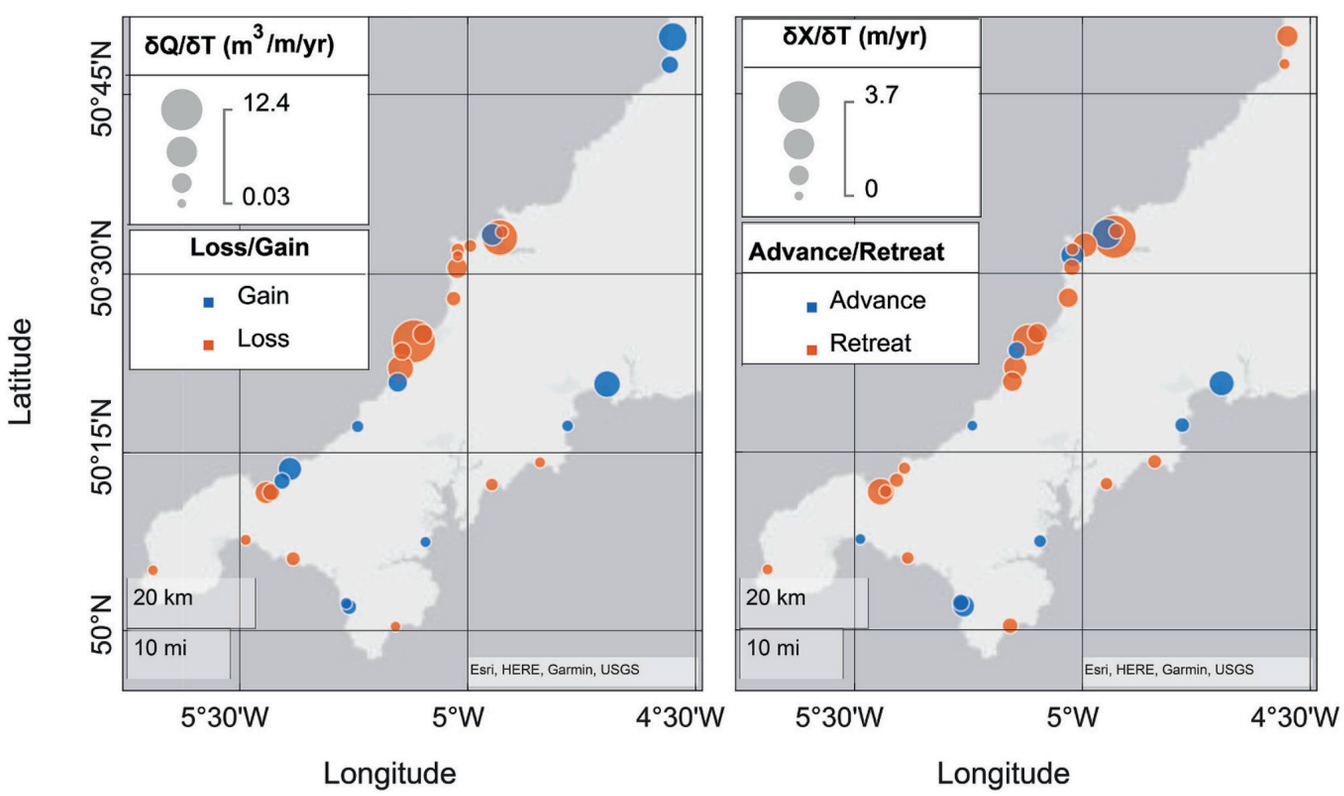
Four distinct modes of dune evolution emerged. **Mode 1**: gained volume and advanced seaward, driven by wind-blown sand delivery from the beach. **Mode 2**: lost volume and retreated, consistent with storm erosion outpacing recovery (the most common mode). **Mode 3**: retreated at the front but gained volume on top through 'rollover', where wind moves sand from the dune face onto the crest. **Mode 4**: some lost volume overall yet still advanced, an effect caused by opposing behaviour at different ends of the same dune frontage.

Most sites did not follow a simple linear trend over the survey period, which limits confidence in projecting future behaviour from short records alone. The more energetic north coast generally showed greater erosion than the sheltered south coast, but both coasts contained a mix of eroding and accreting sites.

The study compared observed dune retreat rates with predictions from the Bruun Rule, which is a simple equation that estimates how far a shoreline will retreat in response to sea-level rise. At many sites, observed retreat far exceeded Bruun Rule estimates, suggesting that storms, estuarine shifts, or sediment supply changes are currently the dominant drivers. At a few sites, dunes were advancing — something the standard Bruun Rule cannot account for.

The Bruun Rule was applied probabilistically using Monte Carlo sampling to account for uncertainty in sea-level rise projections and local shoreface geometry. Under a high-emission scenario (RCP 8.5), projected retreat by 2100 ranged from 13 m at the steepest sites to 61 m at the most gently sloping locations.

The study proposes a three-stage approach for predicting future dune evolution: (1) regional first-pass projections combining observed trends with Bruun Rule estimates to identify 'hot-spots'; (2) targeted reduced-complexity modelling at those hot-spots; and (3) detailed process-based modelling where interventions are imminent.



Spatial map of dune change rates (volumes and dune to position) across the 31 Cornwall sites, showing the mix of retreating (orange) and advancing (blue) dunes. Volume change is ∂Q/∂T; change in dune toe position is ∂X/∂T.

Chapter 5: Regional sediment transport processes

Sediment transport connects individual beaches into larger coastal systems, influencing shoreline evolution, erosion patterns and the resilience of the coast to storms and sea-level rise. Understanding how sediment moves within embayments, around headlands and across the nearshore environment is essential for effective regional-scale coastal management. The papers in this chapter investigate the processes controlling sediment pathways, beach rotation and headland bypassing, combining field observations with numerical modelling to improve understanding of coastal sediment budgets. Together, they provide valuable evidence to support strategic shoreline management, beach nourishment and long-term adaptation planning.

The impact of waves and tides on residual sand transport on a sediment-poor, energetic, and macrotidal continental shelf.

King, E.V., Conley, D., Masselink, G., Leonardi, N., McCarroll, J., and Scott, T., 2019.

Key message

Residual sand transport on macrotidal continental shelves is strongly controlled by waves and nonlinear wave-tide interactions. While tides set the baseline transport pathways, waves can enhance, redirect, or even reverse sediment transport, with interactions between waves and tides often dominating overall transport rates.



Take away thought

Sediment transport on continental shelves cannot be predicted reliably using tides alone. Waves and their interaction with tides play a dominant role, particularly during storms. Representing coupled wave-tide processes provides a more robust basis for understanding and predicting sediment transport pathways, improving sediment budget assessments and supporting a better understanding of long-term coastal evolution.

Summary

This study investigates how waves, tides, and their interactions control regional sand transport patterns across the energetic, sediment-poor continental shelf of South West England. Using a coupled Delft3D hydrodynamic, wave, and sediment transport model, the authors simulate residual sediment transport under a range of wave and tidal conditions to understand the dominant processes shaping shelf sediment pathways.

The South West UK shelf provides an ideal natural laboratory due to its combination of large tidal ranges (macrotidal conditions) and high-energy Atlantic waves (see map on page 3). These conditions generate complex sediment transport pathways that cannot be explained by tides alone.

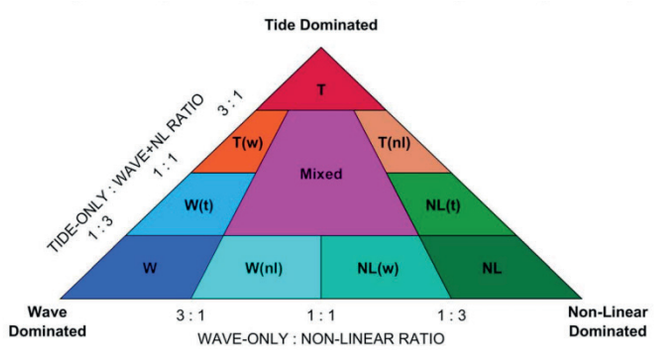
Results show that waves exert a major control on sediment transport, even in strongly tidal environments. Under median wave conditions, waves tend to enhance tidal transport pathways, reinforcing existing sediment flux directions. However, during extreme wave events, waves can dominate transport processes, reversing sediment pathways and shifting the dominant transport phase (e.g., from flood- to ebb-dominated transport).

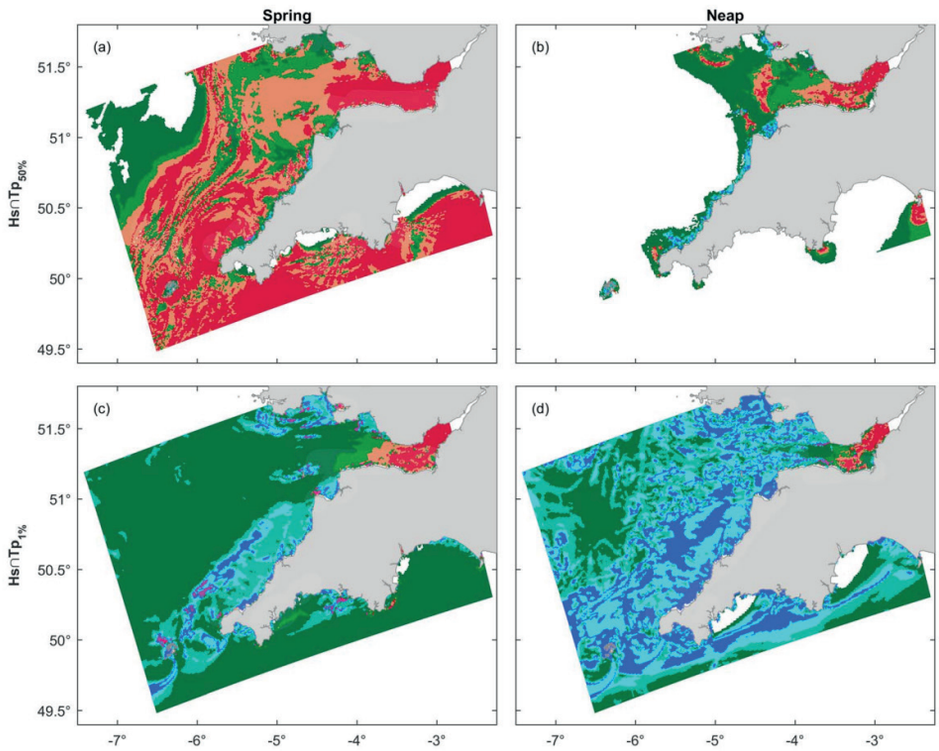
A key finding is the importance of nonlinear wave–tide interactions. These interactions, arising from processes such as enhanced bed shear stress, Stokes drift, and wave-current coupling, can contribute more to total sediment transport than the sum of wave-only and tide-only effects. This demonstrates that treating waves and tides independently can significantly underestimate sediment transport rates.

The study also shows that storm waves can mobilise sediment at much greater depths than previously assumed, with transport occurring below 120 m water depth. This highlights the far-reaching influence of extreme wave events on continental shelf sediment dynamics.

To synthesise these findings, the authors propose a new classification of continental shelf environments based on the relative dominance of wave forcing, tidal forcing, and nonlinear wave–tide interactions. This classification varies depending on wave and tidal conditions, meaning that the same region can shift between different transport regimes over time.

Overall, the study demonstrates that accurate prediction of regional sediment transport requires fully coupled wave-tide modelling, particularly in energetic coastal environments where nonlinear processes are significant.





Wave- tide dominance classification of the South West UK during different wave and tide forcing, accounting for the relative influence of nonlinear wave- tide interactions (W = wave; T = tide; NL = non-linear). Left panels are: (a) median waves (50% exceedence) and spring tides; (b) median waves and neap tides; (c) extreme waves (1% exceedence) and spring tides; (d) extreme waves and neap tides. Colours relate to diagram above.

Wave, tide and topographical controls on headland sand bypassing.

King, E.V., Conley, D., Masselink, G., Leonardi, N., McCarroll, J., Scott, T. and Valiente, N., 2021.

Key message

Headland sand bypassing is widespread on energetic embayed coastlines and can be predicted using measurable morphological and hydrodynamic parameters. Bypassing is primarily wave-driven, modulated by tides and sediment availability, and strongly controlled by headland geometry (e.g., cross-shore extent, toe depth) and surf zone width.



Take away thought

Headland bypassing is a key mechanism of along-coast sediment exchange, rather than an occasional process. Wave climate, headland geometry and sediment availability determine whether headlands function as sediment barriers or conduits. Accounting for these controls improves understanding of regional sediment connectivity, providing a stronger evidence base for sediment budget assessments and long-term coastal management.

Summary

This study investigates the controls on sand transport around headlands (headland bypassing) along a 75-km stretch of the macrotidal, embayed coastline of north Cornwall. Using a high-resolution Delft3D numerical model, the authors simulate sediment transport under a wide range of wave, tide, and sediment conditions across 29 headlands to better understand and parameterise bypassing processes.

The research addresses a key gap in coastal science: while previous studies showed that bypassing can occur, its predictability under realistic coastal morphology remained uncertain. This study tests and extends existing parameterisations by incorporating real-world variability in headland shape, bathymetry, and sediment distribution.

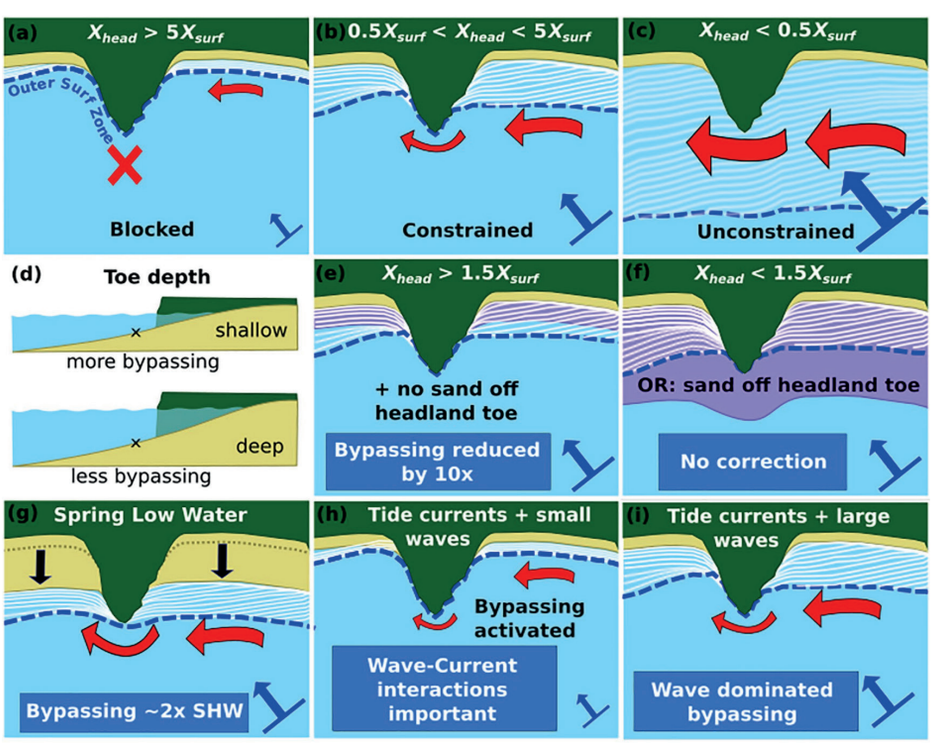
Results demonstrate that headland bypassing is nearly ubiquitous under energetic wave conditions, confirming that embayed beaches are rarely closed sediment systems. Bypassing rates are primarily controlled by wave forcing, with larger waves generating greater sediment flux around headlands. Tides play a secondary role, mainly by altering water levels and modifying wave-current interactions. Under moderate wave conditions, wave-current interactions can dominate sediment transport, sometimes increasing bypassing rates significantly.

A key finding is that headland geometry strongly controls bypassing efficiency. Bypassing decreases significantly when the cross-shore length of a headland exceeds approximately five times the surf zone width, effectively acting as a barrier. Additionally, the depth at the headland toe influences how waves interact with the seabed, moderating sediment transport offshore.

Sediment availability is also critical. Delft3D simulations with realistic spatial sediment coverage show that limited sand near the headland apex can reduce bypassing rates by up to an order of magnitude. This highlights that morphological and geological controls can strongly constrain sediment exchange even under energetic forcing.

The study refines existing predictive models of headland bypassing by incorporating additional parameters such as headland toe depth and sediment coverage. These improved parameterisations can predict wave-driven bypassing rates with reasonable accuracy (mean error within a factor of ~4.6), offering a practical alternative to computationally intensive numerical modelling.

Overall, the findings demonstrate that sediment exchange between embayments is a fundamental and predictable process on wave-exposed coastlines, governed by interactions between waves, tides, and coastal morphology.



Schematic summary for instantaneous headland bypassing. Red arrows show simplified sand transport pathways. Blue arrows indicate wave power and direction, and the blue dashed line indicates the outer limit of the surf zone.

Role of waves and tides on depth of closure and potential for headland bypassing.

Valiente, N.G., Masselink, G., Scott, T., Conley, D. and McCarroll, R.J., 2019.

Key message

Sediment transport remains active much farther offshore than previously recognised. While the morphological depth of closure (DoC) is typically 10–15 m, significant sediment transport can occur beyond 30 m, increasing the potential for headland bypassing. This challenges the concept of embayments as closed sediment cells and suggests that sediment exchange between neighbouring embayments is more frequent than current assumptions suggest.



Take away thought

Standard wave-based estimates of depth of closure may significantly underestimate the extent of sediment transport on macrotidal coasts. Accounting for the combined effects of waves, tidal currents and headland bypassing provides a more robust basis for defining the extent of active sediment transport, improving sediment budget assessments and supporting coastal management.

Summary

The depth of closure (DoC) is a fundamental concept in coastal science used to define the offshore limit of significant morphological change on the shoreface. Traditionally, DoC has been estimated using wave-based empirical formulations developed for microtidal sandy coasts, often neglecting the role of tidal currents and geological controls such as headlands. This study re-evaluates the concept for macrotidal, high-energy, embayed coastlines along southwest England.

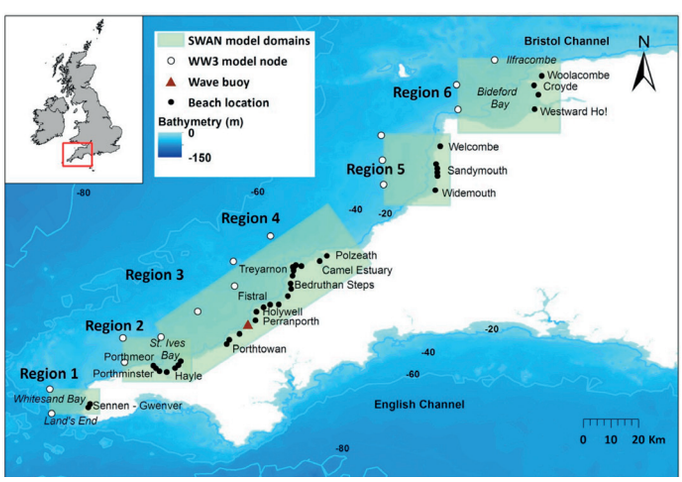
A multi-criteria methodology is applied, combining (1) long-term morphological observations, (2) sedimentological analysis, (3) wave-based parameterisations, and (4) numerical modelling of wave- and tide-induced bed shear stress. Observations from Perranporth beach show that the morphological depth of closure occurs at approximately 14.5 m depth, defined as the point beyond which bed-level changes fall below the measurement uncertainty (~0.14 m).

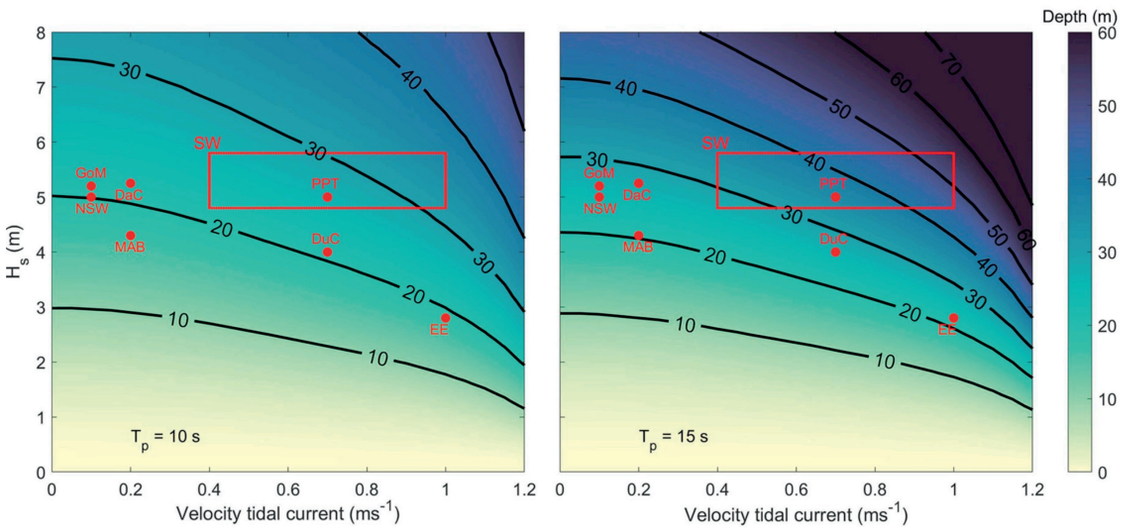
Wave-based formulations provide comparable estimates of DoC (typically 10–15 m), but results vary depending on whether offshore or transformed inshore wave conditions are used. Importantly, inshore wave transformation highlights strong spatial variability linked to embayment orientation and sheltering effects, demonstrating that offshore wave conditions can overestimate closure depth if not adjusted for local morphology.

Sedimentological observations indicate a transition from sand to gravel at depths around 25–30 m, suggesting that sediment transport processes extend significantly beyond the morphological DoC. This deeper limit corresponds to the maximum depth of transport (DoT), which reflects conditions where sediment motion occurs without necessarily producing measurable morphological change.

Numerical modelling of bed shear stress shows that extreme wave conditions alone can mobilise sediment to depths of ~20–30 m, but when combined with tidal currents, the depth of significant sediment transport increases further (by ~10 m). This demonstrates that tidal currents play a crucial role in extending the active shoreface in macrotidal environments.

The key implication is that sediment transport pathways can extend beyond the base of headlands and well beyond the traditional depth of closure. Therefore, embayed beaches that appear morphologically constrained may still exchange sediment with adjacent systems, particularly during energetic wave and tidal conditions.





Top: Model domains for the study of depth of closure and bed shear stress. Black dots indicate the studied embayments and white circles are MetOffice UK Waters Wave Model nodes used as model input.

Variation of depth of transport (DoT) across a broad wave-current parameter space using significant wave height (H_s) and tidal current speed for medium sand (D_{50}=0.3 mm). The red box indicates the range of values for the coast of Cornwall. Location codes are: PPT = Perranporth, UK; GoM = Gulf of Mexico; NSW = New South Wales; MAB = Middle Atlantic Bight; DaC = Danish Coast; DuC = Dutch Coast; EE = East England.

Wave and tidal controls on embayment circulation and headland bypassing.

McCarroll, R.J., Masselink, G., Valiente, N., Scott, T., King, E. and Conley, D., 2018.

Key message

Headland sediment bypassing on an exposed, macrotidal coast is controlled by the interaction of waves, tides, and embayment current circulation. Three distinct bypassing modes were identified, with sediment flux increasing by orders of magnitude from low to extreme wave conditions. A simple, site-specific formula was shown to accurately predict bypass rates. Results showed that this alongshore headland bypassing contributed little to short-term sediment budgets compared to storm-driven cross-shore transport.



Take away thought

Headlands do not necessarily prevent sediment transport between embayments. During storms, sediment bypassing can rapidly transfer large volumes of sediment, with waves acting as the primary control and tides influencing transport direction. Recognising these episodic exchanges provides important context for long-term sediment budgets, beach nourishment and coastal adaptation planning.

Summary

Understanding sediment budgets within coastal cells requires quantifying both cross-shore and alongshore sediment transport. While alongshore transport on open coasts is relatively well understood, the presence of headlands complicates sediment pathways by acting as partial barriers. Headland bypassing, the transport of sediment around these barriers, is therefore a key but poorly quantified process, particularly on natural, embayed coastlines where complex wave-current interactions occur.

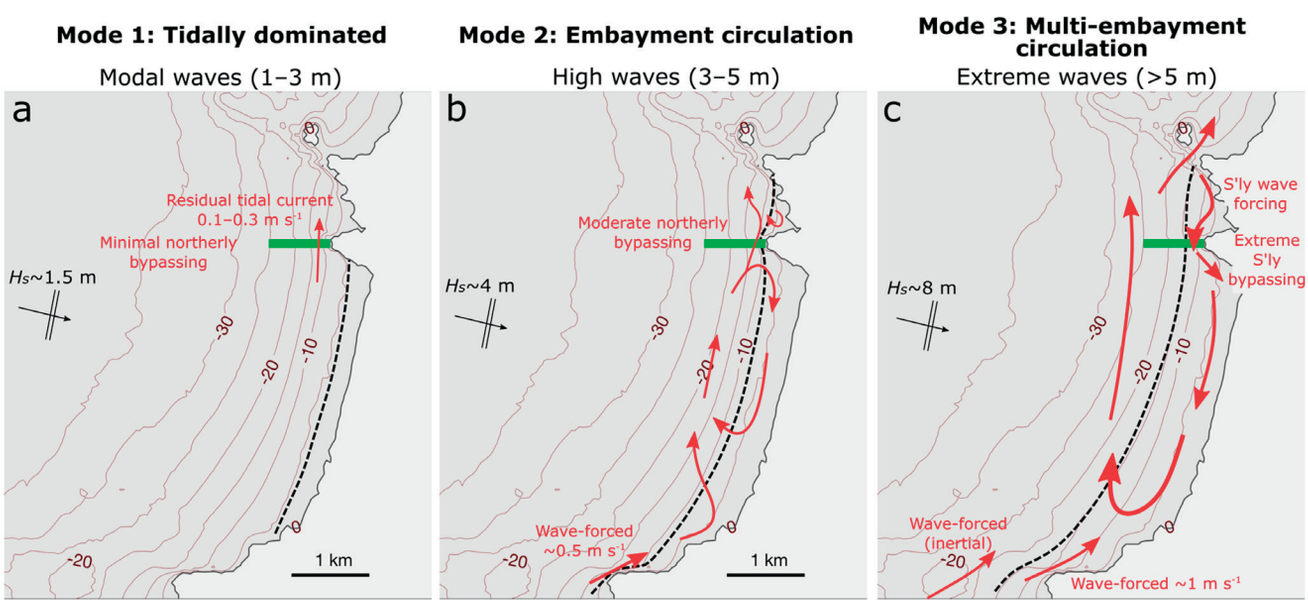
This paper investigated headland bypassing at Perranporth Beach (Cornwall), an exposed, macrotidal embayment, using a combination of field observations and process-based numerical modelling. Wave, current, and water level measurements were collected offshore of a headland and used to validate a Delft3D morphodynamic model. The model was then used to simulate a wide range of wave and tidal conditions, allowing detailed analysis of embayment circulation patterns and associated sediment transport pathways.

