JGR Oceans

COMMENTARY

10.1029/2021JC018269

Key Points:

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

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Citation:

George, D. A., Castelle, B., & Mulligan, R. P. (2022). Crossing the boundaries: How key advancements in understanding of headland sediment bypassing improves definition of littoral cells. *Journal of Geophysical Research: Oceans*, *127*, e2021JC018269. https://doi.org/10.1029/2021JC018269

Received 22 NOV 2021
Accepted 15 AUG 2022

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Crossing the Boundaries: How Key Advancements in Understanding of Headland Sediment Bypassing Improves Definition of Littoral Cells

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Abstract Headland sediment bypassing connects short-term physical forcing and long-term morphological response. The contributions from King et al., 2021, https://doi.org/10.1029/2020JC017053 are a substantial step in understanding the complexities by combining field observations, process-based numerical modeling, and empirical generalization with the development of an improved parametrization of headland sediment bypassing. This study adds to the growing body of knowledge about littoral cell boundaries, or as proposed in this commentary, littoral cells that respond to varying wave energy and water levels that may influence the results from shoreline change models. Evolution of the shoreline in the context of climate change can be better understood by considering variability in littoral cell boundaries.

Plain Language Summary To better understand how shorelines will change with sea level rise and more storms, we need to widen how we view sediment moving along the coast. An important step involves using field research and computer models to improve our knowledge about how rocky headlands affect sand and mud moving in the coastal areas. The paper we write about provides a roadmap to do those types of studies about sediment movement around headlands. The next step is to consider changes to the size and shape of regions of the coast that sediment pulses through instead of boxes that trap sediment.

1. Background

Along rocky shorelines with embayed beaches, physical and geological processes together play key roles in shaping and responding to coastal geomorphology. One example is headland sediment bypassing, defined as the sediment connectivity between adjacent embayments driven by sediment migration around the headland from the updrift to the downdrift beach compartments (Klein et al., 2020). Therefore, headland sediment bypassing is a critical component to understand coastal processes across the full beach system (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) (Vieira da silva et al., 2018), and sediment (availability, grain characteristics) (George et al., 2015, 2019; Goodwin et al., 2013). 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 driving the development of a “leaky” boundary (Davies, 1974; van Rijn, 2010). The bypassing can be episodic as when sediment accumulates to a critical volume to trigger a bypassing event (Battalio, 2014; Goodwin et al., 2013), 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 associated with a rocky headland is critical when that headland is used as a littoral cell boundary, which will be discussed in this commentary.

The complexity of headland sediment bypassing needs deeper understanding, especially how temporal variability relates short-term physical forcing and long-term morphological response. With improved understanding, more sustainable coastal engineering and climate change adaptation techniques can be developed using headland sediment bypassing knowledge for longevity of investments in regional sediment management (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 (a) field (direct and remote sensing), (b) modeling, or (c) 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 presents 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 modeling 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 the opportunity to unify and generalize concepts, if desired. However, their calibration and validation require reliable field measurements while concurrently, simplifying essential longshore transport processes. Hence, all three approaches are needed to develop a more comprehensive and 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., 2020). Lesser attention has been given to geological controls, such as erosional differences leading to geomorphic structures (e.g., exposed bedrock), or resolving dynamics at headland apexes in the field. Additionally, multi-approach studies (e.g., field-modeling or modeling-theoretical) can amplify limitations of the individual approach if not constrained appropriately, for example, by incorrect calibration of model parameters. Hence, place-based studies that build from field observations to numerical modeling and then generalization are welcome additions to refining headland sediment bypassing understanding.

2. Contributions From King et al., 2021

Given this context, King et al., 2021 is a substantial step forward in understanding headland sediment bypassing. The authors build on several threads described above, primarily in the physical forcing topic, while utilizing all three research approaches of field observations, process-based numerical modeling, and generalization with the development of an improved parametrization of headland sand bypassing that also includes headland toe depth and areal sand coverage for 29 headlands in the United Kingdom. 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. The variation in tidal range from micro-to macro-tidal environments affecting currents 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 surficial sediment deposits. Taken together, these thresholds provide a new and more general approach to predict sediment bypassing rates around headlands that also incorporates the potential for leaky boundaries.

