Crossing the boundary: how key advancements to headland sediment bypassing improve definition of littoral cell zones

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Abstract

Headland sediment bypassing relates short-term physical forcing and long-term morphological response. The contributions from King et al., 2021 are a substantial step in understanding the complexities by using all three research approaches of field observations, process-based numerical modeling, and generalization with the development of an improved parametrization of headland sediment bypassing. This latest study adds to the growing body of knowledge around littoral cell boundaries, or as proposed in this commentary, littoral cell zones that recognize the importance of temporal variability and how this may influence shoreline position models. Anticipated climate change-induced evolution of the shoreline can be better understood with these additions.

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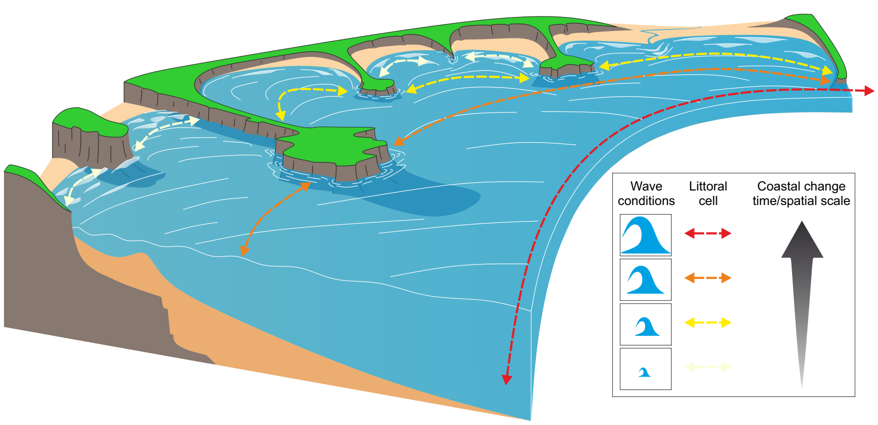

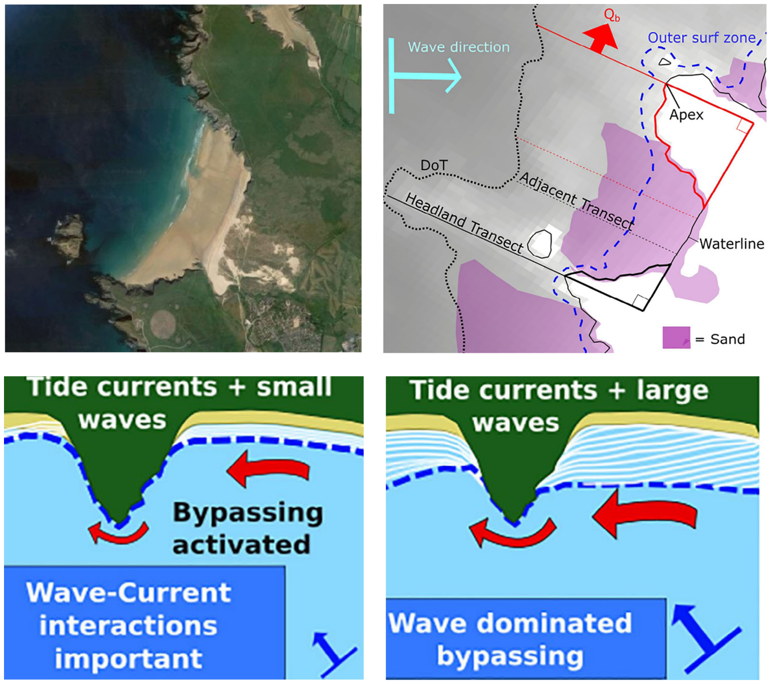
Wave direction
Q$_b$
Outer surf zone
Apex
DoT
Adjacent Transect
Headland Transect
Waterline
= Sand
Tide currents + small waves
Bypassing activated
Wave-Current interactions important
Tide currents + large waves
Wave dominated bypassing

Title

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Abstract

Headland sediment bypassing relates short-term physical forcing and long-term morphological response. The contributions from King et al., 2021 are a substantial step in understanding the complexities by using all three research approaches of field observations, process-based numerical modeling, and generalization with the development of an improved parametrization of headland sediment bypassing. This latest study adds to the growing body of knowledge around littoral cell boundaries, or as proposed in this commentary, littoral cell zones that recognize the importance of temporal variability and how this may influence shoreline position models. Anticipated climate change-induced evolution of the shoreline can be better understood with these additions.