The results showed that bypassing was controlled by the interaction between wave-driven currents, tidal flows, and large-scale embayment circulation. Three distinct modes of bypassing were identified. Under low to moderate wave conditions, sediment transport was dominated by tidal currents, with relatively small fluxes (on the order of 10^2 m^3/day). Under moderate to high wave conditions, both tides and embayment circulation contributed, increasing sediment transport to around 10^3 m^3/day. During extreme wave events, large-scale embayment circulation (including mega-rips) dominated, producing the highest bypass rates (up to 10^4 m^3/day).

A key finding was that wave-induced bed shear stress was essential for significant bypassing. Simulations showed that tidal currents alone produced negligible sediment transport, whereas waves provided the energy required to mobilise sediment. Tides then modulated the direction and magnitude of transport by influencing residual currents around the headland.

Despite the occurrence of significant bypassing during storms, the study found that bypassing was relatively unimportant at annual timescales. Hindcast simulations indicated that bypassing fluxes were an order of magnitude smaller than cross-shore sediment transport during extreme events. This suggests that, for this site, storm-driven offshore transport is the dominant control on sediment budgets and morphological change.

Finally, the study introduced a simple, site-specific parameterisation for predicting bypass rates based on wave and tidal conditions. This parameter showed strong agreement with modelled results (R^2 = 0.95), providing a potential basis for developing more general predictive tools for headland bypassing.



Conceptual embayment circulation modes showing how current patterns drive sediment transport and potential headland bypassing. Red lines indicate main current pathways and associated sediment transport. The green line is the transect used in the analysis. The black dashed line indicates the seaward edge of the surf zone.

Nearshore sediment pathways and potential sediment budgets in embayed settings over a multi-annual timescale.

Valiente, N.G., Masselink, G., McCarroll, R.J., Scott, T., Conley, D. and King, E., 2020.

Key message

Regional-scale numerical modelling using Delft3D shows that embayed coastlines are not closed sediment systems. Instead, sediment exchange between bays is significant, particularly during high-energy events, with headland bypassing rates reaching 10^3–10^4 m^3/day and annual fluxes up to 10^5 m^3. Sediment transport pathways extend offshore beyond headlands and are strongly controlled by wave direction, embayment-scale circulation, and tidal currents.



Take away thought

Embayed beaches cannot always be considered isolated sediment cells, as storms can drive significant sediment exchange between embayments. This highlights the importance of adopting a regional-scale perspective that considers headland bypassing, offshore transport pathways and the influence of extreme events when assessing sediment budgets and long-term coastal evolution.

Summary

The study investigates nearshore sediment pathways and sediment budgets along a 15 km macrotidal embayed coastline in north Cornwall using the Delft3D numerical model. The focus is on understanding how sediment is transported between embayments over event- to multi-annual timescales, addressing the long-standing assumption that embayed beaches function as closed sediment cells.

The modelling framework combines wave transformation and hydrodynamic simulations (waves + tides) to resolve circulation patterns and sediment fluxes across a wide range of wave conditions, including extreme storm events. Model validation against field measurements shows good agreement for wave height, water levels, and alongshore currents, supporting the reliability of the simulations.

Results reveal three dominant circulation modes controlled primarily by wave direction and energy. Under moderate-to-high waves from the west, clockwise embayment-scale circulation develops, with strong northward currents near headlands and offshore-directed rip currents (including mega-rips) exporting sediment beyond the surf zone. When wave direction shifts slightly (e.g., W to WNW), circulation patterns reorganise significantly, altering sediment transport direction within embayments. During extreme events (e.g., H_s ~ 7 m), large-scale circulation can span multiple embayments, with strong offshore and alongshore currents driving sediment transport to depths exceeding 20 m.

Sediment flux analysis shows that the majority of transport occurs between the shoreline and ~20 m depth, with a rapid decay beyond ~25 m. However, transport still reaches depths exceeding the base of headlands, enabling sediment bypass between adjacent embayments. The largest sediment fluxes occur at major embayments (e.g., Perranporth), where transport rates are 1–2 orders of magnitude greater than at smaller headlands.

Extreme wave events dominate sediment transport, generating bypassing rates of 10^3–10^4 m^3/day and driving most of the annual sediment exchange. Over multi-annual timescales, estimated headland bypassing ranges from 10^3 to 10^5 m^3/year, assuming sufficient sediment supply. These results indicate that sediment budgets along embayed coastlines are highly dynamic and strongly event-driven.

Overall, the study demonstrates that embayed coastlines may often behave as partially open systems, where sediment exchange between bays is governed by complex interactions between waves, tides, and coastal morphology. This challenges traditional conceptual models of isolated sediment cells and highlights the importance of connectivity between embayment on long-term sediment budgets.

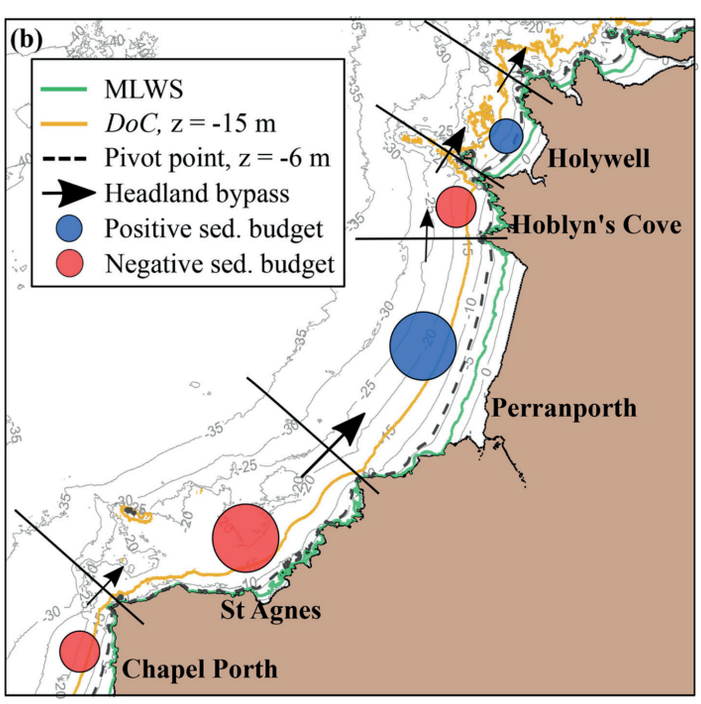


Figure shows the sediment budget model from Chapel Porth to Holywell over 2011–2018. Arrows indicate qualitatively net headland bypassing paths. Arrows and circles size represents magnitude. The green line and yellow lines represent Mean Low Water Springs (MLWS) and the Depth of Closure (DoC), while the black dashed line indicates the seaward edge of the surf zone (pivot point).

Sediment characteristics, distribution and pathways on a macro-tidal, energetic and sediment-limited embayed coast.

Seksaf, W., Scott, T., Masselink, G., Valiente, N.G. and Conley, D., 2026.

Key message

Beach and dune evolution along Cornwall's sediment-limited coastline depends not only on waves and tides, but also on the distribution, characteristics and connectivity of mobile sediment. Integrating sediment characteristics and geomorphology with hydrodynamic modelling revealed previously unrecognised coastal cell boundaries and the dominant controls on sediment connectivity, providing a more robust understanding of regional sediment pathways and long-term coastal evolution.



Take away thought

Mapping regional sediment connectivity and coastal cell boundaries alongside coastal morphology provides a stronger evidence base for understanding regional sediment pathways, identifying areas of sediment connectivity or isolation, providing a stronger evidence base to support long-term coastal management and adaptation planning and shoreline evolution modelling.

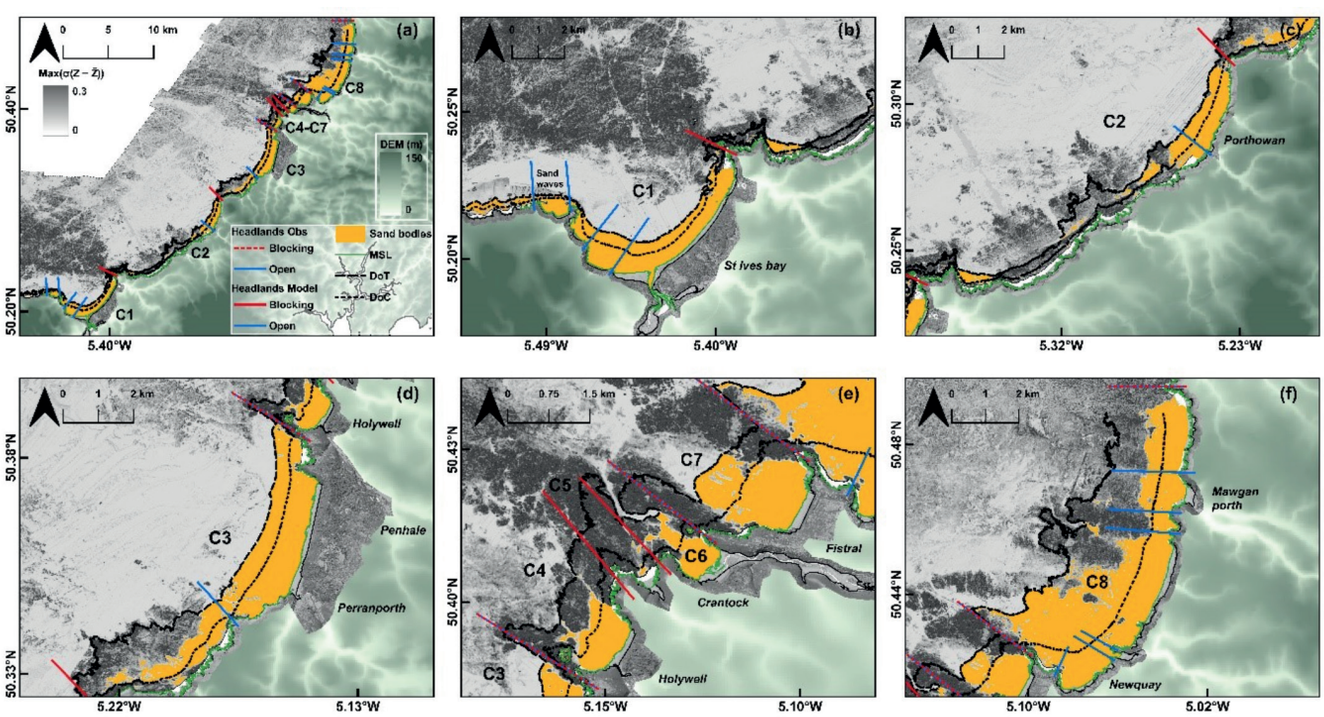
Summary

Sandy beaches and dune systems are critical natural buffers that protect coastal communities, infrastructure, and ecosystems. Yet, they are increasingly vulnerable to climate-driven sea-level rise and changing wave climates, which are expected to accelerate coastal erosion. The extent to which erosion can be offset depends partly on potential sediment supply from offshore zones.

This study investigated sediment characteristics, distribution and connectivity along a 45 km section of the north Cornish coast. Extensive field observations were combined with high-resolution bathymetry, LiDAR topography and previous hydrodynamic modelling to map the extent of active coastal sand bodies and assess sediment exchange between embayments. A total of 348 sediment samples were analysed for grain size and carbonate content, while headland geometry and seabed morphology were used to determine where sediment movement was constrained or permitted. This integrated approach provided a regional assessment of sediment resources and coastal connectivity.

The analysis identified eight coastal cells separated by headlands that either blocked or constrained sediment exchange. Large, continuous sand bodies occurred within major embayments such as St Ives Bay, Penhale and Newquay, while long stretches of rocky coastline contained only limited offshore sediment resources. Distinct spatial patterns in sediment characteristics also emerged. Fine, silica-rich sands were associated with large sediment accumulations and major dune systems, whereas coarse, carbonate-rich sediments characterised sediment-starved areas where long-term sediment supply was limited. These consistent differences between neighbouring embayments highlights headlands that effectively restrict sediment exchange and helped inform regional coastal cell boundaries.

By combining sediment observations with geomorphological mapping and previous hydrodynamic modelling, the study provided a more robust understanding of regional sediment pathways than could be achieved through modelling alone. The results demonstrated that observations of sediment distribution and composition provide essential evidence for identifying coastal connectivity, validating conceptual sediment transport pathways. This improved understanding of regional sediment dynamics provides a stronger scientific basis for predicting long-term coastal evolution and supporting strategic sediment management along sediment-limited coastlines.



Maps combining the sedimentological and morphological observations from this study with previous headland bypassing modelling results. Sand bodies are represented by yellow areas, delineated by the maximum depth at which sediment can be moved by waves (DoT) (dashed black line) offshore, and the mean sea level MSL (green line) onshore. Headlands are colour-coded to indicate if they allow sediment bypassing or not. Solid blue lines indicate open headlands based on both observations and modelling; dashed red lines show observed blocking headlands, while solid red lines represent headlands that were classed as closed based on the hydrodynamic modelling results alone. The greyscale background shows the seabed roughness with darker areas indicating a rougher seabed. Land elevation is shown in light green.

Coastal embayment rotation: Response to extreme events and climate control, using full embayment surveys.

Wiggins, M., Scott, T., Masselink, G., Russell, P. and McCarroll, R.J., 2019.

Key message

Full-embayment multi-method topographic/bathymetric surveys of Start Bay, Devon, showed that barrier beach rotation in a bi-directional wave climate was controlled by the balance of wave direction and magnitude. Sub-embayment rotation occurred under moderate forcing, but full embayment rotation required sustained, high-energy conditions and headland bypassing. A new directional wave power index linked beach rotation to climate variability, providing a basis for predicting future coastal change.



Take away thought

Beach rotation as a result of alongshore redistribution of sediment is a key response mode on embayed gravel beaches. Wave direction and climate indicators, such as NAO and WEPA, can be used to anticipate rotational change, providing valuable context for interpreting shoreline change, assessing coastal vulnerability and supporting long-term coastal management.

Summary

Gravel barrier beaches provide an important buffer against storms. They are highly dynamic, responding rapidly to changes in wave climate. In embayed settings, where wave approach is often oblique, sediment transport is typically dominated by longshore processes, leading to shoreline rotation. Understanding how these systems respond to both extreme events and longer-term wave climate variability is critical for predicting coastal change and managing associated risks.

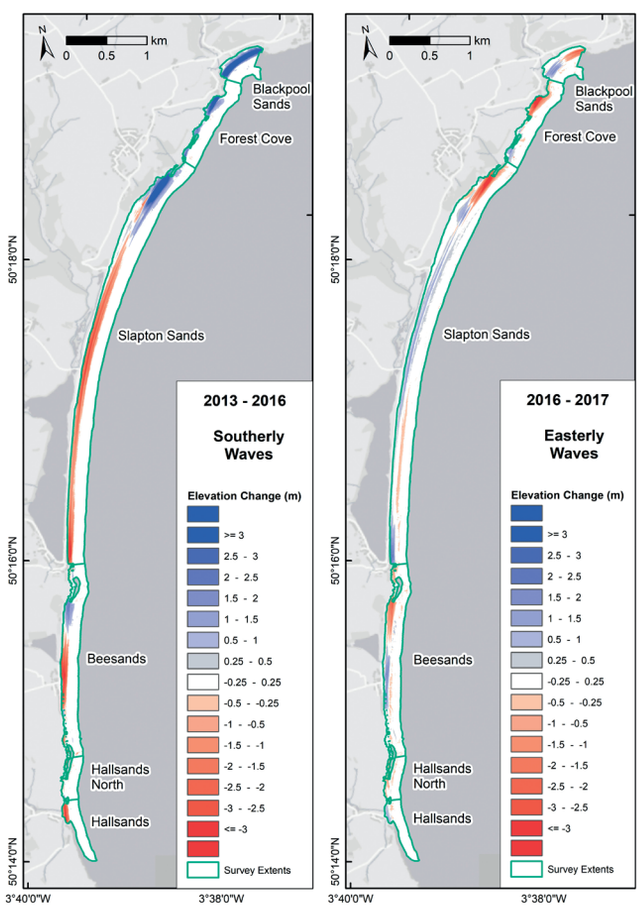
This paper investigated the morphological response of a full gravel barrier embayment (Start Bay, Devon) to contrasting wave conditions using a comprehensive dataset of topo-bathymetric surveys. Multiple survey methods were combined to produce full embayment sediment budgets spanning sub-aerial to sub-tidal zones. The study analysed changes across two key periods: a high-energy, southerly-dominated phase (2013–2016), including the extreme 2013/14 winter storms, and a lower-energy, more easterly phase (2016–2017). A new directional wave power index was developed to quantify the balance between opposing wave directions and relate this to observed morphological change.

The results showed that beach rotation was strongly controlled by the directional balance of wave energy. During the southerly-dominated period, the entire embayment underwent pronounced clockwise rotation, with sediment transported northwards. This involved large-scale redistribution of material between sub-embayments, including headland bypassing, with approximately 6×10^5 m^3 of sediment moved alongshore. In contrast, during the easterly phase, anti-clockwise rotation occurred but was largely confined to individual sub-embayments, with significantly smaller volumes of sediment redistributed and little evidence of headland bypassing.

A key finding was that different magnitudes of forcing controlled different spatial scales of response. Sub-embayment rotation occurred under more moderate, shorter-term wave conditions, whereas full embayment rotation required sustained, high-energy conditions from a dominant direction. Importantly, although large volumes of sediment were redistributed, the embayment behaved as a closed system overall, with no significant net loss or gain of sediment when accounting for uncertainty.

The study also demonstrated that a substantial proportion of sediment transport (approximately one third) occurred in the sub-tidal zone, highlighting the importance of considering the full coastal profile when assessing sediment budgets. Analysis of decadal profile data showed strong correlations between beach volume changes and the directional wave power index, particularly during winter months when wave energy is highest.

Finally, the study linked wave direction to climate variability, showing that winter wave conditions were associated with atmospheric indices, particularly the North Atlantic Oscillation (NAO) and West Europe Pressure Anomaly (WEPA). This provided a basis for predicting future beach rotation based on climate forcing, suggesting that changes in storm tracks and wave direction could drive long-term shifts in embayment morphology.



Maps of elevation change showing clockwise (2013–2016) and anti-clockwise (2016–2017) embayment rotation, illustrating large-scale sediment redistribution and reversal of transport direction.

Regionally-coherent embayment rotation: Behavioral response to bi-directional waves and atmospheric forcing.

Wiggins, M., Scott, T., Masselink, G., Russell, P. and Valiente, N., 2019.

Key message

Beach rotation along the south coast of England is regionally coherent and primarily controlled by the balance of bi-directional wave energy (south-westerly vs easterly). This balance is strongly linked to atmospheric indices (WEPA and NAO). Rotation is most pronounced on south-east-facing, steep (often gravel) beaches, and can be predicted using a wave directionality index, with potential for seasonal forecasting based on climate signals.



Take away thought

Beach rotation is driven by the balance of opposing wave directions and can be coherent at a regional scale across multiple embayments. WEPA and NAO are closely related to both the directional wave climate and the resulting regional beach rotation. Seasonal forecasts of these indices offer the potential to anticipate regional patterns of erosion and accretion months in advance.

Summary

Beach rotation has been widely observed at individual embayed sites, where opposing wave directions drive alongshore sediment transport resulting in alternating erosion and accretion at beach ends. Earlier work at sites such as Start Bay demonstrated how this behaviour is controlled by the balance of bi-directional wave energy and can lead to large-scale sediment redistribution during extreme winters. However, it remained unclear whether such behaviour was site-specific or representative of a broader regional response.

This paper extended earlier work by investigating beach rotation across the entire south coast of England. Wave data from 14 offshore locations (1980–2016) confirmed a strongly bi-directional wave climate, with dominant south-westerly waves and secondary easterly waves. A Wave Directionality Index (WDI) was developed to quantify the balance between these opposing wave directions and provide a consistent metric for linking wave forcing to coastal response.

Morphological behaviour was analysed at 22 coastal sites using decadal records of beach profile surveys. A Beach Morphological Response (BMR) metric was used to determine whether beaches behaved in a rotational (longshore-dominated) or cross-shore manner. Negative BMR values indicated rotation, where opposing ends of the beach responded out of phase, while positive values indicated uniform cross-shore change.

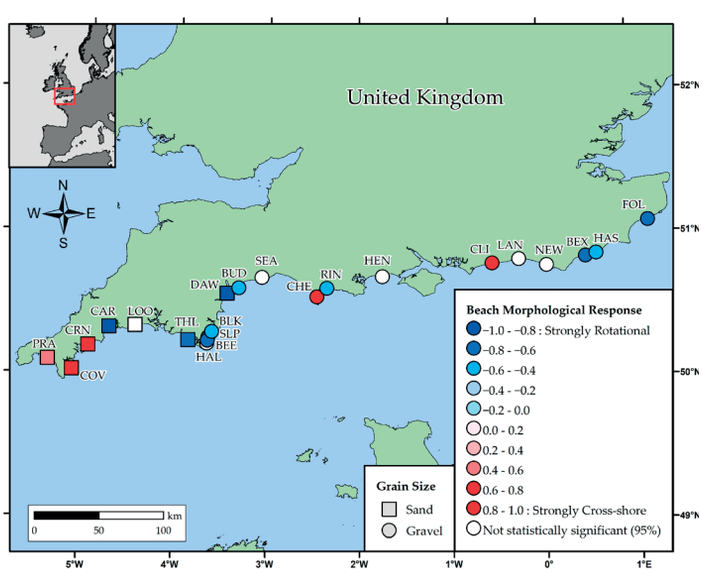
The results showed that 11 of the 22 sites exhibited significant rotational behaviour, demonstrating that beach rotation is not confined to individual embayments but occurs at a regional scale. As in the earlier embayment-scale study, rotation was strongly linked to the balance of wave direction. Positive WDI values (dominant south-westerly waves) drove clockwise rotation, while negative values (increased easterly influence) resulted in anticlockwise rotation.

A key control identified was shoreline orientation. Rotational behaviour was most pronounced on south-east-facing beaches, where incoming waves are highly oblique. In contrast, south-west-facing beaches (aligned with dominant wave approach) showed mainly cross-shore responses. This finding provides a simple geometric explanation for where rotation is most likely to occur.

The study also highlighted the role of beach morphology and sediment type. Rotational responses were most common on steep, gravel beaches, while flatter, sandy beaches tended to respond more uniformly. This indicates that local physical characteristics influence how regional wave forcing translates into morphological change.

Importantly, the study demonstrated strong links between wave climate and atmospheric forcing. South-westerly wave power was positively correlated with WEPA, while easterly wave power was associated with negative NAO phases. The WDI showed significant correlations with both indices, confirming that large-scale atmospheric patterns control the balance of wave direction.

At key sites such as Slapton Sands and Carlyon Bay, beach rotation showed a strong positive relationship with WEPA, suggesting that seasonal forecasts of atmospheric indices could be used to predict rotational beach state. This extends the earlier embayment-scale findings by demonstrating that climate-driven rotation is not only locally important but regionally consistent.



Regional map showing Beach Morphological Response (BMR) across 22 sites. Strongly rotational beaches (blue) are spatially clustered and mainly south-east-facing, demonstrating regional coherence of behaviour.

High frequency in-situ field measurements of morphological response on a fine gravel beach during energetic wave conditions.

Poate, T., Masselink, G., Davidson, M., McCall, R., Russell, P. A. and Turner, I.L., 2013.

Key message

Fine gravel beaches can remain remarkably stable during energetic storms, with sediment being redistributed along the shoreline rather than lost from the beach system. Storms enhance cusp development and alongshore sediment redistribution, highlighting the importance of sediment redistribution, rather than net sediment loss, dominates storm-driven beach response.



Take away thought

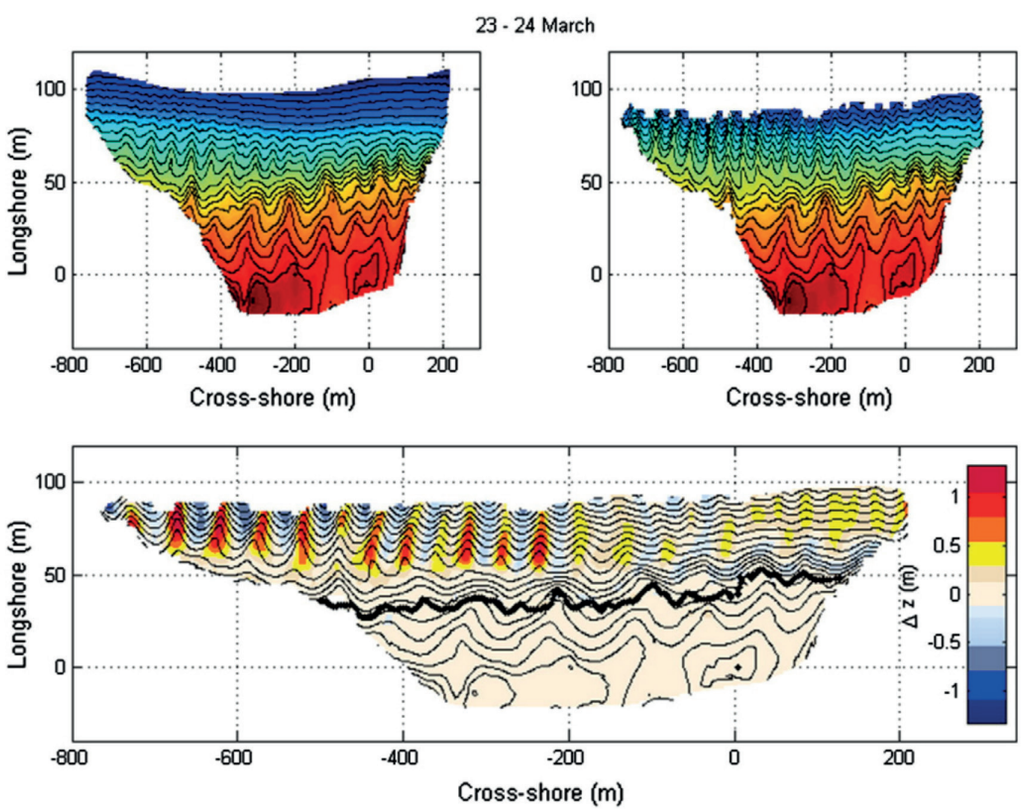
Fine gravel beaches can remain resilient during energetic storms despite substantial short-term sediment redistribution. Beach-step development plays an important role in dissipating wave energy and limiting upper beach erosion, making beach-step morphology and wave steepness valuable indicators of storm response for coastal monitoring and management.