King et al. (2021) also provide a very practical, and important, four-step guidance for analytically assessing headland sediment bypassing with implications for modeling shoreline change. 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 enables coastal science practitioners and managers to rely less on 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 are important to constrain the analytical model results. 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 and/or absence of high-resolution observational datasets. Additional important validations include analyzing parametrization results from headlands with varying dimensions (specifically width) and shoreline complexity. There are likely more complications for much wider and/or complex coastal configurations than the proposed parametrization may account for. Even without those opportunities, however, the guidance is important to expand where headland sediment bypassing rates have yet to be estimated.

3. 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, however, 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. Subsequent work expanded these delineations to the coast of Australia (Short, 2020; Thom et al., 2018) with Kinsela et al. (2017) providing high-resolution tertiary level maps for the state of New South Wales. The nuanced conclusions of the studies in Australia contrast 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 in many other coastal regions around the world.

Littoral cells should therefore be presented as more dynamic regions with variable boundaries that have allowances for sediment grain sizes, seasonality of physical forces, and exclusivity, which is a measure of the amount of connectedness to other cells (Davies, 1974). The littoral cells therefore should be viewed as variable in size and shape as a function of the wave conditions which affect the sediment transport pathways. Conceptually, this would be represented as Figure 1, with wave conditions driving the variable scales of the littoral cell. As conditions exceed low-level thresholds, the smaller cells would merge into medium-sized cells. Subsequently, larger wave conditions would push littoral cell boundaries offshore causing the amalgamation of medium-sized cells into more expansive regions that would activate transport across usually isolated embayments. The frequency of these events could be predicted using wave climate records and the magnitude of the sediment bypassing estimated using 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. While the regional approach departs from the visually simpler boundary approach, it better reflects the current understanding of headland sediment bypassing, including development and practice of tiered zones (Kinsela et al., 2017; Thom et al., 2018).

The regional approach still relies upon understanding headland sediment bypassing and therefore additional research is needed. Some recommended lines of inquiry to refine the conceptual model include examining the influence of islands and reef structures, considering the volume of available sediment (or thickness of sediment deposits from seafloor surface to a basement depth), parameterizing connectivity on and between compound headlands (e.g., a large peninsula consisting of a variety of headlands), studying the influence of the configuration and orientation of the adjacent embayments, improving field observations of seasonality and episodic events, investigating the criticality of understanding shoreface sediment pathways, and testing the King et al. (2021) suite of equations in other locations with extensive data (e.g., California, USA, or Australia). This last recommendation would demonstrate applicability and by extension, offer insight on how to best develop littoral cell boundaries for different coastal segments. As acknowledged by King et al. (2021), generic headland sand bypassing parameterizations are important to improve hybrid shoreline models. Such models often do not include headland bypassing,