Plain Language Summary

To better understand how our shorelines will change with sea level rise, we need to expand how we view sediment moving along the coast. An important step is using field research and computer models to create more knowledge about how rocky headlands affect sand and mud drifting in the coastal areas. The paper we write about provides a roadmap to do those types of studies about headlands. The next step is to think about regions of the coast that sediment pulses through instead of boxes that trap sediment.

Key Points

1. Headland sediment bypassing relates short-term physical forcing and long-term morphological response, which is vital for shoreline position.
2. The paper we comment on creates a useful guide to examine headland sediment bypassing and littoral cell boundaries.
3. The concept of littoral cell zones includes temporal variability and anticipated climate change-induced evolution of the shoreline.

Body

1. Background

Along rocky shorelines, physical and geological processes together play strong roles in shaping and responding to coastal geomorphology. One example is headland sediment bypassing, defined as the connectivity between adjacent embayments by sediment migration around the headland from the updrift to the downdrift beach compartments (Klein et al., 2020). Headland sediment bypassing, therefore, is a critical component to understand coastal processes across the full beach profile (i.e., backbeach to nearshore beyond the surf zone). The primary parameters that affect bypassing include geomorphology (headland size, shape, orientation, offshore bathymetry) (George et al., 2015), physical forces (waves, tides, currents) (Veira da Silva et al., 2018), and sediment (availability, grain characteristics) (George et al 2015; George et al 2019). Bypassing is also an important process in sandy environments where, for example, sand can bypass coastal structures or inlets and influence beach and barrier island morphology (Fitzgerald et al. 1984) since bypassing influences sediment availability (Ciarletta et al., 2021). Temporal and spatial variability across all of these adds a transient element into bypassing, also characterized as "leaky" boundary (Davies, 1974; van Rijn, 2010). The transient bypassing can be episodic as when sediment accumulates to a critical volume to trigger a bypassing event (Battalio, 2014), on a seasonal basis when dominant wave direction shifts (Short, 1999), or even on multi-year to multi-decadal timescales in relation with climate patterns of atmospheric variability (da Silva et al., 2021). Quantifying the net transport rate and the leakiness caused by a rocky headland is critical when that headland is used as a littoral cell boundary, which will be discussed later in this commentary.

The complexity of headland sediment bypassing is in need of deeper understanding and is an active area of research, especially related to how temporal variability translates between short-term physical forcing and long-term morphological response. With improved understanding, more sustainable coastal engineering and climate change adaptation techniques can be developed that rely upon minimizing headland sediment bypassing for longevity (e.g., beach nourishment). Interest in this topic has grown rapidly since the mid-2010s. Klein et al. (2020) identified 100 studies published since 2014 that investigated either subaqueous or subaerial transport pathways, or both, through field, modeling, or theoretical approaches resulting in the development of conceptual models of headland sand bypassing (for comparison there were only 59 studies between 1943 and 2014). Each of these approaches present benefits and drawbacks and for a more comprehensive discussion, see Klein et al., 2020. In summary, the dynamic nature of the ocean around headlands creates extremely challenging conditions for observations, especially at the apex where rapidly changing bathymetry and exposed hard substrates become dangerous for instrument deployment and recovery. Consequently, process-based modelling approaches have tried to address field observational study gaps, ultimately to develop parametric expressions of headland sand bypassing quantities (e.g. McCarroll et al., 2021). Such empirical or semi-empirical expressions provide unification and generalization of concepts. However, their calibration and validation require reliable field measurements while concurrently, simplifying essential longshore transport processes. Hence, all three approaches are needed to develop the nuanced understanding of headland sediment bypassing.