Summary

This paper presents novel high-frequency field measurements of the morphological and hydrodynamic responses of a fine gravel beach (D_{50} = 3.5 mm) at Loe Bar, a 4.3 km long barrier on the south-west coast of the UK, exposed to energetic wave conditions with peak significant wave heights up to 2.5 m. The study employed a combination of remote sensing (headland and crest-mounted cameras) and in-situ instrumentation, including a 70-m scaffold rig fitted with 45 acoustic bed-level sensors and RTK GNSS topographic surveys, to capture 3D beach morphology, bed-level changes, and wave runup dynamics over a 6-week period in early 2012.

Results showed that overall beach volume remained remarkably stable under energetic wave conditions despite small intertidal volume losses associated with high wave steepness (H_0/L_0 > 0.01). The most pronounced morphological adjustments were related to alongshore sediment redistribution driven by the development and evolution of a three-dimensional beach cusp system. Energetic waves promoted cusp horn growth and embayment deepening, enhancing cusp definition and sediment sorting. Alongside cusp dynamics, the study highlighted the important role of the beach step, a morphological feature on gravel beaches, whose height increased by appproximatelly 1 m during energetic, long-period wave events altered the lower beach profile. The step acted as a focal point for wave breaking, reducing swash energy and vertical runup limits, thus protecting the upper beach from erosion and overwash during storms.

This research provides unique insights into the dynamic feedback mechanisms between hydrodynamics and gravel beach morphology under storm conditions, a domain with limited prior field data. The findings underline the significance of wave steepness, cusp-related sediment transport, and beach step dynamics in governing gravel beach stability. The data and conceptual advances presented are fundamental for enhancing predictive modeling and informing coastal management strategies for gravel-dominated barrier systems, especially under increasing storm scenarios expected in a changing climate.



Surface change plot for energetic conditions at the end (23–24 March) of the field period at Loe Bar. The top panels show digital elevation models of the morphology before and after the energetic event with corresponding elevation changes (Δz) in the bottom panel. The thick black line on the bottom plot marks the runup extent based on video data. The beach change during this energetic event was dominated by beach cusp dynamics.

Chapter 6: Extreme storm impacts

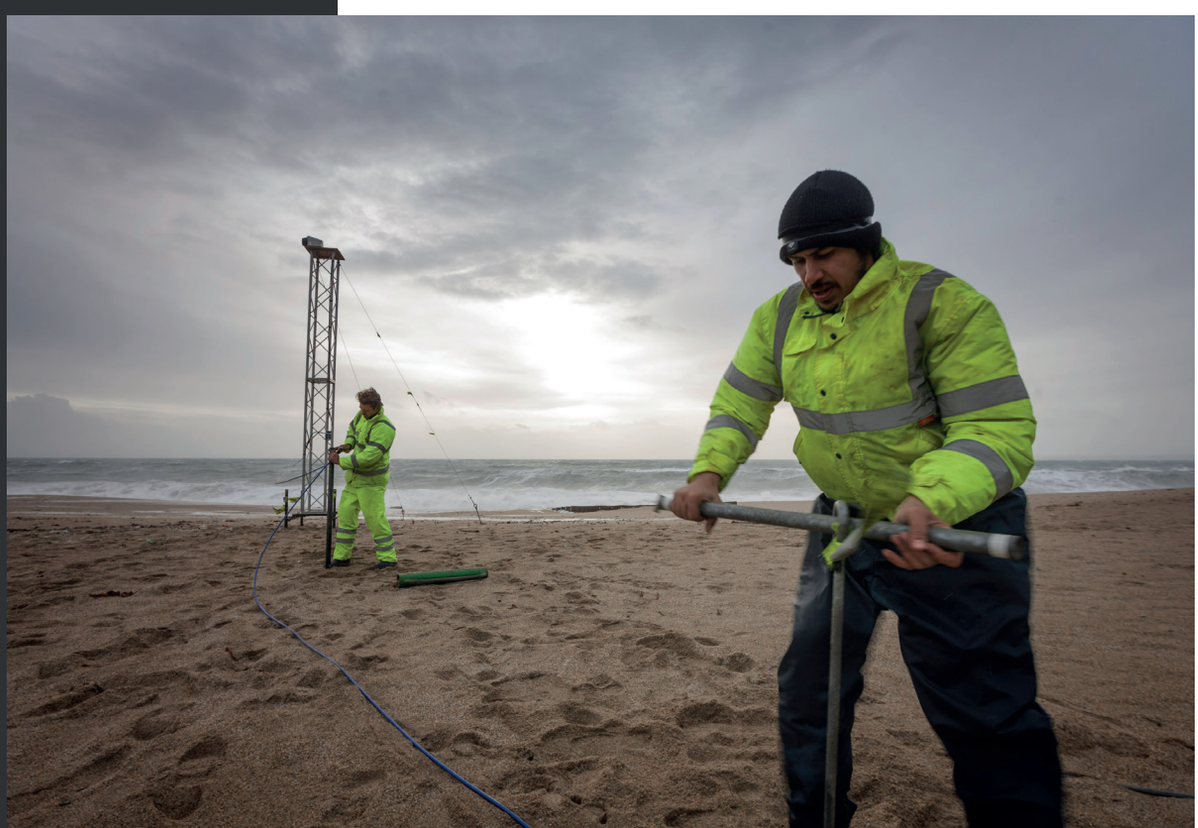
Extreme storms can transform coastlines within hours, causing erosion, flooding and damage to both natural environments and coastal infrastructure. Understanding how different coastal systems respond to these events, and how they recover afterwards, is essential for building long-term coastal resilience. The papers in this chapter examine the impacts of major storm events on beaches, gravel barriers and coastal cliffs, with particular emphasis on the exceptional 2013–2014 winter storms that affected southwest England. Together, they provide valuable insights into storm-driven coastal change, recovery processes and the evidence needed to support resilient coastal management and adaptation.

Observations of gravel beach dynamics during high energy wave conditions using a laser scanner.

Almeida, L.P., Masselink, G., Russell, P.E. and Davidson, M.A., 2015.

Key message

A 2D laser-scanner was deployed at the high tide runup limit of a pure gravel beach (Loe Bar, Cornwall) to measure swash action and topographic changes during an energetic wave event. Results indicate that despite the small net morphological changes to the beach over the recorded tidal cycle, significant sediment mobilization occurred and these changes were mainly associated with the migration of the beach step.



Take away thought

Terrestrial laser scanning provides a practical, relatively low-cost approach for high-resolution coastal monitoring. It can simultaneously measure beach morphology, wave conditions, wave run-up and overtopping, providing valuable evidence for understanding coastal processes and supporting long-term coastal monitoring and management.

Summary

Loe Bar in south Cornwall is an example of a pure gravel beach, characterised by a steep reflective profile and prominent secondary morphological features, such as ridges, berms, steps and cusps. Because breaker bars tend to be absent on pure gravel beaches, storm waves tend to break violently by plunging directly onto the beachface. This creates extremely energetic conditions and highly turbulent flows capable of mobilising significant amounts of gravel over individual swash events.

It is important to understand whether such energetic wave motion remains constrained to the beachface, or whether wave runup reaches the crest of the beach, resulting in overwash and coastal flooding. For Loe Bar it is also useful to know under which conditions waves wash over the crest of the gravel barrier and flow into the freshwater lagoon behind the beach as this may have implications for the lagoon ecology.

It is, however, extremely challenging to make meaningful measurements of wave processes on gravel beaches. This paper is the first of several in which a new instrument, namely a laser scanner, is used to measure wave conditions on gravel beaches under challenging storm conditions.

The laser scanner is deployed from a scaffold tower installed at the top of the beach and is thus elevated well above the immediate zone of wave impact. Several tens of metres of beach are scanned at either side of the tower, several times per second, and both the water level and the beach level can be extracted from the raw data. This enables an analysis of the hydrodynamic conditions (waves, swash and runup), as well as the changes in the morphology and sediment transport across the beach at timescales ranging from individual waves to complete tidal cycles.

It was found that the net change to the beach recorded over the modest storm event (offshore waves were just over 2 m) was limited: the shape of the beach during the low tide before the storm was very similar to the shape after the storm. However, the laser scanner also recorded changes during the storm, and the beach shape changed significantly over the rising and the falling tide (but in opposite directions, so the net change was minimal). These changes were mainly associated with the migration of the so-called beach step, a bar-like feature located at the bottom of the swash zone on gravel beaches, and which moved up and down with the rising and falling tide, respectively.

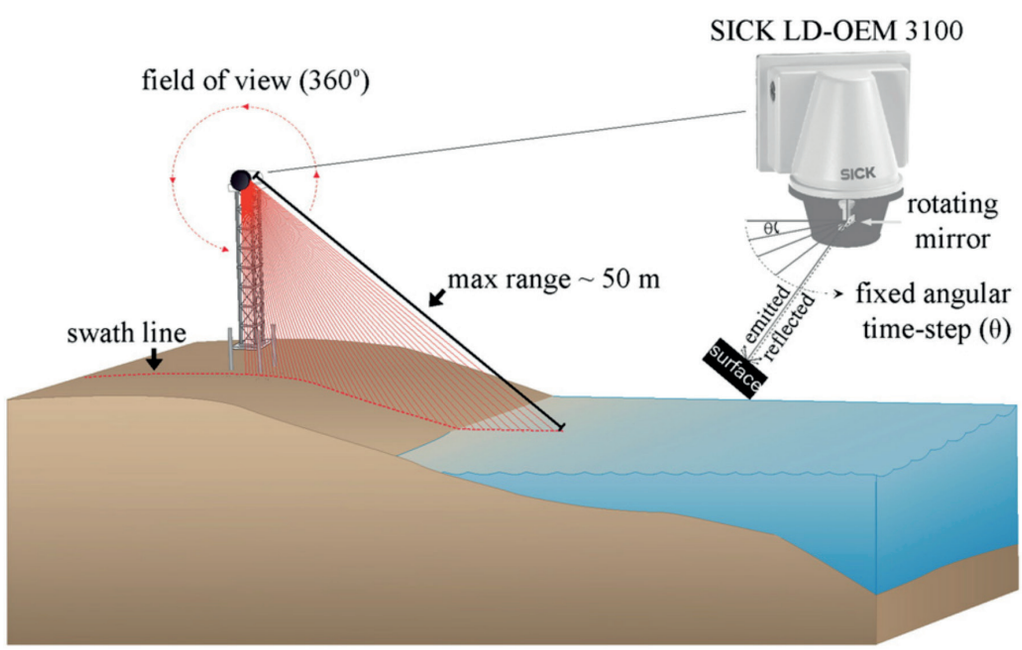


Diagram of the 2D laser-scanner LD-OEM3100 (SICK) showing working principles in the field.

The extreme 2013/2014 winter storms: hydrodynamic forcing and coastal response along the southwest coast of England.

Masselink, G., Scott, T., Poate, T., Russell, P., Davidson, M. and Conley, D., 2016

Key message

The southwest coast of England was subjected to very energetic Atlantic storms during the 2013/14 winter. On the north coast, the prevailing storm response was offshore sediment transport, leading to extensive beach and dune erosion. Some beaches were completely stripped of sediment, exposing a rocky platform. On the south coast, the storm response was mainly longshore transport, resulting in beach rotation, with the western part of the beaches eroding and the eastern part accreting.



Take away thought

Extreme storm impacts are expected to increase in the future regardless of changes in storminess, as rising sea levels will allow storm waves to reach higher elevations. In addition, storm track changes can modify wave exposure as well as longshore transport patterns. The widespread and costly impacts of the 2013/14 winter demonstrate the vulnerability of many coastlines to extreme events, highlighting that long-term coastal adaptation will be required under all plausible sea-level rise scenarios.

Summary

The 2013/14 winter was the most energetic winter in terms of wave conditions in at least 60 years and affected almost the entire Atlantic coast of Europe. Based on the regional monitoring of both the hydrodynamic forcing (wave buoys, tide gauges) and the morphological response (LiDAR and beach surveys) along the coast of SW England, this paper investigates the storm impacts that occurred along this c. 1000 km stretch of coast during this winter. A detailed statistical analysis of all 22 storms that occurred during this winter is presented, where a storm is defined as an event during which the peak wave height exceeds the 99th percentile (significant wave height of 5.9 m at the Sevenstones Lightship at the tip of Cornwall).

Five key findings of the regional analysis are:

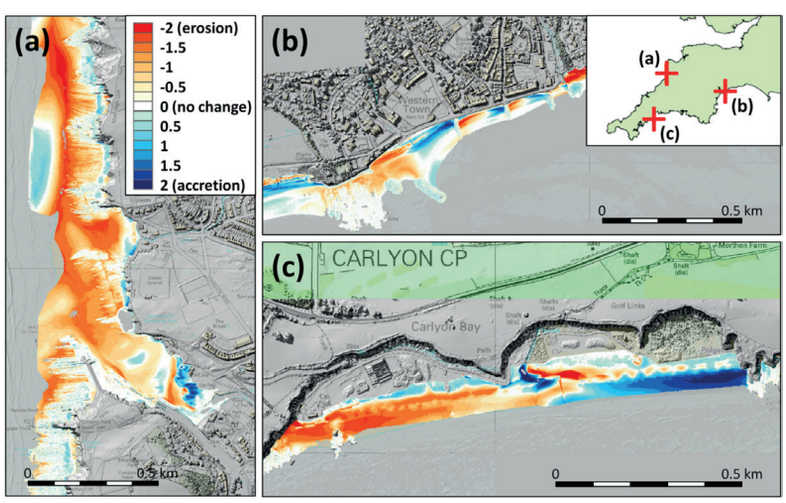
1. Storm events with the largest wave height did not necessarily have the largest impact in terms of beach and dune erosion, coastal flooding and damage to coastal infrastructure. The storm events that did stand out in terms of their coastal impacts were characterised by energetic inshore wave conditions coinciding with extreme (spring) high tide levels.

2. Extreme storm impacts along the south coast of SW England are associated with a relatively southerly storm track, enabling storm waves to propagate up the English Channel relatively unimpeded.

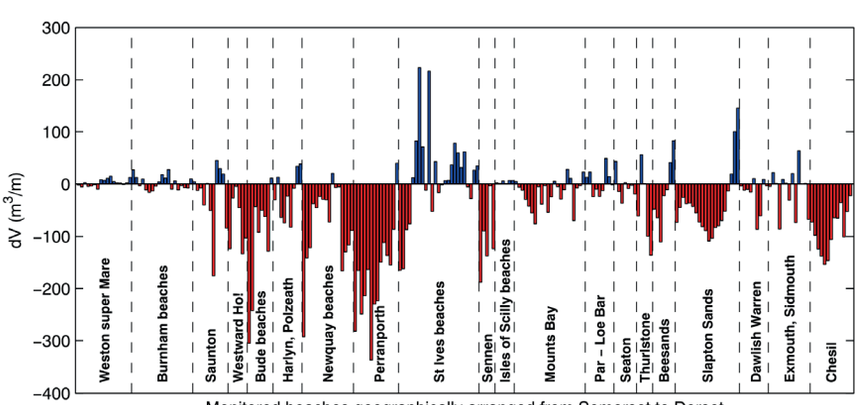
3. Site-specific conditions can be key to determining the coastal storm impacts. The considerable spatial variability in storm response along the SW coast of England is attributed to the embayed nature of the coastline and the associated variability in coastal orientation.

4. The response on practically all north coast beaches to the westerly storm waves was offshore sediment transport due to the prevailing shore-parallel wave approach. Many north coast beaches experienced extensive beach and dune erosion, and some of the beaches were completely stripped of sediment, exposing a rocky shore platform.

5. On many south coast beaches, the combination of southerly inshore storm waves and SW-NE oriented beaches resulted in a large range of incident wave angles and strong eastward littoral drift. As a result, many south coast beaches exhibited rotation, with the western part of the beaches eroding and the eastern part accreting.



Elevation change derived from air-based LiDAR for three beaches in SW England: (a) Bude, north Cornwall, flown on 08/10/2010 and 01/03/2014 (sediment transport offshore beyond the low tide level); (b) Sidmouth, south Devon, flown on 04/11/2013 and 09/02/2014 (sediment transport redistributed within the groyne embayments); and (c) Carlyon, south Cornwall, flown on 21/03/2012 and 01/04/2014 (beach rotation due to eastward transport due to SW waves).



Regional variability in coastal response, quantified by the change in beach sediment volume dV in m^3 per unit meter beach width along the coast of SW England during the 2013/14 winter. Study sites have been positioned along the x-axis to run in an anticlockwise fashion from the northwest (Weston Super Mare, north Somerset) to the southeast (Chesil, Dorset) of the study area. Every bar represents a single beach profile and the profiles have been grouped by beach.

Extreme wave activity during 2013/2014 winter and morphological impacts along the Atlantic coast of Europe.

Masselink, G., Castelle, B., Scott, T., Dodet, G., Suanez, S., Jackson, D. and Floc'h, F., 2016.

Key message

The 2013/2014 winter wave conditions that severely impacted the Atlantic coast of Europe were the most energetic along most of the Atlantic coast of Europe since at least 1948. Along exposed open-coast sites, extensive beach and dune erosion occurred due to offshore sediment transport. More sheltered sites experienced less erosion and one site even experienced accretion due to beach rotation induced by alongshore sediment transport.



Take away thought

Changes in Atlantic storminess, whether through increased storm intensity, storm frequency or shifts in storm tracks, are likely to alter long-term coastal evolution along the Atlantic coast of Europe. Some beaches may narrow while others widen, highlighting the importance of considering spatially variable shoreline responses when planning long-term coastal adaptation.

Summary

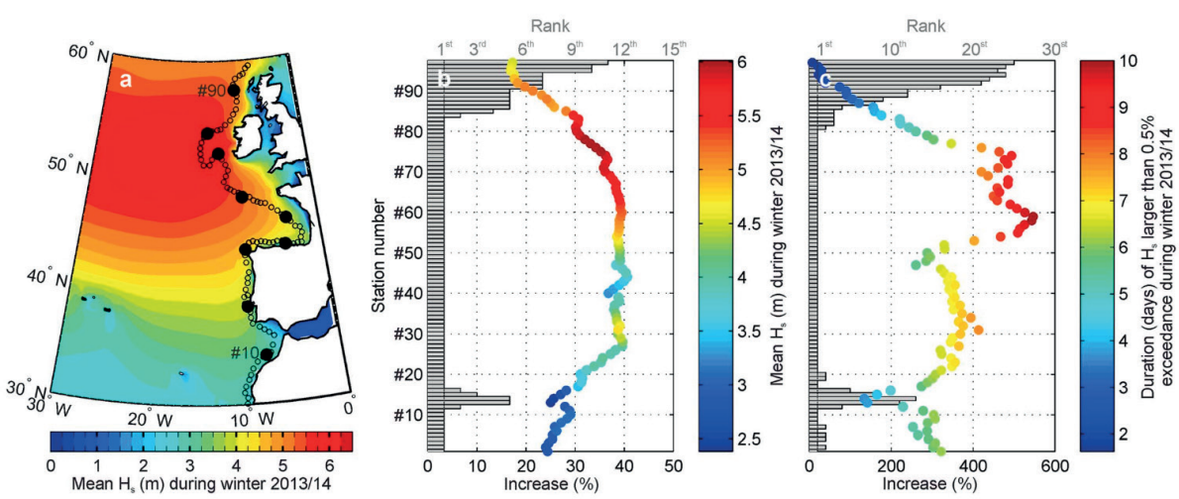
Previous work on the impact of the 2013/14 winter storms on beaches and dunes in SW England demonstrated that, along the coast of SW England, this winter season was the most energetic period in terms of waves since at least 1948 and led to widespread and unprecedented coastal erosion and flooding. In this paper, written with international co-authors, the impact of these winter storms along the entire Atlantic coast of Europe, from Ireland to Portugal, is discussed. The key finding is that the very energetic wave conditions and significant impacts along the SW coast of England during the 2013/14 winter are replicated along most of the Atlantic coast of Europe.

The paper uses wave data from the WaveWatch III model to compare the 2013/14 winter waves along the Atlantic coast of Europe with those recorded over the period 1948–2015. With the exception of south Portugal and north Ireland, the 2013/14 winter ranked the highest in terms of the winter-averaged significant wave height and the number of days with exceptionally energetic conditions. The largest winter-averaged wave conditions, with significant wave heights of 5–6 m were experienced off the coast of SW England, south Ireland and Brittany. For most of the Atlantic European seaboard, the winter-averaged wave conditions were approximately 40% higher than the long-term average.

Most climate change models predict increased storminess of the northeast Atlantic and it is tempting to ascribe the record extreme storm wave conditions during the 2013/14 winter to climate change. However, these predictions are associated with a large amount of uncertainty as the predicted future trends in storminess are quite heterogeneous and depend on the climate model used.

The paper investigates the impact of the extreme 2013/14 winter storms on seven beaches in SW England, Ireland and France. These are the only beaches along the Atlantic coast of Europe for which quasi-monthly beach monitoring data are available since at least 2007. All studied beaches showed significant storm impacts, with five of the seven beaches being at their most depleted by the end of the 2013/14 winter. Along exposed open-coast sites, extensive beach and dune erosion occurred due to offshore sediment transport. More sheltered sites experienced less erosion and one site experienced accretion due to beach rotation induced by alongshore sediment transport.

If conditions such as those experienced during the 2013/14 winter become more common in the future, they have the potential to considerably change the equilibrium state of beaches along the Atlantic coast of Europe. Along exposed sites dominated by cross-shore sediment transport processes, such as the north coast of Cornwall, sediments may transfer from supratidal and intertidal stores to the subtidal region (nearshore bar systems), resulting in depleted subaerial beaches and scarped dune systems. Along coastlines with a bimodal wave climate characterized by both long-period ocean swell and short-period local seas, such as the south coast of SW England, increased Atlantic storminess is likely to disrupt the balance between the different alongshore sediment transport contributions and may destabilize the coastal alignment by causing beach rotation.



Left panel shows the average significant wave height (H_s) during the 2013/14 winter. The centre and right panels show results of analysis of 67 years of modelled wave data, demonstrating that the winter wave height (centre panel) and the number of extremely high wave conditions (right panel) for Ireland, SW Engand France were exceptional during the 2013/14 winter (ranked 1st).

The extreme 2013/2014 winter storms: beach response and multi-annual recovery along the southwest coast of England.

Scott, T., Masselink, G., O'Hare, T., Saulter, A., Poate, T., Russell, P., Davidson, M. and Conley, D., 2016.

Key message

The extreme 2013/14 winter storms caused unprecedented erosion across the southwest coast of England, but recovery varied markedly between beach types. The study showed that storm response and recovery are governed by dominant sediment transport pathways (1) cross-shore transport, (2) longshore redistribution and (3) overwash, and that recovery may take years to decades. Importantly, energetic wave events were often essential for beach recovery rather than periods of calm weather.



Take away thought

Beach recovery following extreme storms is highly variable and cannot be assumed to occur within a predictable timescale, and can take months to years. Recovery depends on dominant sediment transport pathways at each site, highlighting the importance of long-term monitoring when assessing coastal resilience and planning adaptation.

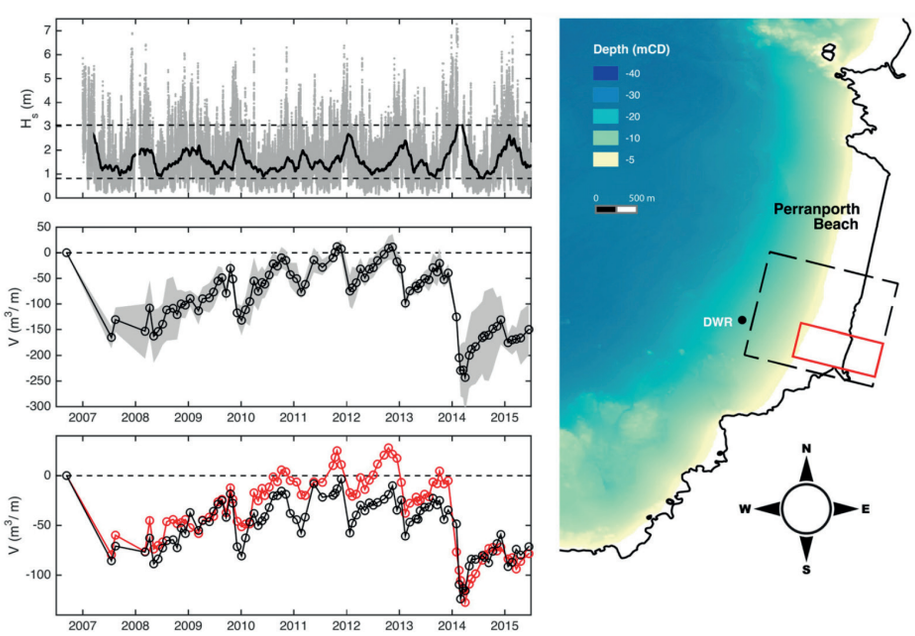
Summary

Sand and gravel beaches provide a natural buffer against coastal flooding by absorbing wave energy and adjusting their morphology in response to changing wave conditions. Extreme storms can rapidly erode beaches and dunes, increasing coastal vulnerability and reducing protection for infrastructure and coastal communities. While the erosional impacts of storms are well recognised, much less is understood about how beaches recover afterwards, particularly following sequences of exceptional storms. Understanding recovery mechanisms and timescales is therefore essential for predicting future coastal change and improving long-term coastal management.

This study examined the geomorphic response of 38 beaches across southwest England to the exceptional winter storms of 2013/14, the most energetic winter since at least 1948. The beaches represented a wide range of coastal environments, including exposed sandy beaches, gravel barriers and semi-sheltered embayments. Regional beach monitoring data were combined with detailed long-term surveys at three representative sites, Perranporth, Loe Bar and Slapton Sands, to investigate both the immediate storm response and subsequent recovery over several years.