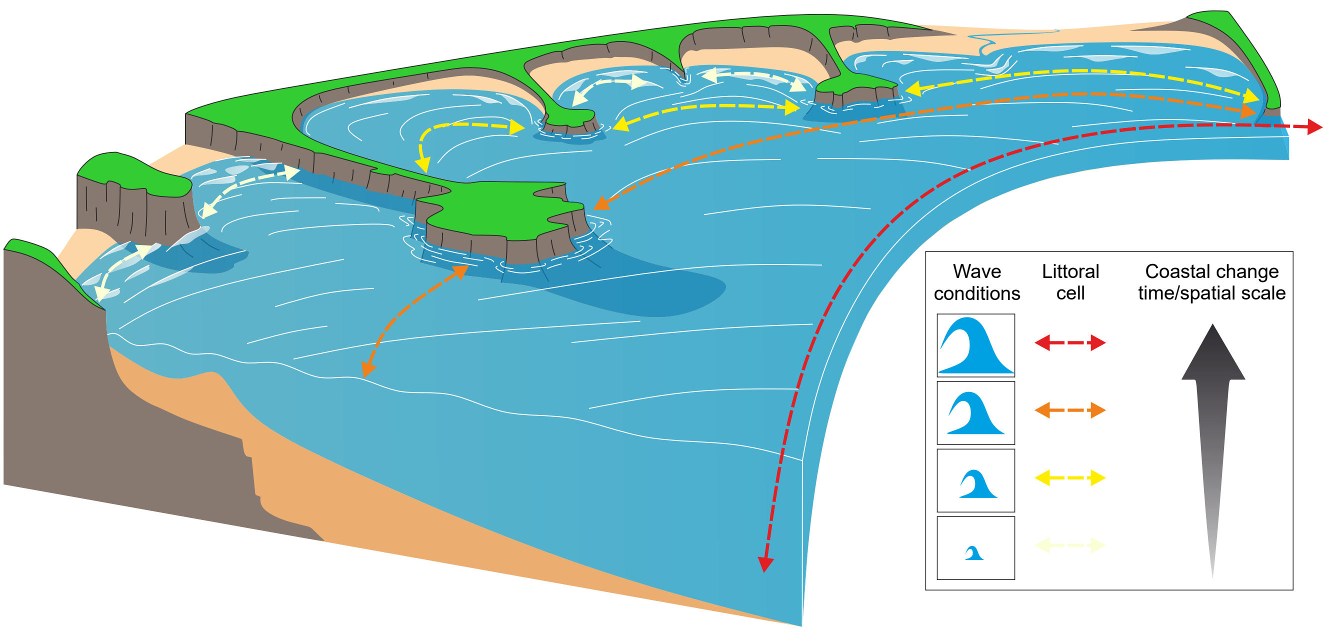

Figure 1. Conceptual diagram of littoral cell boundary expansion and sediment pathways along a series of coastal embayments. Littoral cells merge and increase in size during periods with increased incident wave energy. Headland sediment bypassing progressively activates over a larger region when boundaries expand offshore past the longer headlands.

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 cells as a basis for coastal planning units better connects natural processes to coastal management. One benefit of this approach is to better incorporate 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 and attendant erosion but headland sediment bypassing will continue to be a feature 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.

Data Availability Statement

No new data were used in producing this manuscript.

Acknowledgments
The authors thank Mike Kinsela, Carlos Loureiro, and an anonymous reviewer for comments that improved the manuscript.

References

Battalio, B. (2014). Littoral processes along the Pacific and bay shores of San Francisco, California, USA. *Shore and Beach*, *82*, 3–21.

Castelle, B., Robinet, A., Idier, D., & D'Anna, M. (2020). Modelling of embayed beach equilibrium planform and rotation signal. *Geomorphology*, *369*, 107367. https://doi.org/10.1016/j.geomorph.2020.107367

Ciarletta, D. J., Miselis, J. L., Shawler, J. L., & Hein, C. J. (2021). Quantifying thresholds of barrier geomorphic change in a cross-shore sediment-partitioning model. *Earth Surface Dynamics*, *9*(2), 183–203. https://doi.org/10.5194/esurf-9-183-2021

Da Silva, A. P., Vieira da Silva, G., Strauss, D., Murray, T., Woortmanna, L. G., Taber, J., et al. (2021). Headland bypassing timescales: Processes and driving forces. *Science of the Total Environment*, *793*, 148591. https://doi.org/10.1016/j.scitotenv.2021.148591

Davies, J. L. (1974). The coastal sediment compartment. *Australian Geographical Studies*, *12*, 139–151. https://doi.org/10.1111/j.1467-8470.1974.tb00270.x

Fitzgerald, D. M., Penland, S., & Nummedal, D. A. G. (1984). Control of barrier island shape by inlet sediment bypassing: East Frisian Islands, West Germany. *Marine Geology*, *60*(1–4), 355–376. https://doi.org/10.1016/s0070-4571(08)70154-7

George, D. A., Largier, J. L., Pasternack, G. B., Barnard, P. L., Storlazzi, C. D., & Erikson, L. H. (2019). Modelling sediment bypassing around idealized rocky headlands. *Journal of Marine Science and Engineering*, *7*(40), 40. https://doi.org/10.3390/jmse7020040

George, D. A., Largier, J. L., Storlazzi, C. D., & Barnard, P. L. (2015). Classification of rocky headlands in California with relevance to littoral cell boundary delineation. *Marine Geology*, *369*, 137–152. https://doi.org/10.1016/j.margeo.2015.08.010