Given the rapid expansion of research, gaps are being identified and addressed with each new contribution. Assuming the primary parameters presented above (geomorphology, physical forces, and sediment) are sufficiently broad to incorporate most areas for improvement, substantial focus has been placed on hydrodynamics and their interactions with the physical shape of a headland (e.g. Mouragues et al., 2021). Lesser attention has been given to geological controls, such as erosional differences leading to reefing structures, or resolving dynamics at headland apexes in the field. Additionally, multi-approach studies (e.g., field-modeling or modeling-theoretical) can amplify disadvantages of the individual approach if not constrained appropriately. Hence, place-based studies that build from field observations to numerical modeling and then generalization are welcome additions to refining headland sediment bypassing understanding.

1. Contributions from King et al., 2021

Given this context, King et al., 2021 is a substantial step in understanding headland sediment bypassing. The authors build on several threads described above, primarily in the physical forcings topic while utilizing all three research approaches of field observations (at 29 headlands in the United Kingdom), process-based numerical modeling, and generalization with the development of an improved parametrization of headland sand bypassing that also includes headland toe depth and sand coverage. In their own words, "this study tested the influence of wave, tide and morphological controls on instantaneous headland sand bypassing using a coupled wave-tide numerical model, and tested the performance of an existing parameterization when applied to realistic headland morphologies and sediment coverage." The exploration of the combined wave and tide forces refine the nuances for how tidal currents are a significant factor in some locations under particular wave conditions but not others (Figure 1). The variation from micro- to macro-tidal environments is important to properly apply sediment bypassing parameters. King et al. (2021) explore this variability in the context of changing wave conditions for a macrotidal environment and delineate significant wave height thresholds that trigger non-linear wave-current interactions.

One of the most substantial scientific contributions from King et al. (2021) is the refinement of the relationship between morphology, surf zone width, and availability of sediment. The authors develop thresholds based around parameters that can be derived from aerial imagery, wave records, bathymetry, and sediment maps. The suite of equations describing headland sediment bypassing rates establish a set of relationships that are responsive to changing conditions. For example, surf zone width varies throughout the year so the ratio between width and headland length must be dynamic to accurately characterize bypassing. King et al (2021) present that option within the suite of equations. Similarly, the amount of sediment available may fluctuate, which would be resolved by sediment maps from different periods. The suite of equations allows for spatially and temporally varying sediment deposits. Taken together, these thresholds provide a new and hopefully more universal approach to predict sediment bypassing rates around headlands that acknowledge the potential for leaky boundaries.

King et al. (2021) also provide a very practical, and important, 4-step guidance for analytically modeling shoreline change that uses the suite of headland sediment bypassing equations. The steps involve quantifying morphometric parameters (e.g., beach orientation, headland dimensions, headland underwater toe depth, sediment availability), transforming waves from offshore to breakpoint, estimating longshore flux, and applying the bypassing formulations. The elegance of this guide frees coastal science practitioners and managers from computationally expensive process-based models. If a numerical model is available for a location or stretch of coastline containing many headlands, the analytical model results can be cross-checked for the degree of agreement. Alternatively, if observational data from the field is available, it too could be cross-checked with the analytical model results. These cross-checks can bracket the results with robust statistical boundaries and create downscaled model results with high degrees of confidence. Such future work will be important to verify the validity of the equations in a wide range of coastal environments where there are limits to sediment availability. Even without those opportunities, however, the guidance is important to expand where headland sediment bypassing rates have yet to be estimated.

1. Future Research Considerations for Headlands and Littoral Cells

Quantifying headland sediment bypassing is an essential component to defining littoral cells. A littoral cell is defined as an alongshore region in which sand is retained and recirculated without alongshore export (Rosati, 2005). Implicit to this definition are blockages in the cross-shore direction, which have typically been associated with headlands. As the dozens of studies reviewed in Klein et al 2020 indicate, headlands should not be assumed to successfully block alongshore transport. Littoral cell boundaries at headlands could evolve as wave energy and incident angles fluctuate resulting in substantial changes to beaches and shoreline geomorphology (George, et al 2019). Stul et al. (2012) described littoral cells as tiered according to primary, secondary, and tertiary levels along the coast of Western Australia with sediment exchange possible among the lower levels, especially on a seasonal basis. The nuanced conclusions of the Australia studies contrasts with the extensive work on littoral cells along the coast of southern England that implies static boundaries dependent on headlands (New Forest District Council, 2017). The King et al. (2021) study provides additional support for revisiting the usefulness of headlands as littoral cell boundaries, and therefore is relevant to understanding morphological changes at many other coastal regions around the world.