The storms produced extensive erosion throughout the region, although the nature of the response varied according to beach type and wave exposure. Exposed sandy beaches experienced large cross-shore sediment transport, with substantial erosion of the intertidal beach and transfer of sediment offshore into nearshore bar systems. Semi-sheltered embayed beaches responded differently, with obliquely incident waves driving strong alongshore sediment transport and beach rotation, redistributing sediment within individual embayments. Gravel barrier beaches were dominated by overwash, transporting sediment landward across barrier crests and, in some locations, causing permanent losses from the active beach profile. These contrasting responses demonstrated that no single model of storm erosion applies to all beaches, even within the same region.

The study also revealed that recovery was strongly controlled by the mechanism of sediment loss. Beaches where sediment had been stored in nearshore bars gradually recovered as energetic swell conditions transported sediment back onshore. Rotational beaches recovered through changes in wave direction that reversed alongshore transport, while beaches affected by barrier overwash showed little natural recovery because sediment had been permanently transferred landward. Recovery times ranged from months to many years, with some beaches remaining below their pre-storm condition throughout the monitoring period. These findings demonstrated that extreme storms should be considered within a longer-term climatic context, as the sequence, direction and intensity of storms can influence coastal recovery as much as the initial erosion event itself.



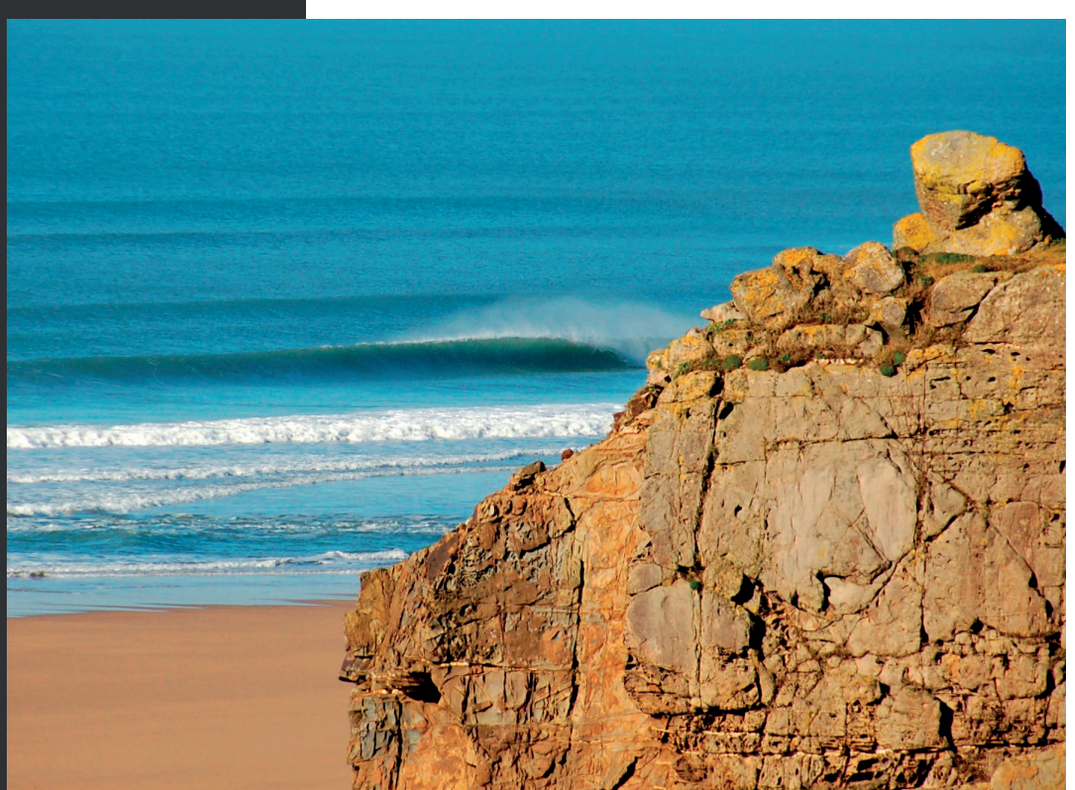
Beach change at Perranporth beach. Right panel shows bathymetry of Perranporth with location of wave buoy (DWR), red box shows beach survey region. Left upper panel shows 8-year record of wave height (H_s). Left middle panel shows mean intertidal beach sediment volume V (m^3/m alongshore). Left lower panel shows the upper (red) and lower (black) intertidal sediment volume V (m^3/m) above and below mean sea level.

The extreme 2013/14 winter storms: Regional patterns in multi-annual beach recovery.

Konstantinou, A., Stokes, C., Masselink, G. and Scott, T., 2021.

Key message

Beaches that respond similarly to extreme storms also recover in similar ways, indicating that the controls that govern how beaches respond to extreme storms also determine how they recover. Recovery pathways and timescales are strongly linked to wave exposure, incident wave angle and beach geometry, allowing post-storm recovery to be anticipated more reliably than previously recognised.



Take away thought

Distinct behavioural response types provide a framework for anticipating how similar beaches are likely to respond to and recover from major storms. This can support more targeted and efficient coastal monitoring programmes by helping prioritise representative sites and making better use of limited monitoring resources. The most exposed beaches may require continued long-term monitoring to capture prolonged post-storm adjustment.

Summary

The extreme 2013/14 winter storms represented the most energetic storm season in at least 65 years, causing widespread erosion along the Atlantic coast of Europe. While previous studies have focused primarily on storm impacts, there remains limited understanding of how beaches recover over longer timescales or across regions. Earlier studies were mostly based on short-term observations or a small number of sites, making it difficult to generalise recovery behaviour or link it to controlling processes such as wave climate, exposure, and sediment transport pathways. This lack of regional, multi-annual analysis limits the ability to anticipate how different beach types evolve following extreme events. This study addresses that gap by examining post-storm recovery patterns across 23 beaches along the southwest coast of England over a three-year period, using consistent, high-resolution monitoring data. By building on an existing storm response classification framework the study aims to improve understanding of the processes controlling recovery at regional scale.

The analysis uses repeated LiDAR-derived topographic datasets to quantify changes in intertidal and supratidal sediment volumes between pre-storm (2012), post-storm (2014), and recovery (2017) epochs. This allows both the magnitude of storm-driven erosion and the subsequent recovery trajectory to be assessed in a consistent manner across a diverse range of beach types and wave exposure settings.

A key finding is that beach recovery is multi-annual and often incomplete. Only 7 of the 23 beaches recovered more than 90% of their pre-storm sediment volumes within three years, highlighting the persistence of storm impacts. The study also showed that subsequent winter conditions strongly influence recovery, indicating that sequences of energetic winters can significantly delay recovery and prolong beach vulnerability.

The study identified that recovery behaviour can be grouped into four coherent response classes, reflecting differences in wave exposure, coastal setting, and shoreline orientation, that also control storm response. Fully exposed beaches subjected to shore-normal, high-energy wave forcing experienced the greatest sediment losses and gains (during recovery), but exhibited slow recovery rates and remained in a more vulnerable state. In contrast, beaches influenced by a bi-directional wave climate showed recovery patterns controlled by shifts in wave direction and associated changes in alongshore sediment transport, making recovery more variable and sensitive to future wave conditions.

Findings demonstrate that post-storm beach recovery follows coherent patterns, which can be used to inform coastal management. The identification of consistent behavioural classes suggests that regional monitoring strategies could be optimised by focusing on representative sites, rather than uniformly monitoring all beaches, while still capturing the dominant recovery dynamics across a coastline.

Typical site characteristics				Response characteristics		Recovery characteristics		
beach class		exposure/ geological control (NBL)	wave forcing (Burvingt *et al.*, 2017a)	magnitude (dQ_{net}/dQ_{gross})	spatial pattern	magnitude (dQ_{net}/dQ_{gross})	spatial pattern	recovery rate
CL1		fully exposed/ unconstrained (4.0)	angle: O(10°) cross-shore wave power: O(170kWm^{-1})	Largest (>0.9)	alongshore uniform (net offshore)	largest (>0.85)	alongshore uniform (net onshore)	O(25%/yr)
CL2		semi-exposed/ semi-constrained (3.5)	angle: O(20°) cross-shore wave power: O(120kWm^{-1})	moderate (0.4 to 0.9)	alongshore uniform (net offshore)	moderate (0.4 to 0.8)	alongshore uniform (net onshore)	O(33%/yr)
CL3		Sheltered / constrained (3.5)	angle: O(60°) cross-shore wave power: O(30kWm^{-1})	limited (0.1 to 0.9)	variable (complex redistribution)	limited (0.1 to 0.95)	variable (complex redistribution)	variable
CL4		Sheltered / semi-constrained (8.5)	angle: O(55°), bi-directional cross-shore wave	marginal (< 0.30)	Rotation (alongshore transport)	marginal (< 0.25)	opposing rotation (alongshore transport)	variable

Conceptual model showing how the four beach response types respond to and recover from extreme storms. The left panel summarises the typical beach setting and wave conditions, while the middle and right panels illustrate the magnitude and pattern of storm-driven erosion, recovery, and the typical recovery rate for each beach type.

Single extreme storm sequence can offset decades of shoreline retreat projected to result from sea-level rise.

Harley, M.D., Masselink, G., Ruiz de Alegria-Arzaburu, A., Valiente, N.G. and Scott, T., 2022.

Key message

Three high-resolution morphological datasets of extreme storm-recovery sequences from the UK, Australia and Mexico are used to quantify the nearshore sediment budget and relate these episodic volume changes to long-term coastal projections. It is shown that the sediment gains over the shoreface at all locations were sufficient to theoretically offset decades of projected shoreline retreat due to sea-level rise, even for a high-end greenhouse gas emissions scenario (SSP5-8.5).



Take away thought

Extreme storms can make substantial positive contributions to the nearshore sediment budget by redistributing sediment between offshore and nearshore sediment stores. These exchanges can offset decades of shoreline retreat predicted by simplified sea-level rise models. Accounting for such storm-driven sediment exchanges can substantially improve long-term shoreline projections and coastal adaptation planning.

Summary

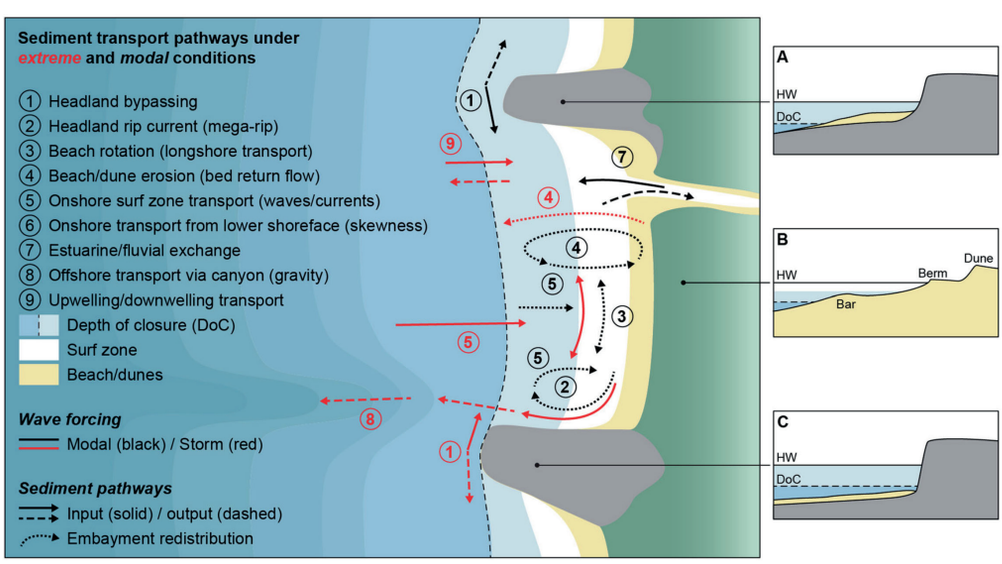
The Bruun rule has emerged as the most widely used method for predicting shoreline change due to sea-level rise. In its most simple and original form, the Bruun rule reduces to R = S/tanß, where R is the amount of shoreline retreat, S is the sea-level rise and tanß is the gradient of the active part of the shoreface. The active shoreface is here defined as that part of the coastal profile that extends from the top of the beach to the depth of closure (DoC), defined as the depth beyond which morphological change is very limited. Application of the Bruun rule involves a simple upward and backward translation of the shoreface profile to a location where the volumetric losses from the upper part of the profile are matched by the gains across the lower part; the Bruun rule thus assumes offshore sediment transport takes place. Sediment gains and losses can be included in the Bruun rule, but their inclusion requires a rigorous insight into the nearshore sediment budget. Of particular relevance in this context is the impact of extreme storm activity on the sediment budget, as it is under these forcing conditions that sediment fluxes are maximized and the impact of the sediment budget on long-term shoreline change is potentially greatest.

This paper presents three unique coastal morphological datasets (UK, Australia and Mexico) each of which encompasses a sequence of an extreme storm or an extended storm cluster, followed by a milder period of beach recovery. The sediment budget analysis unequivocally points towards unbalanced (or non-zero) sediment budgets at all three sites. Specifically, at all sites large sediment gains across the shoreface occurred over the storm-recovery sequence. These short timescale events can have important implications for long-term coastal evolution and, when placed in the context of projections undertaken using the common Bruun-rule approach, can theoretically offset decades of predicted shoreline retreat due to SLR, even under a high-range greenhouse gas emissions scenario (SSP5-8.5).

Perranporth is the UK site in this data set where the impact of the 2013/14 winter storms and the subsequent recovery on the total sediment budget was considered. Perranporth experienced a total sediment gain of 140 m^3 per meter beach width during the 2013/14 winter storm period and subsequent recovery. In absolute terms, Perranporth gained 420,000 m^3 across the entire beach. The direct source of this sediment gain cannot be conclusively ascertained, but it is suggested that the sediment gains occurred primarily over the recovery phase and particularly across the southern part of the beach. This increase in sediment is attributed to alongshore headland sand bypassing input at the southern extremity (Pathway 1 in the Figure).

The observed sediment gains over the shoreface was subsequently characterized in terms of equivalent years of theoretical shoreline retreat predicted by the Bruun rule. For Perranporth, the observed sediment gains over the extreme storm-recovery sequence are equivalent to 10 years of recession due to sea-level rise predicted by the Bruun rule for the 'extreme' SSP5-8.5 scenario, or 17 years for the 'sustainable' SSP1-2.6 scenario.

The results highlight major limitations of the Bruun-rule approach for long-term coastal projections and emphasize the need for enhanced shoreface monitoring worldwide to better quantify changes in sediment budgets due to climate change.



Key sediment transport pathways under modal and extreme wave conditions on an embayed sandy beach. Red arrows denote sediment transport pathways during extreme storm conditions and black arrows during less-energetic modal conditions. Example cross-sections at three locations in the beach compartment are: A: a rocky headland with sandy bed above the depth of closure (DoC); B: a completely sandy beach system; and C: a rocky headland with the sandy bed below the depth of closure.

Coastal cliff ground motions and response to extreme storm waves.

Earlie, C.S., Masselink, G., Russell, P.E. and Shail, R.K., 2015.

Key message

Over January–February 2014, during the largest Atlantic storms in at least 60 years with deepwater significant wave heights of 6–8 m, cliff-top ground motions showed vertical ground displacements in excess of 50–100 μm. Repeat terrestrial laser scanner surveys over a two-week period encompassing the extreme storms revealed a cliff face volume loss of two orders of magnitude larger than the long-term erosion rate.



Take away thought

Large storm waves impacting coastal cliffs during high tide generate measurable ground motions that may progressively weaken cliffs. This provides new insight into the mechanisms driving episodic cliff erosion, with the importance of this mechanism depending strongly on the frequency and severity of extreme storm wave events. As sea level rises, wave attack at the cliff toe is expected to become more frequent, suggesting this mechanism may become increasingly important even if future storminess remains unchanged.

Summary

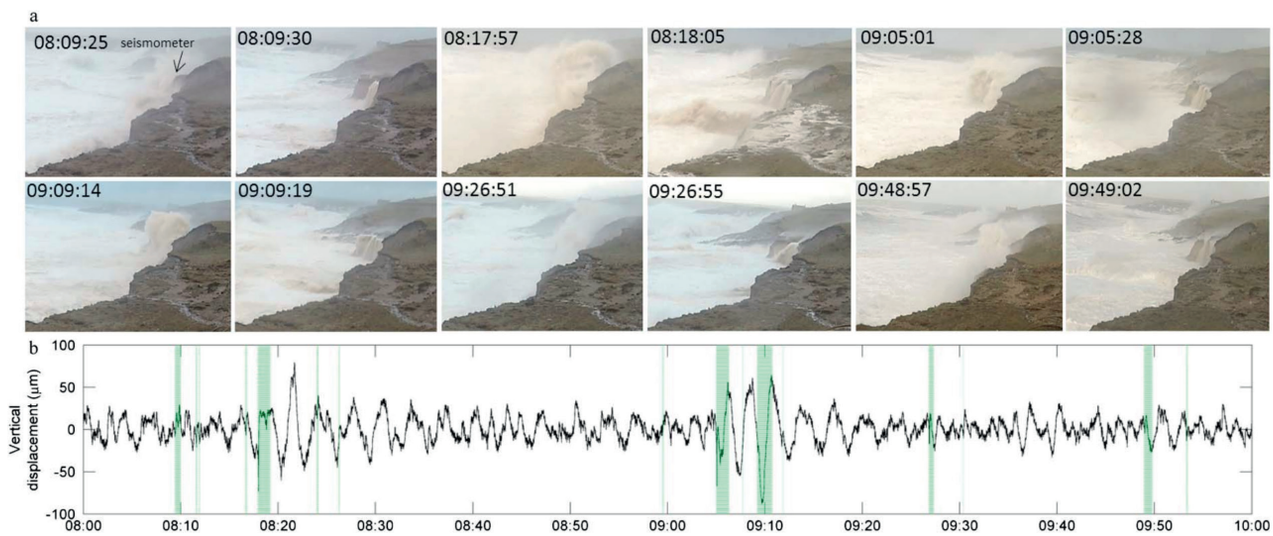
When large waves crash into coastal cliffs, the impact causes the cliff to undergo tiny displacements. It has been suggested that this repetitive shaking of the cliffs ultimately fatigues rock strength and can lead to cliff failure. Measurements in wave conditions with significant wave height less than 3 m have shown vertical ground displacements in the region of 0.5–10 μm during each wave loading cycle. Observations of cliff motion under extreme wave events are rare.

This study describes a unique set of observations made during exceptionally energetic storm conditions on a coastal cliff in the southwest England from 31 January to 6 February 2014. As demonstrated in previous studies, the winter of 2014 was one of the most energetic periods the region had seen since the 1950s and brought over 10 storms with significant wave heights in excess of 6 m (the 1% exceedance limit). This study reports for the first time on cliff-top seismic observations using both in-situ and remote instrumentations under extreme wave conditions. The cliff-top observations are placed in a longer-term context by comparing cliff-face changes that occurred over this extremely energetic period, obtained from terrestrial laser scanning, with the annual cliff-face development over the preceding 50 years.

These unique field measurements were made on the south coast of Cornwall, along a 300-m stretch of uninhabited cliffed coastline near Porthleven. The cliffs rise 8–10 m above a steep beach and the elevation of the cliff toe is 2–4 m ODN. The cliff-top ground motion was recorded using a seismometer buried about 1 m below the ground surface of the cliff-top and about 5 m from the cliff edge. A video camera was deployed to provide a visual record of the waves impacting the coastal cliff during the most energetic period on 5 February 2014. Monthly scans of the 300-m cliff section were conducted using a terrestrial laser scanner over a one-year period from July 2013 to July 2014. This enabled linking the short-term wave impacts on the cliff to the longer-term cliff development. Complementary wave data were taken from directional wave buoys deployed at Porthleven and Looe Bay.

Camera footage captured during the storm event shows different types of interactions between waves and the cliff structure: (1) wave breaking on the beach without reaching the cliff; (2) wave breaking at the cliff toe; and (3) wave overtopping of the entire cliff elevation. Under energetic conditions, the largest vertical displacements, of 50–100 μm (that is a maximum of 0.1 mm) were coincident with periods of successive cliff overtopping followed by water cascading down the cliff face.

The long-term annual retreat rate for Porthleven is c. 0.1 meter per year, which equates to an annual cliff volumetric loss of 1 m^3 per meter length of cliff assuming a cliff height of 10 m. Terrestrial laser scans over a two-week bracketing the extreme storm on 5 February demonstrate a cliff volumetric loss of 4.5 m^3 average erosion volume per meter length of cliff which equates to an annual cliff volumetric loss of 113 m^3 per meter length of cliff. The rate of cliff volumetric loss over the two-week storm period is therefore two orders of magnitude greater than volumetric loss based on the long-term cliff recession.



Stills from camera footage illustrating successive wave overtopping and subsequent drainage events on 5 February 2014 from 08:09 to 09:49. The lower panel shows the vertical displacement during this period. The green shaded regions correspond to the pairs of photos (taking with c. 10 s from each other), where the first photo shows a large wave breaking against the cliff face and the second photo showing overtopped water cascading down the cliff face.

The role of beach morphology on coastal cliff erosion under extreme waves.

Earlie, C.S., Masselink, G. and Russell, P.E., 2018.

Key message

The slope of beaches fronting coastal cliffs and the elevation of the beach-cliff junction both influence the magnitude and frequency of wave action on the cliff face. Numerical modelling showed that under highly energetic wave conditions, cliffs fronted by steep gravel beaches can experience significantly more wave impact than those fronted by flat sandy beaches.



Take away thought

Extreme wave and water level conditions play a key role in coastal cliff erosion, but fronting beaches can substantially reduce the wave energy reaching the cliff toe. The effectiveness of this natural protection depends strongly on beach morphology and is maximised where beaches are wide, gently sloping and have a high beach-cliff junction. This highlights the importance of considering beaches and cliffs as an interconnected coastal system when assessing cliff erosion risk and long-term coastal management.

Summary

Erosion of hard-rock coastal cliffs is caused by a combination of both marine (waves and tides) and sub-aerial (rainfall, mass movements) processes. The impact of high water levels and extreme waves is commonly implicated in the occurrence of cliff failure, but an important potentially mediating role can be played by the beach in front of the cliff. In fact, many cliff erosion and rocky coast geomorphological studies have considered the role of beach morphology (width, height and volume) in modifying the dissipation of wave energy. It is typically understood that a decrease in beach volume or elevation fronting a cliff will lead to an increase in cliff erosion, whereas an increase in beach volume results in a decrease in cliff erosion.

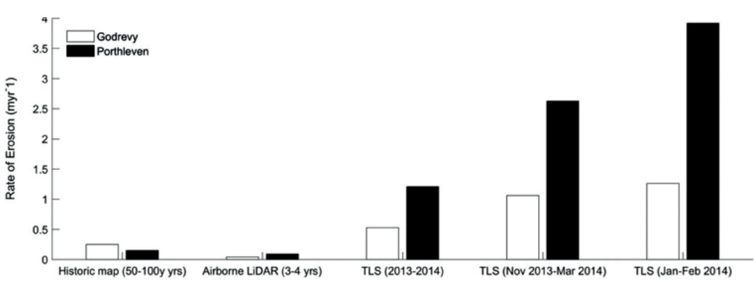
Monthly Terrestrial Laser Scanner (TLS) surveys of coastal cliffs were conducted at two particularly vulnerable sites in Cornwall over a one-year period. One site (Godrevy, north Cornwall) is fronted by a gently-sloping dissipative beach with a relatively low beach-cliff junction (around MSL), whereas the other (Porthleven, south Cornwall) is fronted by a steep reflective beach with a relatively high beach-cliff junction (around MHWS). Both sites experienced extreme wave conditions, but the maximum significant wave height H_s at the reflective site (H_s = 8 m) was higher than at the dissipative site (H_s = 5.5 m); average winter wave conditions were similar (H_s < 2 m). At both sites, the 8–15 m cliffs are characterized by fractured meta-sedimentary rocks capped with less resistant head deposits.

A strong seasonal variability in cliff erosion was apparent with more than 90% of the cliff volumetric losses occurring during the winter months (December–March). Erosion volumes over the one-year period were found to be twice as great at the cliff site fronted by the reflective beach (1.1 m/yr) compared with at a dissipative beach (0.5 m/yr). These cliff erosion rates are a factor three to five times larger than the long-term average.

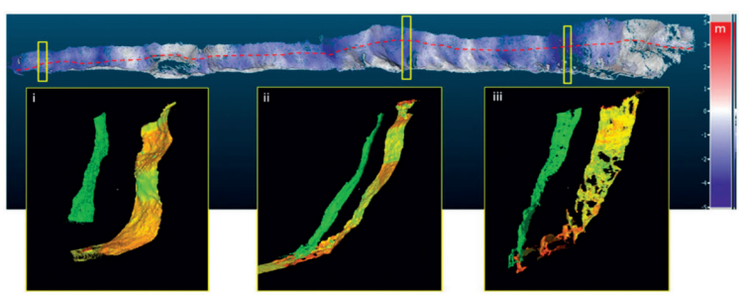
The larger erosion rate at the reflective site is partly attributed to the more energetic inshore wave conditions at this site; however, a very significant role is also played by the beach morphology through its influence on the delivery of wave energy to the base of the cliff. This role was explored using the numerical model XBeach-G forced with local conditions (waves, tides and beach morphology).

The numerical model results demonstrate that under relatively modest wave conditions (H_s < 2 m), the elevation of the beach-cliff junction relative to the tide level was the most important factor in controlling the delivery of wave energy at its base (favouring more frequent inundation at the gently-sloping dissipative site). However, under storm wave conditions (H_s > 5), the beach gradient, through its control on wave run-up, was the more important factor (favouring more frequent inundation at the steep reflective site), especially under extreme wave conditions.

Simulating the maximum wave conditions experienced at both sites, the amount of wave energy reaching the base of the cliff fronted by the reflective beach was more than four times higher than at the dissipative site. Simulating the same maximum wave conditions at both sites highlighted that even under the same forcing conditions, cliffs fronted by the reflective beach are subjected to waves 3.5 times more powerful than cliffs fronted by the dissipative beach.



Cliff erosion rate in metres per year for Godrevy (north Cornwall) and Porthleven (south Cornwall) computed over different time periods using different methods: historic maps (century time scale); airborne LiDAR (decadal time scale); terrestrial laser scanning (TLS) from monthly scans over a one-year period (annual time scale); TLS with only scans over the winter period (monthly time scale); and TLS with only scans during the storm period weekly time scale).