Goodwin, I. D., Freeman, R., & Blackmore, K. (2013). An insight into headland sand bypassing and wave climate variability from shoreface bathymetric change at Byron Bay, New South Wales, Australia. *Marine Geology*, *341*, 29–45. https://doi.org/10.1016/j.margeo.2013.05.005

King, E. V., Conley, D. C., Masselink, G., Leonardi, N., McCarroll, R. J., Scott, T., & Valiente, N. G. (2021). Wave, tide and topographical controls on headland sand bypassing. *Journal of Geophysical Research: Oceans*, *126*, e2020JC017053. https://doi.org/10.1029/2020JC017053

Kinsela, M. A., Morris, B. D., Linklater, M., & Hanslow, D. J. (2017). Second-pass assessment of potential exposure to shoreline change in New South Wales, Australia, using a sediment compartments framework. *Journal of Marine Science and Engineering*, *5*(4), 61. https://doi.org/10.3390/jmse5040061

Klein, A. H. F., Vieira da Silva, G., Taborda, R., da Silva, A. P., & Short, A. D. (2020). Headland bypassing and overpassing: Form, processes and applications. In D. Jackson, & A. Short (Eds.), *Sandy beach morphodynamics* (pp. 557–591). Elsevier. https://doi.org/10.1016/b978-0-08-102927-5.00023-0

McCarroll, R. J., Masselink, G., Valiente, N. G., King, E. V., Scott, T., Stokes, C., & Wiggins, M. (2021). An XBeach derived parametric expression for headland bypassing. *Coastal Engineering*, *165*, 103860. https://doi.org/10.1016/j.coastaleng.2021.103860

Mouragues, A., Bonneton, P., Castelle, B., Marieu, V., McCarroll, R. J., Rodriguez-Padilla, I., et al. (2020). High-energy surf zone currents and headland rips at a geologically constrained mesotidal beach. *Journal of Geophysical Research: Oceans*, *125*, e2020JC016259. https://doi.org/10.1029/2020jc016259

New Forest District Council. (2017). 2012 Update of Carter, D., Bray, M., & Hooke, J. 2004 SCOPAC Sediment Transport Study. Retrieved from www.scopac.org.uk/sts

Roelvink, D., Huisman, B., Elghandour, A., Ghonim, M., & Reyns, J. (2020). Efficient modeling of complex sandy coastal evolution at monthly to century time scales. *Frontiers in Marine Science*, *7*, 535. https://doi.org/10.3389/fmars.2020.00535

Rosati, J. D. (2005). Concepts in sediment budgets. *Journal of Coastal Research*, *21*, 307–322. https://doi.org/10.2112/02-475a.1

Sherwood, C. R., Dongeren, A. V., Doyle, J., Hegermiller, C. A., Hsu, T. J., Kalra, T. S., et al. (2021). Modeling the morphodynamics of coastal responses to extreme events: What shape are we in? *Annual Review of Marine Science*, *14*, 457–492.

Short, A. D. (1999). *Handbook of beach and shoreface morphodynamics*. NewYork: John Wiley.

Short, A. D. (2020). Australian coastal systems: Beaches, barriers and sediment compartments. *Coastal Research Library* (Vol. 32). Springer. https://doi.org/10.1007/978-3-030-14294-0

Stul, T., Gozzard, J., Eliot, I., & Eliot, M. (2012). Coastal sediment cells between cape naturaliste and the Moore river, Western Australia. Report prepared by Damara WA Pty Ltd and Geological Survey of Western Australia for the Western Australian Department of Transport, Fremantle (p. 44).

Thom, B. G., Eliot, I., Eliot, M., Harvey, N., Rissik, D., Sharples, C., et al. (2018). National sediment compartment framework for Australian coastal management. *Ocean & Coastal Management*, *154*, 103–120. https://doi.org/10.1016/j.ocecoaman.2018.01.001

van Rijn, L. C. (2010). *Coastal erosion control based on the concept of sediment cells* (p. 80). The NetherlandsConscience Deltares.

Vieira da Silva, G., Toldo, E. E., Jr., Klein, A. H. F., & Short, A. D. (2018). The influence of wave-wind- and tide-forced currents on headland sand bypassing – Study case: Santa CatarinaIsland North Shore, Brazil. *Geomorphology*, *312*, 1–11. https://doi.org/10.1016/j.geomorph.2018.03.026