Littoral cell “boundaries” should therefore be presented as more fluid and dynamic “zones” with allowances for sediment grain sizes, seasonality of physical forces, and exclusivity, which is a measure of the amount of connectedness to other cells. The littoral cells therefore should be viewed as variable in size and shape as a function of the wave conditions, and thus change sediment transport pathways. Conceptually, this would be represented as Figure 2, with wave conditions driving the variable scales of the littoral cell zone. As conditions exceed low-level thresholds, the small zones would merge into medium-sized zones. Subsequently, larger wave conditions would amalgamate medium-sized zones into more expansive zones that would activate transport across usually isolated embayments. The frequency of these events could be predicted using wave climate records and the King et al. (2021) relationships, in particular the width of the surf zone to identify when a headland loses the ability to block alongshore transport. Incorporating variable sediment grain size would set expectations for target locations to maximize longevity of beach nourishment or dredge material placement activities. Arguably, the zonal approach departs from the visually simpler boundary approach. However, the zonal approach better reflects the current understanding of headland sediment bypassing.

The zonal approach still relies upon understanding headland sediment bypassing and therefore additional research is needed. Some recommended lines of inquiry that would refine the conceptual model include examining the influence of islands and reef structures, parameterizing connectivity on and between compound headlands (e.g., a large peninsula consisting of a variety of headlands), the influence of the configuration and orientation of the adjacent embayments, improving field observations of seasonality and episodic events, and testing the King et al. (2021) suite of equations in other locations with extensive data (e.g., California, USA, or Western Australia). This last recommendation would demonstrate applicability and by extension, offer insight on how to best develop littoral cell zones for different coastal segments. As acknowledged by King et al. (2021), generic headland sand bypassing parameterizations are important to improve hybrid shoreline models. Such one-line shorelines often do not include headland bypassing, or at best in a too simplistic way (Roelvink et al., 2020). It has been shown with such models that frequency and degree of headland sand bypassing can control both time-averaged embayment planshape and beach rotation patterns (Castelle et al., 2020). Including such parameterization in state-of-the-art hybrid shoreline models will allow simulating coastal embayments on short to long timescales, including the effect of climate change, where intensity and frequency of headland bypassing events will change in time, ultimately switching off and on new embayment connectivity. In addition, bypassing is a process that can govern large-scale coastal change during extreme events (e.g., Sherwood et al., 2021) and should be evaluated using process-based morphological models over a range of scales and conditions.

Overall, using littoral cell zones begins to shift toward better connecting coastal planning units to natural divergence zones. The benefit of this maximizes natural processes for sustainable coastal engineering, regional sediment management, and ecosystem restoration. Linking littoral cells to future beach conditions and shoreline positions under climate change scenarios is essential to minimize damages to communities and habitats, at least over the next several decades. Eventually sea level rise will alter coastal geomorphology by submergence, with headland sediment bypassing continuing to be an integral part of coastal processes. Understanding it now may provide tools, similar to the ones developed by King et al. (2021), to develop resilience for the future.

Figure 1. Sand bypassing rocky headlands with excerpts from the study of King et al. (2021): top left - headlands and beaches at Holywell Bay in the Cornwall region of the UK; top right - schematization of an embayment with headland apex transects and adjacent beach transects; bottom row - selected key findings related to instantaneous headland bypassing for different wave conditions with red arrows indicating simplified sand transport pathways and blue dashed line indicating the outer limit of the surf zone (see King et al. (2021) for details).

Figure 2. Conceptual diagram of littoral cell zone expansion and sediment pathways along a series of coastal embayments. Littoral cell zones merge and increase in size with increasing incident wave energy as sand bypassing progressively activates off the longer headlands.

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