Point cloud comparison plot of Porthleven cliff face for the period July 2013 to July 2014, with colour bar scale ranging from blue (-5m) to red (+5 m). Dotted red line indicates the boundary between underlying basal layer of Mylor slates and overlying, less resistant Quaternary head deposit. (i–iii) Three dimensional (3D) sections through the cliff at three locations where the majority of cliff failure (> 1 m cliff retreat) occurred. Initial surface (July 2013) is depicted in brighter green, superimposed over the later scan (July 2014, yellow-green).

Chapter 7: Predicting coastal change

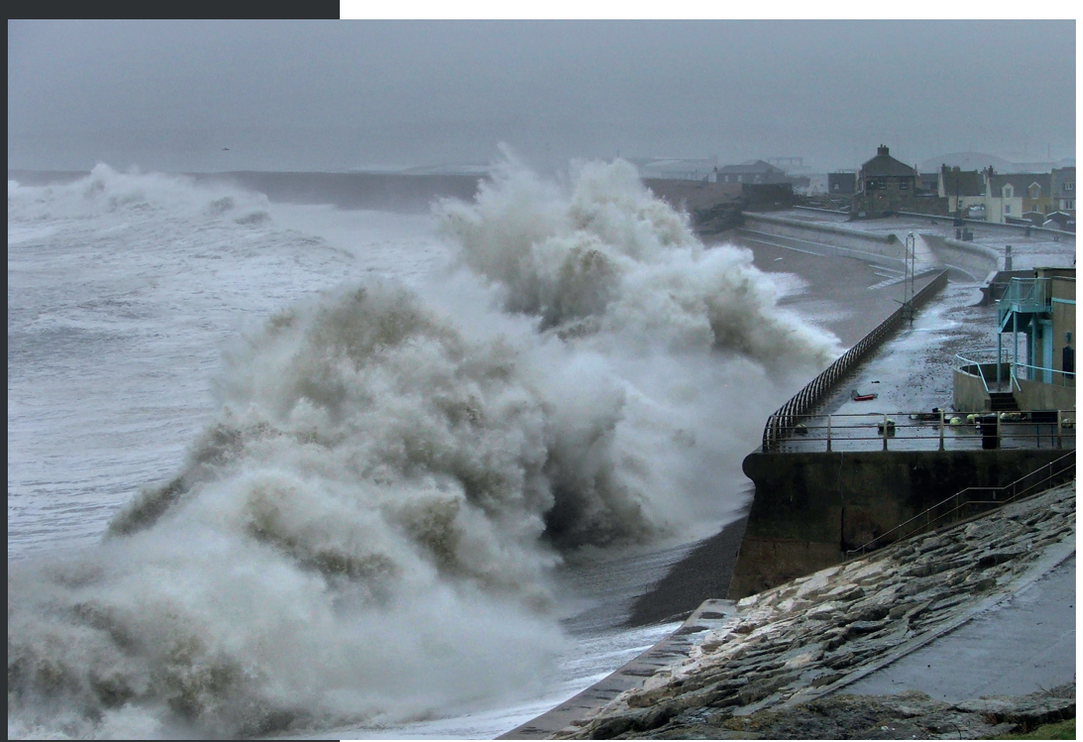
Predicting how coastlines will respond to changing waves, storms and sea levels is fundamental to proactive coastal management and climate adaptation. Advances in numerical modelling and forecasting now allow coastal change to be assessed over timescales ranging from individual storm events to decades of shoreline evolution. The papers in this chapter present a range of predictive approaches, including models of shoreline change, gravel barrier response, wave runup and coastal overtopping, together with methods for forecasting beach behaviour from atmospheric conditions. Together, they demonstrate how robust scientific predictions can support risk assessment, infrastructure planning and evidence-based coastal management.

Modelling storm response on gravel beaches using XBeach-G.

Masselink, G., McCall, R., Poate, T. and van Geer, P., 2014.

Key message

Despite the clear societal importance of gravel beaches and barriers in protecting coastal areas from flooding, there are currently no reliable numerical models for predicting the morphological response of gravel beaches to storm events. This paper introduces a storm impact model for gravel beaches and barriers, describes a user-friendly graphical user interface (GUI) for the model and applies the model to demonstrate its use in decision-making processes related to coastal flooding and beach maintenance.



Take away thought

This paper describes a freely-available numerical model with an accessible Graphical User Interface (GUI) that can be used to assess the resilience of gravel barriers to sea-level rise and extreme storms. The model provides a practical tool for evaluating coastal flood risk, informing beach maintenance and supporting coastal management decisions.

Summary

Most numerical models for predicting beach change due to storms are for application to sandy beaches. These models have been developed based on field and laboratory measurements conducted on sandy beaches and they should not be applied to gravel beaches. As part of an EPSRC-funded project, an extensive set of field measurements of wave processes and beach change was collected under storm conditions on a number of gravel beaches in SW England. These field observations were complemented by measurements made in a large physical laboratory in the Netherlands (Delta Flume) to develop a gravel-specific morphodynamic model for predicting beach change under extreme wave conditions.

The new model (freely downloadable from https://oss.deltares.nl/web/xbeach/xbeach-g) represents an extension to the very widely used XBeach storm response model developed for sandy barrier systems, and the gravel version of the model is called XBeach-G. A graphic user interface (GUI) was developed for the new model to encourage its use by coastal managers and practitioners.

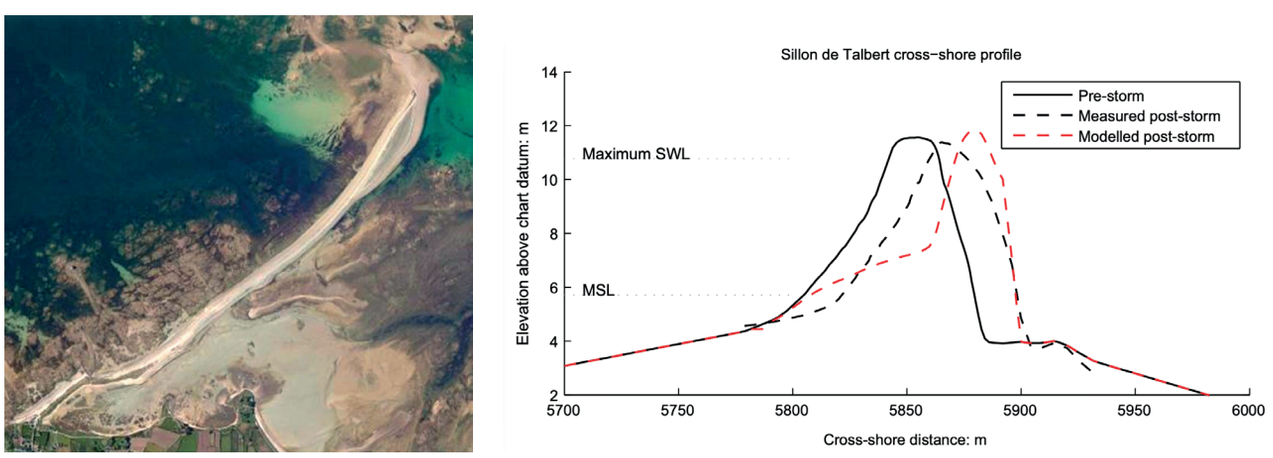
Compared to the sandy XBeach model, XBeach-G includes three gravel-specific modifications:

1. On sandy beaches during storm conditions, the wave motion on the beach is mainly at periods of minutes rather than seconds (at so-called wave group or infragravity frequencies). On gravel beaches, on the other hand, ocean waves tend to break directly on the beach resulting in runup that generally far exceeds that on sandy beaches. In XBeach-G, the ocean waves are modelled directly, providing a more accurate description of the hydrodynamics.

2. Gravel beaches are fundamentally different from sandy beaches due to their increased permeability. When waves run up a gravel beach, a significant amount of the water during the onshore stroke of the wave (the uprush) will infiltrate into the beach, weakening the seaward-returning backwash. This has implication for the stability of the beach and also the gradient of the beach. XBeach-G accounts for these interactions between the wave motion on the beach and the beach groundwater table.

3. Sediment transport on sandy beaches is mainly by sand grains suspended in the water column, whereas on gravel beaches the larger grains tend to roll over the seabed as bedload. The physics controlling sediment transport on gravel beaches are therefore very different from that on sandy beaches, and therefore different sediment transport equations are implemented in XBeach-G.

XBeach-G is a one-dimensional model, meaning that wave processes, groundwater dynamics, sediment transport and morphological change are only modelled along a single cross-shore transect. An example of how the model can be applied is as follows. Imagine a coastal manager would like to examine whether a gravel barrier is capable of providing flood protecting for future wave events under different sea-level scenarios. Using the GUI, the manager can setup models using the actual beach profile and sediment characteristics, and force the model with various combinations of wave and sea-level conditions. Following an initial set of model runs, the manager can redesign the gravel barrier to increase flood protection and coastal resilience. The model can thus be used in decision-making processes related to coastal flooding and beach maintenance.



Left panel shows aerial photograph of the 3 km-long gravel barrier of Sillon de Talbert on the north coast of Brittany, France. Right panel shows comparison between cross-shore barrier profile before (solid black line) and after (dashed black line) storm Johanna (10 March 2008). The dashed red line shows the post-storm profile modelled by XBeach-G.

Storm overwash of a gravel barrier: Field measurements and XBeach-G modelling.

Almeida, L.P., Masselink, G., McCall, R. and Russell, P.E., 2017.

Key message

High frequency in-situ observations were performed using a 2D laser-scanner to validate the numerical model XBeach-G. Several simulations were performed with the numerical model to investigate coastal flooding thresholds for the different storm impact regimes characterised by a variety of water levels and wave heights. Long period waves or strongly bimodal waves were found to result in enhanced runup, thereby increasing the risk of barrier overtopping, overwashing and coastal flooding.



Take away thought

Overwash of gravel barriers is a threshold-controlled process requiring a specific combination of water level, wave conditions and elevation of the barrier crest. These interacting controls must be understood for predicting overwash events and assessing barrier vulnerability during extreme storms.

Summary

Gravel barriers are widespread on many high-latitude, wave-dominated coasts around the world, including the UK and Ireland. Their dynamics and long-term evolution are mainly controlled by three hydrodynamic regimes: (1) swash, when runup is confined to the beachface, resulting in construction of the berm and/or beach erosion; (2) overtopping, when runup exceeds the barrier crest, resulting in the raising of the crest; and (3) overwash, when runup exceeds the crest and promotes major modifications over the entire barrier, resulting in barrier transgression via rollover, as well as coastal flooding.

This study presents field measurements of a very mild overwash event on the fine-gravel barrier system of Loe Bar on the south Cornwall coast during a storm in February 2014. Measurements were made using a 2D laser scanner. The offshore significant wave height during the storm event peaked at 4.5 m and the waves were characterised by a peak wave period of 10–15 s. The maximum water level was 2.5 m ODN (Ordnance Datum Newlyn) and during the peak of the tide several waves washed over the gravel barrier.

Loe Bar is a 1 km-long fine gravel (D_{50} = 2–4 mm) beach on the south coast of Cornwall. The gravel barrier has an average width of 250 m, a 1:10 seaward gradient and an average crest elevation of 8.7 m ODN. The barrier is exposed to energetic Atlantic swell and wind-waves with an annual average significant wave height of 1.2 m, an average peak period of 10 s and a direction of 235°. The tidal regime is macrotidal with mean high and low water spring at 2.5 m and -2.2 m ODN, respectively. A freshwater lagoon, Loe Pool, is present behind the Loe Bar gravel barrier.

The field measurements made with the laser scanner were compared with predictions of a numerical model, called XBeach-G, specifically designed to predict storm impacts on gravel beaches. The validated model was then used to explore which hydrodynamic conditions define the thresholds for the different storm impact regimes (e.g., swash, overtopping and overwash) on Loe Bar. The key results from this modelling are:

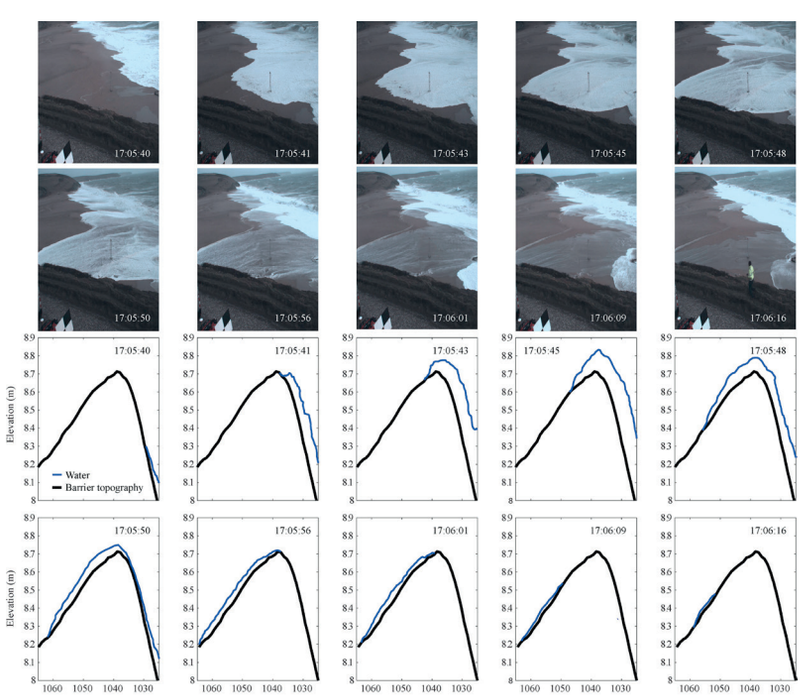
1. Validation of the field measurements with the XBeach-G model showed great skill in predicting the hydrodynamics during the storm event when overwashing occurred.

2. The two main hydrodynamic factors that control the occurrence of overwash are the wave height and the water level, but wave period and the shape of the wave spectrum also play important key roles.

3. Wave bimodality (wave spectrum with two peaks) encourages the development of higher wave runup, enhancing the likelihood of overtopping and overwash.

4. While short-period waves dissipate most of their energy by breaking before reaching the swash zone and produce short runup excursions, long-period waves, because of their low steepness, shoal without breaking arriving at the swash zone with greater heights, producing large runup excursions.

5. On a fine-gravel beach like Loe Bar, the groundwater has limited effect on the extreme runup and definition of the thresholds for storm impact regimes.



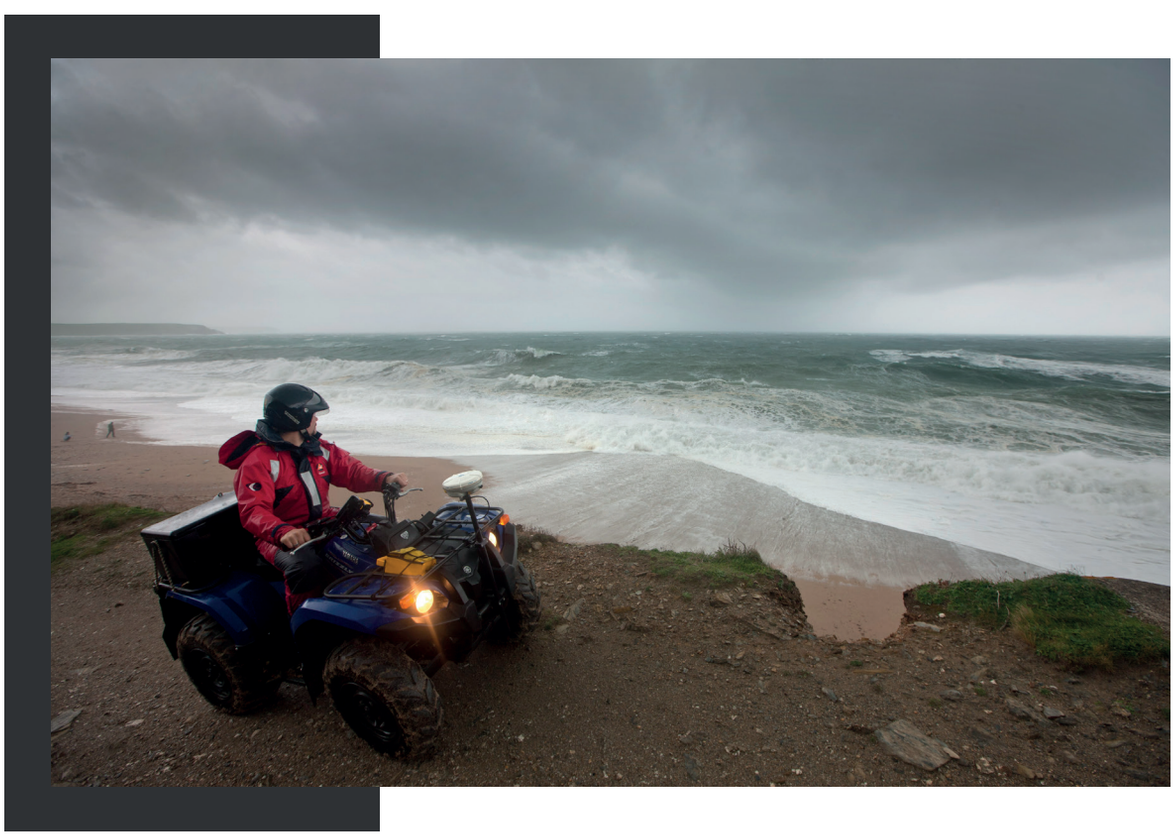
Sequence of video snapshots (top) and corresponding laser-scanner measurements (bottom) during an overwash event over the barrier. The black line in the lower panels represents the beach surface, whereas the blue line is the water surface; waves are travelling from right to left during a single 36-s long overwash event.

A new parameterisation for runup on gravel beaches.

Poate, T., Masselink, G and McCall, R., 2016.

Key message

This paper shows that existing runup equations, especially sandy-beach predictors such as Stockdon equation, systematically underpredict wave runup on gravel beaches, often by up to 50% under energetic conditions. Using ten field datasets from six UK gravel beaches, the authors develop a new gravel-specific empirical runup parameterisation for 2% exceedance runup. The most important controls are, in order, significant wave height, spectral mean period, beach slope, and grain size.



Take away thought

Coastal flood and overtopping risk on gravel beaches is underestimated when using sandy beach runup approaches. Unlike sandy beaches, runup on gravel coasts is strongly influenced by sediment size, as well as beach slope and wave conditions, and the maximum vertical runup can exceed the significant wave height. Gravel-specific runup predictions provide a more robust basis for hazard assessments and the design and evaluation of coastal flood risk management measures.

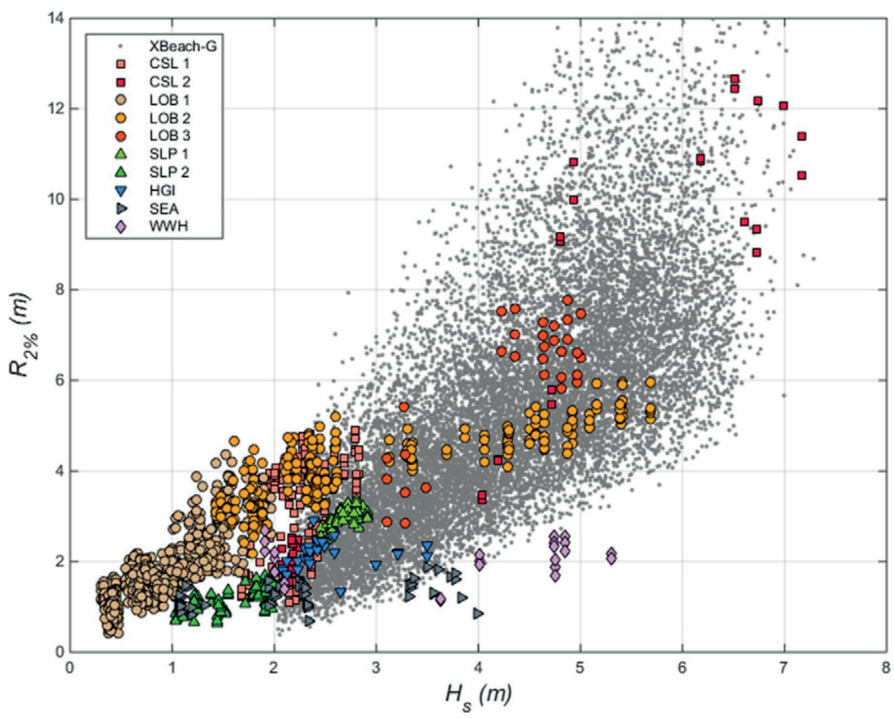
Summary

This paper presents a major advance in predicting wave runup on gravel beaches, addressing a key limitation in coastal hazard assessment: most commonly used runup equations were developed for sandy beaches and perform poorly on steep, reflective gravel coasts. The paper shows that formulas such as the Stockdon equation consistently underpredict runup on gravel beaches, especially during energetic storm conditions, in some cases by more than 50%. This matters because runup is a critical control on overtopping, overwash, flooding, and barrier vulnerability.

To address this, the authors compiled the largest gravel-beach runup dataset to date, using 10 field deployments at 6 UK meso- to macrotidal gravel sites over a two-year period, covering storm conditions with significant wave heights of 1–8 m and sediment sizes from 2 mm to 160 mm. Runup was extracted from video observations, and beach morphology was measured using RTK-GPS surveys. XBeach-G, a gravel-specific numerical model that includes infiltration and exfiltration processes, was used to reproduce the field observations and generate a much larger synthetic dataset spanning a wider range of conditions.

From this combined approach, the authors developed a new gravel-specific empirical parameterisation for 2% exceedance wave runup ($R_{2\%}$). The most important controls on runup were, in decreasing order, significant wave height (H_s), spectral mean period ($T_{m-1,0}$), beach slope (tanß), and grain size (D_{50}). The new equation performed very well, against the synthetic model dataset ($r^2 = 0.97$) and against field data ($r^2 \approx 0.88$), substantially outperforming existing predictors.

Scientifically, the paper shows that pure gravel beaches remain steep and reflective during storms, with waves often breaking directly on the beachface rather than dissipating offshore in a wide surf zone. This explains why gravel beaches can experience exceptionally large runup under storm waves and why gravel-specific models are essential for reliable coastal engineering and hazard planning.



Scatter plot of 2% runup exceedance ($R_{2\%}$) and significant wave height (H_s) for XBeach-G generated dataset combined with measured field data (colours symbols) from gravel beaches (CSL - Chesil; LOB = Loe Bar; SLP = Slapton Sands; HGI = Hayling Island; SEA = Seascale; WWH = Westward Ho!).

Forecasting coastal overtopping at engineered and naturally defended coastlines.

Stokes, C., Poate, T., Masselink, G., King, E., Saulter, A. and Ely, N., 2021.

Key message

The paper presents and validates SWEEP-OWWL, a computationally efficient system for forecasting wave overtopping and coastal flooding across southwest England. Wave runup and overtopping are major but often underestimated flood drivers. By combining regional wave–tide modelling with empirical equations, the approach replaces costly process-based models and enables near real-time forecasts along about 1,000 km of coastline. Accurate, up-to-date beach and cliff profiles are essential, improving predictions by up to an order of magnitude. The model correctly predicts overtopping occurrence in about 97% of cases.



Take away thought

Wave overtopping is a major driver of coastal flooding and an important component of coastal flood warning and response systems. Regional wave overtopping forecasting provides a practical tool for coastal flood preparedness and demonstrates how research can be translated into operational coastal flood warning systems. Forecast accuracy depends on up-to-date beach and defence surveys, highlighting the value of combining forecasting with monitoring and expert judgement.

Summary

This paper presents a new system (SWEEP-OWWL) for operational forecasting of wave overtopping, a key driver of coastal flooding that is often neglected in large-scale risk assessments. The study focuses on southwest England, a region with diverse coastlines (sandy, gravel, and engineered defences) and energetic wave conditions.

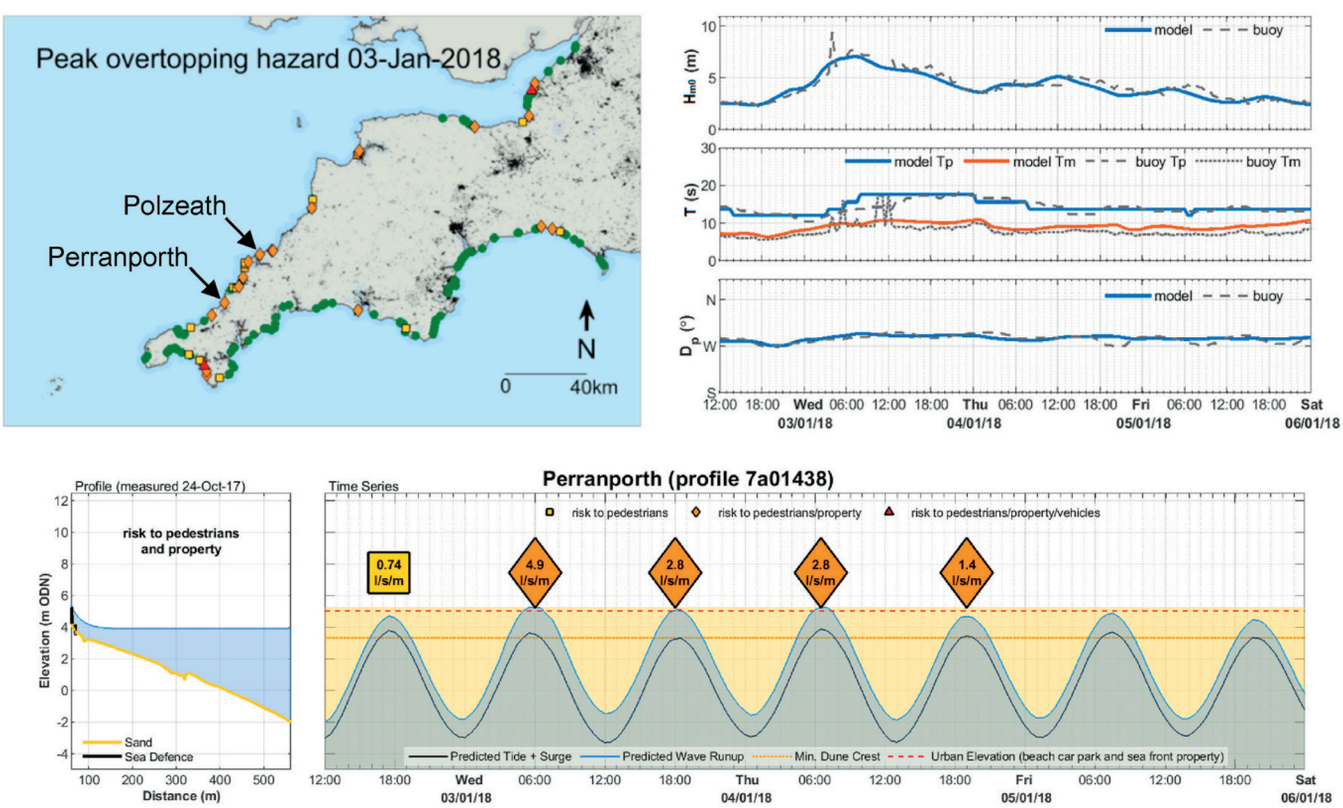
The system combines a regional hydrodynamic model with empirical equations for wave shoaling, breaking, runup, and overtopping. This hybrid approach avoids the high computational cost of process-based models, enabling real-time forecasts up to three days ahead across ~1000 km of coastline using a standard desktop computer.

A major innovation is the use of an extensive, updateable database of coastal profiles, allowing forecasts to reflect changing beach morphology. Results show that incorporating updated profiles can improve overtopping predictions by up to an order of magnitude, highlighting the importance of coastal morphology in flood risk assessment.

Validation using webcam observations and storm case studies shows strong performance: the system correctly predicts the presence or absence of overtopping 97% of the time, and reasonably distinguishes between hazard levels.

The study also demonstrates that wave runup can significantly elevate total water levels, increasing flood risk beyond that associated with tide and surge alone. While uncertainties remain, especially for natural beaches and complex structures, the system provides a practical, scalable tool for early warning.

Overall, the paper shows that accurate, efficient overtopping forecasts are achievable and can greatly enhance coastal flood preparedness and management. The system is currently operational and provides daily three-day water level forecasts (https://coastalmonitoring.org/ccoresources/sweep/)



Forecasted wave conditions and overtopping for Storm Emma, 1st – 2nd March 2018. Top left: 3-day regional hazard forecast. Top right: forecasted and measured significant wave height (H_{m0}), peak (T_p) and mean (T_m) wave period, and peak wave direction (D_p) at 12 m ODN depth contour at Slapton Sands. Middle left: measured beach profile and predicted water level/runup. Middle right: time series of predicted water level and runup with overtopping volumes and hazard warnings. Dashed red line indicates the elevation of the road.

Forecasting coastal evolution on timescales of days to decades.

Davidson, M., 2021.

Key message

This study presents a new computer model, Forecasting Coastal Evolution (ForCE), that predicts long-term beach change while accounting for tides, storm surges, sea level rise, and the movement of sand across beaches and dunes. The model was tested for Perranporth (Cornwall) and successfully reproduced observed shoreline movement, beach volume changes, and sandbar behaviour, demonstrating its value for coastal planning and management.



Take away thought

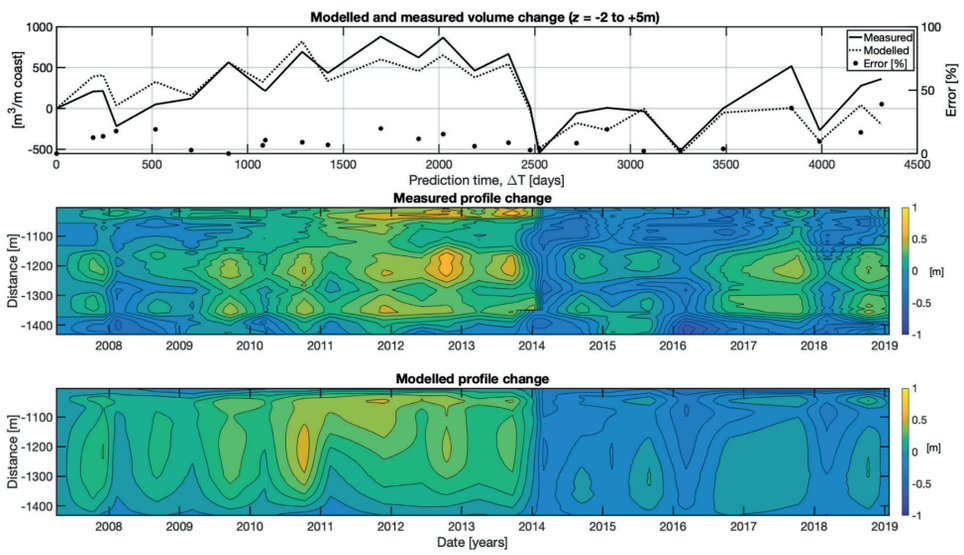
Reliable predictions of coastal change are vital for managing the growing risks associated with sea-level rise and storms. The ForCE model provides a practical and computationally efficient framework for forecasting beach erosion and recovery over years to decades, strengthening the evidence base for coastal planning, protecting infrastructure and ecosystems, and supporting the resilience of communities adapting to a changing climate.

Summary

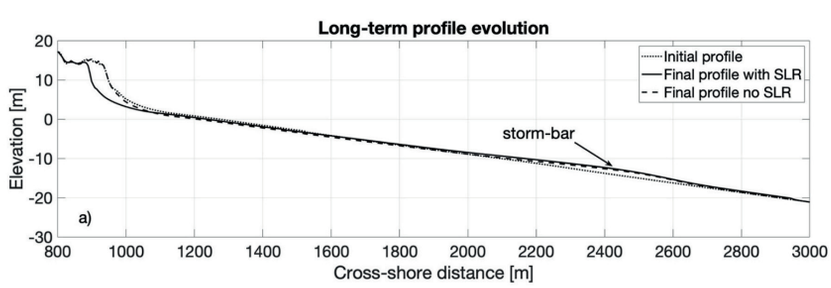
Coastal environments are increasingly affected by sea-level rise, storms and erosion, making accurate predictions of shoreline change essential for protecting communities and ecosystems. So-called equilibrium models for forecasting coastal evolution have become increasingly popular as these models include key physical processes whilst at the same time being computationally efficient. This means they can be used to predict the impact of distinct wave events, like an extreme storm, as well as dealing with longer-term beach recovery over a summer period with calm conditions. They can even be used to predict the coastal response over decades due to sea-level rise.

In this paper the ForCE model (Forecasting Coastal Evolution) is presented. The model is based strongly on equilibrium concepts in a way that predicts erosion of the intertidal zone during storms and recovery (accretion) during quiescent conditions. The model includes a physics-based wave evolution module that predicts wave energy dissipation due to wave breaking across the beach profile and links this directly to sediment transport, without the intermediate step of predicting surf zone currents. It is thus classified as a reduced-physics model. Beach evolution is predicted by assuming that mass is conserved, meaning that erosion must be balanced by accretion across the beach profile.

The equilibrium concepts and reduced-physics approach applied in this model means that the model is fast and stable, and can run days-to-decades forecasts in a few hours on a standard desktop PC. Simplifications in the modelling framework means that the model is best suited to energetic coastlines dominated by cross-shore sediment transport processes.



Comparison of the volumetric change of a beach profile measured at Perranporth with bi-annual and post-storm surveys of the same. The upper panel shows the modelled (solid line) and measured (dashed line) profile volume change (in m3 per unit meter of coast) relative to the first profile in 2007. The lower two panels show the change in beach elevation relative to the first profile with respect to time (x-axis) and chainage (y-axis, increasing positively seawards). Yellow/orange indicates a relatively full beach relative to 2007, while dark blue indicates a depleted beach relative to the start of 2007. Note that the model predicts both seasonal erosion and accretion, as well as the significant erosion during the 2013/14 winter.



Long-term modelling of the impact of sea-level rise on Perranporth beach modelled with ForCE. The figure shows the profile evolution over a 110-year simulation with a 1-m sea-level rise. Two simulations are shown, one with sea-level rise (solid line) and one without (dashed line). The simulation with sea-level rise predicts 60–80 m of shoreline retreat through upper beach erosion and accretion across the lower part of the beach.

Shoreline modelling on timescales of days to decades.

Hunt, E., Davidson, M., Steele, E.C., Amies, J.D., Scott, T. and Russell, P., 2023.

Key message

So-called reduced complexity models are most effective means of modelling coastal evolution as these models provide the computational efficiency and stability required for days to decades predictions and are capable of dealing with the complexity of real-world simulations that include complex geology and coastal structure. They do require significant observational data for calibration and validation.



Take away thought

A bewildering range of morphodynamic models is available to coastal practitioners and there is a distinct lack of guidance and clarity as to which model to apply to a specific problem. This contribution attempts to categorise coastal models in terms of their complexity and suitability for days-to-decades modelling of coastal evolution, providing a practical framework for selecting an appropriate modelling approach.

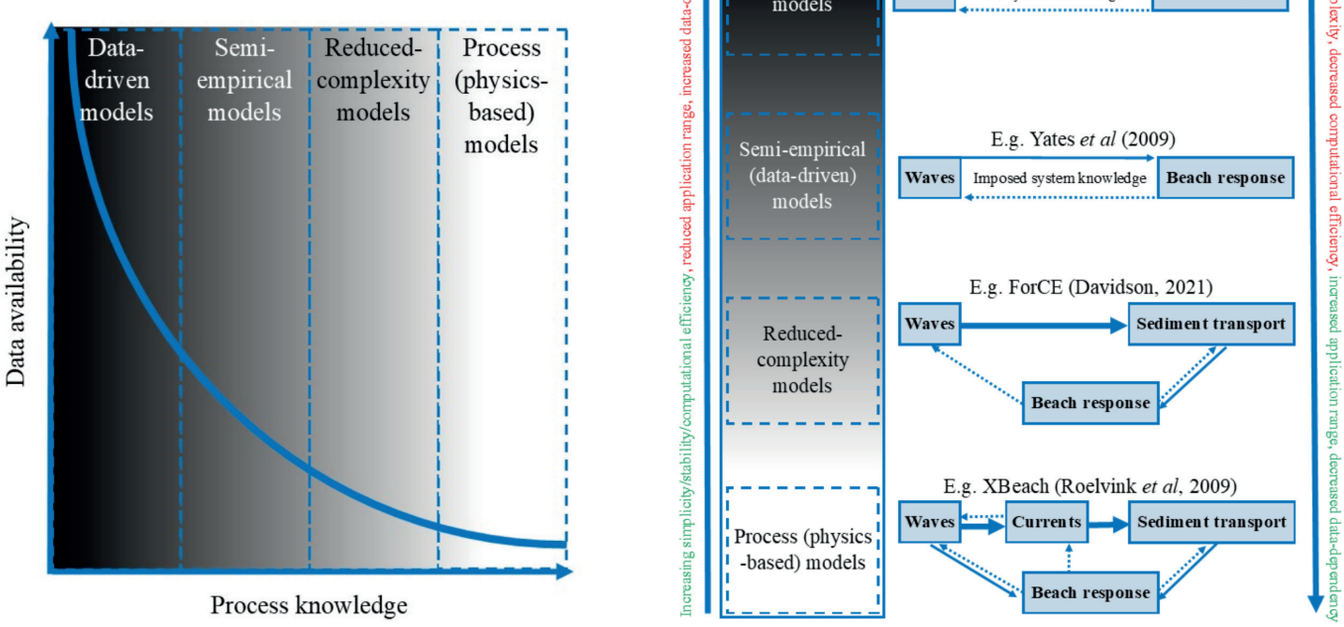
Summary

Climate change is increasing the risk of coastal erosion and flooding through rising sea levels and changing wave climates. Predicting how shorelines will evolve over timescales ranging from individual storms to many decades has therefore become essential for effective coastal planning and adaptation. However, no single modelling approach is suitable for every coastal environment or prediction timescale. Instead, model selection requires balancing accuracy, computational efficiency and the complexity of the coastal system being represented.

This review examines the broad spectrum of numerical approaches used to predict shoreline evolution, from simple empirical and data-driven techniques through to highly detailed physics-based process models. The paper introduces a modelling complexity spectrum, illustrating how different approaches are suited to different spatial and temporal scales, data availability and levels of process understanding. Particular attention is given to reduced-complexity and equilibrium-based models, which combine key physical processes with computational efficiency, making them well suited to forecasting shoreline evolution over timescales spanning days to decades.

The review highlights the strengths and limitations of each modelling approach. Process-based models provide the most detailed representation of hydrodynamics and sediment transport and are particularly effective for predicting short-term responses to storms. However, they remain computationally demanding and increasingly sensitive to uncertainties when applied over longer timescales. Conversely, data-driven and machine learning models are computationally efficient and capable of exploiting large monitoring datasets, but their performance is often constrained by the quality and range of the data used for calibration, limiting their ability to predict conditions beyond those previously observed. Reduced-complexity models occupy an effective middle ground by retaining the dominant controls on shoreline behaviour while remaining sufficiently efficient and stable for long-term forecasting.

The authors conclude that reduced-complexity models, particularly those based on equilibrium concepts, currently provide the most practical solution for predicting shoreline evolution from daily to multi-decadal timescales. Future advances will depend on improving representation of processes that become increasingly important over long periods, including sea-level rise, sediment supply, headland bypassing, geological controls and mixed sediment systems, while integrating improved climate projections, data assimilation and uncertainty analysis. Rather than seeking a universal modelling solution, the paper advocates selecting models that are appropriate to the management question, available data and prediction horizon, providing a practical framework for future shoreline evolution modelling.



Left panel shows schematic diagram demonstrating the relationship between typical model classifications, the availability of data and the current knowledge of processes. Right panel shows the modelling complexity spectrum on the left with corresponding simplified model examples on the right. Advantages/disadvantages are shown in green/red, respectively.

Predicting beach rotation using multiple atmospheric indices.

Wiggins, M., Scott, G., Masselink, G., McCarroll, R.J. and Russell, P., 2020.

Key message

Combining two atmospheric indices (NAO and WEPA) significantly improved prediction of wave directionality, a key control on beach rotation. Building on earlier work linking rotation to wave direction at embayment and regional scales, this study showed that multi-index models can predict rotation more skilfully and reconstruct long-term coastal change, providing a basis for seasonal to centennial-scale understanding.



Take away thought

Combining atmospheric indices (WEPA and NAO) substantially improves prediction of regional wave directionality, a key control on sediment transport and beach rotation. Seasonal forecasts of these indices offer the potential to anticipate rotational shoreline impacts months in advance. Long-term analysis of these indices in combination with historical shoreline data can improve our understanding of long-term coastal evolution. The approach can be applied more widely, as rotational behaviour is often coherent across embayed coastlines experiencing the same atmospheric forcing.

Summary

Beach rotation is a key mechanism of shoreline change in embayed coasts, particularly where wave climates are bi-directional. Previous studies have shown that rotation is driven by the balance of wave direction and can lead to significant alongshore redistribution of sediment, increasing coastal vulnerability when sediment is depleted from one end of an embayment. More recent work has demonstrated that this behaviour is regionally coherent and linked to atmospheric forcing, although the ability to predict these changes remains limited.

This paper built on that foundation by investigating whether combining atmospheric indices could improve prediction of wave directionality and, in turn, beach rotation. The study focused on Start Bay (Devon), using wave model data, sediment transport modelling, and long-term morphological records. A Wave Directionality Index (WDI), previously shown to control beach rotation, was modelled using a stepwise multiple linear regression combining the North Atlantic Oscillation (NAO) and West Europe Pressure Anomaly (WEPA).

The results showed that combining NAO and WEPA significantly improved prediction of WDI compared to using either index alone (R^2 increased to 0.66, when compared to 0.23 and 0.31 for NAO and WEPA individually). This confirmed that different atmospheric indices control different components of the wave climate, and that their combined effect governs the balance of wave direction responsible for driving rotation. The predicted WDI was shown to correlate with both observed beach rotation and modelled longshore sediment transport, demonstrating that atmospheric forcing can be used as a proxy for coastal behaviour.

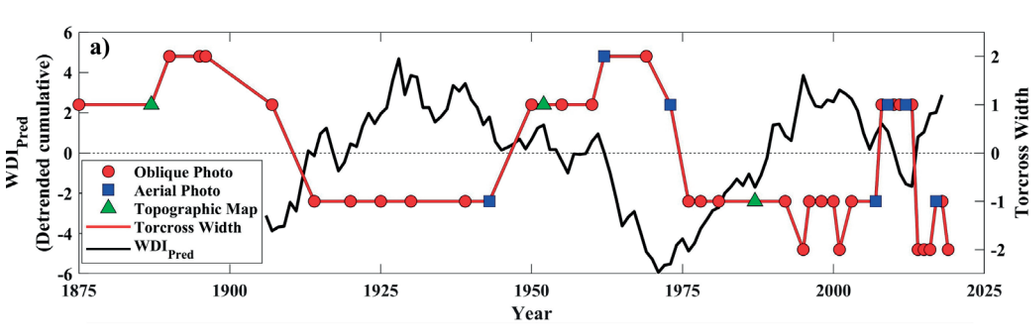
The study also highlighted limitations. While the model performed well at seasonal to interannual scales, it did not capture extreme single events (e.g. Storm Emma, 2018), which caused significant rotation but were not reflected in seasonal-mean atmospheric indices. This emphasises that event-scale processes can be superimposed on broader climatic controls in the short term.

A key contribution was extending the analysis over longer timescales. Using historical records of NAO and WEPA, the study reconstructed a WDI time series back to 1906 and compared it with proxy records of beach change, including historical photographs and maps. These showed coherent multi-decadal patterns, with periods of sustained wave direction dominance linked to prolonged phases of beach rotation and shoreline change.

The results suggested that low-frequency (~60-year) climate variability drives long-term rotation patterns, influencing the overall planform state of embayments. This provides important context for contemporary observations, indicating that recent changes may be part of longer-term cycles rather than isolated events. The study also highlighted evidence from historical settlement patterns, suggesting that past communities adapted to these long-term shifts in beach position.

Finally, the study demonstrated the potential for forecasting. Improvements in seasonal prediction of atmospheric indices mean that wave directionality, and therefore beach rotation, may be predicted months in advance. This represents a step change from earlier work, moving from understanding processes to predicting coastal response.





Above are examples of beach width images at Torcross ranging from very narrow (-2) to very wide (2). Left is long-term comparison of predicted wave direction trends and historical beach width, illustrating multi-decadal rotation linked to climate variability.

Chapter 8: Coastal management

Effective coastal management depends on translating scientific understanding into practical decisions that balance environmental, social and economic priorities. As pressures from climate change, sea-level rise and coastal development increase, evidence-based approaches are becoming ever more important for managing risk and building resilient coastlines. The papers in this chapter explore a range of management challenges, including coastal resilience, shoreline monitoring, climate change adaptation and planning for future coastal change. Together, they demonstrate how scientific research can support informed policy, sustainable management and long-term adaptation of our coasts.

Application of airborne LiDAR to investigate rates of recession in rocky coast environments.

Earlie, C.S., Masselink, G., Russell, P.E. and Shail, R.K., 2015.

Key message

Airborne LiDAR (Light Detection and Ranging) data were used to gain a quantitative understanding of cliff erosion along the rocky coastline of north Cornwall. Rates of retreat ranged from 0.01 to 0.37 meter per year and recession rates were statistically correlated with significant wave height and rock mass characteristics.



Take away thought

Historical maps and aerial photographs provide valuable information on long-term (20–100 years) cliff recession rates, while LiDAR captures shorter-term (1–20 years) changes to the cliff morphology. Combining these complementary datasets provides a more robust evidence base for understanding historical cliff evolution and supporting long-term coastal management.

Summary

Coastal cliff erosion is a widespread problem that threatens property and infrastructure along many of the world's coastlines. Rates of erosion used for shoreline management are generally based on analysis of historic maps and aerial photographs which, in rocky coast environments, does not wholly capture the detail in the processes and the failures occurring across the cliff face. This study uses airborne LiDAR (Light Detection and Ranging) data to gain a quantitative understanding of cliff erosion along the rocky coast of north Cornwall.

The method to derive cliff recession rates from LiDAR data consists of the following steps:

Step 1: Obtain two LiDAR datasets from a cliff region, at least several years apart.

Step 2: Derive a Digital Elevation Model (DEM) for each time step.

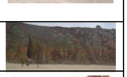
Step 3: Subtract the two DEMs to obtain a difference DEM, representing positive and negative changes in the elevation.

Step 4: Identify a region of interest (ROI) that represents the active section of the cliff coast that excludes the beach in front of the cliff and the land behind the cliff edge.

Step 5: Compute the volumetric change within the ROI, but only consider vertical changes that exceed a certain threshold (depending on the vertical accuracy of the LiDAR data).

Step 6: Divide the total volumetric change within the ROI (in m^3) by the average height of the cliff (in m) and the longshore length of the cliff section (in m) and the number of years between the two LiDAR surveys (in years). This then gives the average recession rate in meter per year.

The rates of retreat determined using the LiDAR data were larger than those derived from analysis of historical maps and aerial photographs, and ranged from 0.01 to 0.37 meter per year. Cliff recession rates varied geographically according to the spatially varying boundary conditions (rock mass characteristics, beach elevation/ cliff toe exposure) and forcing parameters (significant wave height and peak wave period). Recession rates were statistically correlated with significant wave height and rock mass characteristics.

Location	Average Cliff height (m)	Lithology	GSI	Failure Mechanism	Activity	Recession Potential (m yr^{-1})	Image
Hemmick	11	Hard sandstones and mudstones with some superficial deposits, cliffs (Dodman Phyllites) thrust over Pendower Formation (brecciated slates and limestones with igneous intrusions)	55-58	Mainly rotational failure of superficial material, block removal or planar failure unlikely. Debris slides and rockfalls possible	Inactive	<0.1	
Pendower	20	Superficial head deposits above emerged beach, above emerged shore platform, above Pendower formation bedrock	37-40	Undercutting, some block removal and collapsing, low potential for planar failure or slippage	Inactive	0.1 – 0.5	
Church Cove	20	Sandstones and mudstones overlain by head deposits	30-35	Block removal, of toe material and wedge and planar failure of upper cliff material. Topples occurring in superficial deposits	Inactive	<0.1	
Porthleven	5-25	Sedimentary gramscatho beds with interbedded slates and sandstones. Mylor slates overlain by head of clay, silt, sand and gravel. Porthleven cliffs are SSSI, Devonian sediments with basaltic intrusions	25-30	Mainly block removal, and wedge failure leading to slumping or collapse of superficial material. Block removal in fault (Caca stull Zawn) leads to toppling and planar failure	Inactive	<0.1	
Porthcurno	50	Mostly granite	70-75	Block removal rarely, some topples and rockfalls	Inactive	<0.1	
Godrevy	15	Rubbly head, varying from 3-8 m over pebbly emerged beach, sitting upon Pleistocene emerged shore platform, cutting over Porthtowan slates with interbedded sandstones	40-50	Block removal of bedrock and toppling leading to slumping or rotational failure of superficial deposits. Also terrestrial processes leading to slumping of head	Active	0.1 – 0.5	
Portreath	25	Porthtowan formation slate with mudstones and sandstones	45-50	Failures look more fault controlled than block removal, orientation of discontinuities suggests toppling failures or undercutting within faults leads to collapse	Active	0.1 – 0.5	
Trevellas	50	Metasedimentary Devonian slate with sandstones and limestones some superficial deposits	33-36	Block removal at the toe of the cliffs have led to material above translating down the cliff slope. Rotational sliding and slipping apparent in superficial material	Active	<0.1	
Bedruthan Steps	50	Large exposed slate outcrops on the beach, cliffs are grey and green slates with limestone bands some head	30-34	Block removal of lower material leading to rotational sliding of upper cliff, rockfalls, topples and slipping apparent	Active	0.1 – 0.5	

Characteristics of the sites in Cornwall studied in this paper.

	Net Volume loss (m^3) (V)	Ave cliff height (m) (H_c)	Average slope (°)	Longshore length (m) (L_c)	Time interval (yrs) (T_c)	Rate of retreat (m yr^{-1}) (R)
Hemmick	40.37	11	68	40	3.8	−0.03
Pendower	39.66	10	66	370	3.8	−0.01
Church Cove	1091.80	20	42	64	3	−0.29
Porthleven	1373.50	17	73	265	3.5	−0.09
Caca Stull Zawn	642.00	24	60	20	3.5	−0.37
Porthcurno	0.053	50	73	780	3	0.00
Godrevy	677.83	15	69	660	2	−0.04
Portreath	623.54	26	75	135	3	−0.06
Trevellas	1078.50	70	51	200	1	−0.08
Bedruthan Steps	5422.10	45	43	380	2.5	−0.17

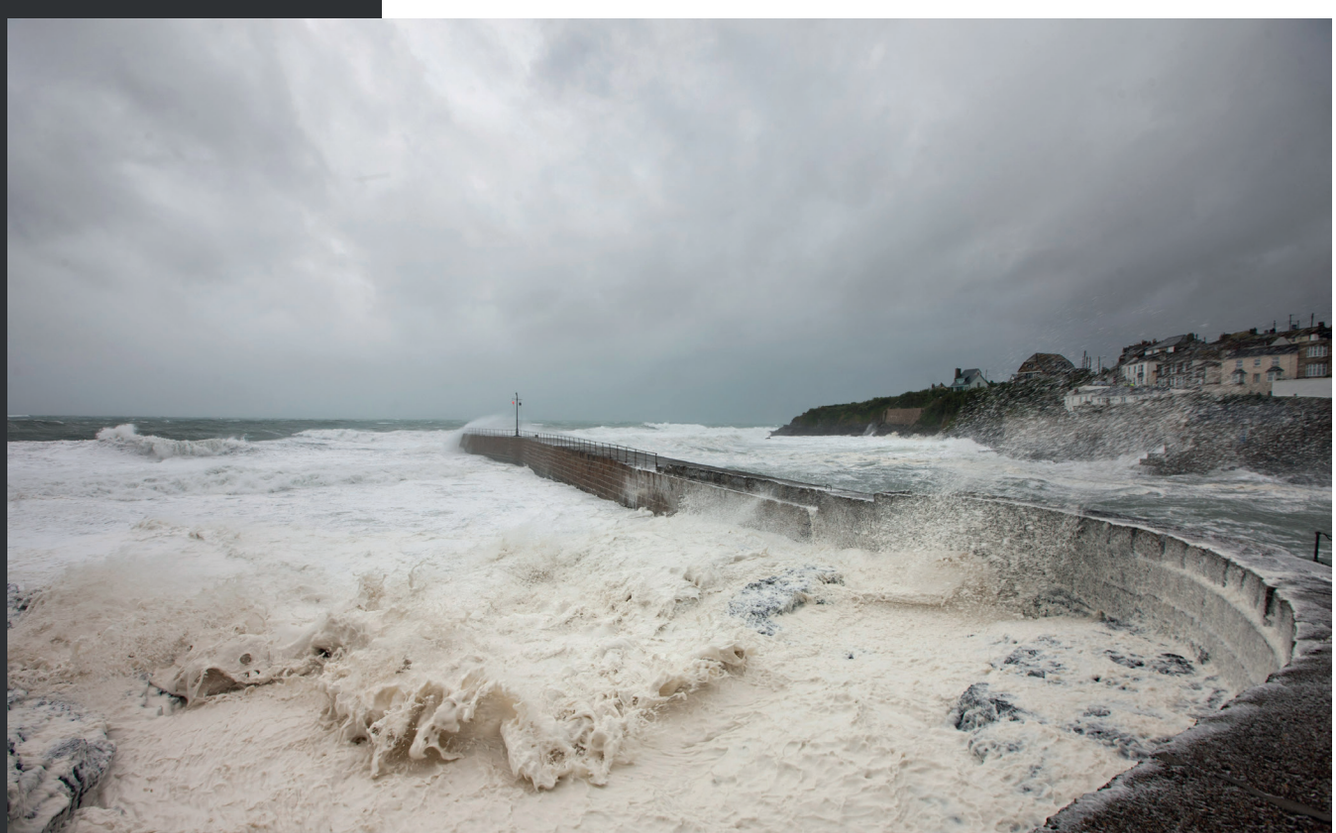
Cliff dimensions and resultant rates of retreat for selected sites in Cornwall obtained from the LiDAR data.

Defining Coastal Resilience.

Masselink, G. and Lazarus, E.D., 2019.

Key message

Coastal resilience is the capacity of the socio-economic and natural systems in the coastal environment to cope with disturbances, induced by factors such as sea-level rise, extreme events and human impacts, by adapting whilst maintaining their essential functions.



Take away thought

Coastal systems can be considered coupled human-environment systems. Coastal resilience therefore has many elements, including ecological, geomorphological, engineering and socio-economical. Evaluating the resilience of coastal systems in terms of ***system functioning***, rather than ***system state***, provides a more holistic basis for understanding and managing coastal change.

Summary

Resilience is seen as a desirable quality of the environment; therefore, coastal management policy and practice are increasingly aimed at maximising it. Coastal resilience is a keystone management concept and fundamental to nature-based adaptation measures and strategies to reduce coastal risk and environmental degradation. However, despite its widespread use, resilience remains ambiguous and poorly defined in management contexts. This is problematic, as the lack of a clear understanding of what resilience is makes it difficult to formulate, implement and evaluate actions and policies that aim to increase it.

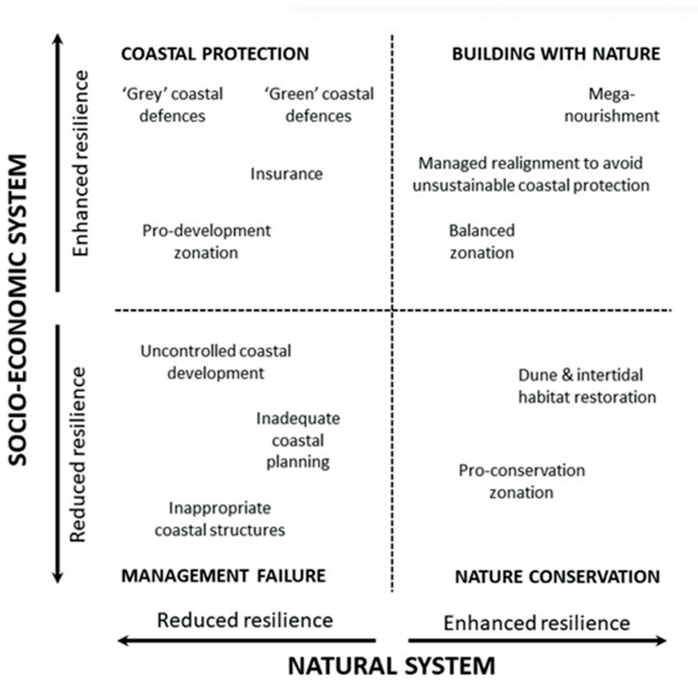
This paper is a comprehensive review of the concept of coastal resilience. The work was originally commissioned by the Environment Agency to inform their Flood and Coastal Resilience Innovation Programme (FCRIP). The primary motivation of the paper was to review the (coastal) resilience literature, clarify the concept of resilience and propose a revised definition of coastal resilience with a holistic scope and emphasis on systemic functionality.

Resilience theory arose from the study of population fluctuations in ecological systems in the 1970s and is generally divided into two types: ecological and engineering resilience. Ecological resilience acknowledges the existence of multiple potential equilibria and is defined as the amount of disturbance that a system can sustain before undergoing a fundamental change in controls and structural organisation (i.e., exceeding a tipping point). By comparison, engineering resilience emphasises conditions that facilitate system stability around a single, global equilibrium steady state. Both types of resilience have since been widely applied to coastal systems, including barriers islands, beaches, coastal dunes, tidal wetlands and coral reef systems.

The generic, widely applied definition of coastal resilience refers to the ability of a coastal system to bounce back from a major shock or disturbance, such as a storm event. Under climate change, however, a more important aspect of coastal resilience is the capacity of a given system to withstand or adapt to a chronic, continuous disturbance, such as sea-level rise, a shift in prevailing wave conditions or a negative sediment budget.

This review paper considers the concept of resilience to extend beyond that of the physical coastal system and argues that the coastal zone should be considered as comprising of the coastal geomorphology and ecology, referred to as the 'natural system', as well as the human use of the coastal zone, referred to as the 'socio-economic system'. These different systems mutually interact and coastal systems can therefore be considered coupled human-environmental systems and these manifest dynamics that differ substantively from the dynamics of their constituent systems in isolation.

Systems can be characterised in terms of state or functioning. In the case of a coastal dune system, for example, system state can be quantified in terms of the height of the dune or the number of plant species present. System functioning can be expressed as the number of visitors per year or the number of properties protected from flooding by a 1:100 year storm event. The paper argues that, from a resilience viewpoint, coastal system functioning is more relevant to resilience than the system state.



Proposed coastal resilience matrix divided into four quadrants and considering the effect of coastal zone management on both socio-economic and natural resilience. A well-designed and executed mega-nourishment scheme can enhance both socio-economic and natural resilience (Building with Nature quadrant), while inappropriate coastal structures can have adverse effects on both systems (Management Failure quadrant). Hard engineering structures generally enhance socio-economic resilience, but almost always reduce natural resilience (Coastal Protection quadrant), whereas pro-conservation measures enhance natural resilience, but this can be at the expense of socio-economic resilience (Nature Conservation quadrant).

Managing coastal risk in the UK: Coastal Change Management Areas.

Poate, T., Stokes, G., Masselink, G. and Kirby, J.A., 2021.

Key message

The paper argues that UK coastal risk is rising because sea-level rise and storm impacts will accelerate erosion and flooding along already vulnerable shores. About 17% of the UK coast is eroding, with 28% of England and Wales eroding faster than 10 cm/year. Past coastal behaviour is the best basis for forecasting future change, using monitoring data such as LiDAR, beach profiles and historical maps. The main message is that Coastal Change Management Areas (CCMAs) provide a practical planning tool to restrict risky development and improve long-term coastal resilience.



Take away thought

Coastal managers should plan for ongoing change rather than rely solely on hard defences. Rising sea levels and stronger storms will increase erosion and flooding, requiring adaptive, evidence-based planning. Historical shoreline data, LiDAR and flood models should inform decisions, while uncertainty is addressed through buffer zones. CCMAs and associated plans help restrict unsuitable development, enable relocation and support long-term resilience and risk reduction.

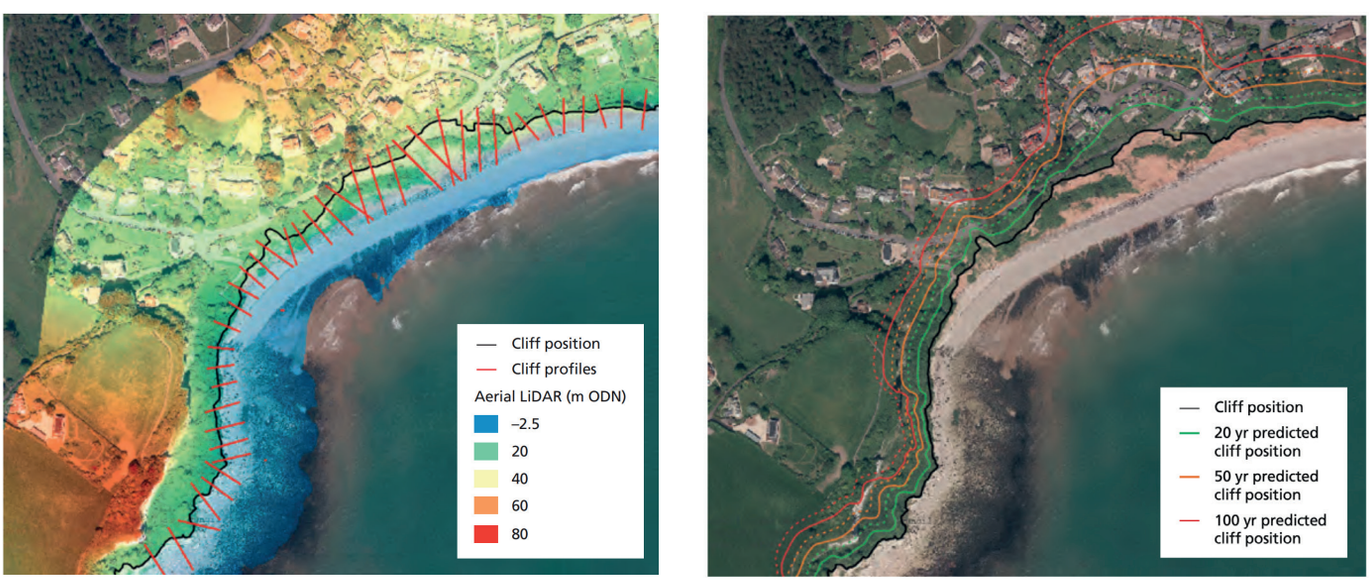
Summary

The paper argues that coastal risk in the UK is increasing because climate change is driving sea-level rise and greater exposure to extreme storm events, which will accelerate both coastal erosion and flooding. It highlights that 17% of the UK coastline is eroding, and in England and Wales 28% is eroding at rates above 10 cm per year, showing that coastal change is already a major national issue rather than a future-only threat.

A central scientific point is that different coastal environments require different prediction methods. For cliffs, researchers use aerial LiDAR, historical maps, aerial photographs and repeated profile measurements to calculate past retreat rates, then combine these with projected sea-level rise to estimate future cliff positions. For beaches, because they erode and accrete irregularly, equations are used to model how the beach profile may shift landward under rising sea level. For estuaries, digital elevation models derived from LiDAR are used to map future flood extents, often based on projected 1:200-year water levels.

The paper stresses that historic coastal behaviour is the best guide to future change, but it also emphasises that uncertainty is unavoidable. Coastal systems are highly variable, especially soft cliffs and beaches, and future sea-level rise depends on uncertain greenhouse-gas emissions pathways. Because of this, the authors recommend using "line buffers" around predicted future shoreline positions to show an uncertainty zone rather than a single exact line.

The final key message is practical: Coastal Change Management Areas (CCMAs) translate science into planning. They allow local authorities to restrict or adapt development in vulnerable areas, helping manage infrastructure relocation and reduce long-term exposure. The paper therefore presents CCMAs as a science-based adaptation tool for building coastal resilience, acknowledging that it is neither realistic nor affordable to defend every stretch of coastline indefinitely.



Left: aerial image of east Devon coastline with aerial LiDAR overlaid. The black line shows the current cliff-top position and the red lines indicate the position of profiles used to measure historic cliff loss. Right: The coastline with the projected future cliff positions for the short term (green), medium term (amber) and long term (red). The dashed lines indicated the 'line buffers' and represent the uncertainty associated with the predictions.

Coastal adaptation to climate change through zonation: A review of Coastal Change Management Areas (CCMAs) in England.

Kirby, J.A., Masselink, G., Essex, S., Poate, T. and Scott, T., 2021.

Key message

Coastal Change Management Areas (CCMAs) are a planning tool designed to manage future coastal risk by restricting development in areas vulnerable to erosion, flooding, and sea-level rise. However, their implementation in England has been limited and inconsistent due to unclear guidance and variability in the datasets used to define coastal change.



Take away thought

Effective coastal adaptation requires planning policy to be supported by consistent, science-based predictions of future coastal change. Strengthening national guidance and standardising methodologies provides a more robust basis for identifying and managing vulnerable coastal areas, enabling more resilient coastal communities.

Summary

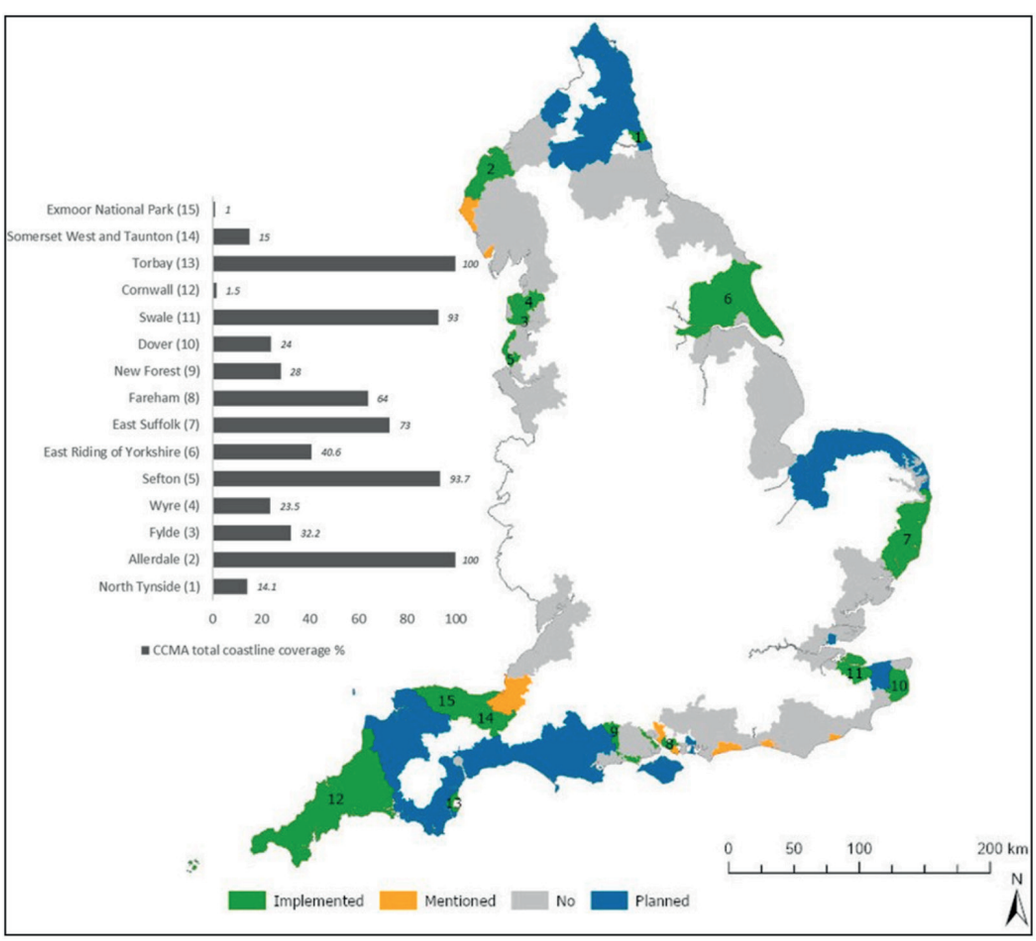
Climate change, particularly sea-level rise and increasing extreme sea levels, is expected to significantly increase coastal erosion and flooding risk. Coastal communities and planners face growing challenges as coastal hazards intensify.

Historically, coastal management has relied on hard engineering defences, but these approaches are becoming increasingly unsustainable and economically unviable. As a result, there has been a shift toward planning-based adaptation strategies, including coastal zonation, which restricts development in areas at risk.

In England, this approach is implemented through Coastal Change Management Areas (CCMAs), introduced in the National Planning Policy Framework. CCMAs are intended to identify areas likely to experience significant coastal change over the next 100 years, including erosion, flooding, or accretion, and to guide development restrictions and adaptation planning.

However, uptake has been limited: only around 15% of coastal planning authorities (CPAs) have designated CCMAs, covering approximately 5.7% of the English coastline. This reflects unclear guidance, inconsistent methodologies, and variability in datasets used to define coastal change. As a result, some high-risk areas are omitted.

The study highlights the need for a robust and standardised methodology, including improved predictions of shoreline response to sea-level rise and clearer national guidance to support coastal planners.



Status of Coastal Change Management Areas (CCMAs) in England (October 2020) showing Coastal Planning Authorities (CPAs) that have CCMAs Implemented, Mentioned, No (not mentioned), or Planned. Locations are numbered to indicate CPA. Insert bar chart shows percentage of the CPA's (implemented only) coastline covered by a CCMA.

Coastal Canaries.

Masselink. G., Lazarus. E. and Townend. I., 2026.

Key message

The 2026 winter storms at Slapton Sands showed that repeated, moderate storms combined with high tides and low beach levels can cause severe cumulative coastal damage, exposing weaknesses in UK coastal adaptation. The study argues that sea-level rise will require transformational adaptation, including relocation of infrastructure and some communities, supported by nationally coordinated, socially just policies that prioritise proactive planning over repeated emergency repairs.



Take away thought

There is a widening gap between UK coastal resilience policy and implementation. Repeated storm impacts can expose vulnerable infrastructure, escalating social and economic risks. A shift from emergency response towards planned, long-term socially just adaptation is urgently needed, including managed realignment, infrastructure relocation, and proactive community planning to address accelerating sea-level rise and coastal change.

Summary

The winter storms of January and February 2026 caused major damage to the coast of southwest England, particularly at Torcross on the Slapton Sands barrier in Devon. Although none of the storms were especially powerful on their own, they arrived close together and coincided with high spring tides and low beach levels. This combination caused severe beach erosion, damaged homes, exposed coastal defences, and washed away part of the A379 road, cutting an important transport link for local communities.

The immediate trigger and cause of the storm damage at Torcross and the A379 were the extreme wave conditions that occurred during the 2025/26 winter. However, there are a number of other critical factors and processes without which the damage would have been a lot less severe, or even insignificant. Firstly, both the first row of houses in Torcross and the Slapton Line have been constructed directly on top of the gravel ridge without any consideration of the ridge being part of the dynamic beach profile. Secondly, since 1984, the mean along-coast averaged shoreline change at Slapton Sands has been 0.1 m/yr and the southern part of Slapton Sands has been retreating at 0.4 m/yr. This retreat is largely, although not fully, attributed to the 0.15-0.2 m sea-level rise that occurred over this period. Thirdly, several studies have highlighted that Slapton Sands, and in fact all beaches of Start Bay have been rotating clockwise as a result of net northward littoral drift, due to an increase in southerly waves at the expense of easterly waves. Fourthly, although seawalls provide protection against flooding, they are increasing considered as maladaptive solutions to erosion by causing beach lowering and downdrift sediment losses. The section of the A379 that was lost during the easterly storm waves lost in February, was the section immediately to the north of the seawall. Fifthly, the removal of an estimated 450,000 m^3 of gravel from the beaches south of Slapton Sands during the period 1897–1901 is likely to have had some long-term impact.

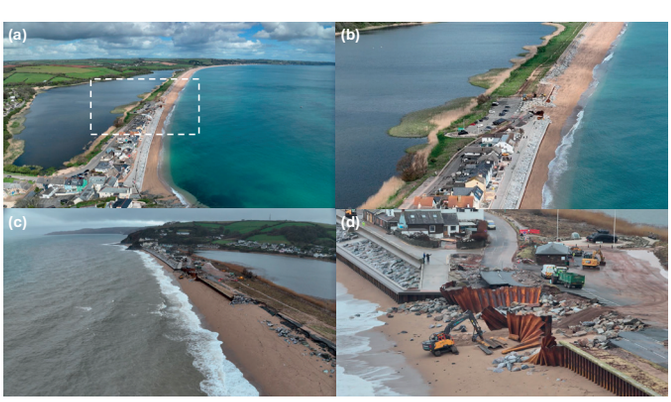
This paper uses Torcross as a case study to demonstrate that many UK coastal communities face similar challenges. Scientists and engineers have understood the risks from coastal erosion and rising sea levels for decades, and Shoreline Management Plans have identified where coastlines should eventually be allowed to move inland through managed realignment. However, these long-term plans have often not been put into practice. Instead, damaged sea defences are repeatedly repaired after storms, delaying difficult decisions about the future.

Roads, railways and sea defences located along the coast can become weak points where a single failure causes widespread disruption to transport, businesses and local communities. As sea levels continue to rise, these problems are expected to become more frequent and more expensive to manage.

The UK needs to move from responding to emergencies towards planning for long-term adaptation. This may include relocating roads, changing how coastlines are managed, and in some places helping communities move away from areas that can no longer be safely protected. These decisions will not be easy and must be made with local communities rather than for them. National leadership, clear funding, and fair, community-centred policies will be essential if coastal communities are to adapt successfully to climate change. Torcross provides an early warning of the challenges that many other coastal communities are likely to face in the coming decades.



During January and February 2026, waves regularly overtopped the seawall at Torcross and under the most energetic wave conditions coinciding with spring high tide, resulted in seawater reaching the rooftops (from: https://www.facebook.com/forestandbeach).



(a) View towards the north of Torcross and the Slapton Sands barrier; (b) close-up of boxed section in (a) showing the northern end of the seawall and the damage to the A379; (c) view towards the south of the damaged road section and Torcross; and (d) close-up of the collapsed road section and northern end of the seawall.

Synthesis

Drawing on the body of academic research presented in this compendium, developed through both our long-standing research on the coast of Cornwall and our four years of research through the Making Space for Sand project, we make the following recommendations:

1. Give beaches and dunes space to adjust

Beaches and dunes are naturally mobile, and their future response will vary considerably between locations. Long-term monitoring and modelling indicate that some dunes will retreat, while others may gain sediment, advance (seaward) or roll back (landward). Regional projections are therefore useful for screening and identifying potential erosion hotspots, but detailed local assessment remains necessary where infrastructure, property or important habitats are at risk. Papers 18 and 20.

Dune erosion cannot always be attributed directly to storms or sea-level rise. At Crantock, migration of the River Gannel altered the configuration of the wider beach–dune system and increased the exposure of the frontal dunes to wave attack. This demonstrates that beach morphology, estuary channels and dunes must be considered together when assessing emerging erosion risk. Paper 19.

The space required for coastal adjustment extends beyond the visible dune front. It may include land needed for dune rollback, barrier migration, channel movement or the redistribution of beach sediment. Restricting these processes with new development or fixed infrastructure can reduce the ability of the natural system to adapt. Planning should therefore identify and safeguard potential accommodation space before erosion becomes critical. Papers 18–20, 46–49.

Beaches can provide important natural protection to cliffs behind them. Wide beaches with relatively high beach–cliff junctions can substantially reduce the wave energy reaching a cliff toe. Conversely, the depletion or narrowing of a fronting beach can increase cliff exposure and erosion risk. Beach volume and cliff behaviour should therefore be monitored and managed as parts of the same system. Papers 36 and 37.

2. Manage sediment as a connected resource

A beach cannot be understood solely from the sediment visible above low water. Sediment may be stored within dunes, the intertidal beach, nearshore bars, the lower shoreface and areas offshore of adjacent headlands. Changes in one part of this system can affect the capacity of another part to respond to storms or sea-level rise. Papers 13, 14, 21–26 and 35.

Headlands do not always form closed boundaries between sediment cells. Waves, tides, headland geometry and sediment availability determine whether a headland acts as a barrier or as a conduit for sediment movement. Substantial quantities of sediment may bypass headlands, particularly during energetic conditions. Papers 22–25.

Standard estimates of the active coastal profile may be too restricted on energetic macrotidal coasts. Wave-based depth-of-closure calculations can underestimate the offshore extent of sediment transport because they do not fully represent tidal currents, wave–tide interactions or headland bypassing. Sediment-budget assessments should therefore consider both the depth of measurable morphological change and the potentially greater depth of active sediment transport. Papers 21 and 23.

Embayed beaches should not automatically be treated as isolated systems. Regional modelling, seabed mapping and sediment analysis demonstrate that neighbouring embayments may be connected through nearshore and offshore pathways. These connections should be considered before nourishment, sediment removal, dredging or the construction of structures that might interrupt sediment movement. Papers 24–26.

Shoreline movement does not necessarily represent a net gain or loss of sediment. Embayed beaches can rotate as sediment is transferred from one end of a beach to the other. Rotation can also occur coherently across several embayments responding to the same directional wave climate. Monitoring only one location on a beach may therefore give a misleading impression of whole-beach change. Papers 27, 28 and 44.

Extreme storms do not only remove sediment from the coast. They may also transfer material from offshore stores into the active nearshore system. At some locations, this contribution can offset substantial amounts of long-term retreat predicted using simplified sea-level-rise models. Long-term sediment budgets should therefore represent both erosional and constructive storm-driven exchanges. Paper 35.

3. Monitor the whole coastal system

Shoreline position alone is not an adequate measure of coastal resilience. A shoreline can move while the beach retains its total sediment volume through cross-shore or alongshore redistribution. Monitoring should therefore consider beach and dune volumes, barrier crest elevations, dune toe and crest positions, nearshore bars and, where relevant, offshore sediment stores. Papers 13–15, 18–20, 25–30 and 33–35.

The condition of the beach before an event strongly influences its response. Beaches entering winter with depleted sediment reserves may respond differently from beaches beginning the same period in a relatively healthy state. Antecedent morphology should therefore be recorded and included in seasonal risk assessments. Papers 2, 13–15 and 31–34.

Monitoring boundaries should reflect how the coastal system functions. At estuary and river-mouth beaches, this may require measurement of channel migration and discharge as well as beach and dune morphology. On cliffed coasts, fronting beach levels and cliff response should be considered together. Within embayments, monitoring should extend across the full beach rather than relying on a single profile. Papers 11, 19, 27, 36 and 37.

Different monitoring methods answer different questions. Airborne LiDAR topographic is effective for measuring detailed recent regional change (multi-annual and regional to national), while historical maps and aerial photographs provide longer-term context (multi-decadal). 2D terrestrial laser scanning can capture beach morphology, runup and overtopping during individual events, while 3D terrestrial laser scanning can reveal complex local 3D cliff erosion as well as shore platform topography and roughness. Satellite shorelines can extend spatial and temporal coverage (multi-decadal and national and international), but their accuracy varies substantially with beach type, tidal range and exposure. Papers 16, 30 and 45.

Satellite-derived shorelines require local validation. Errors are particularly significant on exposed, dissipative and macrotidal beaches. Satellite products should not be used uncritically as precise indicators of erosion or accretion; corrections, uncertainty bounds and comparison with ground-based surveys are required. Paper 16.

Post-storm monitoring is as important as measuring the initial impact. Beach recovery may take months or years, and some beaches may remain depleted or continue adjusting long after the storm has passed. Monitoring programmes should therefore capture recovery trajectories rather than ending once the immediate emergency has subsided. Papers 33 and 34.

4. Prepare for thresholds, storm sequences and uneven recovery

Storm impact is controlled by more than maximum wave height. Important factors include wave direction, tidal water level, storm duration and sequencing, infragravity-wave energy and the morphology of the beach before the event. Assessments based on offshore wave height alone are likely to overlook important controls on erosion, overwash and flooding. Papers 2, 4, 15, 31 and 32.

Infragravity waves should be represented in storm-impact assessments. These long-period waves can dominate shoreline runup, dune erosion and overwash during extreme conditions. Models or design methods that neglect them may underestimate impacts on low-gradient sandy beaches and dunes. Paper 4.

Overwash and overtopping are threshold processes. Relatively small differences in water level, wave conditions or barrier crest elevation can determine whether a gravel barrier is merely overtopped or experiences substantial overwash. Regular measurement of barrier morphology is therefore essential for maintaining reliable forecasts and identifying emerging vulnerability. Papers 39–41.

Gravel beaches require gravel-specific assessment methods. Runup relationships developed for sandy beaches can substantially underestimate overtopping on gravel coasts. Sediment size, beach slope and gravel permeability influence runup and should be represented when assessing flood risk or designing interventions. Papers 38–40.

Gravel barriers and their backing lagoons should be treated as connected systems. A barrier may provide both physical and hydraulic protection against saline intrusion, but that protection can be compromised by overwash, breaching or changes in lagoon water level. Paper 17.

Recovery should not be assumed or assigned a standard timescale. Some beaches recover relatively quickly through onshore sediment transport, while exposed beaches may undergo prolonged adjustment. Behavioural classifications can help identify comparable response types, but they do not remove the need for site-specific monitoring. Papers 33 and 34.

Apparent short-term instability does not always indicate loss of resilience. Fine-gravel beaches may undergo substantial internal sediment redistribution while limiting erosion of the upper beach through the formation and migration of a beach step. Interpreting change therefore requires understanding the mechanisms involved, rather than relying only on measured displacement. Paper 29.

5. Use forecasting and models to support, not replace, local evidence

Atmospheric indices could provide early warning of potentially energetic winters. WEPA is strongly associated with winter wave activity along the Atlantic coast of Europe, while combinations of WEPA, NAO and other indices help describe both wave height and wave direction. Seasonal forecasts may therefore in future provide advance context for erosion, flooding and beach rotation. Papers 1–3, 27, 28 and 44.

Wave direction can be as important as wave height. The balance between opposing wave directions controls longshore sediment transport and beach rotation on many embayed coasts (e.g., south coast of England). Directional forecasts can therefore help practitioners anticipate where erosion and accretion may occur within a beach or across a group of beaches. Papers 3, 27, 28 and 44.

Climate indices provide context rather than deterministic site forecasts. Individual storms, tidal levels, antecedent beach condition and local sediment availability can all modify the response. Seasonal forecasts should therefore be combined with current site monitoring and professional judgement. Paper 2.

Model complexity should be matched to the management question. The most sophisticated model is not automatically the most useful. Selection should reflect the coastal setting, required timescale, available data, processes that must be represented and the uncertainty acceptable for the decision being made. Papers 42 and 43.

Different tools are appropriate for different problems. XBeach-G can examine storm response and overwash on gravel barriers; gravel-specific runup methods improve overtopping assessment; regional forecasting systems can support flood warnings; and computationally efficient shoreline models can explore erosion and recovery over periods from individual events to several decades. Papers 38–43.

Model predictions should be updated as the coast changes. Forecast accuracy depends on contemporary information on beach levels, barrier crest elevations, defences and sediment distribution. Monitoring and modelling should therefore operate as an iterative process rather than as separate activities. Papers 20, 41 and 42.

6. Make public access and safety part of adaptation

Changing beach morphology can alter bathing hazards as well as erosion risk. Rip-current strength and location depend on the interaction between waves, tidal stage and local bar–rip morphology. Changes to beach form should therefore be reflected in beach-safety assessments and operational warnings. Papers 6–8 and 12.

The most dangerous conditions are not necessarily the most visually severe. Strong rip currents may occur around low water under moderate waves, when beaches are busy and users may perceive conditions as safe. Risk communication and lifeguard planning should account for this mismatch between apparent and actual hazard. Papers 7 and 8.

Risk depends on both the physical hazard and the number of people exposed. Beaches combining hazardous morphology, high visitor numbers and good accessibility may require greater priority for lifeguard services, warnings and public education. Paper 9.

Estuary-mouth beaches require specific assessment. Estuarine flow, tidal stage and channel position can combine with wave-driven currents to produce hazards that differ from conventional open-coast rip currents. Paper 11.

Research has greatest operational value when practitioners are involved. Long-term collaboration between coastal scientists and the lifeguard community has enabled process understanding to be translated into forecasting systems, risk assessments, resource planning and public messaging. Paper 10.

7. Turn evidence into adaptation

Coastal resilience should not be defined simply as maintaining the present shoreline. Beaches, dunes, habitats, infrastructure and communities form a coupled human–environment system. Resilience is better assessed in terms of whether that system can continue to function as conditions change. Paper 46.

Planning should anticipate continuing change rather than respond only after damage occurs. Historical mapping, LiDAR, monitoring and modelling can identify areas likely to experience future erosion or flooding. This evidence can support development restrictions, buffer zones, Coastal Change Management Areas and the identification of land needed for future relocation or realignment. Papers 45, 47 and 48.

Uncertainty should be represented explicitly, but it should not prevent adaptation. Predictions should be expressed through scenarios, ranges and adaptive pathways that can be revised as new evidence becomes available. Waiting for certainty may allow development or infrastructure decisions to remove future adaptation options. Papers 20, 42, 43, 47 and 48.

Repeated repair may not be sustainable where exposure is increasing. At some locations, long-term resilience will require managed realignment, infrastructure relocation or changes in land use rather than continued emergency intervention. These decisions need early planning, national coordination and meaningful engagement with affected communities. Paper 49.

Adaptation must also be socially just. The costs, disruption and benefits associated with coastal change will not be distributed evenly. Communities should be involved before risk becomes acute, while there is still time to examine options and develop locally appropriate adaptation plans. Papers 47–49.

8. Closing remarks and priorities for future action

The coast of Cornwall is highly variable in its geology, wave and tidal forcing, sediment availability and coastal morphology. This site-specific character means that every beach and dune system responds rather uniquely to coastal change. The coast is also highly dynamic, responding to short-term storms, medium-term changes in longshore sediment transport and post-storm recovery, and long-term sea-level rise. Although much of Cornwall's coastline remains natural and undeveloped, many communities, infrastructure assets and developed areas occupy the dynamic coastal zone and are therefore exposed to increasing coastal risk.

Sea-level rise will increase this exposure even without any increase in storm frequency or intensity, because the same storm conditions will act from a higher water level. Reducing future risk will therefore require both improved understanding and mitigation of coastal hazards, and more effective action to reduce the exposure of communities and infrastructure. This should be supported by continued monitoring, improved modelling, a clearer understanding of sediment resources and connectivity, and stronger translation of scientific evidence into coastal planning and adaptation.

Recommendations:

Improve understanding and modelling of coastal hazards. In particular, gain better insights into how sea-level rise will influence shoreline evolution, erosion, flooding and coastal resilience, while accounting for the wider connected sediment system, rather than treating individual sites in isolation. Key steps are the:

> ***Development of more complete regional sediment budgets,*** including sediment movement between adjacent embayments and exchange between the lower and upper shoreface.
>
> ***Quantification of sediment volumes within dunes, beaches and the shoreface*****,** because the amount and availability of sediment are fundamental controls on coastal resilience.
>
> ***Maintenance of long-term monitoring of Cornwall's coast*** so that generic coastal process models (for predicting, for example, impact of sea-level rise, storm response, dune erosion) can be improved using site-specific data and incorporation of changing coastal conditions.

Move from reactive management to planned adaptation using a broad and flexible toolkit. Use scenarios, narratives, dynamic adaptive pathways, SMPs and Coastal Change Management Areas to anticipate change before risk becomes critical, drawing on measures including hard engineering, nourishment, nature-based solutions, accommodation, managed realignment and, where necessary, relocation, with early involvement of affected communities.

Promote the integration of SMPs within statutory planning and decision-making. A key aspect here is a wider implementation of Coastal Change Management Areas into local planning, to ensure that future development and infrastructure decisions anticipate, rather than react to, long-term shoreline evolution, sea-level rise and changing coastal risks.

Strengthen collaboration between researchers, practitioners and policy-makers. This will ensure that existing and emerging scientific evidence is translated into practical guidance, planning policy and implementable coastal management actions.

Afterword

The coast of Cornwall is one of the most dynamic and diverse in Europe. Shaped by waves, tides, sediment movement, geology, storms and sea-level rise, it is a constantly evolving landscape. It is a landscape that also supports communities, habitats, infrastructure, recreation and livelihoods. The scientific studies brought together in this compendium demonstrate that coastal change is rarely simple or predictable. Beaches are connected to wider sediment systems, storms can have impacts that last for years and local responses to climate change are often governed by complex interactions between natural processes and human activity.

A consistent message emerges throughout the papers; effective coastal management depends on understanding processes, places and timescales. The evidence presented highlights the value of long-term monitoring, regional thinking and adaptive approaches that work with natural processes rather than against them. It also shows that resilience is not simply about resisting change, but about understanding, anticipating and adapting to it.

As climate change accelerates and pressures on the coast increase, the need for robust evidence has never been greater. We hope this compendium helps bridge the gap between coastal science and coastal practice, providing researchers, practitioners, planners and communities with knowledge that supports informed decision-making and long-term stewardship of Cornwall's coast.

The coast will continue to change. Our challenge is not to prevent that change, but to understand it well enough to make wise, sustainable and resilient choices for future generations.

Glossary

A

Accretion - The accumulation of sediment, producing an increase in beach, dune or seabed volume and sometimes a seaward movement of the shoreline.

Active shoreface - The part of the coastal profile over which sediment is exchanged on the timescale being considered, commonly extending from the upper beach to the depth of closure.

Alongshore (or longshore) sediment transport - Movement of sediment approximately parallel to the shoreline, usually driven by waves approaching the coast at an angle and by the currents they generate.

Atmospheric index (sometimes referred to as a climate index) - A numerical measure of a large-scale atmospheric pressure pattern used to describe climate variability. Indices used in this book include the North Atlantic Oscillation (NAO), West Europe Pressure Anomaly (WEPA), East Atlantic pattern (EA), Scandinavia pattern (SCAND), Arctic Oscillation (AO) and East Atlantic/West Russia pattern (EA/WR).

B

Bathymetry - The shape and elevation of the seabed, usually expressed as water depth relative to a stated vertical datum.

Beach berm - A near-horizontal ridge or terrace on the upper beach formed by the deposition of sediment at the landward limit of normal wave runup.

Beach cusp - A rhythmic, scalloped pattern of sediment on the beachface, consisting of regularly spaced seaward-projecting horns and landward-curving bays.

Beach morphology - The three-dimensional form of a beach, including its slope, width, elevation, bars, channels, berms and other sedimentary features.

Beach profile - A cross-section through the beach and nearshore, normally measured perpendicular to the shoreline to show how elevation changes with distance offshore.

Beach recovery - The rebuilding of a beach after erosion, commonly through onshore or alongshore sediment transport and re-establishment of pre-storm morphology.

Beach rotation - Alongshore redistribution of sediment within an embayment, causing one end of the beach to erode while the opposite end accretes. The direction may reverse when wave direction changes.

Beach state - The current morphological configuration of a beach, such as reflective, intermediate or dissipative, including the arrangement of bars and rip channels.

Beach step - A steep, step-like feature near the lower limit of the swash zone, especially common on gravel beaches. It can focus wave breaking and influence runup and sediment movement.

Beachface - The sloping part of the beach that is regularly covered and uncovered by swash under prevailing wave and tidal conditions.

Bed roughness - Small- to large-scale irregularity of the seabed or rock surface that can create friction and modify waves and currents passing over it.

Bed shear stress - The force per unit area exerted by moving water on the seabed. Sediment begins to move when this stress exceeds the threshold required to mobilise the grains.

Bedload - Sediment transported close to the bed by rolling, sliding or short hops. Gravel beach transport is commonly dominated by bedload rather than sediment suspended in the water column.

Bi-directional or bimodal wave climate - A wave climate in which waves commonly arrive from two distinct directional sectors. The balance between the two directions can strongly control beach rotation and alongshore transport.

Breaker zone - The part of the nearshore where incoming waves become unstable and break. Its position moves across the beach as waves and water levels change.

Bruun Rule - A simplified method for estimating shoreline retreat caused by sea-level rise. It assumes that the active profile moves upward and landward while sediment eroded from the upper profile is deposited offshore.

C

Calibration - Adjustment of model parameters so that model outputs reproduce an observed dataset. Calibration should normally be followed by validation against independent observations.

Climate scenario (RCP or SSP) - A defined pathway used to explore possible future greenhouse-gas emissions, climate conditions and sea-level rise. Projections are conditional on the selected scenario rather than predictions of one certain future.

Coastal cell - A section of coast within which sediment sources, pathways and sinks are treated as a connected system. The studies in this book show that cell boundaries may be permeable during storms and headland bypassing.

Coastal Change Management Area (CCMA) - A planning designation used in England to identify land expected to experience significant coastal change and to guide development restrictions, relocation and adaptation.

Coastal erosion - The removal of sediment from the coast, causing lowering, narrowing or landward retreat of beaches, dunes, cliffs or other landforms.

Coastal resilience - The capacity of linked natural and socio-economic coastal systems to cope with disturbance, adapt and continue to provide their essential functions.

Continental shelf - The relatively shallow seabed extending from the coast to the shelf edge. Waves, tides and their interactions can transport sediment across large areas of the shelf.

Correlation coefficient (r and r^2) - A statistic describing the strength of a relationship between variables. The coefficient r ranges from -1 to +1; r^2 expresses the proportion of variance explained by a simple statistical relationship. Sometimes referred to as R.

Cross-shore sediment transport - Movement of sediment approximately perpendicular to the shoreline. Storm waves commonly move sediment offshore, while lower-energy swell is often assocated with a return of sediment onshore.

D

D_{50} (median grain size) - The sediment diameter for which 50% of a sample is finer and 50% is coarser. It is widely used to describe representative sand or gravel size.representative sand or gravel size.

Depth of closure (DoC) - The offshore depth beyond which measurable seabed-level change becomes very small over a stated period. It is often used to define the seaward boundary of the active shoreface.

Depth of transport (DoT) - The maximum depth at which sediment can be mobilised or transported. It may be substantially deeper than the depth of closure because transport can occur without producing detectable bed-level change.

Digital Elevation Model (DEM) - A gridded representation of ground or seabed elevation. Repeated DEMs can be subtracted to map erosion, deposition and volumetric change.

Dissipative beach - A wide, gently sloping beach with a broad surf zone in which waves break progressively and lose much of their energy before reaching the shoreline.

Dune foot or dune toe - The break in slope at the base of the seaward dune face where the dune meets the upper beach. Its elevation and position are commonly used to measure dune exposure and retreat.

Dune retreat - Landward movement of the dune front or dune toe caused by erosion exceeding sediment recovery over the period considered.

Dune of barrier rollover - Landward or upward migration of a dune/barrier as sediment is removed from the seaward face and deposited on the crest or landward side.

E

Embayment - A curved or recessed section of coast commonly bounded by headlands. Beaches within embayments may exchange sediment around their boundaries rather than functioning as completely closed systems.

Equilibrium model - A model that predicts coastal change from the tendency of a beach or shoreline to move towards a condition considered to be in balance with the prevailing forcing.

Exceedance level - A statistical threshold defined by how often it is exceeded. For example, a 1% exceedance wave height is exceeded for 1% of the record, while $R_{2\%}$ is the runup level exceeded by 2% of runup events.

F

ForCE - A computationally efficient beach-profile evolution model that links wave-energy dissipation to sediment transport and predicts erosion and recovery from storms to decadal timescales.

Foredune - The first substantial dune ridge immediately landward of the active beach. It is often the dune most directly exposed to storm-wave attack.

G

Geomorphology - The study of landforms, the processes that create and modify them, and how they change through time.

Gravel barrier - A ridge of gravel that separates the sea from lower land, a lagoon or an estuary. It can provide flood protection but may overtop, overwash, breach or migrate during storms.

Groundwater table - The level below which the pore spaces within sediment are saturated with water. On coastal barriers it responds to tides, waves and lagoon or inland water levels.

H

Headland bypassing - Transport of sediment around or seaward of a rocky headland, connecting neighbouring embayments. Its occurrence depends on waves, currents, water depth, headland geometry and sediment availability.

Hindcast - A model simulation of a past period using historical or reconstructed forcing. Hindcasts are used to reconstruct long records and test whether a model reproduces known events.

Hydraulic conductivity - A measure of how readily water can flow through a porous material such as sand or gravel. High hydraulic conductivity allows rapid groundwater response within coastal barriers.

Hydrodynamic forcing - The waves, tides, currents and water levels that drive sediment transport, flooding and morphological change.

I

Infragravity waves - Long-period waves, typically with periods of about 30 seconds to several minutes, that grow in relative importance towards the shore and can dominate runup, dune erosion and overwash during storms.

Inshore - Coastal waters close enough to the shore for water depth, coastline shape and local sheltering to modify offshore wave conditions. Its precise seaward limit depends on context.

Intermediate beach - A beach state between reflective and dissipative conditions, commonly characterised by bars, rip channels and strongly three-dimensional morphology.

Intertidal zone - The part of the coast exposed at low tide and submerged at high tide.

L

LiDAR (Light Detection and Ranging) - A remote-sensing method that measures distance using laser pulses. Airborne LiDAR is widely used to map beaches, dunes and cliffs and to quantify change between surveys.

M

Macrotidal - Describing a coast with a large tidal range, conventionally greater than about 4 m. On macrotidal beaches, the surf and swash zones migrate over a wide intertidal area during each tide.

Morphodynamics - The two-way interaction between water motion, sediment transport and coastal morphology: waves and currents change the bed, and the changing bed alters subsequent waves and currents.

N

Nearshore - The coastal zone extending from the shoreline through the surf zone to the outer area where waves, currents and sediment transport continue to interact strongly with the seabed.

Nonlinear wave-tide interaction - A combined wave-and-tide effect that is not equal to the simple sum of separate wave-only and tide-only effects. Such interactions can strongly alter bed shear stress, currents and sediment transport.

North Atlantic Oscillation (NAO) - A major atmospheric pressure pattern over the North Atlantic that influences storm tracks, winds and waves. Its coastal influence varies geographically and is often strongest in the northern Atlantic sector.

Numerical model - A computer-based representation of a coastal system using mathematical equations or statistical relationships to simulate waves, currents, sediment transport, flooding or morphological change.

O

Ordnance Datum Newlyn (ODN) - The standard vertical reference datum used for land elevations in Great Britain, based on mean sea level measured at Newlyn, Cornwall.

Outer bar - A submerged sand ridge near the seaward edge of the surf zone. It stores sediment, focuses wave breaking and can migrate onshore or offshore as wave conditions change.

Overtopping - The passage of wave water over a beach, barrier or defence crest. Overtopping can cause flooding even when the structure or barrier remains largely intact.

Overwash - Wave-driven flow across a beach or barrier crest that transports water and sediment landward, often causing substantial profile change, barrier rollover or flooding behind the barrier.

P

Parameterisation - A simplified equation or relationship used to represent a process that cannot be resolved directly in a model, often derived from observations, experiments or detailed simulations.

Process-based model - A numerical model that resolves interacting physical processes using governing equations for waves, currents, groundwater, sediment transport and morphology. Such models can be detailed but computationally demanding.

R

Reduced-complexity model - A model that retains the dominant controls on coastal change while simplifying less important processes, providing greater speed and stability for simulations from days to decades.

Reflective beach - A relatively steep beach with a narrow surf zone where waves break close to the shoreline and a large proportion of wave energy is reflected or concentrated in the swash.

Relative Tide Range (RTR) - The ratio of spring tidal range to breaking wave height. It is used with other parameters to describe how tides modify beach morphology and beach-state classification.

Residual sediment transport - The net sediment movement remaining after oscillatory transport over waves or tidal cycles has been averaged. It indicates the longer-term direction and magnitude of sediment flux.

Rip current - A concentrated current flowing seaward through or beyond the surf zone. Rip currents commonly form where variations in wave breaking create water-level gradients and may be focused by bars, channels, boundaries or estuary mouths.

Rock shore platform - A gently sloping or near-horizontal rock surface at the foot of a cliff, shaped by marine and subaerial processes and regularly affected by tides and waves.

RTK-GNSS or RTK-GPS - Real-time kinematic satellite positioning that applies correction data to obtain centimetre-scale survey coordinates. It is widely used for repeated beach-profile and topographic surveys.

Runup - The maximum vertical or landward extent reached by individual waves above the still-water level on a beach, barrier or structure.

S

Saline intrusion - The movement of seawater into a freshwater aquifer, gravel barrier or lagoon system, potentially changing groundwater and ecosystem conditions.

Satellite-Derived Shoreline (SDS) - A shoreline position extracted from satellite imagery, commonly using the instantaneous waterline and corrections for tide, wave setup, runup and beach slope.

Scandinavia pattern (SCAND) - A large-scale atmospheric pressure pattern centred on northern Europe that can influence the occurrence and direction of waves around the UK, particularly easterly wave conditions.

Sea-level pressure (SLP) - Atmospheric pressure adjusted to its equivalent value at mean sea level. Pressure differences and gradients are used to construct climate indices such as WEPA and NAO.

Sediment budget - An accounting of sediment entering, leaving and being stored within a defined coastal area over a stated period. A balanced budget has no net gain or loss of sediment.

Sediment connectivity - The degree to which sediment can move between beaches, dunes, nearshore stores, offshore areas and neighbouring embayments. Headlands and geology may restrict or permit this exchange.

Sediment-limited coast - A coast where the supply or thickness of mobile sediment is small relative to the capacity of waves and currents to transport it, so geology and sediment availability strongly constrain change.

Shoreface - The submerged, seaward-sloping part of the coastal profile across which waves and currents can move sediment. The active shoreface commonly extends to the depth of closure.

Shoreline - A selected line used to represent the boundary between land and sea. It may be defined by a waterline, a tidal datum, a contour or a morphological feature, so the definition should always be stated.

Shoreline Management Plan (SMP) - A strategic, non-statutory plan for managing flood and erosion risk around sections of the English and Welsh coast over the short, medium and long term.

Shoreline retreat or recession - Landward movement of a shoreline, dune front or cliff line over time. It may result from erosion, redistribution of sediment or long-term adjustment to sea-level rise.

Significant wave height (H_s) - A representative wave height approximately equal to the mean height of the highest one-third of waves in a record. It is the standard measure used to describe sea-state severity.

Storm impact regime - A category describing how waves interact with a beach or barrier as runup increases, for example swash confined to the beachface, overtopping of the crest, or full overwash and barrier change.

Storm surge - A temporary rise or fall in sea level caused mainly by atmospheric pressure and winds during a storm, additional to the predicted astronomical tide.

Subtidal zone - The part of the seabed that remains below water at low tide.

Supratidal zone - The part of the beach above normal high-tide levels, reached mainly by wave runup, spray or exceptional water levels.

Surf zone - The nearshore area between the main line of wave breaking and the shoreline, where broken waves, currents and turbulence dominate water motion.

Swash zone - The part of the beach alternately covered by the uprush and backwash of waves.

T

Teleconnection - A statistical or physical link between climate variability in widely separated regions, allowing large-scale atmospheric patterns to influence local weather, waves and coastal hazards.

Terrestrial Laser Scanning (TLS) - Ground-based LiDAR that rapidly measures dense three-dimensional point clouds of beaches, barriers or cliffs. Repeated scans can resolve small and rapid morphological changes.

Tidal datums - Standard reference levels derived from the tide, including Mean Sea Level (MSL), Mean High Water Springs (MHWS), Mean High Water Neaps (MHWN), Mean Low Water Neaps (MLWN) and Mean Low Water Springs (MLWS).

Total Water Level (TWL) - The combined elevation reached by the astronomical tide, storm surge and wave-induced contributions such as setup and runup. Its relationship to dune, barrier or defence elevation controls impact.

U

Uncrewed Aerial Vehicle (UAV) - A remotely operated or autonomous aircraft, commonly called a drone, used to collect imagery from which high-resolution coastal topography can be reconstructed.

V

Validation - Testing a calibrated model against observations that were not used to adjust it, to assess whether the model performs reliably under independent conditions.

W

Wave climate - The statistical character of waves at a location over months to decades, including wave height, period, direction, seasonality and the frequency of extreme conditions.

Wave Directionality Index (WDI) - An index describing the balance of wave energy arriving from opposing directional sectors. It is used in the book to relate directional wave climate to beach rotation.

Wave period - The time between successive wave crests. Longer-period waves generally carry more energy shoreward and can generate greater runup than shorter-period waves of similar height.

Wave power - The rate at which wave energy is transmitted per unit length of wave crest. It depends strongly on wave height and period and is commonly used as a measure of coastal forcing.

Wave refraction - The turning of waves as different parts of a wave crest enter different water depths, tending to align the crest with seabed contours and altering wave height and direction at the coast.

Wave setup - The increase in mean water level within and landward of the surf zone caused by wave breaking and the associated transfer of momentum.

Wave steepness - The ratio of wave height to wavelength. It influences the type of wave breaking, runup and the morphological response of beaches.

Wave transformation - The collective changes in wave height, direction, period and shape as waves move into shallower water through processes such as shoaling, refraction, breaking, friction and reflection.

West Europe Pressure Anomaly (WEPA) - A winter climate index based on the sea-level-pressure gradient between southwest Ireland and the Canary Islands. Positive WEPA conditions are associated with enhanced westerly storm waves along much of Atlantic western Europe.

X

XBeach-G - A gravel-beach version of the XBeach numerical model that represents waves, runup, groundwater, bedload transport and morphological change during storms, including overtopping and overwash.